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Generating optimal comfort improving design solution with occupancy survey and Multi-Objective Optimization (MOO) technique: a case study for façade retrofit in a post-war office in London

Chuanrui Yu[1] and Hector Altamirano[1]

[1] MSc Environmental design and engineering, University College London, UK, Institute for Environmental Design and Engineering, Bartlett School Environment, Energy & Resource, University College London, UK. chuanrui.yu.18@ucl.ac.uk.

Abstract: In a UK post-war open-plan office, occupants experienced discomfort from poorly performing façade. A façade retrofit presented a challenge for resolving potentially conflicting comfort considerations, e.g. large views and glare, with simple installations such as vertical fins. This study identified critical comfort issues and generated an optimized façade design with occupancy survey and multi-objective optimization. Sunlight glare, temperature and stability in winter and summer, and noise from colleagues were identified as key comfort factors, and then parameterized with building simulation programs as optimization objectives. A simple façade design was developed with parametric controls on glazing ratio, shading device, and glazing types. The optimal solution was found to be fully opaque insulation on South and West façades, extensive glazing on the North and East façades, and secondary glazing in all façades. Improvements in the heating system and building envelope was found essential for further thermal comfort improvement.

Keywords: Multi-objectives optimization, Occupancy comfort, Post-occupancy survey, Façade retrofit, Building performance simulation

1. Introduction

In the workplace, a good indoor environment promotes workers' satisfaction, comfort, health and wellbeing, which affects productivity (Frontczak *et al.*, 2012). Health and wellbeing in the built environment are related to physical and psychological factors, including thermal, visual, and aural comfort. Comfort is also affected by human factors, e.g. gender and age, and building factors, e.g. personal controls and views (Kwon *et al.*, 2019a). Local discomfort issues, such as drought, also determine overall thermal comfort (CIBSE, 2018). In workplaces, lighting design must assist the visual tasking with a uniformed and sufficient luminance environment (CIBSE, 2012). Daylight can promote wellbeing, and productivity in office but might lead to glare problem, which can be mitigated by applying measures such as vertical shading fins. Human factors, such as gender, and office layout, such as seat orientation, also alter comfort perception and satisfaction (Kim *et al.*, 2013; Kwon *et al.*, 2019b). Kim and de Dear (2012) realized that occupant satisfaction might not be linearly related to indoor environmental quality (IEQ) factors. Occupants may be more sensitive to IEQ changes in poor-performing condition for "Basic factors".

With the absence of performance requirement, non-domestic buildings built between the 1940s and 70s were usually poorly constructed, not well-insulated and with single-glazing thus perform poorly in energy and comfort (Duran *et al.*, 2015). Retrofitting these buildings for energy and comfort improvement can be challenging due to the complicated relationships between IEQ factors and the different requirements from stakeholders. Design optimization can help achieve the best possible performance among several conflicting objectives, such as cost, comfort, and energy with an iterative and experimental process

(Nguyen *et al.*, 2014). Building Performance Simulation (BPS) is an effective tool to compare performance for design options. Parametric modelling helps generate geometry interactively with a series of parameters, instructions, and calculation process (Frazer, 1995, Khabazi, 2012). Under this concept, design alternatives can be easily generated by altering the parameters settings. By combining parametric modelling into design optimization, the design optimization becomes a comparison and selection among a large number of generated design options. Genetic algorithms have been developed by Holland (1992), which integrates Multi-objectives optimization (MOO) and find the best possible solutions for different cases (Pareto front) from numerous design alternatives.

This research aimed to develop a practical method to identify key comfort factors with occupancy survey then generate an optimized design solution for occupancy comfort with MOO algorithm from simple parameterized design rules. This research was based on a case study for an open-plan office in a highly glazed post-war building in the UK. As in the research framework (Figure 1), occupancy survey was analysed to determine key comfort factors with qualitative analysis, benchmarking, correlation, and ANOVA studies. The critical comfort issues were referred for façade design and MOO to generate the optimal façade solution. The generated façade design aims to set general rules for detailed facade design.

2. METHODOLOGY

The BUS methodology was used to assess the occupancy satisfaction concerning the design, temperature, air, lighting and facilities of the office (Parkinson *et al.*, 2017). The seating location of respondents was also collected to link the comfort and satisfaction rating to a specific location in the office. Physical copies of the survey were distributed to all occupants (N=78) in the office and collected after two weeks. The collected data was then qualitatively and statistically analysed to identify the critical issues and the potential causes for discomfort. The mean of all collected satisfaction ratings for IEQ factors was compared to BUS benchmarks to understand the building performance in context. Then, Pearson correlation and ANOVA study tested the correlations among IEQ factors and comfort, implying the impact of these factors on the perceived discomfort. Findings were summarized to determine critical comfort issues. A parametric model and MOO program were then developed to generate optimized design options to improve comfort issues. The key comfort issues were parameterized into quantitative numbers for inputting as optimization objectives with BPS tools. After optimization, the optimal solution was selected from the Pareto front. Several software tools were used in the study: Rhino 5 with grasshopper for parametric modelling; Ladybug and Honeybee Suite for BPS; Octopus MOO program for MOO; and Excel and SPSS for statistical analysis. The optimization only focused on occupied work areas.

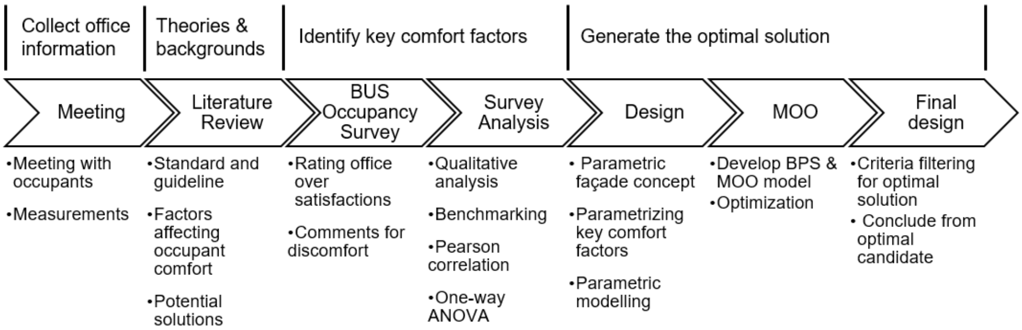

Figure 1. Process for generating optimal solution with occupancy survey and MOO

3. Case building

The case office is a 450 m2 open-plan office at the top floor of a 1970s commercial building located in central London. The building features large windows across all façades which provides an excellent view and natural light across the office (Figure 2). It is a listed building, which has restrictions to changes to the façade. The air conditioning units have been integrated into the window sills. However, the building is poorly insulated and has single-glazing (Duran *et al.*, 2015). Occupants suffered from extreme discomfort conditions such as intense glare and coldness in winter. Restricted by planning and rental requirements, a retrofit can only be applied within the small space on window sills. The baseline parametric model was developed and simplified based on the original building geometry and constructions.

Figure 2. Case building

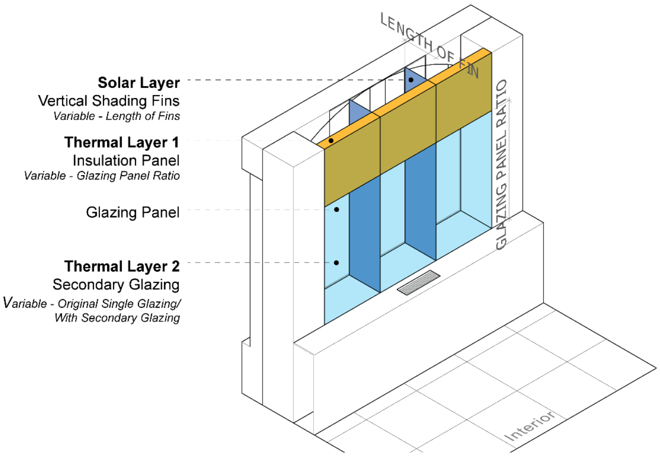

Figure 3. Layered and simplified parametric facade concept

4. Occupancy survey

41% of occupants (32 out of 78) responded to the BUS survey. The participants were well distributed across the office, as well as gender and age. All variables were converted to the same scale type for Pearson correlation and ANOVA. Thermal discomfort in winter, glare, noise and work interruption were some of the most frequent comments from occupants. The thermal comfort of the office was found to underperform, especially in winter; the air in winter was perceived unstable, cold, slightly stuffy and very draughty, while the air in summer was hot and unstable. Noise from colleagues and outside, and noise interruptions were found not to be satisfactory in the office. The sunlight glare issue ranked the worst in the BUS benchmark database. Strong correlations were identified for overall winter air comfort to overall winter temperature comfort (ρ=.892, p=.000, N=30) and overall winter air comfort to overall winter temperature comfort (ρ=.804, p=.000, N=30). Such results imply that the air temperature largely depends on overall comfort to the thermal. Satisfaction to summer air condition is correlated to air temperature (ρ=.804, p=.000, N=30) and its stability (ρ=.500, p=.005, N=30).

Similarly, winter air satisfaction was related to air temperature (ρ=.773, p=.000, N=31), its stability (ρ=.436, p=.014, N=31) and stillness (ρ=.456, p=.010, N=31). Surprisingly, no correlation was found between lighting satisfaction and sunlight glare. However, poor glare condition distorted the distribution of collected rating and might affect the correlation. In ANOVA, no variable showed a significant difference over layout criteria, such as orientation and nearness to a window. The result indicates that the layout was not a critical factor for comfort satisfaction. The simulation for the office also supported the rating and findings in the survey. In summary, sunlight glare, temperature and stability and noise from colleagues were identified as critical variables. The insignificance of location-specific factors suggested that local discomfort issues were not the critical cause of low satisfaction in thermal and visual comfort in the office, which is contradictory to typical discomfort scenarios with single-glazing (CIBSE, 2018).

Table 1. Summary of determined optimization objectives and simulation models

Key comfort factors	Simulation model	Result unit	Description	Direction
Sunlight glare	ASE 1000, 250	%	Percentage of areas fulfilling ASE requirement for 1000lux and 250 hours	Minimize
Thermal comfort	Adaptive comfort + PMV model	- (%+%)	Number of occupied hours within comfort range for summer (adaptive comfort) and winter (PMV model)	Maximize
Daily temperature stability	Daily error	-	Total difference from daily mean for hourly air temperature	Minimize
View for outdoor	Horizontal 60° Cone of vision	%	Average percentage of outside view from interior	Maximize

4.1 Façade design conceptual rules

The design aims to maximize comfort by balancing all critical comfort factors. The critical comfort factors were referred to in façade design and parameterized with suitable BPS models for inputting as optimization objectives as in Table 1. Despite identified as a critical factor, the noise was not considered in the façade design due to the lack of suitable BPS tool. View to outside was a central feature of the original façade and affected overall satisfaction (Osterhaus, 2005). Thus, the view was also considered as a critical design objective.

As shown in Figure 3, a parametric model of the façade was developed in performance layers, i.e. solar and thermal layers. The solar layer (vertical fins) controls access to solar radiation. The performance of the façade was simulated using simple geometry and general thermal properties. Therefore, parametric changes of each modelled measures were directly linked to related BPS program and reflected on building performance changes. The generated optimized façade design would provide the general geometry and properties requirement for further detailed design.

5. Multi-Objective Optimization (MOO)

In total, 101 Pareto front candidates were generated. The optimal solution should achieve a balance for glare, thermal comfort, and human noise. Thus, as seen in Table 2, filtering criteria and process were designed for balanced and objective results to select an optimal solution from large scale data. The chosen optimal façade features large secondary-glazed windows on north and east facades with no window on south and west façades

As shown in Table 3, the generated optimal solution substantially improved the glare issue. The ASE index was at 7.6%, indicating glare probability is lower than the requirement and glare is less likely to affect satisfaction for most time of a year. Meanwhile, the view was still available at an average of 10% view from the large north and west windows. Seasonal thermal conditions only improved marginally. Summer thermal comfort hours increased to 86% from the original 62%, but winter comfort dropped to nearly 0% of occupied hours. The design concept and MOO program failed to address the winter cold problem when trying to balance all four objectives. In general, the optimization process was systematic and gradually working towards the optimal design solution. The returned optimal solution provides the required façade characteristics to achieve the best balance for glare, view, annual thermal comfort and daily temperature stability.

Table 2. Filtering process in this case study

Step	Process	Criteria	No. of remaining candidates
1	Basic filtering	ASE result ≤10%	52
2	Ranking filtering	Result percentile ≤ 50%	4
3	Fine Filtering	Result percentile ≤ 48%	1

Table 3. Comparing the simulated objectives results of the optimal solution to the baseline

Objectives	Optimal Result	Baseline Result	Improvement from baseline
ASE 1000lx,250h	7.57%	29%	Fulfilled LEED glare requirement
Average View	10%	15%	30% reduction
Total Hours index in comfort [1]	87.0	66.3	35% increase
Adaptive comfort for summer [1]	86.1%	62.4%	38% increase
PMV comfort for winter [1]	0.9%	3.9%	77% reduction
Temperature variation index [1]	4165	5482	25% reduction

[1] *Calculated for occupied hours only*

6. DISCUSSION

Because of the single glazing, occupants next to window were initially assumed to be more uncomfortable. However, ANOVA result contradicted this assumption as nearness to a window is insignificant for overall comfort in this office. Participants perceived the same level of discomfort across the office. The window-sill fan-coil air-conditioning units blew the heated air upwards, which potentially mitigated the cold condition next to the window. However, the hot air was kept at a higher level due to stratification, while the cold air was at the occupied zone and not heated adequately across the office (CIBSE, 2016). Eventually, the whole occupied area became cold and stuffy. Improving the ventilation and heating system was critical to the office.

For winter thermal comfort prediction, PMV model assumed a fix clothing level for comfort evaluation and applied a restrict percentage of people dissatisfaction (PPD) threshold at 10% as a typical application. Under this assumption, an upgrade of windows to triple glazing for the generated optimal only improved winter PMV index to 3% of occupied hours. Even the façade solution optimized only for maximum winter thermal comfort had only 5% of occupied hours within comfort. Conversely, tested with the generated façade design, lowing PPD threshold to 15%, e.g. by allowing changes to clothing level, significantly improved winter PMV comfort index to 45% for secondary glazing or 48% for triple glazing. Hence, allowing freedom in clothing level significantly improved winter thermal comfort condition. Façade retrofit can only improve the winter thermal comfort to a tolerable level. Facade retrofit must be combined with other building elements improvements to improve winter thermal condition further.

7. CONCLUSION

This study identified the critical comfort factors in a case office and generated an optimal façade design solution to improve occupants' comfort. The critical issues affecting comfort in the office were identified as sunlight glare, overall thermal comfort perception, daily temperature stability and noise from colleagues. The discomfort perception was determined by the overall poor condition instead of local discomfort in specific areas. The possible causes for discomfort included the open-plan layout for noise propagation and large west-facing clear glazing for sunlight glare. The poor thermal performance of the building envelope leads to low and unstable indoor temperatures in winter. The cold air was cumulated due to the ineffective heating air distribution, which further intensified the winter air coldness. A simple design concept was summarized from MOO as general design rules for design optimization. The generated optimal solution was summarized to be that adding insulation panel to the south and west façades while maintaining high glazing ratio at north and east façades without extra shading devices. Secondary glazing was also essential towards the better thermal condition.

The sample size of occupancy survey analysis was small, thus potentially induced unreliability to results. Several unexpected and logically unreasonable correlations were found. Therefore, an additional analysis had to be conducted to increase result reliability. Moreover, the model was highly simplified for a fast simulation under large optimization sets. The simulations could only consider an overall condition in the office and return a general index for comfort, thus cannot consider the specific local comfort issues.

The optimization workflow is iterative, i.e. design-model-simulate-redesign. Therefore, computer programming could help finish the repetitive works. The workflow used in this study indicated a possible method for automating the design optimization process and generating an optimal solution with MOO, GA, building simulation, and filtering mechanism. Recommendation on MOO settings such as initial population size is not available for avoiding the local optimum issues, which is worth researching for increasing result reliability.

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