The 2020 World Congress on
Advances in Civil, Environmental, & Materials Research (ACEM20)
25-28, August, 2020, GECE, Seoul, Korea

Numerical optimization of the corner shape of the cross-section of tall buildings considering profitability and along-wind response

*Felix Nieto[1)] Miguel Cid Montoya[2)] and Santiago Hernandez[3)]

[1), 3)] *School of Civil Engineering, University of La Coruna, Campus de Elviña, Spain*
[2)] *NatHaz Modeling Laboratory, University of Notre Dame, Notre Dame, IN, USA*
[1)] felix.nieto@udc.es; [2)] miguel.cid.montoya@udc.es; [3)]Santiago.hernandez@udc.es

ABSTRACT

Wind induced vibrations of tall buildings must be carefully assessed in order to avoid reaching acceleration values that might negatively affect the occupants' comfort and the serviceability of the structure. The along-wind response depends on the turbulent buffeting excitation, which is affected by the geometry and height of the building.

The multiobjective shape optimization of the cross-section of tall buildings is addressed in this work applying the reduced basis method, which permits important geometrical changes with a small number of design variables. Two contradictory requirements are considered in the optimization problem: the along wind response and the relative profitability of the real estate development. The gross internal volume of the candidate building designs is constant, introducing additional storeys that compensate smaller floor areas. CFD simulations are conducted to obtain the aerodynamic response of a set of samples over the design domain. These numerical data enable the training of a surrogate model that is used to obtain the aerodynamic characteristics required in the assessment of the along-wind response using the Eurocode.

The weighted Min-Max method is applied, which allows to identify the complete set of Pareto optima, including nonconvex regions in the criterion space. For the considered application case the Pareto front is discontinuous, which is quite infrequent in engineering design, and highlights the intrinsic complexity in wind design of structures. Results show that the along-wind response may be decreased up to a 45%, while the10 years profitability is only reduced a 20%. Also the subset of Pareto optima fulfilling the requirements in ISO 6897:1984 is identified.

1. INTRODUCTION

Wind induced vibrations of tall buildings must be carefully assessed in order to avoid reaching acceleration values that might negatively affect the occupants' comfort and the serviceability of the structure. The along-wind response depends on the turbulent buffeting excitation, which is affected by the geometry and height of the building. Because of this, local modifications of the geometry of the cross-section of tall buildings, such as

[1)] Associate Professor
[2)] Visiting Postdoctoral fellow
[3)] Professor

chamfered or recessed corners, have proved to be feasible means to reduce wind induced responses (Kwok, 2013).

According to Kwok (2013), modifications in the shape of the cross-section of the building may decrease the available floor area, requiring the construction of extra storeys that would show higher wind-induced response, but potentially increasing the revenues associated to top storeys. The goal of this work is to identify optimal aerodynamic shapes for tall buildings of uniform cross-section balancing two contradictory objectives: low along-wind induced response and high profitability.

Application of shape optimization techniques in the aerodynamic design of tall buildings has only been addressed in recent years. Remarkable research works are the ones by Bernardini et al. (2015), Elshaer et al. (2017) and Ding and Kareem (2018). The authors of this conference paper have previously studied the shape optimization of tall buildings (Nieto et al. 2018 and 2019) by means of a multiobjective optimization problem considering contradictory requirements in terms of the cross-section floor area and the drag coefficient. In this work, the problem is further studied by considering more complex objective functions, such as profitability and along-wind response, imposing constant gross volume for candidate designs. Furthermore, the weighted sum method previously considered for identifying Pareto optimal sets, has been substituted by the weighted Min-Max method that permits, contrary to the former one, the identification of Pareto optima in nonconvex regions in the criterion space.

2. FORMULATION

The reduced basis concept is applied defining a shape design domain obtained from the linear combination of a set of basis geometries following the procedure described in Nieto et al. (2018). Consequently, the combination factors of the basis geometries $(a_i, i = 1, \dots, G)$ are the design variables of the multiobjective optimization problem.

The multiobjective optimization problem addressed herein is the following:

$$\text{find } \boldsymbol{a} = (a_i), i = 1, \dots 3,$$

$$\text{minimize } f(\boldsymbol{a}, h) = [f_1(\boldsymbol{a}, h), f_2(\boldsymbol{a}, h)] = \\ = \left[\frac{\hat{\ddot{x}}(\boldsymbol{a}, h) - \hat{\ddot{x}}_{min}}{\hat{\ddot{x}}_{max} - \hat{\ddot{x}}_{min}}, \frac{P^Q_{max} - P^Q(\boldsymbol{a}, h)}{P^Q_{max} - P^Q_{min}}\right] \tag{1}$$

$$\text{subject to: } \sum_{i=1}^{3} a_i = 1, \\ a_i \geq 0, i = 1, \dots, 3. \\ A \cdot h = A_{ref} \cdot h_{ref} = \text{constant.}$$

In Eq. (1), $\hat{\ddot{x}}$ is the peak acceleration for a 5 years return period computed according to the procedure in Eurocode EN 1991-1-4, where the meaning of the symbols in Eq. (2), (3) and (4) can be found. It must be noted that the along-wind response depends, among other variables, on the drag coefficient of the cross-section C_D.

$$\hat{\hat{x}} = k_p \sigma_{a,x}(z), \tag{2}$$

$$k_p = \sqrt{2ln(\nu T)} + \frac{0.6}{\sqrt{2ln(\nu T)}}, \tag{3}$$

$$\sigma_{a,x}(z) = \frac{C_D \rho D I_v(z_s) v_m^2(z_s)}{m_{1,x}} R K_x \Phi_{1,x}(z). \tag{4}$$

Also in Eq. (1), P^Q represents the profit at year Q for the development associated to a certain candidate design. The profit is calculated as:

$$P^Q = R^Q - CC, \tag{5}$$

where the return at year Q, R^Q, is computed following the procedure in Tse et al. (2009), and the construction costs CC, are assessed based on costs models in Strelitz (2005).

In figure 1, the fundamental tasks in the multiobjective shape optimization problem addressed herein are summarized.

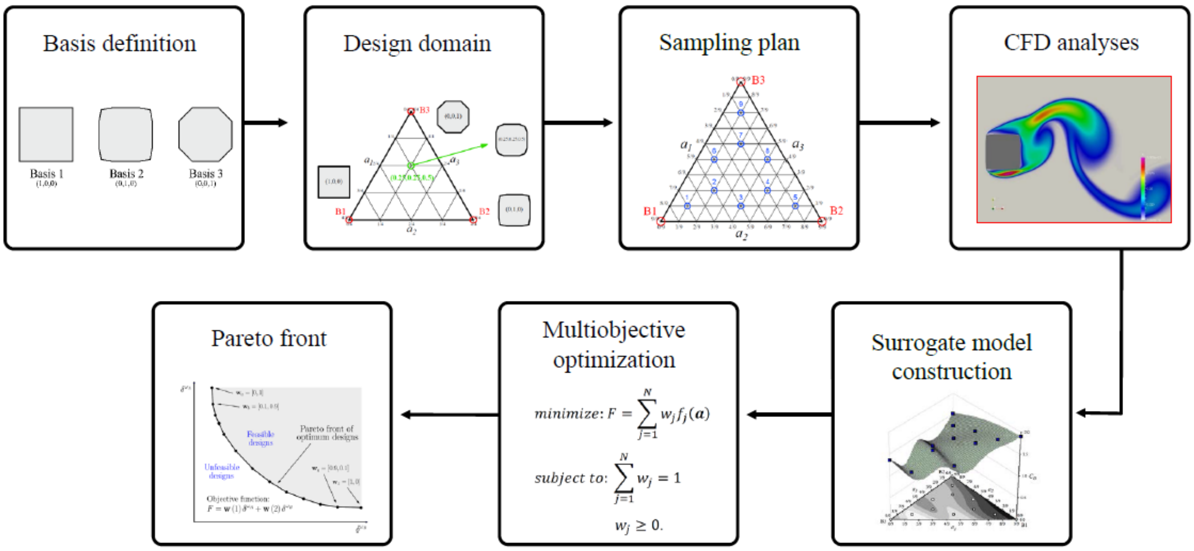

Fig. 1 Multiobjective shape optimization flow chart.

It must be noted that the evaluation of the along-wind peak acceleration for any candidate design requires the value of the drag coefficient for that cross-section geometry (see Eq. 4). Consequently, that information is provided by a surrogate model trained with the data obtained from 2D URANS simulations computed for a set of 12 geometries over the design domain (see Nieto et al., 2018, for the complete description of the CFD simulations, verification and validation studies, and surrogate modelling).

3. APPLICATION CASE

The formulation introduced in the previous section is applied to the case of a tall building with constant gross volume of 144000 m^3. The building geometries corresponding to the three basis designs considered are presented in figure 2, where it is clear how lower floor areas are associated to higher buildings, with larger along wind response but also higher profitability.

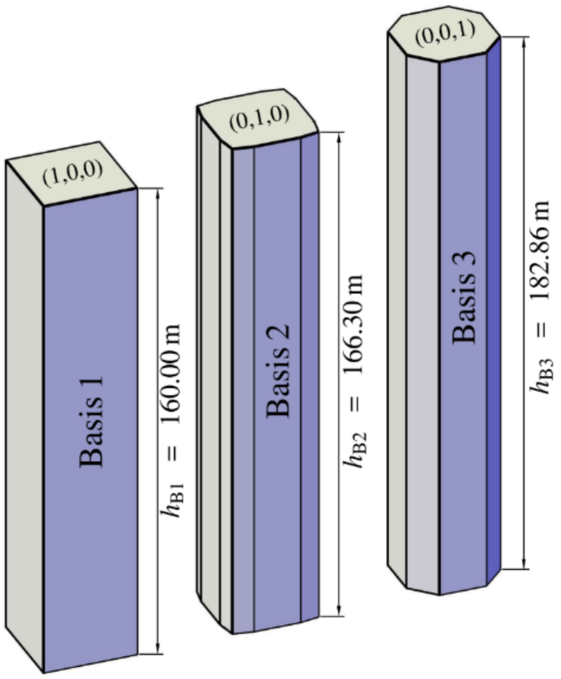

Fig. 2 Building geometries for the basis designs.

In figure 3, the Pareto front obtained for the considered application case is depicted. It can be appreciated how the Pareto front in the criterion space shows two nonconvex regions that have been identified using the weighted Min-Max method. It is remarkable that the Pareto front is discontinuous (Obayashi et al. 2005) due to the nonlinear nature of the objective function associated to the along-wind peak acceleration. The Pareto optima correspond to geometries located in the boundary of the design space due to the shape of the surface responses of both, along-wind peak acceleration and profit, over the considered design space. Reductions in the peak acceleration up to a 45% can be achieved, while 10-years relative-profits may vary up to a 20%.

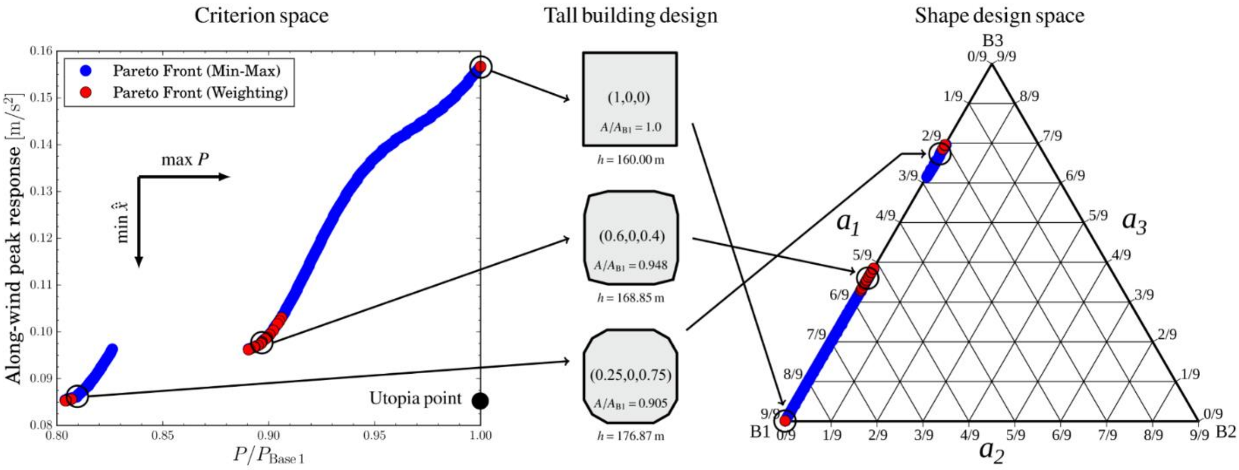

Fig. 3 Pareto optimal set in criterion and design spaces.

4. CONCLUSIONS

The proposed multiobjective shape optimization problem, adopting the reduced basis approach, has been successfully applied for the high-rise building considered herein. A set of Pareto optima has been obtained which enables the designer to choose the one that best balances the requirements of the project in terms of along-wind response and profitability. The peak acceleration may decrease up to a 45%, while profit may change up to a 20%. The Pareto front presents two nonconvex regions and is discontinuous, which shows the complex relationship between the building geometry and its wind-induced response.

REFERENCES

Bernardini, E., Spence, S.M.J. Wei, D., Kareem, A., (2015), “Aerodynamic shape optimization of civil structures: a CFD-enabled Kriging-based approach”. *J. Wind Eng. Ind. Aerod.*, 144. pp. 195-204.

Ding, F., Kareem, A., (2018), “A multi-fidelity shape optimization via surrogate modelling for civil structures”. *J. Wind Eng. Ind. Aerod.*, 178, pp. 49-56.

Elshaer, A., Bitsuamlak, G., El Damatty, A., (2017), “Enhancing wind performing of tall buildings using corner aerodynamic optimization”. *Eng. Struct.*, 136, pp. 133-148.

Kwok, K.S.S., (2013), “Wind-Induced Vibrations of Structures: With Special Reference to Tall Building Aerodynamics”. In *Advanced Structural Wind Engineering*. Y. Tamura and A. Kareem (eds.). Springer.

Nieto, F., Hernández, S., Cid Montoya, M., (2018), “Reduced basis approach for the shape optimization of the cross-section of tall buildings”. In *Proc. Of the 7th International Symposium on Computational Wind Engineering* (CWE2018). Seoul, Republic of Korea.

Nieto, F., Cid Montoya, M., Hernández, S., (2019). “Shape Optimization of Tall Buildings considering Wind Directionality: Surrogate Basis Approach”. In *Proc. of the 15th International Conference on Wind Engineering* (ICWE15). Beijing, China. pp. 93, 94.