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CFD-driven optimization of air supplies deployment in an air-conditioned office

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Abstract. Occupational thermal comfort is one of the key performance indicators for green and sustainable buildings. Within air-conditioned indoor spaces, the deployment of air supplies play an importance role in determining thermal comfort conditions. This becomes more critical when the non-uniformity of heat loads in space increases. The objective in this study is to develop a set of systematic solution procedure for optimizing the locations of air supplies so as to maximize the thermal comfort conditions in a typical air-conditioned office environment. High-fidelity CFD simulations, corresponding to pre-defined locations of air supplies, are performed first, followed by surrogate-based optimization (SBO) process for the pursuit of the optimal location of the air supply. The thermal comfort index, predicted mean vote (PMV), is adopted as the objective function for optimization, which is evaluated at the people's sitting height level. Results real that the most appropriate location of the air supply has been successfully obtained using the proposed optimization algorithm and procedure. Efforts in this study imply that CFD can be extended further to optimize the building designs, with the help of cost-effective optimization approaches.

1. Introduction

Computational fluid dynamics (CFD) approach has been increasingly adopted in the design of green and sustainable buildings (BCA (2015)) mainly to verify the building performances with regard to thermal comfort, occupational health and safety. Compared to empirical design approaches, CFD simulations show their remarkable advantages in cost-effectiveness, higher accuracy and richer field information for characterizing the flow and thermal behaviors in details.

CFD is usually employed to evaluate the building performances for a given design and further to improve the design by effectively assessing plausible mitigation measures. However, it is rarely seen that CFD is used for optimizing the design features as conventional optimization algorithms e.g. gradient-based (Haupt 1995, Jameson 1995) or stochastic algorithms (Xing and Damodaran 2005, Kirkpatrick1984) require for large number of objective function evaluations which are obtained by time consuming CFD simulations. This only could be possible with high standard computational resources including CFD software and computer hardware. They are not practical for building-related applications. Recently, data driven optimization algorithms have been well developed, demonstrating their amazing potentials in industry applications for optimal solutions. Surrogate-based optimization (SBO) algorithm (Forrester et al. 2007, Queipo et al. 2005, Wang and Shan 2007) is one of such algorithms that have established their position as effective techniques for engineering design optimization problems due to their ability to reduce computational costs significantly. The surrogates, which are constructed using the

data drawn from high-fidelity CFD simulations, provide high efficient objective function approximations instead of running high cost CFD simulations, and consequently, making parameter sensitivity and industry design optimization feasible. In addition, they can also serve as cost-effective stand-ins for uncertainty quantification studies.

In this paper, a systematic optimization procedure, based on high-fidelity CFD simulations and surrogates model, has been developed for optimizing performance-based designs. The main objective in this study is to apply the proposed procedure to optimize the location of a single ceiling diffuser in a typical air-conditioned office for maximizing thermally comfortable conditions in space. The physical model of the air-conditioned office of concern is to be first illustrated, followed by the brief introduction of the proposed optimization solution procedure. The flow behaviors and optimization results are addressed in depth in the subsequent section. Some remarks upon the study are finally summarized at the end.

2. Problem definition

The air-conditioned office room of study here is 5m long, 5m wide and 2.5m high, as shown in Figure 1. A single four-way commercial diffuser is designed to be installed on the ceiling, as well as an air return. The supply air temperature is assumed to be 15°C and the amount of air supply is designed to sufficiently remove the heat generated in the space so that the room temperature should be remained approximately at 24°C. In this study, the ceiling diffuser is allowed to be translated along the ceiling surface in order to search for its optimal location for the best thermal comfort conditions within the room.
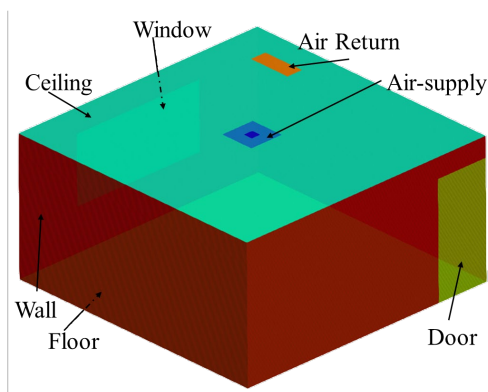

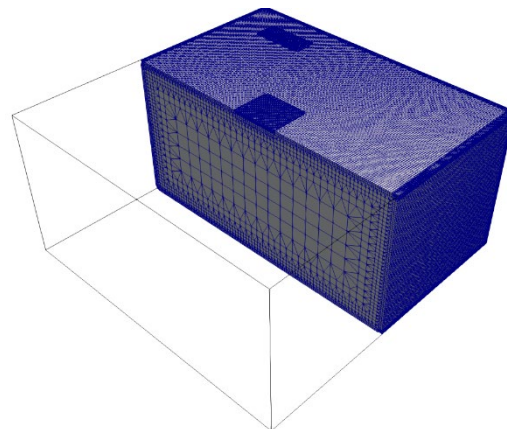| **Figure 1.** Geometry model of an air-conditioned office room | **Figure 2.** Computational grid for the air-conditioned office room of concern |

Table 1 below tabulates the heat loads imposed on the bounding surfaces of the office model. The pronounced heat loads include the heat conducted through walls, ceiling and floor, the solar heat through window, the heat generated by artificial lightings, and the heat loads from two persons and one set of computer system.

Table 1. Heat loads in the office room

Surface	Area	Heat flux
Window	3.19 m^2	45w/m^2
Ceiling	24.36 m^2	7w/m^2
Floor	25 m^2	20w/m^2
Door	2.215 m^2	3w/m^2
Wall	44.685 m^2	5w/m^2

Predicted Mean Vote (PMV), as recommended in ASHRAE (2013), is chosen as the thermal comfort index to assess the comfort conditions in the room. In general, PMV is the function of six parameters: air temperature (T_{air}), mean radiant temperature (T_{mrt}), air speed (V_{air}), relative humidity (RH), metabolic rate (met) and clothing rate (clo). In this study, for simplicity, it is assumed that $T_{mrt} = 26°C$, RH = 65%, met = 1.1 and clo = 0.67. Thus PMV values vary mainly with T_{air} and V_{air}. According to Green Mark code for non-residential buildings in Singapore, the area-averaged PMV value for a horizontal cutting plane at 1.2m above the floor, corresponding to the head location of a sitting person, is evaluated. It is also chosen as the objective function to be optimized. In practice, the acceptable PMV values range from -0.5 to 0.5, and PMV = 0 is the best comfort condition.

For the sake of better computational efficient and accuracy, hexahedra-dominated mesh, as shown in Figure 2, is generated with OpenFOAM (OpenCFD 2016) snappyHex meshing package to discretize the space of the air-conditioned room in CFD simulations.

3. Surrogate-based optimization procedure
In total 72 design locations for the air supply have been first evaluated using CFD approach, and the resultant high-fidelity CFD results are used to form the surrogate using Kriging model with Gaussian processes. The response surface is used for subsequent optimization process. The genetic algorithm (also known as Evolutionary Algorithm) is adopted to search for the approximate optimal location. The overall procedure for the optimization is elucidated in Figure 3.
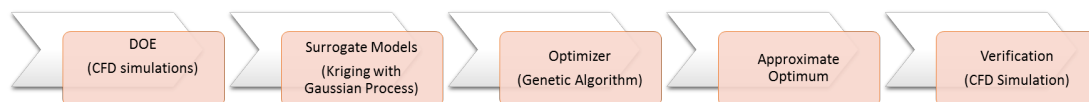

Figure 3. Working flow of surrogate-based optimization (SBO) procedure

4. Results and discussion
The detailed supply air through 4-way ceiling diffuser is first simulated with the consideration of the geometry of air supply. The resultant air supply profiles at the most bottom plate right beneath the 4-way ceiling diffuser are then captured and mapped as velocity inlet conditions in the subsequent simulations where the geometry of ceiling diffuser is excluded. Such a mapping can greatly improve the computational efficiency in the subsequent CFD models without the compromisation of accuracy in air supply. The non-uniform flow through the air supply, with well-known Coanda effect, is shown in Figure 4.
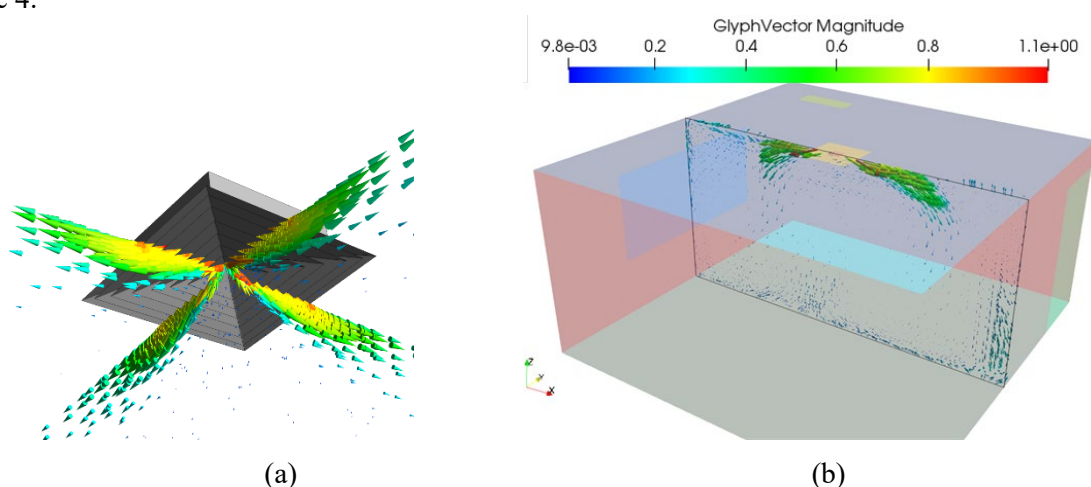

| (a) | (b) |

Figure 4. Vector plot of cool air supply through 4-way ceiling diffuser (a) Cool air supply through diffuser (b) Airflow entering the room

In this study, CFD simulations are first carried out for the ceiling diffusers installed at 72 different locations as the initial sampling for DoE. Square red-dots in Figure 5 denote the centre of the ceiling diffuser to be simulated. The area-weighted average PMV value for each design is monitored at the horizontal cutting plane of 1.2m above the floor. PMV contours for all the 72 design locations are shown in the flat surface in Figure 6. The PMV values fall in the range between 0.108 and 0.51. It is apparent that most design locations lead to acceptable thermal comfort conditions. This may be attributed to the proper sizing and flow rate of the cool air supply, the well mixing of flow induced by the ceiling diffuser, and the air return designed for the room. However, it is also demonstrated that different diffuser locations can result in different comfort levels, which is the rationale to drive such optimization efforts in this study.
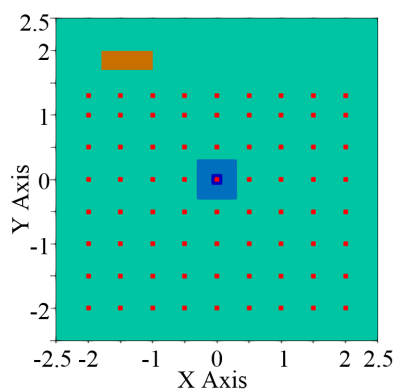

Figure 5. Design locations of the ceiling diffuser evaluated in CFD simulations as DoE
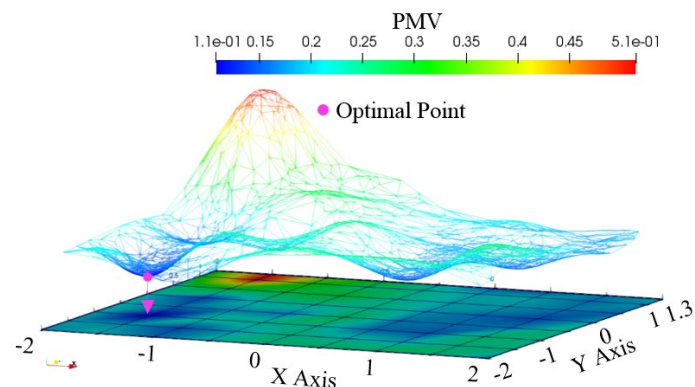

Figure 6. Plots of PMV contours based on CFD samplings and response surface from surrogate optimization

With the DoE sampled data obtained by running CFD simulations, the PMV values are predicted at the untried points in the entire design space by using the SBO approach. The result relevant response surface is shown by curved mesh surface in Figure 6.

The approximate optimal location for the ceiling cool air supply is then successfully found to appear near the window, as shown in Figure 7. The predicted location seems reasonable, which may result in the effective avoidance of hot spots near the window so that more preferable thermal comfort conditions can be produced. A CFD model for the approximate optimal diffuser location is then created and simulated for verification purpose. The PMV values spatially distributed on the sitting height of concern from the CFD model for the approximate optimized design are shown in Figure 7. The area-weighted PMV value is then calculated to be about 0.14, which is only marginally larger than one DoE point very nearby. Such a finding demonstrates that the proposed SBO procedure can succeed in finding the accurate location of the optimal design point.

Although the area-weighted average PMV values on the sitting height level improve to the thermal comforts as desired, there are local areas with PMV values beyond the acceptable range, as shown in Figure 7(a). The area with the acceptable PMV values are displayed in Figure 7(b), where PMV values beyond the acceptable range is marked to be excluded in the plot. It is worthwhile to point out that the way that PMV values are evaluated in this study is compliant with the conventional design practices – one dimensional analysis. When CFD simulations are adopted in performance-based design, three dimensional data within the flow field can be attainable, which should be fully based in the performance assessment. Thus, the future work in this topic will be extended to optimize the room when the non-uniformity of PMV at the sitting height level is factored in the objective function.
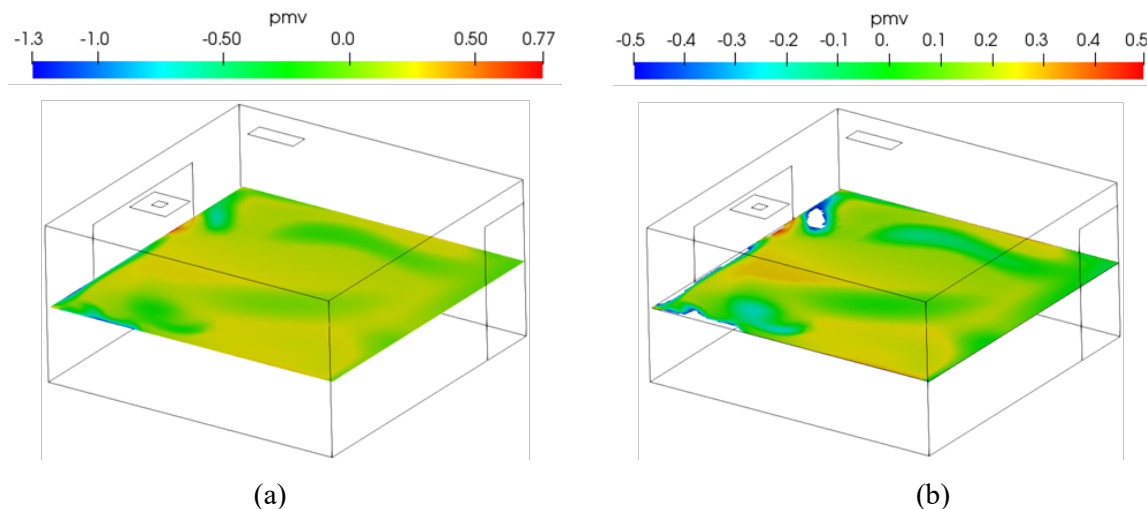
Figure 7. Plots of PMV contours on the sitting height level for the optimized location of ceiling diffuser (a) PMV contours   (b) Clipped PMV contours

5. CONCLUSION

A surrogate-based optimization procedure has been developed and explored to optimize the location of a ceiling diffuser for maximizing the thermal comfort conditions within an air-conditioned office room. The surrogate is built on the basis of high-fidelity simulations for some pre-defined design points.

The proposed optimization procedure leads to reasonably accurate approximation of the optimal design. Efforts here demonstrate that it is feasible to optimize the performance-based building design using CFD approach combining with reliable optimization algorithms. In particular, the fast development and the availability of relevant open source codes, such as OpenFOAM and Dakota (Adams et al. 2014), shed more light to accomplish such a goal in a cost-effective manner.

Continuous efforts will be seen to extend the surrogate-based optimization procedure with the infilled option, in case high-fidelity data is insufficient.

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