A WHOLE-LIFE VALUE BASED ASSESSMENT AND OPTIMISATION MODEL FOR HIGH-PERFORMANCE GLAZED FACADES

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ABSTRACT

Façade design is a complex and multi-disciplinary process. One major barrier to devising optimal façade solutions is the lack of a systematic way of evaluating the true social, economic and environmental impacts of a design. Another barrier is the lack of automated design aids to assist decision-making.

In this paper, we present our on-going study in developing a whole-life value based multi-objective optimisation model for high-performance façades. The principal outcome of this paper is a multi-objective optimisation model for early-stage façade design. The optimisation technique coupled with other 3rd party software and/or specially developed scripts provide façade designers with an integrated design tool of wide applicability.

INTRODUCTION

During the whole life of a commercial building located in central London, the cost of operating the business in the building is 15 times the cost of construction, and 10 times the cost of maintaining and operating the building, i.e., 1 (construction) : 1.5 (facility management) : 15 (operation of business) (Ive, 2006). This suggests that a higher initial expenditure on facades could generate a more comfortable working environment for the occupants, and thereby improve the occupants' productivity and hence the net economic gain.

Façade design is a complex and multi-disciplinary process. The design performance criteria are drawn from various fields including building physics, structural engineering, economics, and sustainable development. Most of the design criteria are people-oriented. However, the major challenge to establishing a holistic design approach is to identify the relationship between façade design and occupants' well-being.

This paper first reviews existing research that relates indoor environmental quality (*IEQ*) to occupants' response. From this, an 'ambient-performance' relationship is established to quantify the relationship between *IEQ* and occupants' productivity. A whole-life-value based multi-objective optimisation model is subsequently constructed to evaluate the social, economic and environmental values of alternative façade designs. Finally, the model was demostrated with a simple application.

INDOOR ENVIRONMENTAL QUALITY AND OCCUPANTS' PRODUCTIVITY

Literature review

The performance or productivity of occupants is affected by façade-related *IEQ* parameters in a complex manner. Figure 1 illustrates this relationship.

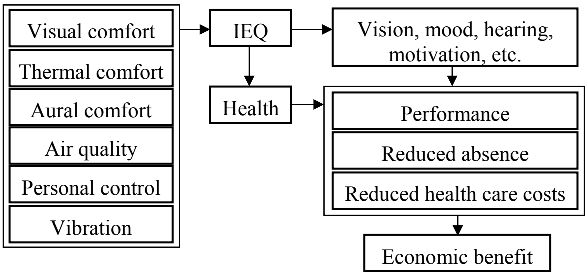

Figure 1 Relationship between IEQ indicators and the economic benefits - adapted from Fisk, 2008 and Stanton et al., 2004.

Fisk reviewed existing data and studies, and estimated the potential health benefits and economic gains from improved *IEQ* in commercial, institutional and residential building in the US. The data (Table 1) showed that the potential economic benefits were significant (Fisk, 2008).

Several studies investigated the relationships between individual indoor environmental aspects and human performance. For example, temperature (Seppanen et al., 2004) and thermal comfort (Roelofsen, 2002; Kosonen et al., 2004) were quantitatively related to occupant productivity. A linear relationship (Wargocki., 2008) was derived from laboratory experiments (Wargocki et al., 1999; Wargocki et al., 2000; Wargocki et al., 2002), showing that a 10% reduction in the proportion of occupants dissatisfied with the air quality could lead to a 1.1% increase in performance, when the percentage of dissatisfied ranges from 25% to 70%. Two field studies (Tham, 2004; Wargocki et al., 2004) found that improvement in air quality could increase the performance of occupants by 5% to 10%. In addition, quantitative relationships between performance of occupants and ventilation rate were established (Seppanen and Fisk, 2006). The main limitation of the above-mentioned studies is that only one *IEQ* aspect was considered. As a result, the predicted productivity of occupants is only valid under the same condition for other *IEQ* aspects as the experiment was carried out, and extrapolating to other conditions will lead to errors.

Some other studies focus on human responses to *IEQ* and from a wider perspective by investigating the effect of simultaneous *IEQ* aspects on human response.

A survey was conducted in offices in Reading (Clements-Croome and Li, 2000). A quantitative relationship between the overall unsatisfactory indoor environment, job dissatisfaction, crowded working space, and self-assessed productivity was established. Similarly, a regression equation was proposed based on a survey on employees of 13 banks in Pakistan, which predicted employee productivity from their satisfaction with furniture, noise, lighting, temperature and spatial arrangements (Hameed and Amjad, 2009). One shortcoming of this study is that it ignores an important factor – air quality. An indoor environment index (*IEI*) was proposed (Chiang et al., 1999) after analysing the results of experts' questionnaires using analytical hierarchy process. It considered the combined effects of acoustics, illumination, thermal comfort, indoor air quality, and electromagnetic field. A common limitation for the three studies is that all the variables need to be obtained qualitatively. Therefore, it is difficult to deploy them during the early-stage design, when the qualitatively evaluated variables are difficult to obtain.

Two further studies considered a wide range of *IEQ* aspects, and were based on variables that could be obtained either through computational building energy simulation or experimental measurements (Wong et al., 2008; Kawamura et al., 2007).

Wong (Wong et al., 2008) developed a model to predict the acceptance of indoor environmental quality (*IEA*) in offices. *IEA* was defined as the ratio of number of occupants who consider the indoor environment 'acceptable' to the total number of occupants work in the environment. The model was based on a survey of 293 occupants in offices in Hong Kong. An empirical relationship was established between *IEA* and thermal comfort, CO_2 concentration, equivalent noise level, and illumination level, as shown in Eq (1) and Eq (2).

$$IEA = 1 - \frac{1}{1+\exp[k_0 + \sum_{i=0}^{4} k_i \varphi_i(\zeta_i)]} \quad (1)$$

where φ_1 to φ_4 are the acceptance indices of thermal comfort, air quality, aural comfort and light level.

$$k_i = \begin{cases} -15.02 \\ 6.09 \\ 4.88 \\ 4.74 \\ 3.70 \end{cases} ;i = 0,...,4. \quad (2)$$

where k_1 to k_4 represent the relative importance of the four factors. φ_1 to φ_4 are calculated from Eq (3) to Eq (6) as follows:

$$\varphi_1 = 1 - \frac{PPD}{100} \quad (3)$$

where *PPD* is the predicted percentage of dissatisfied (Fanger, 1970);

$$\varphi_2 = 1 - \frac{1}{2}[\frac{1}{1+\exp(3.118-0.00215\zeta_2)} - \frac{1}{1+\exp(3.230-0.00117\zeta_2)}];(500 \le \zeta_2 \le 1800) \quad (4)$$

where ζ_2 denotes the CO_2 concentration (ppm);

$$\varphi_3 = 1 - \frac{1}{1+\exp(9.540-0.134\zeta_3)};(45 \le \zeta_2 \le 72) \quad (5)$$

where ζ_3 denotes the equivalent noise level (dBA);

$$\varphi_4 = 1 - \frac{1}{1+\exp(-1.017+0.00558\zeta_4)};(200 \le \zeta_4 \le 1600) \quad (6)$$

where ζ_4 denotes the illumination (lux) at working plane.

This study proposed a quantitative relationship that considered the widest range of aspects of *IEQ* to-date, thereby providing the most comprehensive evaluation. The four indicators are easily measurable, which makes the model ideal for building performance simulations. However, the model has a main limitation, i.e., the indicators are not sufficiently detailed and comprehensive to fully reflect the quality of each *IEQ* aspect. For example, using CO_2 concentration as an indicator of air quality ignores other pollutant gases that might affect occupant performance; glare is ignored while evaluating the satisfaction with lighting.

Kawamura (Kawamura et al., 2007) conducted an experiment in a climatic chamber, where eight environmental conditions were simulated (Table 2). The subjects were asked to perform multiplication tasks, and rank their satisfaction with indoor environment (*IES*) out of -1 to 1, and their performance out of 0 to 100%. The self-assessed performance (*SP*) was related to *IES* with a linear relationship:

$$SP = 15.097 \cdot IES + 75.466 \quad (-1 \le IES \le 1) \quad (7)$$

Table 1 Estimated potential productivity gains in 1996 $US (Fisk, 2000)

Source of Productivity Gain	Potential Annual Health Benefits	Potential Annual Savings or Gains
Reduced respiratory illness	16 to 37 million avoided cases of common cold or influenza	$6-$14 billion
Reduced allergies and asthma	10% to 30% decrease in symptoms within 53 million allergy suffers and 16 million asthmatics	$2-$4 billion
Reduced sick building syndrome symptoms	20% to 50% reduction in SBS health symptoms experienced frequently at work by ~15 million workers	$10-$30 billion
Improved performance from thermal and lighting changes	N/A	$20-$160 billion

Table 2 Environmental conditions tested in Kawamura et al, 2007

Conditions	Air Temperature (°C)	Operative Temperature (°C)	Relative Humidity (%)	Equivalent sound level (dBA)	Illuminance (lx)	CO_2 (ppm)
Control	28.3	28.5	44	63	405	941
T	25.2	25.2	44	64	404	875
N	27.4	27.9	43	51	401	825
L	27.9	28.2	41	64	773	825
TN	25.6	25.7	43	51	401	792
TL	25.1	25.1	44	64	772	862
NL	27.7	28.0	42	51	757	798
TNL	26.1	26.4	42	51	752	963

Table 3 Curve-fitting of Wong-Kawamura data (Wong et al, 2008 and Kawamura et al, 2007)

CURVES	BEST-FIT OF	EQUATION	R^2-VALUE
Filtered 1	all data points	$IEA = 0.95\exp\{-0.0279\exp[1.8038(1-IES)]\}$	0.6732
Filtered 2	all data points except Point *TL* and *L*	$IEA = 0.95\exp\{-0.0225\exp[2.1948(1-IES)]\}$	0.9144
Filtered 3	all data points except Point *TL* and *Control*	$IEA = 0.95\exp\{-0.0312\exp[1.7568(1-IES)]\}$	0.9603

Table 6 The optimal solutions for Net economic cost vs. IEA

WWR (%)	GLAZING TYPE NO.	U_g (W/m²K)	g (%)	T_v (%)	NET ECONOMIC COST (£x10^4)	IEQ ACCEPTANCE (%)
50	67	0.7	13	23	-5.49	97.3
70	67	0.7	13	23	-13.0	97.1
25	54	1.1	17	30	-0.162	97.4
60	54	1.1	17	30	-9.88	97.2
70	54	1.1	17	30	-13.0	97.1
25	53	1.1	15	24	-0.162	97.4
60	53	1.1	15	24	-9.88	97.2
70	53	1.1	15	24	-13.0	97.1

Table 7 The optimal solutions for IEA vs. net GWP

WWR (%)	GLAZING TYPE NO.	U_g (W/m²K)	g (%)	T_v (%)	IEQ ACCEPTANCE (%)	NET GWP (kg CO_2 x10^4)
25	67	0.7	13	23	97.4	-1.17
50	67	0.7	13	23	97.3	-2.05
60	67	0.7	13	23	97.2	-2.33
70	67	0.7	13	23	97.1	-2.56

Table 8 The optimal solutions for Net economic cost vs. net GWP

WWR (%)	GLAZING TYPE NO.	U_g (W/m²K)	g (%)	T_v (%)	NET ECONOMIC COST (£x10^4)	NET GWP (kg CO_2 x10^4)
70	67	0.7	13	23	-13.0	-2.56

An 'ambient-performance' relationship

The *IEA* calculated according to Wong represents the percentage of occupants who will vote 'acceptable' for a specific indoor environment quality. In comparison, the *IES* in Kawamura's experiment denotes the mean score ranging from -1 to 1. However, the relationship between *IEA* and *IES* is unknown, consequently, the relationship between measurable *IEQ* variables and performance of occupants cannot be established directly. Therefore, an attempt was made to establish one.

Firstly, *IEAs* for all conditions in Kawamura's experiment (Table 2) were calculated using Eq (1) to Eq (6). The relative air velocity was assumed to be 0.1m/s. Kawamura did not provide any records on the metabolic rate of the subjects, which is required for calculating *PPD*. The metabolic rate was assumed to be 1.2 met, which is equal to the metabolic rate for normal office work recommended by CIBSE (CIBSE, 2006). *IES* was obtained from Kawamura's experimental results.

Secondly, *IEA* and *IES* were plotted in Figure 2, and compared with an extended Fanger's model. Although Fanger's model (Fanger, 1970) only considers thermal comfort, it is well established and well received, and the variables predicted percentage of dissatisfaction (*PPD)* and predicted mean vote (*PMV)* are conceptually comparable to *IEA* and *IES*, respectively. Therefore, the extended Fanger's model was established as follows. In Fanger's model, *PPD* is calculated as :

$$PPD = 100 - 95\exp\ [-0.03353 PMV^4 + 0.2179 PMV^2] \quad (8)$$

Eq (8) was then manipulated as follows to compare with the data. It was assumed that there was a linear relationship between *PMV* and *IES*. '*PMV* = 0 (thermal neutral)' was equivalent to '*IES*= 1 (clearly satisfied)', and '*PMV* = -2 (very cold)' was equivalent to '*IES*= -1 (clearly dissatisfied)'. *IES* could then be expressed as:

$$IES = PMV + 1 \quad (9)$$

It was assumed that there was a linear relationship between *PPD* and *IEA* as:

$$IEA = 1 - PPD/100 \quad (10)$$

A possible relationship between *IEA* and *IES* derived from Fanger's model gives:

$$IEA = 0.95\exp\cdot[-0.03353\ (IES-1)^4 + 0.2179\ (IES-1)^2] \quad (11)$$

Therefore, an extended Fanger's model, i.e., Eq (11) was plotted in Figure 2. It shows that the extended Fanger's model provides a reasonable fit to Wong's and Kawamura's results.

Finally, efforts were made to establish a quantitative relationship between *IEA* and *IES*. Compared to Points *T*, *N*, *NL*, and *TN*, Point *TL* either overestimated *IEA* or underestimated *IES*. In addition, Point *L* and Point *Control* conflict with each other, so at least one of them should be an outlier. Assuming that the relationship between (1-*IES*) and *IES* is similar to the relationship between *PPD* and *PMV* as in Eq (8), three possible curves of the relationship were obtained using curve-fitting (Table 3), and plotted in Figure 2.

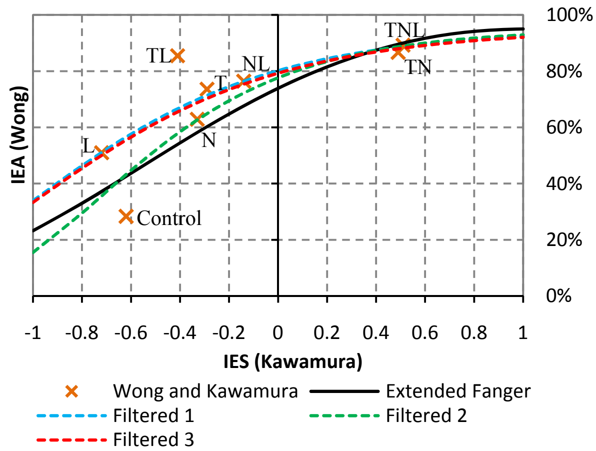

Figure 2 The relationship between IEA (Wong) and IES (Kawamura).

Figure 2 shows that Point *Control* and Point *TL* are likely to be outliers. Since Point *TL* represents the condition with the highest temperature, and Point *Control* represents the condition with the lowest temperature, a possible reason for the deviation could be that Wong's model is very sensitive to temperature. Therefore, Point *Control* and Point *TL* should be eliminated, and Filtered 3 is probably a reasonable relationship between *IEA* and *IES*. The 'ambient-performance' relationship that could be used to convert *IEQ* into the productivity of occupants is summarised in Figure 3. However, it should be noted that further investigation is required to validate the *IEQ vs. IES* relationship suggested by Filtered 3, especially the applicability to people in different regions and the different levels of work being done.

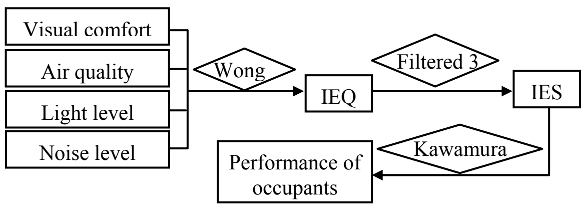

Figure 3 An 'Ambient-performance' relationship

WHOLE-LIFE-VALUE BASED OPTIMISATION MODEL

An optimisation model was developed based on a whole-life-value approach that considers (a) social value, (b) economic value, and (c) environmental value. The assessment of each design objective value is described in detail, and the model is illustrated with a simple application.

Problem description

The objective is to optimise the window for a typical office room in London. The room size is 4.5 x 3 x 4 m[3]. All the surfaces are assumed to be adiabatic internal surfaces, except the south façade which is partly glazed (Figure 4). The room is assumed to be occupied by two employees. More detailed information can be find in Jin and Overend, 2011

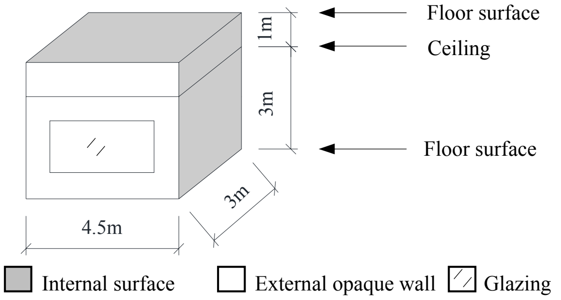

Figure 4 A typical office room in London

The two variables for this optimisation problem were window-to-wall ratio (*WWR*) and glazing type. *WWR*s ranged from 20% to 70%, increasing at an interval of 5%. Glazing type is a discrete variable, too. For each glazing type, three basic thermal performance properties (Thermal transmittance *U-value*, solar heat gain coefficient *g-value* and visible transmittance T_v) were specified (Figure 5). Clear double glazing units with no coatings (Glazing Type 1) are included as a reference case. All other glazing types are numbered from Type 2 to Type 67, and evaluated w.r.t the reference case. It is assumed that the service life of all the glazing units is 25 years.

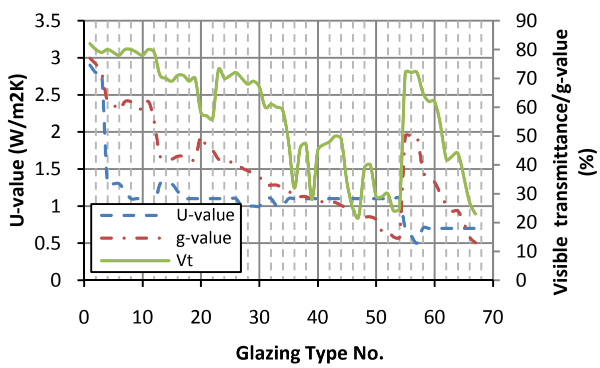

Figure 5 Performance properties for each glazing type.

Objective function F_1 – Social value

The social value is evaluated by *IEA*, calculated according to Eq (1) to Eq (6). It is assumed that the indoor noise level is 41 dBA. Light level, CO_2 concentration and *PPD* are obtained from a building energy simulation software EnergyPlus 6.0. It is assumed that the CO_2 level in the atmosphere is 390ppm (National Oceanic & Atomospheric Administration Research, 2010).

For thermal comfort calculations, it is assumed that the work efficiency of human body for office work is 0, i.e., all the energy produced in the body is converted to heat and none is converted to mechanical energy (Fanger, 1970). The air velocity is assumed to be 0.05m/s (Fanger, 1970). The clothes level is assumed to be 0.7 for summer (May - Sep) 0.85 for winter (Jan – Apr, Oct - Dec) (CIBSE, 2006). From the hourly *PPD*, hourly CO_2 concentration, and hourly light level at a specific reference point obtained from EnergyPlus, the occupancy weighted annual average *PPD*, CO_2 concentration C_{CO_2} and light level *LL* were calculated as follows:

$$\text{weighted annual average } PPD = \sum_{h=0}^{h=8760} w_h PPD_h \quad (12)$$

$$\text{weighted annual average } C_{CO_2} = \sum_{h=0}^{h=8760} w_h C_{CO_2 h} \quad (13)$$

$$\text{weighted annual average } LL = \sum_{h=0}^{h=8760} w_h LL_h \quad (14)$$

where w_h is the weights of the occupancy in Hour *h*.

Objective function F_2 – Economic value

The economic cost consists of three parts: (a) net initial capital cost of glazing, (b) net operating cost, and (c) net *IEQ* cost.

The initial capital cost C_i is obtained by means of the indicative cost range in Table 4. The net initial capital cost for glazing Type *i* NC_i is calculated as the initial capital cost for glazing Type *i* less that of the reference case (Type 1):

$$NC_i = C_i - C_1 \quad (15)$$

Table 4 Indicative cost data for double and triple glazing for UK application(Thompson, 2011)

GLAZING TYPES		INDICATIVE COST (£/m^2)	MEAN (£/m^2)
Double glazing unit	Clear	125-135	130
	Clear with low-*e* coating	135-150	142.5
	Clear with high performance solar control and low-*e* coating	175-200	187.5
Triple glazing unit	Clear	180-195	187.5
	Clear with low-*e* coating	195-215	205
	Clear with high performance solar control and low-*e* coating	235-255	245

The net operating cost was calculated as follows. Firstly, the annual total energy demand, which consisted of annual heating energy demand $AED_{i,h}$, annual cooling energy demand $AED_{i,c}$, and annual lighting energy demand $AED_{i,l}$, was calculated using EnergyPlus 6.0. Secondly, the total energy demand of the office with Glazing Type *i* TED_i for 25 years is calculated as:

$$TED_i = [AED_{i,h} + AED_{i,c} + AED_{i,l}] \times 25 \quad (16)$$

The net energy demand of glazing Type *i* NED_i is:

$$NED_i = TED_i - TED_1 \quad (17)$$

Finally, it is assumed that all the energy is provided by electricity at a constant rate of £0.15/kWh, and the discount rate is 4.35%. The net present cost of net energy demand C_{iNED} (£) for 25 years is:

$$C_{iNED} = NED_i \cdot \sum_{n=1}^{n=25} \frac{0.15}{(1+7\%)^n} \quad (18)$$

In order to evaluate the monetary value of *IEQ*, the ‘performance-ambient’ relationship proposed in the preceeding section was deployed. First of all, *IEA* obtained in objective function F_1 was converted into *IES* using the relationship Filtered 3. Then the performance of employees was obtained using Eq (7). The performance of occupants for Glazing Type *i* was then compared with that for the reference case. The difference was the gain/loss in performance of occupants. The maintenance cost of the façade was not included.

According to the Office for National Statistics (Office for National Statistics, 2010), the employment cost for commercial offices in Inner London in 2010 is £49,034. Discounted at 4.35% for 25 years, the present value is £724,846/employee. The net present cost of employee for Glazing Type *i* CPL_i can therefore be calculated as:

$$CPL_i = \sum_{i=1}^{i=ne} \left(\frac{\text{Maximum productivity of employee}}{\text{productivity of employee for Type } i} - \frac{\text{Maximum productivity of employee}}{\text{productivity of employee for Type 1}} \right) \times 724,846 \quad (19)$$

where *ne* is number of employee.

Finally, the economic cost F_2 is:

$$F_2 = NC_i + C_{iNED} + CPL_i \quad (20)$$

Objective function F_3 – Environmental value

The environmental value is evaluated by the overall global warming potential (*GWP*) through life-cycle analysis. The initial *GWP* for producing glazing type *i* $IGWP_i$ was calculated according to Table 5 (Kellenberger et al., 2008). Due to the limited available data, it is assumed that glazing with different coatings has the same *GWP*. The disposal stage was ignored.

Table 5 GWP and density of coated and uncoated glazing (Kellenberger et al., 2008)

GLAZING TYPES	IPCC 2007 GWP (kg CO_2 eq)	DENSITY (kg/m^3)
Glazing uncoated	0.971	2.5
Glazing coated	1.13	

To account for the operating CO_2 emission, it is assumed that all the energy to maintain an appropriate office work environment is provided by electricity from the grid at current mix of renewable and non-renewable resources. The 2007 5-year grid rolling average electricity emissions factor of 0.54055kg CO_2/kWh was used (DEFRA, 2009). Therefore, the net operating global warming potential of the office room with Glazing Type *i* $OGWP_{net,i}$ can be calculated as:

$$OGWP_{net,i} = 0.54055 \cdot NED_i \quad (21)$$

Finally, the net GWP F_3 is calculated as:

$$F_3 = IGWP_i - IGWP_1 + OGWP_{net,i} \quad (22)$$

Optimisation Technique

Given that the input variables for Wong’s model need to be obtained through building energy simulation, i.e., the objective functions cannot be obtained through closed-form equations, a genetic algorithm NSGA-II (Deb et al., 2002) was chosen to perform the optimisation. The original NSGA-II algorithm was developed by Kanpur Genetic Algorithm Laboratory (K.G.A. Laboratory, 2010), and was only suitable for continuous variables. It was therefore modified to handle discrete variables. The scripts were developed in MATLAB 7.6.

Considering the dimension of the optimisation problem, the number of populations and number of generations were set to 60 and 20, respectively. The analysis was carried out on a Windows-based PC with a 2.83 GHz processor and 8GB of RAM.

DISCUSSION AND RESULT ANALYSIS

The computational time was 28 minutes. The results are plotted in Figure 6. The differences in economic value and *Net GWP* between the best and the worst design are £130,160 and 25,631kg CO_2, respectively. *IEA* ranges from 87.7% to 97.4%. The optimal solutions are described in Tables 6, 7, and 8. Glazing type 67 at 70% *WWR* represents the optimal trade-off of all the three objectives, and therefore should be the ideal design.

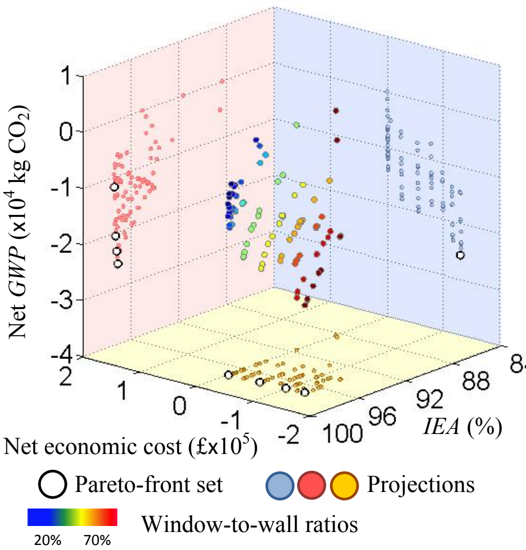

Figure 6 Optimisation result from NSGA-II

In order to verify the accuracy of the optimisation result, an exhaustive search was performed (Figure 7), which required 3.5 hours’ computational time. The exhaustive search produced the same Pareto-fronts set as NSGA-II, but 7 times slower. One interesting observation is that as WWR increases, the results become more scattered, which means the benefit of having high-performance glazing becomes more evident. The ratio of initial capital cost: operating energy cost: cost of employee ranges from 1: 12: 3099 to 1 : 1.5 : 470, as *WWR* increases from 20% to 70%. Therefore, the cost of employee is the dominating component for the whole life economic cost of a facade. In order to properly evaluate the economic value, this component should not be ignored.

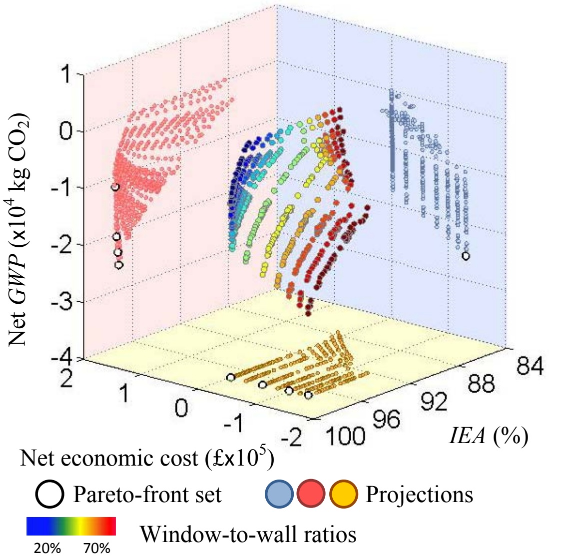

Figure 7 Optimisation result from exhaustive search

CONCLUSION AND FUTURE WORK

An 'ambient-performance' relationship was proposed to quantify the effects of *IEQ* on the productivity of occupants. The relationship was established upon two independent studies by linking them with a third regression equation. This relationship is fundamental to quantifying the economic value of *IEQ*.

Based on the 'ambient-performance' relationship, a whole-life-value based multi-objective optimisation model was constructed and illustrated with a simple application. It was sufficiently robust to identify the global minima with respect to each of the three objectives, and the Pareto-fronts set as trade-offs between the objectives. NSGA-II was suitable for this problem. The only shortcoming of the application is that the dimension of the problem is small. The model could potentially be used for product selection. Especially when the number of glazing types becomes larger and more variables are involved (e.g., orientation, *WWR*, framing, etc), the automated optimisation process provides an efficient way of product design. In addition, the cost of employee is a key component for the whole-life economic cost of a façade, which should not be ignored during the valuation.

Some future work has been identified.

1. The 'performance-ambient' relationship was established based on two existing studies. Further validation is required to gain more confidence in the accuracy of the relationship.
2. Further information is required for a detailed and accurate life-cycle analysis and whole-life-costing analysis. Such information should be obtained through literature review and contacting manufacturers.
3. The model should be extended to include the effects of façade framing systems. Thereby, the capability of the optimisation model to handle more complex problems should be investigated.
4. The design and optimisation tool should be trialed on real-world projects, and the computed optimal designs should be compared with the actual designs.

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NOMENCLATURE

PPD - Predicted percentage of dissatisfied (%)
w_h - Weight of the occupancy in Hour *h*
$C_{CO2\,h}$ - Average CO_2 concentration in Hour *h* (ppm)
C_i - Initial capital cost of Glazing Type *i* (£)
NC_i - Net initial capital cost of Glazing Type *i* (£)
TED_i - Total energy demand of the office with Glazing Type *i* for 25 years (kWh)
$AED_{i,h}$ - Annual heating energy demand (kWh)
$AED_{i,c}$ - Annual cooling energy demand (kWh)
$AED_{i,l}$ - Annual lighting energy demand (kWh)
NED_i - Net energy demand of glazing Type *i* (kWh)
CPL_i - Net cost of employee for Glazing Type *i* (£)
IEA - Acceptance of indoor environmental quality (%)
IEQ - Satisfaction of indoor environmental quality
ζ_2 - the CO_2 concentration (ppm);
ζ_3 - the equivalent noise level (dBA);
ζ_4 - the illumination (lux) at working plane.
φ_1 - the acceptance of thermal comfort (%)
φ_2 - the acceptance of air quality (%)
φ_3 - the acceptance of aural comfort (%)
φ_4 - the acceptance of light level (%)
k_1 - the relative importance of thermal comfort
k_2 - the relative importance of air quality
k_3 - the relative importance of aural comfort
k_4 - the relative importance of light level
PMV - Predicted mean vote (%)
WWR - Window-to-wall ratio (%)
$IGWP_i$ - Initial global warming potential for glazing type *i*
$OGWP_i$ - Operating global warming potential for glazing type
LL – light level at a specific point (lux)