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Towards an integrated computational method to determine internal spaces for optimum environmental conditions

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ABSTRACT

Computational Fluid Dynamics tools and Response Surface Methodology optimization techniques were coupled for the evaluation of an optimum window opening design that improves the ventilation efficiency in a naturally-ventilated building. The multi-variable optimization problem was based on Design of Experiments analysis and the Central Composite Design method for the sampling process and estimation of quadratic models for the response variables. The Screening optimization method was used for the generation of the optimal design solution. The generated results indicated a good performance of the estimated response surface revealing the strength correlations between the parameters. Window width was found to have greater impact on the flow rate values with correlation coefficient of 73.62%, in comparison to the standard deviation 55.68%, where the window height prevails with correlation coefficient of 96.94% and 12.35% for the flow rate. The CFD results were validated against wind tunnel experiments and the optimization solution was verified with simulation runs, proving the accuracy of the methodology followed, which is applicable to numerous environmental design problems.

1. Introduction

A successful building design improves the quality of life and facilitates the functional needs of the users. However, the achievement of acceptable design solutions presupposes the contribution of rational multidisciplinary decisions [1]. An important and mandatory step prior to every engineering solution is the conceptual design phase that tends to establish the holistic integrity of the design. The development of software tools has facilitated the decision-making process, by offering the opportunity to evaluate the performance and efficiency of the initial design concept under numerous objective parameters during the conceptual design phase.

Computational Fluid Dynamics (CFD) software is used to perform multiple types of analysis, regarding a rational approach to design investigation that enables the simulation of air flow and prediction of physical phenomena within building spaces [2]. This technique has been adopted by numerous researchers, to study the thermal comfort of occupants in buildings [3], the positioning of building services [4], natural ventilation [5], heat transfer effects [6], contaminant dispersion [7] and the interaction between indoor and outdoor environments [8].

This study presents an integrated computational method to optimise design spaces in the built environment. The work is based on simulation-driven optimisation techniques, using a CFD simulation software integrated with Response Surface Methodology-based design optimisation algorithms and validated against wind tunnel experiments. The method is applied to a generic cross-ventilated building structure to investigate natural ventilation efficiency. Since 1992 [9] up to present [10], studies on cross-ventilated buildings have been performed using CFD techniques and validated with real scale measurements, wind tunnel experiments and flow visualization methods [11]. However, the increasing need for adopting integrated design solutions demands further information beyond what it is offered by the investigation of the naturally occurring wind flow in buildings, and it is this research gap under investigation here.

2. Previous related work

Stavrakakis et al. [12] investigated the optimum window-opening configuration, to improve the indoor thermal comfort in a naturally-ventilated building (NVB). Using a coupled CFD-ANN (Artificial Neutral Network) technique that enabled the evaluation of 126 data pairs to minimise discomfort for 3 different activity levels. On the investigation of the influential behaviour of the air speed and direction towards the ventilation rates in NVB, Shen et al. (2012) combined CFD and Response Surface Methodology (RSM) optimization techniques. They evaluated different De-

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sign of Experiment (DoE) methods for the generation of experimental models in a stand-alone software. The obtained results were validated with CFD simulation cases.

In a more recent study, Shen et al. [13] assessed the performance of different DoE methods on the estimation of the ventilation rate in a naturally ventilated livestock. The parameters evaluated were the window opening characteristics and wind conditions. The results indicated that the most accurate response surface model was developed by the Box-Behnken design, followed by the central composite rotation design (CCRD) method. The work also highlighted that the performance of the DoE method may differ, depending on the case study. On the optimization of ventilation efficiency and indoor homogeneous conditions in livestock buildings, Norton et al. [14] employed CFD tools and Box-Bohnken design methods for the generation of a response function based on the geometrical characteristics of the building. The verified RSM method indicated that the environmental heterogeneity is more correlated to the geometrical characteristics of the building and particularly when the most restrictive eave opening conditions, regarding porosity and height, are applied.

Both ANN and RSM are well-recognised techniques that enable the approximation of the interrelated nature of the independent design parameters and their design solutions [15]. However, the aforementioned research topics within the NVB framework, generated the experimental case studies in independent software and used CFD codes to perform parametric analyses and/ or validation of the results.

In this study, a commercial CFD software integrated with RSM optimisation techniques is employed to present a parametric simulation method for the analysis and optimisation of a simple cross-ventilated building. The RSM technique is used to determine the interrelationships between the design parameters and design responses. The Screening optimization technique is employed to identify the optimum window opening dimensions that improve the natural ventilation efficiency in terms of the air flow rate and flow homogeneity. The CFD results were validated against wind tunnel experiments to establish the accuracy of the method.

In Section 3, the theoretical background of the RSM, which is used in the parametric-optimization study, is briefly presented. In Section 4, the case study is introduced followed by the CFD methodology, results and validation study. The optimisation methodology is presented in Section 5, along with the interpretation and verification of results. Finally, the discussion and conclusions are covered in Sections 6 and 7, respectively.

3. Response Surface Methodology (RSM)

Pioneers in the exploration of the impact of the design parameters on several design responses were Hotelling [16] and Friedman and Savage [17]. In mathematical terms, the unknown functional relationship between the design parameters (x) and their design responses (y) can be described by the low-degree polynomial model given by the Eq. (1):

$$y = f(x, \theta) + \varepsilon \tag{1}$$

where ε is treated as a statistical error. By employing mathematical and statistical methods, first-order (Eq. (2)) and second-order (Eq. (3)) polynomial regression models are constructed, based on physical or computer experiments [18].

$$\eta = \beta_0 + \beta_1 x_1 + \ldots + \beta_k x_k \tag{2}$$

$$\eta = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{\substack{i=1 \\ i<j}}^{k} \sum_{j=1}^{k} \beta_{ij} x_i x_j \tag{3}$$

where η represents a design solution (i.e. velocity, temperature, stresses, etc), x_1, x_2, …, x_k the design variables (i.e. height, thickness, load, etc) and β_0, $\beta_1,\ldots,\beta_k$ the unknown regression coefficients.

Box and Wilson [19] introduced a statistical tool that enables the evaluation of several design parameters, targeting an improved design solution (or response) by satisfying specific requirements. They defined the “experimental region” as the region within which the design parameters vary and the optimum design solution is localized, with the minimum possible number of conducted experiments. This method is known as Response Surface Methodology (RSM) and targets finding an improved, if not optimum, response of given controllable variables.

The RSM calculates approximate values for the regression coefficients, based on the evaluation of either experimental or simulation results generated for a specific number of sample design points. Once the best fitted approximation function is found, several design combinations can be examined, without the need to conduct deterministic response analysis that is an extremely time-consuming process. It is therefore apparent that the performance of a fully accurate design study may necessitate the simultaneous consideration of several independent design variables, resulting in complex mathematical functions/systems.

RSM has been widely used in various projects and disciplines, due to its advantageous performance in approaching mathematically the behaviour of multiscale phenomena, regardless of the nature of the studied parameters [16]. The integration of this method with expensive computer simulation codes has launched a new generation of research studies, which allows the optimization of designs with either large or small number of input and output parameters.

Fegade and Patel [20] studied a parametric finite element model of a rotor, by employing Design of Experiments (DOE) techniques integrated in ANSYS simulation software. They performed 48 simulation runs, aiming at investigating the effect of different rotor diameters on the rotor’s frequency. For the purpose of this, two levels factorial design with eleven input parameters per Plankett–Burman[1] design was considered and it two rotor diameters were found to have major impact on frequency for the fluid film.

Mandloi and Verma [22] employed Central Composite Design (CCD) experimental design in order to improve the performance and efficiency of an in-cylinder engine intake port. Based on RSM from ANSYS software, they established a goal-driven optimum design solution, determined by independent geometrical characteristics.

Ng et al. [23] evaluated the performance index of an air diffusion system integrated in a displacement-ventilated office. With the aid of commercial statistical and CFD software, they used RSM to predict the optimum position for the diffusers, the supply temperature and the exhaust position, in order to provide optimum thermal comfort in the space. The results obtained from the Box–Behnken design models were found to agree 95% with the CFD simulation results, indicating the accuracy of the method, as well as the very promising benefits and results.

4. Case study description

The achievement of an accurate and reliable simulation research study requires full compliance with the fundamental steps and in depth understanding of the CFD simulation and optimization processes. For the purpose of this, a simple benchmark building model was designed, as illustrated in Fig. 1. The geometrical

[1] Plankett–Burman experimental design is a factional factorial design, which is manly used for the identification of the most important variables of a partly known system with a large number of independent factors [21].