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Towards a methodology to include building energy simulation uncertainty in the Life Cycle Cost analysis of rehabilitation alternatives

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ABSTRACT

The selection of the best alternative for building rehabilitation should involve LCC analysis to account for all the costs involved. A significant part of those costs relates to energy consumption, which can only be assessed with an intrinsic level of uncertainty. This work proposes an integrated methodology that can quantify and integrate that uncertainty in LCC estimation. The methodology relies on Monte Carlo simulation to calculate statistical distributions of energy demand. The associated costs can then be introduced in an LCC analysis and provide decision makers with a measure of rehabilitation alternatives economic impact uncertainty. The paper describes the methodology and applies it to an example case. The results are mainly intended to illustrate the methodology application and pinpoint key aspects such as input data pre-processing, convergence analysis, and adequate economic measures. The methodology is not ready for a generalized application as reliable stochastic input data are not frequently available yet. Nevertheless, the results found in this work showed how this approach can influence decisions if the robustness of each alternative is known.

1. Introduction

Energy conservation projects are expected to reduce the annual energy consumption and the long-run operational costs of a building. Therefore, measuring/estimating buildings energy demand is essential. These estimates can be based on computer simulations using a dynamic energy simulation software. These tools are fundamental for building designers and constitute an added value for both new construction and building retrofit projects. Traditionally, buildings energy simulation requires the definition of a set of input parameters, which are handled according to more or less complex mathematical models generating a final deterministic result. These input parameters can be found in national regulations, guidelines or standards, and is common to get different recommendations depending on the consulted document. Thus, this methodology, although its simplicity, does not consider the stochastic nature of the input parameters, and, accordingly, the obtained simulation results might be far from reproducing the real performance of buildings, directly affecting the consequent economic evaluation of the building energy conservation projects. Hence, if one intends to evaluate the uncertainty in economic evaluation of project alternatives due to the variability in the definition of the input parameters (e.g. building energy consumption), stochastic methods, such as Monte Carlo simulations should be employed. The measure of uncertainty is critical for the appraisal of a project's economic robustness. With a sound methodology using reliable data, a decision maker may be lead to the selection of an alternative that, although presenting a higher mean Life Cycle Cost (LCC) is less influenced by the project's variability.

LCC analysis is an economic method of project evaluation in which all costs arising from owning, operating and maintaining are considered to be potentially important. The required input data for the method include present and future costs, a discount rate and a study period. With the same set of input data it is also possible to calculate supplementary measures of economic performance such as the Savings-to-Investment Ratio (*SIR*) that expresses the relationship between savings and increased investment cost (present value) as a ratio. Building energy conservation projects provide excellent examples for the application of LCC analysis, since there are abundant opportunities for improving the thermal performance of building envelope components in both new and existing buildings [1].

Over the past few years, there has been a growing interest among researchers [2] and consultants in uncertainty analysis applied to building related problems [3]. Some try to quantify uncertainty in predicting buildings energy consumption [4] by applying random conditions to determine the dynamic thermal

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response of a building with an arbitrary number of loads and zones. Others focus on including a probabilistic approach in a model developed to analyze the energy performance of buildings at urban scale, identifying the main parameters affecting energy consumption in a particular building sector and using that information to quantify the relative benefits of alternative energy saving measures with requisite quantification of uncertainties [5].

The influence of the climate change on the energy efficiency of light-weight steel residential buildings was assessed by Santos et al. [6] using advanced dynamic simulation of the operational energy performance.

Hopfe and Hensen [7] studied the integration of uncertainty analysis into building performance simulation. An office building was used as case study and uncertainty analysis was carried out to highlight its implications for the simulation results and associated performance parameters concerning energy consumption and thermal comfort. Building energy simulation uncertainty was also tested by Calleja Rodríguez et al. [8]. In this study, a methodology using a detailed model of the building, defining and propagating uncertainties of input parameters, calculating macroparameters that characterize the building and getting sensitivity indices was proposed. A dwelling was used as case study and climate and occupancy were found to be the most important input parameters for energy consumption.

Uncertainty can also affect the Life Cycle Assessment (LCA) of building materials. Cellura et al. [9] analyzed the impact of several uncertainty sources on LCA of Italian tiles. The authors identified the most relevant sources of uncertainty and then performed a sensitivity analysis. Results revealed that, in some cases, significant differences in the energy and environmental indices can be obtained. Hoxha et al. [10] tested a method to identify the sensitivity and robustness of LCA models to uncertainties related to building materials. The idea was to use this information in the assessment of building environmental performance calculation. Zheng et al. [11] tested a fuzzy analytic hierarchical process method applied to LCA for building energy conservation evaluation.

LCC and uncertainty were combined in building related problems, namely for building components performance assessment and for risk management of building projects. Zhu at al. [12] analyzed the performance of a ground source heat pump using deterministic and probabilistic LCC analysis. Differences between the two approaches became clear as the payback time was estimated to be 15 years using the deterministic method and 12 years using the probabilistic method. Risk management of public private partnerships and private financial initiative projects was studied by Wang et al. [13]. Monte Carlo simulation was used and a school project was chosen as case study. The results identified high risk in life cycle assumptions providing decision-makers with crucial information to define risk in building management.

An attempt to combine building simulation and economic analysis was made by Burhenne et al. [14]. A methodology based on Monte Carlo method that combines building simulation with cost–benefit analysis was proposed and evaluated. According to the authors this method helps to enhance the design process and supports related decision-making.

Although the research described above demonstrates the relevance of the subject, little work was found regarding the effect of uncertainty in combining building simulation with LCC analysis. In this paper, a school building energy conservation project constitutes an example case where the opportunities and difficulties of the method are explored. Initially, a methodology for the stochastic simulation of school buildings for tackling input data uncertainty is presented. A school building model was simulated with EnergyPlus [15] and five input parameters were considered as variables with an associated uncertainty, namely: occupation, metabolic rate, lighting, ventilation and envelope thermal resistance. The parameters' uncertainty was defined by a mean value and a standard deviation and a normal distribution was considered. The Monte Carlo simulations were performed for 25, 50, 100, 200 and 500 cases, generated with Latin Hypercube Sampling, with the purpose of analyzing the convergence of the results. The procedure for implementing a manageable simulation is explained and the sensitivity analysis of the results is performed. The simulation output (school building heat demand) is then used as a stochastic input on the economic evaluation of an energy conservation project: the cost effectiveness of the windows replacement.

The following sections of this paper are organized as follows: a description of the methodology, including details of the Monte Carlo simulation and the LCC analysis, the simulation results, the effect of uncertainty in the LCC analysis and the main conclusions of the research.

2. Methodology

2.1. Monte Carlo simulation

Monte Carlo simulation has been widely used in engineering and science researches and uses computing power to explore all of the possible outcomes to a problem given certain bounds of variability expressed in the model. Furthermore the impacts of input variables can be measured by sensitivity analysis [13]. This method propagates simulation cases within probability range of selected uncertain inputs, performing the respective simulation runs. A careful choice of uncertain input characteristics is crucial for the final result [16].

Monte Carlo simulations are, therefore, based on a sequence of random numbers derived from the initial input variables, from which probabilistic distributions are known or can be estimated. Thus, for each of the i input parameters analyzed ($X_1, X_2, \ldots, X_i$) a set of N random numbers is generated, in accordance with the initially assumed probability distributions. Simulations are performed and for output Y, N results will be obtained ($Y_1, Y_2, \ldots, Y_N$).

The accuracy of the methodology depends on the number of simulations performed. However, no consensual rule exists to define the sample dimension. Sensitivity studies that address this issue can be found in Macdonald [17] and Burhenne et al. [14]. Understandably, the complexity and number of input parameters considered in the analysis are key factors to establish reliable sets of input data.

When the input parameters and sample dimension are defined, the following step is to use a sampling technique to generate the random numbers. In this research Latin Hypercube Sampling (LHS) method was chosen since it provides good convergence of parameter space with relatively few samples compared to the simple random sampling. This method is a form of stratified sampling since it divides the input into strata and then generates samples so that the value generated for each parameter comes from a different stratum [18].

Lomas and Eppel [19] compared Monte Carlo method with other sensitivity analysis techniques for the special case of building thermal simulation. The applicability of the methods to simple programs was considered and uncertainty was introduced into 70 input parameters. Monte Carlo method arises as the best performant technique. The accuracy of Monte Carlo method was also tested by Macdonald and Strachan [20].

2.2. Life Cycle Cost analysis

LCC allows one to organize and compute the costs of acquiring, owning, operating and ultimately disposing a building or a