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An ‘Ambient-performance’ relationship and its application

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1 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) [1]. Quite often, designers focus too much on the initial capital cost while ignoring the subsequent performance values to business operation and people. The whole-life value design approach provides the opportunity to redress this imbalance. For façade design, three main aspects should be considered, i.e., social values (occupant comfort), economic value (whole-life cost), and environmental value (environmental benefit/impact). A higher initial expenditure on facades could generate a more comfortable working environment for the occupants, and thereby improve the occupant productivity and ultimately result in a net economic gain.

This report describes the study in developing a whole-life value based optimisation model for façade design. Two alternative approaches are identified for the whole-life value of a design. The first approach is to approximate the social value and environmental value using monetary values, and therefore a single indicator that sums up the equivalent monetary social value, the whole-life cost, and the equivalent monetary environmental value could be used to indicate the whole-life value of a particular design. The second approach is to use different indicators for each aspect of whole-life value, i.e., social value, environmental value and economic value, and show the three objectives in a 3-D coordinate.

The aim of this report is to explain the theory that could be used for both approaches, and illustrate the second approach using a simple case study (Approach 1 will be illustrated in the near future when more data is obtained). Section 2 reviews existing research on the quantitative relationships between indoor environment quality and performance of people. Section 3 proposes a relationship to evaluate the indoor environment quality and to convert it into monetary value, based on the literature review in Section 2. A comparative study is carried out to validate this relationship. Section 4 describes a case study that illustrates a preliminary multi-objective optimisation model for the whole life value analysis of glazing.

2 Literature review

The performance/productivity of people is affected by indoor environment quality (IEQ) in a complex manner. Figure 2.1 illustrates this relationship. It should be noted that IEQ indicators listed here are those relevant to façades. Fisk [2] 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 (Table 2.1). Estimations on improved health and performance due to better IEQ are very crude due to the paucity of existing data, but the potential economic benefits is significant.

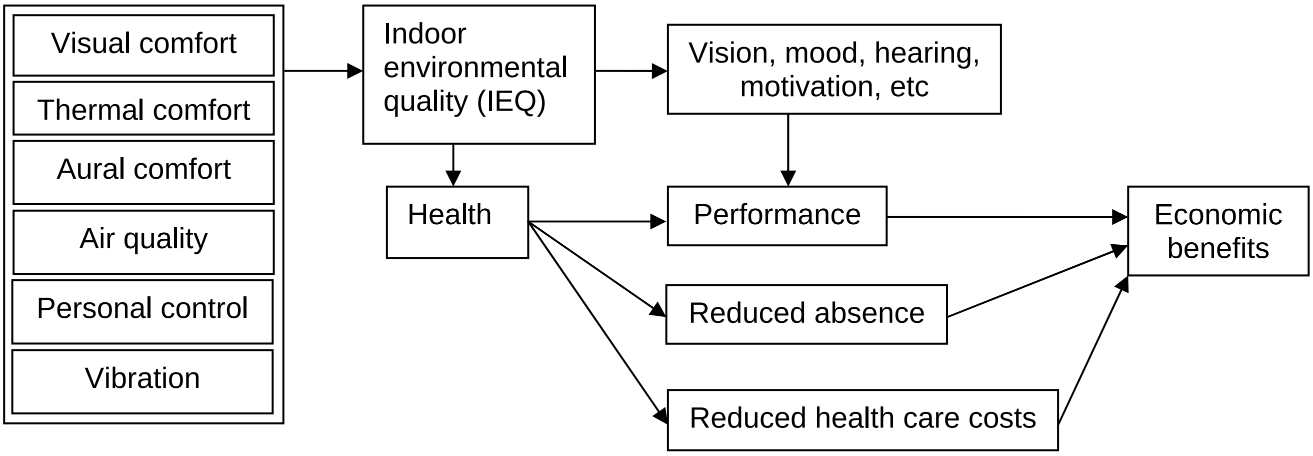
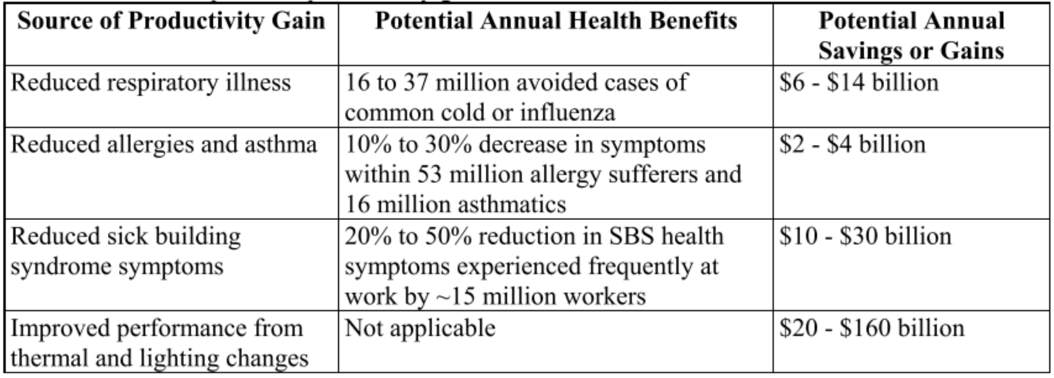


Figure 2.1: Relationship between IEQ indicators and the economic benefits (adapted from [3] and [4]).

Table 2.1: Estimated potential productivity gains in 1996 $US. [2]



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 sufferers 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	Not applicable	$20 - $160 billion

There are three ways of measuring the performance of occupants: physiological, objective, and subjective. Physiological measurement involves measuring the cardiovascular system, respiratory system, nervous system, and biochemistry. The main limitations are: (1) the relationship between physiological and other workload indices is not evident and difficult to interpret; (2) the measurements are very sensitive to other irrelevant conditions which might distort the result; and (3) the measurement interfere the operator’s normal performance. Objective measurements are usually task performance. The advantage is that quantitative results can be obtained. However, they are based on a limit number of resource models, and the measurements are usually carried out in a highly controlled manner, which might distort the results. Subjective measurements, which aim to gain the subjects’ perception on their level of performance by means of questionnaires and interviews, have gained support because people are likely to perform according to their feelings [5] [6]. Therefore, studies using subjective measurements to establish a quantitative relationship between IEQ and performance are reviewed in this section.

Early studies investigated the relationships between individual indoor environment aspect and human performance.

Seppanen *et al.* [7] reviewed and summarised previous studies in the effect of temperature on productivity, and proposed a simple model (Figure 2.2). Roelofsen [8], combined the experimental work of Gagge [9] and Fanger [10], and proposed a relationship between loss of performance and PMV using regression analysis. Kosonen *et al*. [11] studied the experimental work by Wyon [12] [13] [14], and reported quantitative relationships (Figure 2.3) between PMV and performance of two typical office work activities, i.e., thinking task and typing task. One assumption in the study was that the air temperature in the office was close to the radiant temperature of the surfaces within the office, which might not always be the case.

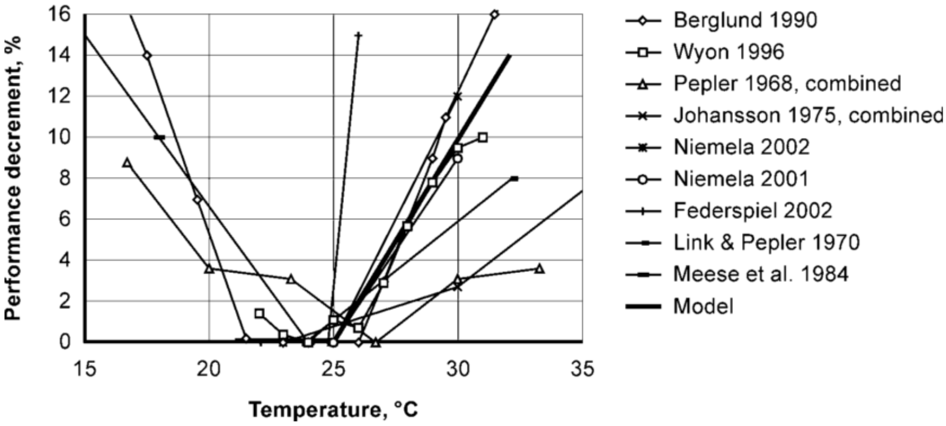


Figure 2.2: Summary of the studies on the effect of room temperature on decrement of performance and productivity. 'Model' denotes Seppanen *et al.* [7].

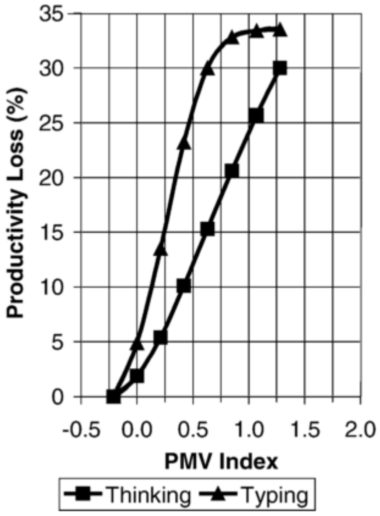


Figure 2.3: Curve fitting of thinking and typing tasks *vs*. productivity loss.

Three independent laboratory experiments were performed to investigate the effects of air quality on human health, comfort and productivity of office occupants [15] [16] [17]. Based on this data, Wargocki [18] derived a linear relationship showing that a 10% reduction in the proportion of people 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 by Tham [19] and Wargocki [20] found that improvement of air quality could increase the performance by 5% to 10%, which agreed with Wargocki [18]. In addition, Seppanen and Fisk [21] made use of experimental data from 7 independent previous studies and established quantitative relationships between performance and ventilation rate.

More recent studies focus on human responses to the indoor environment quality and from a broader perspective by incorporating the interaction between various indoor environment aspects.

Based on a comparative study of experiments in two climatic chambers, Clausen *et al* [22] concluded that 1°C change in operative temperature had the same effect on human comfort as a 2.4 decipol change in perceived air quality, or a 3.9 dB change in noise level, when the operative temperature ranges from 23°C to 29°C. This is the first quantitative relationship that was established to describe the relationship between air quality, thermal load, and noise level and the resultant effects on comfort. In addition, a quantitative relationship between percentage dissatisfied and traffic noise level was proposed in this study.

Clements-Crome *et al*. [23] carried out a survey in offices in Reading. The questionnaire asked the occupants to rank a series of factors using scores from 1 to 7 or 1 to 9. A quantitative relationship between the overall unsatisfactory indoor environment *En* (1-7), job dissatisfaction *JD* (1-7), crowded working space *CS* (1-7), and self-assessed productivity *P* (1-9) was established using multiple regression analysis of the questionnaire data, as indicated in Eq 2.1, 2.2 and 2.3.

$$P = 6.8510 - 0.3625En - 0.1542JD - 0.1329CS \tag{2.1}$$

$$En = -0.7211 - 0.5997Th - 0.4082SBS - 0.3222CS \tag{2.2}$$

$$JD = 1.2055 + 0.3157JS + 0.2572En + 0.1329CS \tag{2.3}$$

Where *Th* is suffer from thermal conditions (1-7), *SBS* is suffer from symptoms (1-7), JS is job stress (1-7). This study identified the main factors that affect productivity, and suggested that improvement of office environmental conditions could lead to 4-10% improvement in productivity. Similar to Clements-Crome *et al*. [23], Amina *et al*. [24] surveyed employees of 13 banks in Pakistan and proposed a regression equation:

$$\text{Employee Productivity} = -0.645 + 0.015F - 0.068N + 0.739L + 0.021T + 0.162SA \tag{2.4}$$

where *F* = furniture, *N* = noise, *L* = lighting, *T* = temperature and *SA* = spatial arrangements, which were ranked using 1 to 5. One flaw of this study is that it ignored an important factor – air quality. Chiang *et al*. [25] presented an indoor environment index (*IEI*) after analysing the results of experts' questionnaires using analytical hierarchy process (AHP) as:

$$\begin{aligned} \text{IEI} = {} & 0.203S_{acoustics} + 0.164S_{illumination} + 0.208S_{thermal\ comfort} \\ & + 0.290S_{indoor\ air\ quality} + 0.203S_{electromagnetic\ field} \end{aligned} \tag{2.5}$$

where *S* can be rated from 0-100 by occupants, and the coeffients are the weights for each aspect. A common limitation for the previous three studies is that, since all the variables need to be obtained subjectively, it is difficult to connect the outcome to a building energy simulation model, without knowing the relationship between the subjectively determined variables in those equations, and the objectively calculated simulation results from the model.

Kawamura *et al* [26] conducted an experiment in a climatic chamber, where eight environmental conditions were simulated. The subjects were asked to perform multiplication tasks, and rank their satisfaction with indoor environment (out of -1 to 1) and performance (out of 0 to 100%). Both self-assessed performance and the scores of the tasks were related to the satisfaction with indoor environment with a linear relationship. The self-assessed performance is more useful, because the subjects were asked to indicate their performance imagining they were doing office work under the current condition. In comparison, the scores of the tasks only provide a measurement of the participant's performance on the multiplication task, which might not be a good representation of office work.

Wong *et al*. [27] developed a multivariate-logistic model to predict the acceptance of IEQ in offices. The model was based on a survey of 293 occupants in offices in Hong Kong. A quantitative relationship was established between four IEQ indicators, i.e., operative temperature (°C), CO_2 concentration (ppm), equivalent noise level (dBA), and illumination level (lux). The overall IEQ acceptance, which is the ratio of number of people who consider the IEQ 'acceptable' to the total number of people work in the environment. This is the quantitative study that considers the widest range of aspects of IEQ to-date, and therefore provides the most comprehensive evaluation. The four indicators are easily measurable, which thereby makes the model ideal for using with building performance simulations. However, the model has two main limitations. Firstly, the indicators might not be sufficiently detailed and comprehensive to fully reflect the quality of each 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 in this model. Secondly, the survey was limited to in Hong Kong, and given that people residing in different climates might have different perceptions and responses to a particular indoor environment, it might not be representative of acceptance levels in other global regions.

3 Proposal of an ambient-performance relationship and a comparative study

3.1 Introduction

In order to assign a quantitative monetary value to IEQ, a combination of Wong [27] and Kawamura [26] is proposed to establish the links shown in Figure 3.1. This chapter describes the comparative studies that were carried out by the author to test the model against a number of independent studies.

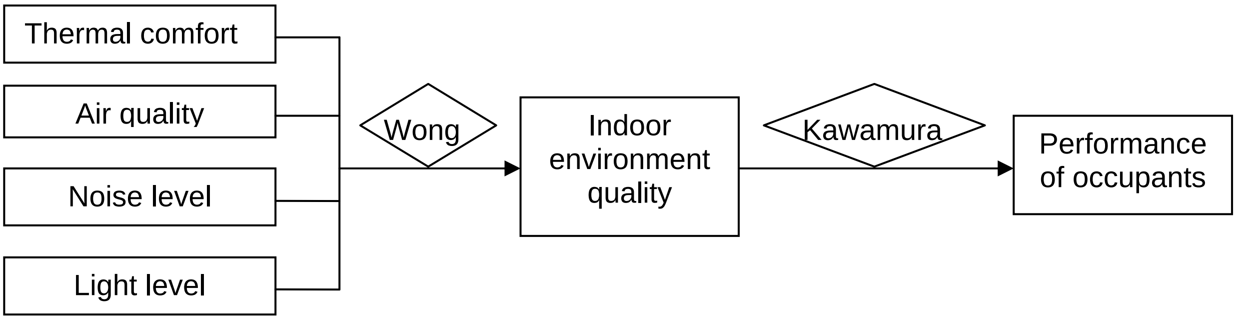


Figure 3.1: An ambient-performance relationship

3.2 Wong's model

Wong *et al* [27] proposed an overall IEQ acceptance as the indicator for indoor environment quality for office buildings. This is the only quantitative relationship that combines all four main factors, i.e, thermal comfort, aural comfort, lighting level, and air quality, which are then related to quantifiable indicators. The relationship was based on a survey of 293 occupants in the offices in Hong Kong. The IEQ acceptance θ was determined from a multivariate logistic regression model Eq (3.1) fitted to data from the questionares.

$$\theta = 1 - \frac{1}{1 + \exp[k_0 + \sum_{i=1}^{4} k_i \phi_i(\zeta_i)]}$$

$$k_i = \begin{cases} -15.02 \\ 6.09 \\ 4.88 \\ 4.74 \\ 3.70 \end{cases} ;i = 0,...,4. \qquad (3.1)$$

where φ_1 to φ_4 are the acceptance indices of thermal comfort, air quality, aural comfort and light level, and k_1 to k_4 represent the relative importance of the four factors. φ_1 to φ_4 are calculated from Eq (2), (3), (5), and (6). θ ranges from 0.4% to 97.9%. The acceptance factors will be explained and compared with results from other studies individually in the ensuing sections.

3.2.1 Acceptance of thermal comfort

3.2.1.1 Description of Wong's model

Wong [27] defines the acceptance index of thermal comfort as:

$$\phi_1 = 1 - \frac{PPD}{100} \tag{3.2}$$

where PPD is the predicted percentage of dissatisfied developed by Fanger [10], and Φ_1 denotes the acceptance of the thermal environment ranging from 23.2% to 95.0%. The recommended comfort criteria from CIBSE [28] for open-plan office is an operative temperature of 21-23 °C for winter, and 22-24 °C for summer.

3.2.1.2 Comparison with Fanger

Since Wong [27] is based on Fanger [10], good agreement is expected. Figure 3.2 compares the two models.

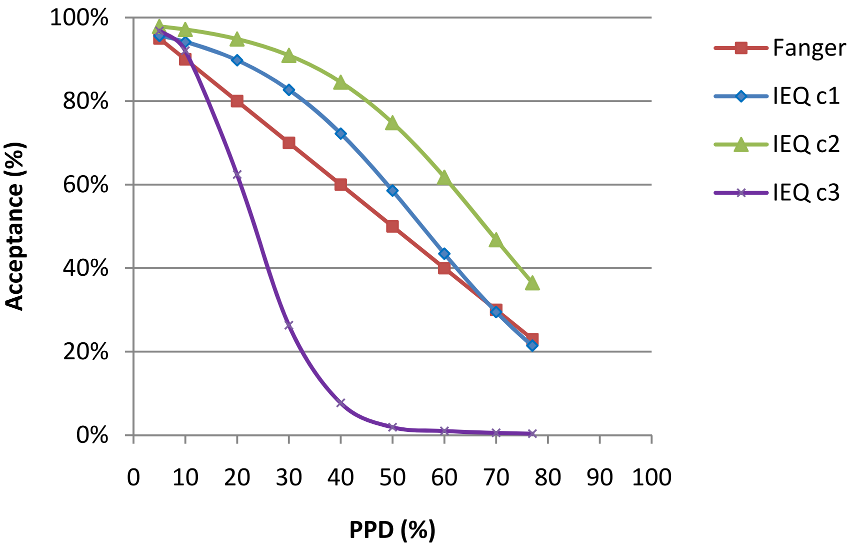


Figure 3.2: Acceptance of indoor environment quality/ thermal environment *vs.* PPD

The representations of the four curves are explained as follows:

Fanger: This curve describes Fanger's model [10]. The acceptance of thermal environment is calculated according to Eq (3.2).

IEQ c1: The acceptance of the overall indoor environment is calculated according to Wong's model i.e., Eq (3.1) and (3.2), with the assumption that illuminance =500lux, noise level =35NR = 41dBA, CO_2 concentration is 900 ppm. (These are the recommended conditions by CIBSE [28].)

IEQ c2: The acceptance of the overall indoor environment is calculated according to Wong's model i.e., Eq (3.1) and (3.2), with the assumption that the light level, aural comfort, air quality are at the highest level of satisfaction recorded by Wong's surveys, i.e., φ_2= 97.6%, φ_3= 97.1%, and φ_4=100%.

IEQ c3: The acceptance of the overall indoor environment is calculated according to Wong's model i.e., Eq (3.1) and (3.2), with the assumption that the level of satisfaction with light level, aural comfort, air quality are equal to thermal comfort satisfaction, i.e., $\varphi_1 = \varphi_2 = \varphi_3 = \varphi_4$, but bounded by their own lower boundaries.

Since Wong [27] makes use of Fanger [10], it is expected that Fanger and IEQ c1 agree well. IEQ c2 assumes all other conditions are satisfied 100%, and therefore has a positive effect on the overall IEQ acceptance.IEQ c3 assumes all other conditions are equally satisfied compared to thermal comfort. It shows that when the acceptances of all the 4 factors drop to less than 60%, the overall IEQ acceptance approaches zero. Compared to Fanger, IEQ c1, c2 and c3 exhibit a nonlinear relationship, since they consider the combined effects of the other indoor environment aspects (light, noise, and air quality). The uneven variation between Fanger and IEQ c1, c2 and c3 shows that the contribution of air quality, light level, and aural comfort to the overall acceptance of the indoor environment quality vary with different levels of thermal comfort.

3.2.2 Acceptance of air quality

3.2.2.1 Description of Wong's model

Wong [27] defines the acceptance index of air quality as:

$$\phi_2 = 1 - \frac{1}{2}\left[\frac{1}{1+\exp(3.118-0.00215\zeta_2)} - \frac{1}{1+\exp(3.230-0.00117\zeta_2)}\right]; (500 \le \zeta_2 \le 1800) \qquad (3.3)$$

where ζ_2 denotes the CO_2 concentration (ppm), and Φ_2 denotes the acceptance of the air quality ranging from 97.6% to 78.3%. The recommended comfort criteria for open-plan office by CIBSE [28] is an air supply rate of 10L/s per person. This equates to 900 ppm CO_2 concentration [29].

3.2.2.2 Comparison with PD CR 1752

PD CR 1752 [30] defines the percentage of dissatisfied of air quality as:

$$PD = 395 \cdot e^{-15.15 \cdot C_{co_2}^{-0.25}} \qquad (3.4)$$

where C_{CO2} is CO_2 concentration above outdoors. The outdoor CO_2 concentration is typically around 350ppm.

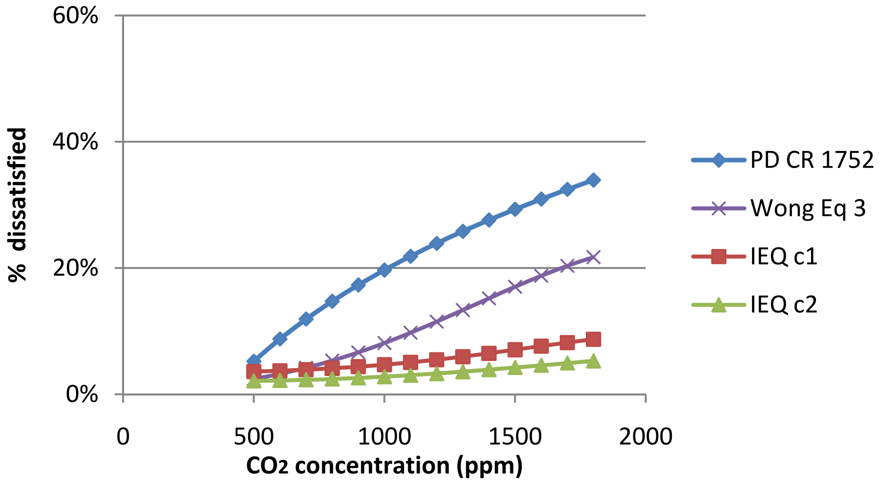


Figure 3.3: Percentage of dissatisfied of indoor environment quality/ indoor air quality *vs.* CO_2 concentration.

Figure 3.3 compares the two models. Four curves are plotted as follows:

PD CR 1752: calculated according to Eq (3.4).

Wong Eq 3: The percentage of dissatisfied is equal to 1- φ_2, where φ_2 is obtained from Eq (3.3).

IEQ c1: Then percentage of dissatisfied is equal to 1- θ, where θ is obtained from Wong's model with the assumption that illuminance =500lux, noise level =35NR = 41dBA, PPD is 5%.

IEQ c2: The percentage of dissatisfied is equal to 1- θ, where θ is obtained from Wong's model, with the assumption that the light level, aural comfort, air quality are at the highest level of satisfaction, i.e., φ_1= 95%, φ_3= 97.1%, and φ_4=100%.

Compared to PD CR 1752 [30], Wong's model [27] underestimates the affect of air quality on acceptance of indoor environment quality.

3.2.3 Acceptance of noise level

3.2.3.1 Description of Wong's model

Wong [27] defines the acceptance of noise level as:

$$\phi_3 = 1 - \frac{1}{1+\exp(9.540 - 0.134\zeta_3)};(45 \le \zeta_2 \le 72) \qquad (3.5)$$

where ζ_3 denotes the equivalent noise level (dBA), and Φ_3 denotes the acceptance of the noise level ranging from 97.1% to 47.3%. The recommended comfort criteria [28] for open-plan office is 35 NR. (For ordinary intrusive noise found in buildings, dBA is usually 4-8dB greater than the corresponding NR; dBA=NR+6 [28]).

3.2.3.2 Comparison with Balazova

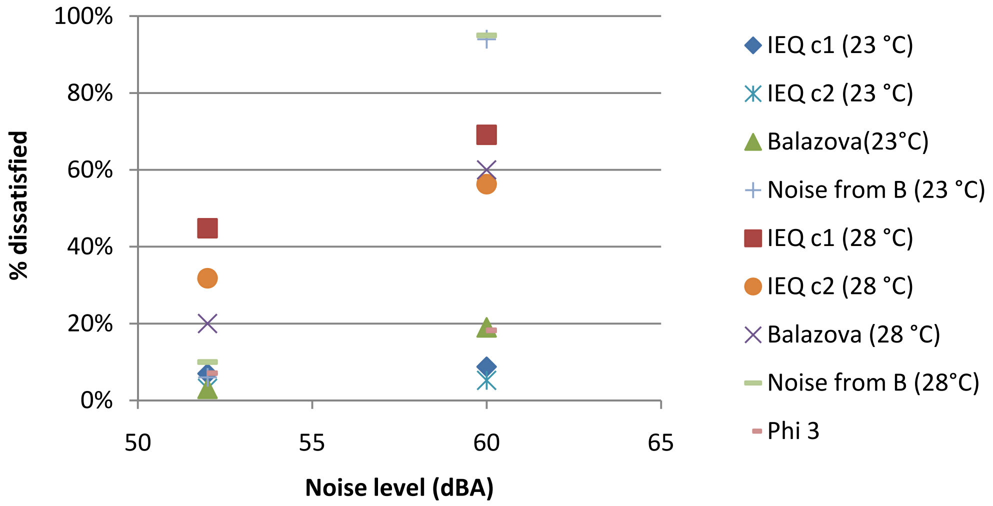


Figure 3.4 Percentage of dissatisfied of indoor environment quality/ aural comfort *vs* noise level

Figure 3.4 compares the two models. The representations of the data points are explained as follows:

Balazova: Experiment results. The experiment was run under two operative temperatures, i.e., 23°C and 28°C. The resultant percentage of dissatisfaction is mutually affected by thermal comfort and noise level.

IEQ c1: The percentage of dissatisfied is equal to 1- θ, where θ is obtained from Wong's model, with the assumption that illuminance =500lux, CO_2 concentration is 900 ppm, and operative temperature is 23/28°C.

IEQ c2: Then percentage of dissatisfied is equal to 1- θ, where θ is obtained from Wong's model, with the assumption that the light level, aural comfort, air quality are at the highest level of satisfaction, i.e., φ_1= 95%, φ_2= 97.6%, and φ_4=100%.

Phi 3: The percentage of dissatisfied is 1- φ_3, where φ_3 is obtained from Eq (3.5).

Noise from B: The percentage of dissatisfied of noise level is evaluated by the subjects in Balazova.

Balazova [31] did not consider the effects of lighting or CO_2 concentration. For 23°C, IEQ c1 fits Balazova better than IEQ c2. For 28°C, IEQ c2 fits Balazova better than IEQ c1. However, Wong generally predicts a lower sensitivity of noise level than Balazova. Phi 3 agrees well with Balazova at 23°C (thermal neutral temperature). Phi 3 and 'Noise from B' describe the percentage of dissatisfied with noise level only, but there is a substantial discrepancy between the two. A possible reason is that in Balazova, the subjects are only exposed to two noise levels, i.e., 52 dBA and 60 dBA, and therefore they would tend to have a higher dissatisfaction with the higher noise level.

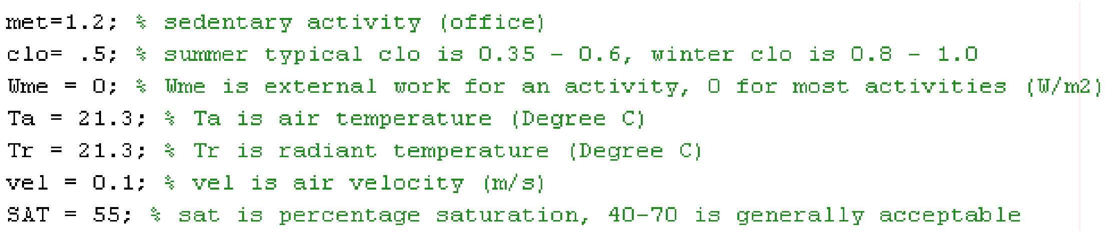
3.2.3.3 Comparison with Clausen

Figure 3.5 compares Wong and Clausens. The representations of the curves are explained as follows:

Clausen: experiment data [22].

Phi 3: The percentage of dissatisfied is 1- Φ_3, where Φ_3 is calculated according to Eq (3.5).

IEQ: Then percentage of dissatisfied is equal to 1- θ, where θ is obtained from Wong's model, with the assumption that illumination is 100% satisfied, CO_2 concentration is 900 ppm (in the experiment, air quality is measured by perceived air quality = 0.6 decipol), and operative temperature is 21.3 °C. Other factors, which are required to calculate PMV but not available from the paper, are assumed as follows:



```
met=1.2; % sedentary activity (office)
clo= .5; % summer typical clo is 0.35 - 0.6, winter clo is 0.8 - 1.0
Wme = 0; % Wme is external work for an activity, 0 for most activities (W/m2)
Ta = 21.3; % Ta is air temperature (Degree C)
Tr = 21.3; % Tr is radiant temperature (Degree C)
vel = 0.1; % vel is air velocity (m/s)
SAT = 55; % sat is percentage saturation, 40-70 is generally acceptable
```

There is a large discrepancy between Wong's model and Clausen's experimental data, when the noise level is larger than 50 dBA. A good agreement between IEQ and Clausen is obtained when the noise level is lower than 50 dBA. This is promising because the noise level will be used as a constraint in the mutli-objective optimisation model, and the recommended noise level in an office room is 41 dBA [28].

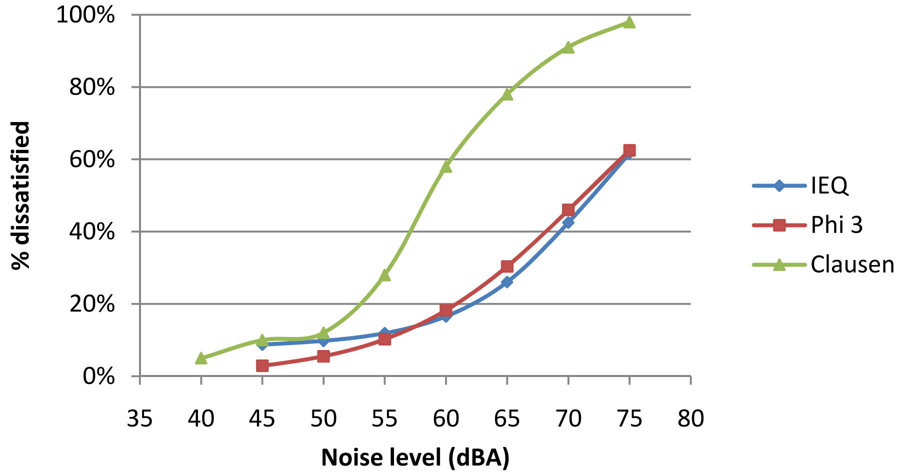


Figure 3.5**:** Percentage of dissatisfied of indoor environment quality/ aural comfort *vs* noise level

3.2.4 Acceptance of lighting level

Wong [27] defines the acceptance of light level as:

$$\phi_4 = 1 - \frac{1}{1+\exp(-1.017+0.00558\zeta_4)}; \qquad (200 \le \zeta_4 \le 1600) \tag{3.6}$$

where ζ_4 denotes the illumination (lux) at working plane, and Φ_4 denotes the acceptance of light level, ranging from 52.5% to 100.0%. This relationship is plotted in Figure 3.6.

The recommended comfort criteria for open-plan office by CIBSE is 300-500lux. There is no experimental study that shows a quantitative relationship between illuminance and acceptance. Assuming that the noise level =35NR = 41dBA, PPD is 5%, CO_2 concentration is 900 ppm, IEQ acceptance calculated according to Wong [27] is plotted in Figure 3.6. It shows that the overall acceptance of IEQ is not as sensitive as the acceptance of light level, especially when the illuminance is low. This is probably because at a lower illuminance level, good conditions in other aspects help to improve the overall perception of IEQ, while at a higher illuminance level, this contribution becomes smaller.

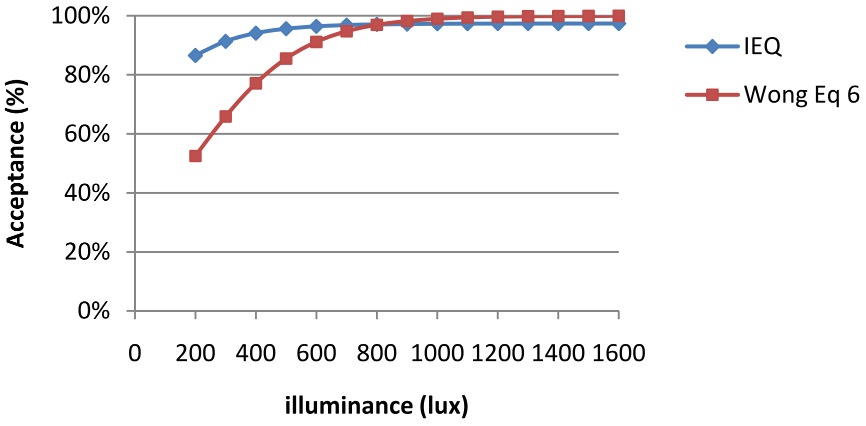


Figure 3.6**:** Overall IEQ acceptance/ acceptance of light level *vs* illuminance.

3.2.5 A possible relationship between Wong’s model and Kawamura’s experiment

The experiments in Kawamura [26] were carried out in a in a climatic chamber that simulated 8 conditions (Table 3.1). The whole experimental process is described as follows. Firstly, the subjects were asked to enter the chamber and indicate their satisfaction with indoor environment. Then they rested in the chair and indicate their satisfaction again after the rest. After that, they were asked to perform 4 independent multiplication tasks, and indicate their satisfaction after finishing each task (Figure 3.7). In Fanger [3], the percentage of dissatisfied is defined as ‘percentage of people predicted to perceive it as unacceptable just after entering the space’. Since Wong [1] is based on Fanger [3], the result should be compared with ‘before resting’ in Kawamura [26], as highlighted with a red frame in Figure 3.7.

Table 3.1: Environmental conditions tested in Kawamura [26]

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

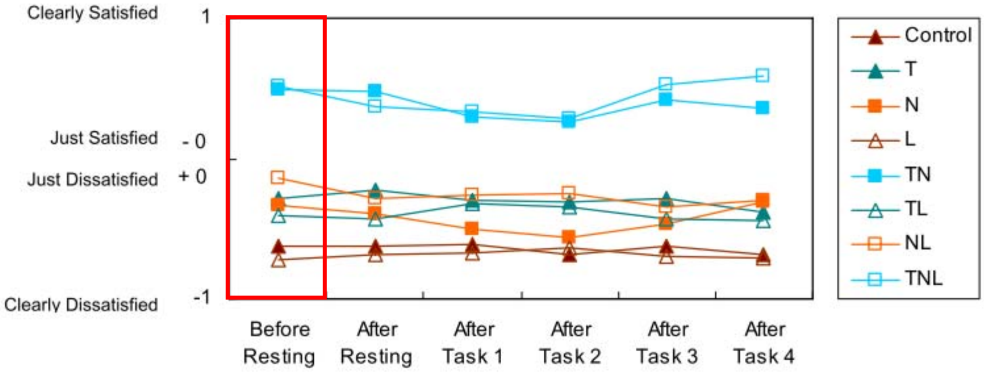


Figure 3.7: The votes of satisfaction with indoor environment [26]

The IEQ acceptance calculated according to Wong represents the percentage of people who will vote ‘acceptable’ for a specific indoor environment quality. In comparison, the ‘votes of satisfaction’ in Kawamura’s experiment denotes the mean score ranging from -1 to 1. The relationship between the two is unknown. Therefore, an attempt is made to establish one.

First of all, the IEQ acceptance for each experimental condition (Table 3.1) is calculated using Wong [1], and listed in Table 3.2. The relative air velocity is assumed to be 0.1m/s. It should be noted that Kawamura [26] did not provide any records on the metabolic rate of the subjects, which is required for calculating PPD. The metabolic rate is assumed to be 1.2 met, which is equal to the metabolic rate for normal office work recommended by CIBSE [28]. The satisfaction of IEQ is obtained from Kawamura’s experiment [26] directly, and listed in Table 3.2.

Table 3.2: Comparison of calculated IEQ acceptance according to Wong [1] and measured satisfaction of IEQ by Kawamura [26].

	Wong					Kawamura
Experimental conditions	**Φ_1 Eq (3.2)**	**Φ_2 Eq (3.3)**	**Φ_3 Eq (3.5)**	**Φ_4 Eq (3.6)**	**IEQ acceptance Eq (3.1)**	**IEQ satisfaction**
Control	0.516	0.928	0.75	0.776	28.36%	-0.62
T	0.850	0.937	0.724	0.775	73.60%	-0.29
N	0.592	0.944	0.945	0.772	62.87%	-0.33
L	0.567	0.944	0.724	0.964	50.97%	-0.72
TN	0.816	0.948	0.937	0.772	86.69%	0.49
TL	0.856	0.939	0.724	0.964	85.49%	-0.41
NL	0.587	0.947	0.937	0.961	76.44%	-0.14
TNL	0.760	0.925	0.937	0.960	89.24%	0.51

Secondly, the IEQ acceptance and IEQ satisfaction are plotted in Figure 3.8, and compared with Fanger's model [10]. Although Fanger's model [10] only considers thermal comfort, it is well established and well received, and the variables PPD and PMV are very comparable to IEQ acceptance and IEQ satisfaction, respectively. To be specific, IEQ acceptance is like (1-PPD); IEQ satisfaction is like PMV. Therefore, Fanger's model [10] was manipulated to compare with the data. In the manipulation, it is assumed that there is a linear relationship between PMV and IEQ satisfaction, 'PMV = 0 (thermal neutral)' is equivalent to 'IEQ satisfaction = 1 (clearly satisfied)', and 'PMV = -2 (very cold)' is equivalent to 'IEQ satisfaction = -1 (clearly dissatisfied)'. IEQ satisfaction can be calculated as:

$$\text{IEQ satisfaction} = \text{PMV}+1 \qquad \text{(Eq 3.7)}$$

According to Fanger's model [10], PPD is calculated as:

$$\text{PPD} = 100 - 95\exp\left[-0.03353\text{PMV}^4+0.2179\text{PMV}^2\right] \qquad \text{(Eq 3.8)}$$

Assume that there is a linear relationship between PPD and IEQ acceptance as:

$$\text{IEQ acceptance} = 1-\text{PPD}/100 \qquad \text{(Eq 3.9)}$$

Therefore, a possible relationship between IEQ acceptance and IEQ satisfaction extended from Fanger's model is:

$$\text{IEQ acceptance} = 0.95\exp\left[-0.03353\,(\text{IEQ satisfaction} -1)^4+0.2179\,(\text{IEQ satisfaction} -1)^2\right] \qquad \text{(Eq 3.10)}$$

This relationship is plotted in Figure 3.8. It shows that the data from the combination of Wong [1] and Kawamura [26] roughly follows the extended Fanger.

Finally, an attempt was made to establish the relationship between IEQ acceptance and IEQ satisfaction. Compared to Points T, N, NL, and TN, it is clear that Point TL overestimated the IEQ acceptance or underestimated the IEQ satisfaction. In addition, Point L and Point Control conflict with each other, so at least one of them should be an outlier. Assume that the relationship between

(1-IEQ acceptance) and IEQ satisfaction is similar to the relationship between PPD and PMV as in Eq 3.8. Three curves of the relationship were made using curve-fitting (Table 3.3), and plotted in Figure 3.8.

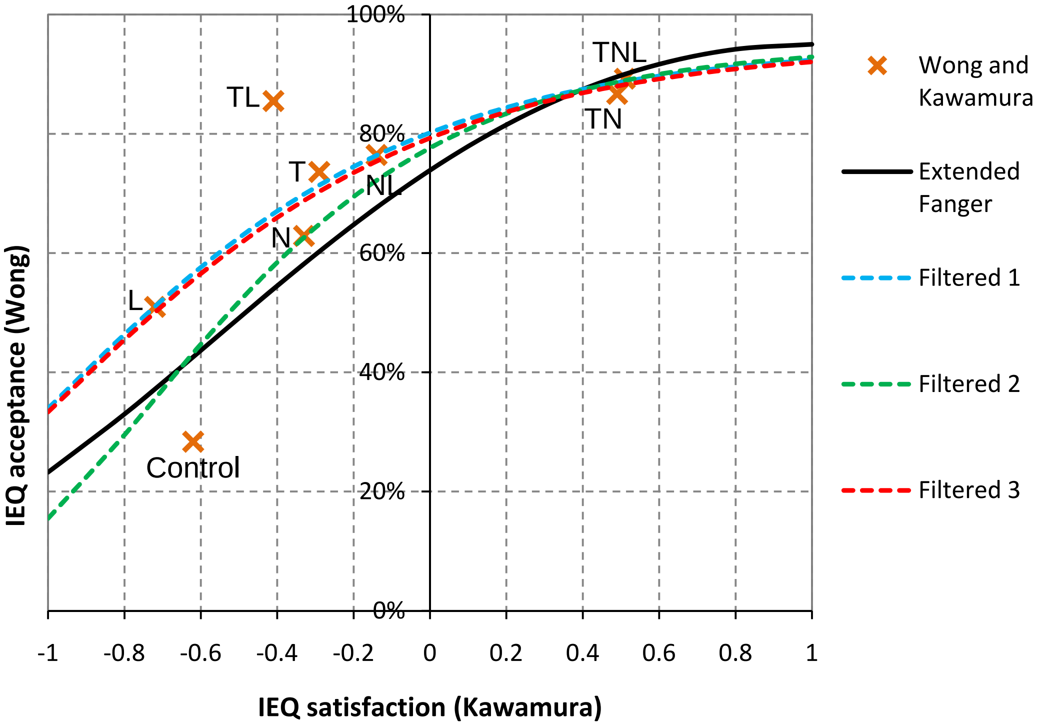


Figure 3.8 The relationship between IEQ acceptance (Wong) and IEQ satisfaction (Kawamura).

Table 3.3: Curve-fitting of Wong-Kawamura data.

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

IEA: Acceptance of IEQ; *IES*: Satisfaction of IEQ.

According to Figure 3.8, Filtered 2 predicts a lower IEQ acceptance than Filtered 1 and 3 when IEQ satisfaction is less than 0, mainly because Point Control remains and thereby ‘drags’ the curve downwards. Even so, Filtered 2 still shows that Point Control underestimated the IEQ acceptance or overestimated the IEQ satisfaction. Therefore, it is very likely that Point Control is an outlier. As explained before, Point TL is likely to be an outlier, too. 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.

In conclusion, Point Control and Point TL should be eliminated, and Filtered 3 is probably a reasonable relationship between IEQ acceptance and IEQ satisfaction. Therefore, Filtered 3 will be used in the whole-life value optimisation model to convert indoor environment quality into the productivity of people. However, it should be noted that further investigation is required to validate this relationship.

3.3 Kawamura’s model

3.3.1 Description of Kawamura’s model

Kawamura’s [26] experiment procedure was described in Section 3.2.5. Based on the experimental data, Kawamura proposed a quantitative relationship between the overall indoor environment quality and performance of people as follows:

$$PP = 15.097x + 75.466 \; ; \qquad (-1 \le x \le 1) \tag{3.11}$$

where PP is self-predicted performance. It is obtained from one of the scale questions in the questionnaire – “Imagine you are working in office under this environment, mark how much you can perform on a segment that represents 0 to 100. If thermal, lighting, acoustic environment were well-suitable to work, you should mark at 100.” x is satisfaction with indoor environment ranging from -1 to 1, where -1 represents “clearly unsatisfied”, -0 represents “just unsatisfied”, +0 represents “just satisfied”, and +1 represents “clearly satisfied.” It is noticed that even if the environment is clearly satisfied, the predicted self-performance is 90.6%. It could be explained that even if the environment is very suitable to work, people are unlikely to consider themselves being able to work at 100% performance for the whole working time. Similarly, even if the environment is clearly unsatisfied, people are unlikely to consider themselves having a productivity of zero. This agrees with the climatic chamber test results from Balazova *et al* [31], and a detailed environmental survey in an office building carried out by Clements-Croome *et al* [23].

3.3.2 Comparison with Roelofsen and Kosonen

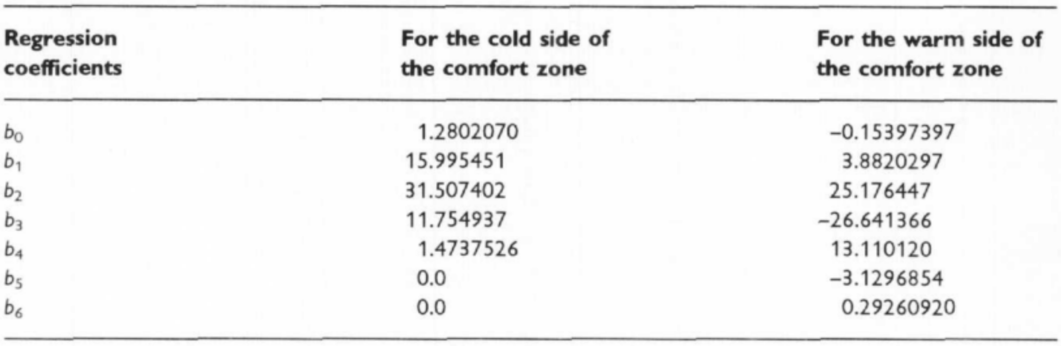
This section compares the results from a combination of Wong and Kawamura with two existing relationships, i.e., Roelofsen [8] and Kosonen [11].

The relationship between PMV and performance in Roelofsen [8] is:

$$P = b_0 + b_1 PMV + b_2 PMV^2 + b_3 PMV^3 + b_4 PMV^4 + b_5 PMV^5 + b_6 PMV^6 \tag{3.12}$$

where P is the loss of performance (per cent), and b_0 – b_6 are regression coefficients shown in Table 3.2. The relationship was obtained by a regression analysis of the experimental work of Gagge [9] and Fanger [10].

Table 3.4: The regression coefficients for the Eq (3.8).



Regression coefficients	For the cold side of the comfort zone	For the warm side of the comfort zone
b_0	1.2802070	−0.15397397
b_1	15.995451	3.8820297
b_2	31.507402	25.176447
b_3	11.754937	−26.641366
b_4	1.4737526	13.110120
b_5	0.0	−3.1296854
b_6	0.0	0.29260920

Kosonen *et al.* [11] performed a study to predict the productivity loss with respect to PMV index. The study was based on the assumption that the room temperature is equal to the radiant temperature. Different mathematical expressions were developed for two types of office work, i.e., typing task and thinking task. The two equations applied for the operative temperature ranging from 20°C to 27°C.

Figure 3.9 compares the two models. The representations of the curves are explained as follows:

Roelofsen: Performance of people is obtained from Eq (3.8).

IEQ: this is a combination of Wong and Kawamura. First, calculate PPD using PMV; then, calculate acceptance of thermal environment using Eq (3.2); then, assume that the light level=500lux, noise level=45dB and air quality =900 ppm, and therefore IEQ acceptance could be obtained from Eq (3.1); IEQ satisfaction is then calculated according to the relationship proposed by Filter 3 in Table 3.3; finally calculate the performance using Eq (3.7).

Kosonen thinking/typing: this is the mathematical expressions proposed from Kosonen's study [11].

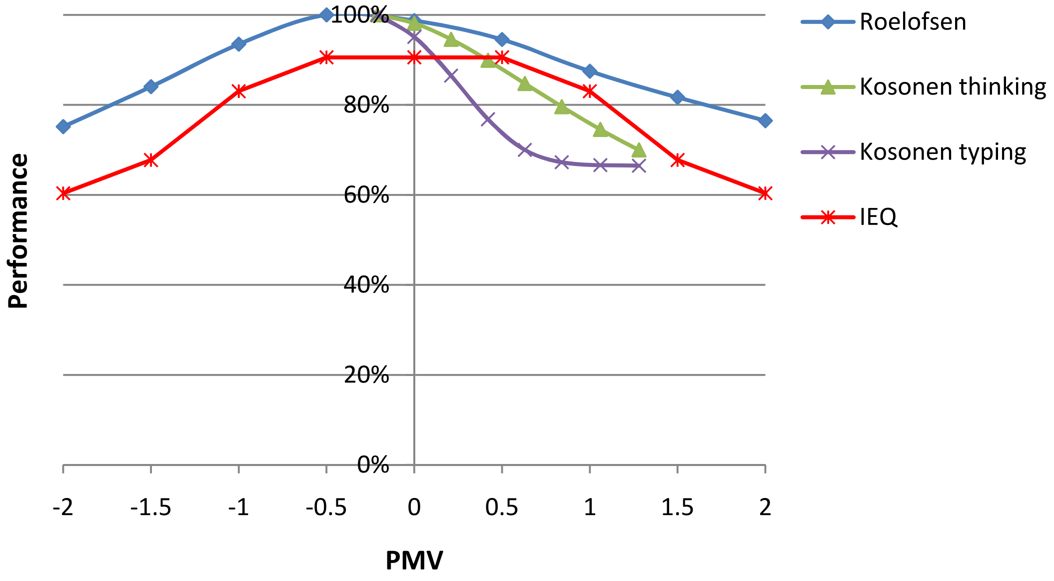


Figure 3.9: Performance of occupants *vs.* PMV

Kosonen predicts a higher sensitivity of performance to PMV than the other two models. Both Roelofsen and Kosonen describe asymmetric curves, while IEQ provide a symmetric prediction. This could be a limitation from Wong's model. In addition, 100% predicted performance is unachievable in IEQ, and the possible reason is explained in Section 3.3.1. There are not big variations when PMV ranges from -0.5 to 0.5, which might be the real situation or a limit of the model. Admittedly, there are discrepancies among the three models. However, since IEQ goes between Roelofsen and Kosonen across most range of PMV, it should be considered as a reasonable representation between PMV and Performance of the occupants.

3.3.3 Comparison with Wargochi and Bako-Biro

This section compares the results from a combination of Wong and Kawamura with two regression relationships proposed by Wargochi [32] and Bako-Biro [33].

Kawamura is obtained using the following approach: assume that light level, noise level and thermal comfort are satisfied to the highest level, i.e., φ_1= 95%, φ_3= 97.1%, and φ_4=100%, calculate the IEQ acceptance from acceptance of air quality using Eq (3.1), and then calculate the performance using Eq (3.7).

The three models are shown in Figure 3.10. Compared to Wargochi [32] and Bako-Biro [33], Kawamura underestimate the performance by around 10%.

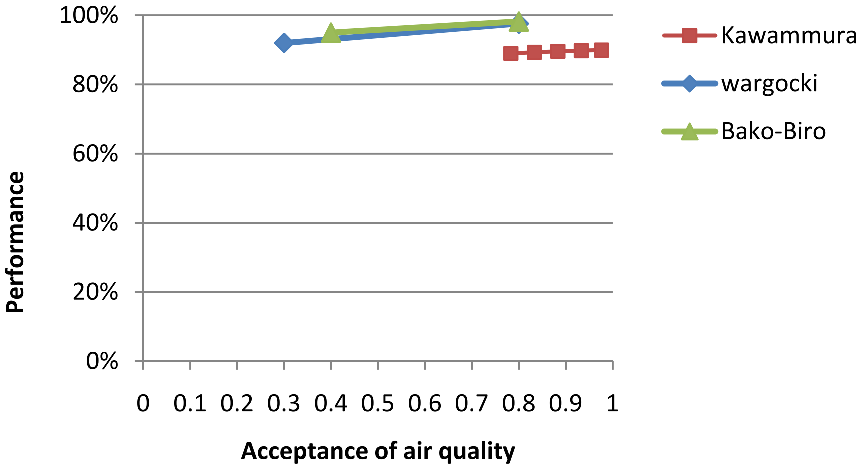


Figure 3.10: Performance of people *vs.* acceptance of air quality.

3.4 Conclusions

Wong's model describes the relationship between overall indoor environment quality and various physical parameters. It agrees well with Fanger when predicting the relationship between the thermal comfort and the overall IEQ acceptance. Prediction of acceptance of air quality does not agree very well with PD CR 1752. Regarding to noise level, there are significant variations at high noise levels, but as long as we assume that the noise level is low enough to satisfy CIBSE, the good agreement with Clausen proves the validity of Wong's model. There are no known studies which have established the quantitative relationship between satisfaction of light level and illuminance. However, IEQ acceptance calculated from Wong is not very sensitive to light level, especially when the illuminance is above 500 lux. Kawamura's experimental data was compared with Wong's model in predicting the overall IEQ acceptance. Three indoor environment conditions agree well, but others not.

Kawamura's model describes the relationship between indoor environment quality and performance of people. A combination of Wong and Kawamura provides the opportunity to assign economic values to indoor environmental quality. The results from this combination were compared with Roelofsen and Kosonen from the aspect of thermal comfort, and with Wargochi and Bako-Biro from the aspect of air quality. Except for Kosonen, the other models generally agree with the combination. It also should be noted that the thermal comfort and air quality are the factors that affect the perception of indoor environment quality the most – according to Wong's model, they have higher relative importance factors. Although no other studies could be found to validate the effects of light level, it will be modelled as constraints to satisfy predefined criteria, and therefore should not have large effects on the overall acceptance of indoor environment quality.

Since Both Wong and Kawamura were obtained through subjective methodology, the accuracy and reliability are indeed subject to further investigation, and large discrepancies with some other studies are understandable. However, given that a combination of Wong and Kawamura generally agree well with a number of independent studies on the aspects of thermal comfort and air quality, which are the most important two factors, it is concluded that this combination should be robust in predicting the economic value of indoor environment quality. However, the prediction of performance cannot achieve 100% using this combination, and the sensitivity to PMV (-1, 1) is not visible. This could be true that people’s performance is not largely affected within the thermal comfortable region. More data is required for further investigation.

4 Application: Selecting the optimal glazing type for a typical office room.

4.1 Introduction

There have been numerous studies on the performance of advanced glazing (Table 4.1). Among the studies, Sullivan *et al*. [34] considered the performance of the widest range of advanced glazing types in nine European countries, Australia and the US, although not all the types of glazing were investigated for each location. There have been significant changes to the performance properties in the 15 years since Sullivan's research. And several properties of the advanced glazing used in Sullivan's research are now outdated. A more recent study by Carmody *et al*. [35] compared most aspects of performance, including heating/cooling/lighting energy demand, view factor, daylight factor, glare, and peak energy demand. However, the technologies included were not as comprehensive as Sullivan's study.

The aim of this study is: (1) to establish a preliminary multi-objective optimisation model for high-performance glazing, and (2) to identify the optimal glazing type for a typical south-facing office room located in London, with varying window-to-wall ratio (WWR).

4.2 Description of the typical office room

In order to obtain results more representative of a real-world senario, a building energy simulation model was constructed to represent a typical office room. The geometry of the room is illustrated in Figure 4.1.

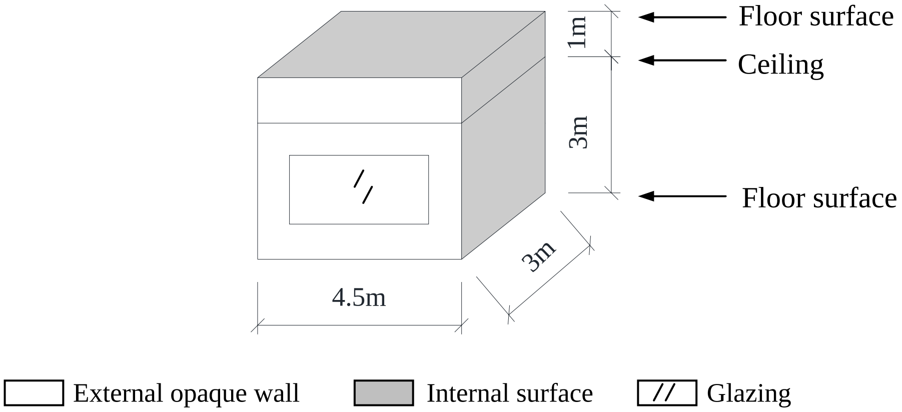


Figure 4.1 Typical office room in London

The floor to ceiling height is 3m and the total floor zone height is 1m. The construction of floor is 0.25m concrete slab with 0.15m cavity raised floor tiles above it. The ceiling is 0.6m below the slab with ceiling tiles hung from the slab.

It is assumed that only one surface of the room is exposed to the external environment, while the other surfaces are adjacent to ambient rooms which have the same thermal condition with the simulated room and are therefore assumed to be adiabatic. The internal walls are steel stud partition systems with 2x12mm gypsum boards on each side. The U-value of the exposed wall is improved to $0.35W/m^2 \cdot K$ to satisfy the requirements of Building Regulations for England and Wales[36]. The cooling and heating set points are 24°C and 22°C in summer, and 23°C and 21°C in winter in accordance with CIBSE recommendations [28]. The ventilation rate is assumed to be 15L/s per person [28].

The internal gains from people, artificial lighting, and equipment were specified in accordance with CIBSE recommendations [28] as follows: the office was assumed to be occupied by two occupants with an activity level of 125W/person. The internal heat gain from fluorescent lighting level is 12 W/m^2. The internal heat gain from electric equipment is 18W/m^2. Automatic dimming of the artificial lighting triggered by daylight levels was applied in this model. The two reference points for daylight control were 2m away from the window and 0.8m above the floor level. The illuminance setpoint was 500lux, which means that when the illuminance was above 500lux, the artificial light could be dimmed gradually to maintain 500lux.

It is assumed that all the energy is provided by electricity at a constant rate of £0.15/kWh, and the discount rate is 4.53% (calculated from the mean of 20-year and 30-year UK government bond yields on 29/04/2011) [37].

4.3 Problem description

The two variables for this optimisation problem are WWR and the glazing type. WWR ranges from 25% to 95%, increasing at an interval of 5%. Glazing type is a discrete variable. For each glazing type, three basic thermal performance properties (U-value, solar heat gain coefficient g-value and visible transmittance T_v) were specified from Interpane's product sheets [38], as shown in Figure 4.2 and Figure 4.3. Conventional DGs are clear double glazing units with no coatings, which are included as a comparison to the Interpane's product. All the glazing types are numbered from Type 1 to Type 67. It is assumed that the service life of all the glazing units is 25 years.

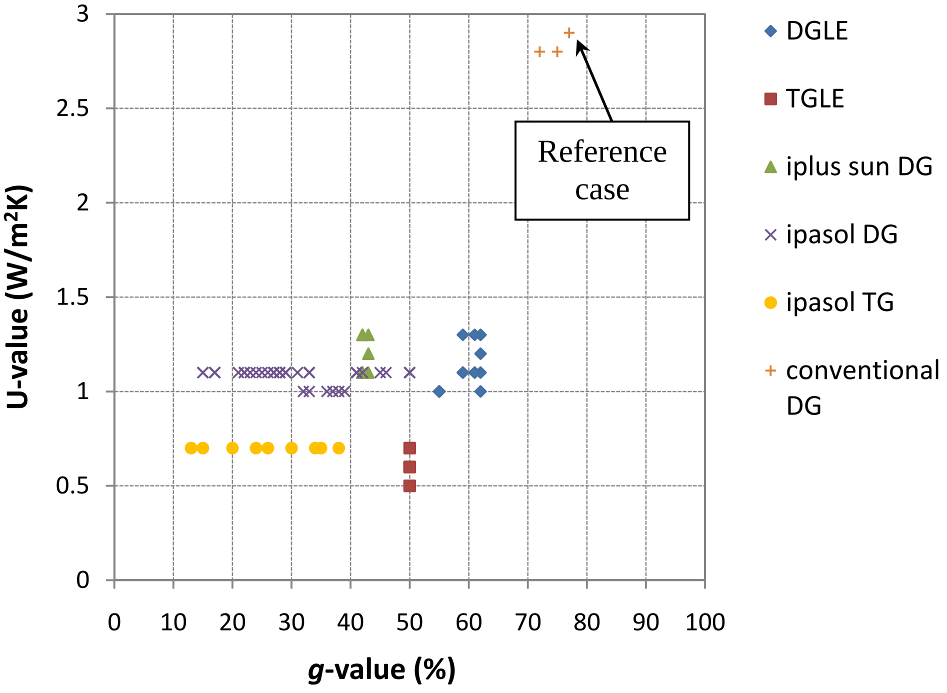


Figure 4.2: U-value *vs.* g-value of Interpane's 67 glazing types

Table 4.1 Performance-based comparison of high-performance glazing

Reference	Compared coatings/technologies									other variables	Methodology
	multi-pane window (S/D/T/Q glazing)	glass types (clear/ body tinted)	**low-e**	**anti-reflective**	**reflective**	**solar control**	**electro-chromic**	vacuum /aerogel	thermo-chromic		
Saeli *et al*. 2010[39]	D	X	X		X				X	WWR, climates	EnergyPlus to calculate heating, cooling and lighting energy demand
Nilsson & A. Roos 2009 [40]	D		X		X	X	X			climates, orientations	WinSel modelling heating/cooling energy balance
Rosencrantz *et al*. 2005 [41]	D/T		X	X						Nordic climates, orientations	ParaSol to calculate heating demand; Rayfront to calculate daylight factor and illuminance
Carmody *et al*. 2004 [35]	S/D/T/Q	X	X		X	X				Climates, orientations, WWR, shading strageties	DOE2.1 to calculate cooling/heating/lighting energy, daylight factor, view factor, glare index, peak energy demand
Karlsson 2001 [42]	N/A		X			X				orientations, climates	Improved karlsson model (DH model) to calculate energy balance and total energy saved
Kontoleon & Bikas 2002 [43]	D		X		X					WWR	A lumped capacitance one-dimensional network model to calculate max/min temperature, heating and cooling energy consumption
Sekhar *et al*. 1998 [44]	D	X	X		X					-	DOE2.1 to calculate total energy consumption; BLCC to calculate life cycle cost
Cordoba 1998 [45]	D	X	X			X				WWR	DOE2.1 to calculate heating/cooling/lighting energy demand
Sullivan *et al*. 1995 [34]	S/D/T/Q	X	X	X	X	X	X	X		climates, orientations	DOE2.1 modelling heating/cooling/lighting

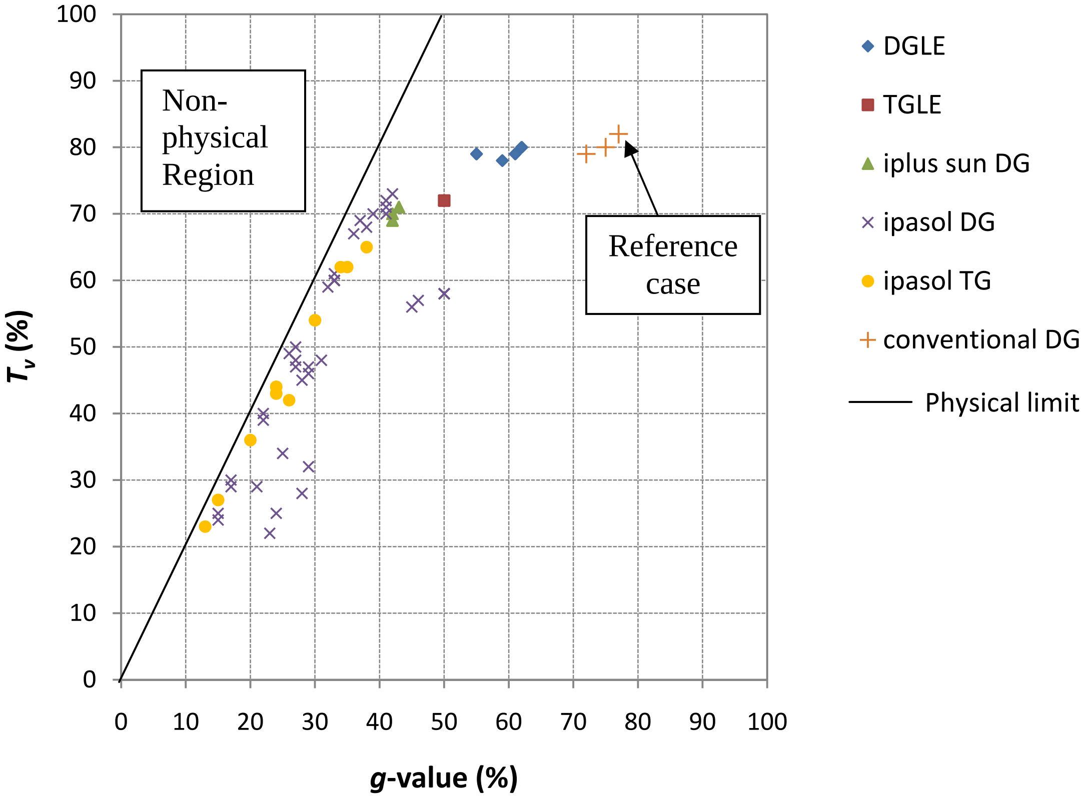


Figure 4.3: T_v *vs.* *g*-value of Interpane's 67 glazing types.

The optimisation problem has three objectives: F_1 - to maximise the social value, i.e., the overall IEQ acceptance, F_2 - to minimise the economic cost, and F_3 – to minimise the environmental impact, i.e., the global warming potential (GWP). The three objective functions are calculated as follows:

Reference Case

In order to focus on the glazing and minimise all other effects such as the geometry of a room, the furniture, etc, a reference case was established. The reference case (Type 1) is a conventional double glazing unit consisting of two 4mm glass sheets and 12mm air cavity, with a *U*-value of 2.9, a *g*-value of 77% and a T_v of 82%, as indicated in Figure 4.2and Figure 4.3.

Objective function F_1:

The social value is evaluated by the overall IEQ acceptance, where IEQ acceptance is calculated according to Wong's model using Eq 3.1, 3.2, 3.3, 3.5, and 3.6. The noise level is assumed to be 41 dBA. CO_2 concentration and PPD are obtained from the computational energy analysis performed in EnergyPlus. It is assumed that the CO_2 generation rate per person is $3.82\text{x}10^{-8}$ $m^3/s{\cdot}W$ (obtained from ASHRAE Standard 62.1-2007 value at 0.0084cfm/met/person over the general adult population) [46], and the CO_2 level in the atmosphere is 390ppm [47].

For thermal comfort calculation, 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 [10]. The air velocity is assumed to be 0.05m/s [10]. The clothes level is assumed to be 0.7 for summer (May - Sep) 0.85 for winter (Jan – Apr, Oct - Dec) [28]. From the hourly PPD , hourly CO_2 concentration, and hourly light level at a specific point obtained from EnergyPlus, the occupancy weighted annual average PPD, CO_2 concentration and light level are then calculated as follows:

$$\text{weighted annual average } PPD = \sum_{h=0}^{h=8760} w_h PPD_h \tag{4.1}$$

$$\text{weighted annual average } C_{CO_2} = \sum_{h=0}^{h=8760} w_h C_{CO_2 h} \tag{4.2}$$

$$\text{weighted annual average } LL = \sum_{h=0}^{h=8760} w_h LL_h \tag{4.3}$$

Where w_h is the weights of the occupancy in hour h.

Finally, The IEQ acceptance at reference point 1 and reference point 2 are calculated according to Wong's model, i.e., Eq 3.1, 3.2, 3.3, 3.5, and 3.6, and the overall IEQ acceptance F_1 is calculated as the mean of the two.

Objective function F_2:

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

The initial capital cost C_i is obtained by taking the middle level from the indicative cost range provided by Thompson [48] (Table 4.2). And then the net initial capital cost for glazing Type i NC_i is calculated as the initial capital cost for glazing Type i net that of the reference case (Type 1).

$$NC_i = C_i - C_1 \tag{4.4}$$

Table 4.2: Indicative cost data for double and triple glazing for UK application.

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 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 Low E coating	235-255	245

The operating cost was calculated as follows. Firstly, the annual energy demand, including heating, cooling, and lighting energy, was calculated using a validated thermal model constructed in EnergyPlus 6.0, a detailed description is provided in [49]. The total energy demand is calculated as 25 (years) times the annual total energy demand, as Eq 4.4.

$$\begin{aligned} \text{Total Energy Demand } TED \text{ (kWh)} = [&\text{annual heating energy demand (kWh)} \\ &+ \text{annual cooling energy demand (kWh)} \\ &+ \text{annual lighting energy demand (kWh)}] \times 25 \text{ (years)} \end{aligned} \quad (4.5)$$

Then, the net energy demand *NED* of glazing Type *i* is:

$$NED_i = TED \text{ (Type } i\text{)} - TED \text{ (Type 1)} \quad (4.6)$$

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

$$C_{iNED} = NED_i \cdot \sum_{n=1}^{n=25} \frac{0.15}{(1+4.35\%)^n} \quad (4.7)$$

In order to evaluate the monetary value of IEQ, Wong's model and Kawamura's model (for details refer to Section 3) are deployed. First of all, the IEQ acceptance obtained in objective function 1 was converted into satisfaction of IEQ using the relationship Filtered 3 in Table 3.3. Then the performance of employees was calculated using Eq.3.11. The performance of people for Glazing Type *i* was then compared with that for Glazing Type *1*. The difference is the gain/loss in performance of people.

According to the Office for National Statistics [50], 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 25 yrs. Therefore, the net cost employee for Glazing Type *i* CPL_i can be calculated as:

$$CPL_i = 2 \times 724{,}846 \times \left(\frac{\text{Maximum performance of employee}}{\text{performance of employee for Type } i} - \frac{\text{Maximum performance of employee}}{\text{performance of employee for Type 1}}\right) \quad (4.8)$$

Therefore, the economic cost F_2 is:

$$F_2 = NC_i + C_{iNED} + CPL_i \quad (4.9)$$

Description of objective function F_3:

The initial GWP for producing each glazing type was calculated using the information in Table 4.3 [51]. Due to the limited available data, it is assumed that glazing with different coatings has the same GWP. Further information is required for more detailed analysis on the environmental impacts.

Table 4.3: Density and GWP of coated and uncoated glazing.

	Density (kg/m^3)	**IPCC 2007 GWP (kg CO_2 eq)**
Glazing uncoated	2.5	0.971 [51]
Glazing coated		1.13 [51]

To account for the operation CO_2 emission, it is assumed that all the energy to maintain an appropriate office work environment is provided by electricity. The 2007 5-year grid rolling average electricity emissions factor of 0.54055kg CO_2/kWh was used [52]. Therefore, the operating GWP of the office room can be calculated as:

$$\text{Operating GWP (kg } CO_2\text{)} = \text{Total Energy Demand (kWh) x } 0.54055\text{kg } CO_2\text{/kWh} \quad (4.10)$$

Therefore, the net GWP F_3 is calculated as:

$$F_3 = \text{Initial GWP (Type } i\text{)} + \text{Operating GWP (Type } i\text{)} - \text{Initial GWP (Type 1)} - \text{Operating GWP (Type 1)} \quad (4.11)$$

4.4 Methodology

The optimisation model was based on NSGA-II [53] and constructed in MATLAB 7.6. The original algorithm NSGA-II was developed by Kanpur Genetic Algorithm Laboratory [54], and was only suitable for continuous variables. The algorithm was therefore modified to handle discrete variables. The automatic information exchange between EnergyPlus and MATLAB was achieved through a batch file from EnergyPlus software, the code in MATLAB was modified based on Evins [55]**.** The optimisation process is described as follows:

Step 1: A population P_0 is randomly generated;

Step 2: The objective function F_1, F_2, and F_3 are evaluated according to Section 4.2. The fitness of each solution is then calculated;

Step 3: Individuals are selected from the current generation P_t (t =0, 1, 2, 3…) based on their fitness, and then modified to form a new population Q_t using crossover and mutation operators;

Step 4: The fitness of solutions in Q_t is calculated, and the next generation P_{t+1} is then formed by a selection of solutions from P_t U Q_t based on their fitness;

Step 5: The fitness of solutions in P_{t+1} is evaluated. The algorithm terminates if the maximum number of generation is reached or the required fitness level is achieved; otherwise the next iteration starts from Step 3.

Considering the dimension of the optimisation problem, the number of populations and number of generations are 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.

4.5 Results and discussions

The optimisation ran for 28 minutes. The results are plotted in Figure 4.4. In general, as window-to-wall ratio increases, the benefit of high-performance glazing becomes more evident. For such a small office room, the difference in economic value between the best and the worse design is £133,480. The IEQ acceptance ranges from 87.4% to 97.4%. The range in net GWP reaches around 25,909kg CO_2. The optimal solutions are described in Table 4.4, Table 4.5, and Table 4.6

WWR (%)	**GLAZING TYPE NO.**	***Ug* (W/m²K)**	***g* (%)**	***Tv* (%)**	**IEQ ACCEPTANCE (%)**	**NET GWP (kg CO2 x104)**
35	67	0.7	13	23	97.4	-2.46
65	67	0.7	13	23	97.3	-3.63
85	67	0.7	13	23	97.2	-4.42
95	67	0.7	13	23	97.1	-4.49

Table 4.6. Glazing type 67 at 95% WWR represents the optimal trade-off of all the three objectives, and therefore would be an ideal design. In order to verify the accuracy of the optimisation result, an exhaustive search was performed (Figure 4.5) It took 3.5 hours, and produced the same Pareto-fronts.

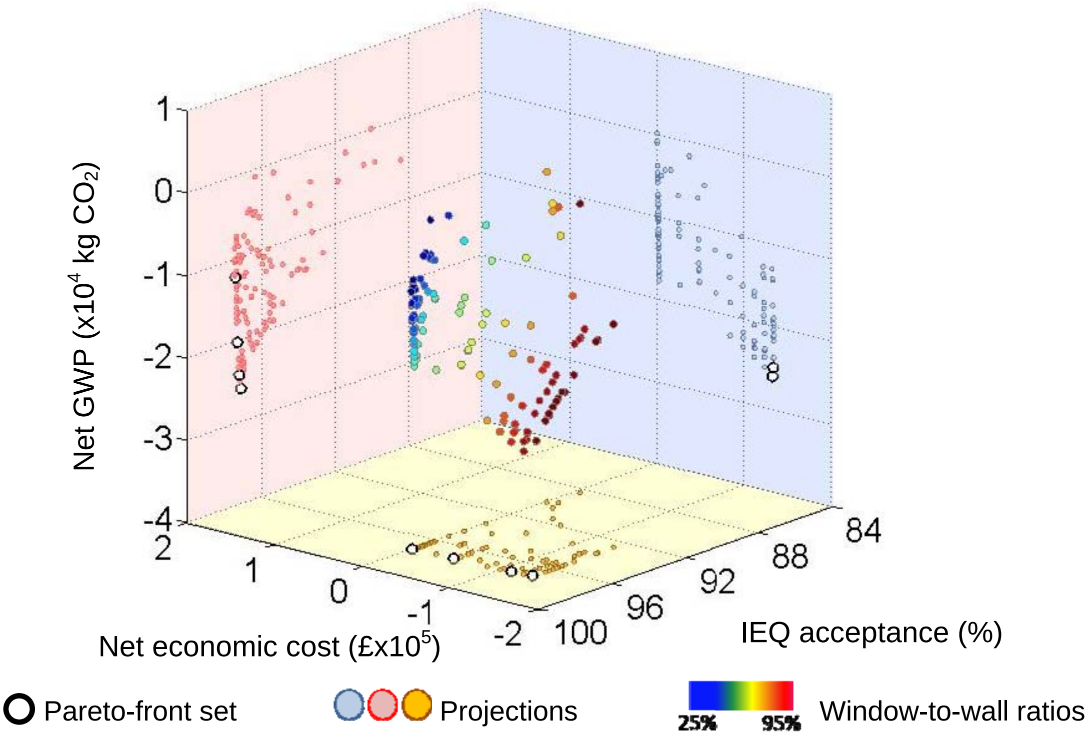


Figure 4.4 Optimisation result from NSGA-II.

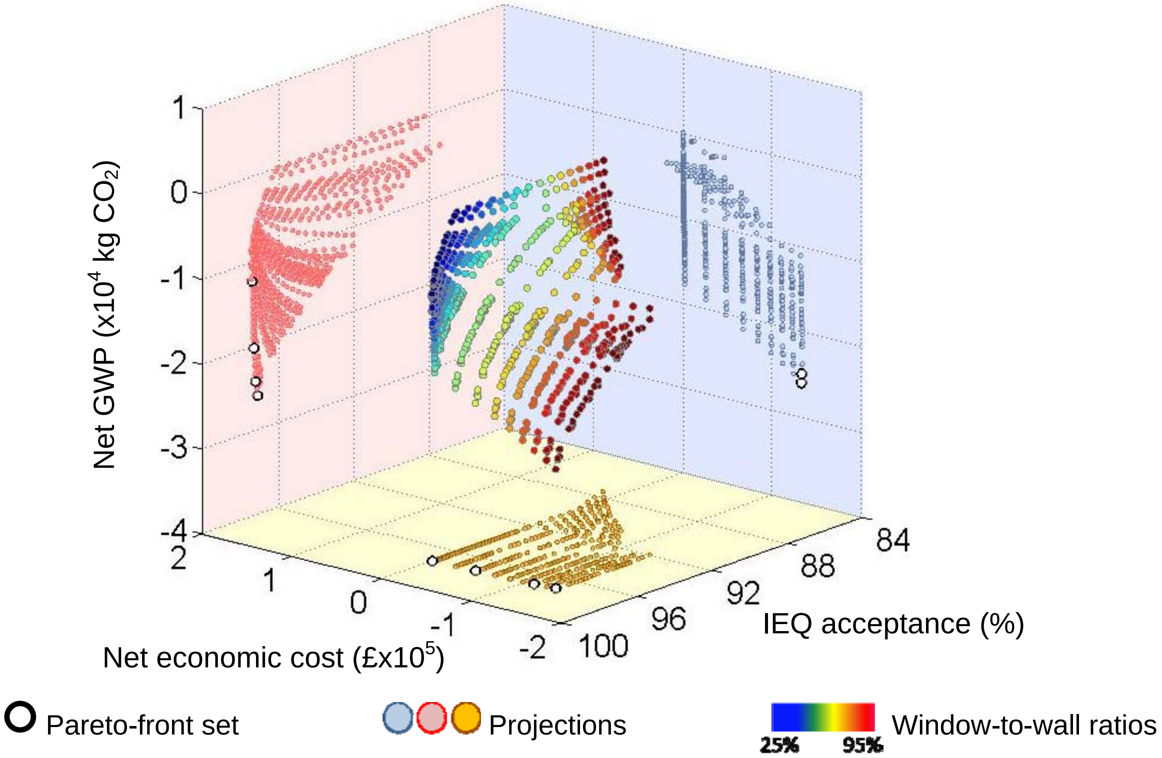


Figure 4.5 Optimisation result from an exhaustive search.

Table 4.4**:** The optimal solutions for Net economic cost *vs.* IEQ acceptance.

WWR (%)	**GLAZING TYPE NO.**	**U_g (W/m^{2}K)**	**g (%)**	**T_v (%)**	**NET ECONOMIC COST (£x10^4)**	**IEQ ACCEPTANCE (%)**
65	67	0.7	13	23	-4.80	97.3
85	67	0.7	13	23	-11.1	97.2
95	67	0.7	13	23	-13.3	97.1
35	54	1.1	17	30	-0.169	97.4
35	53	1.1	15	24	-0.169	97.4

Table 4.5**:** The optimal solutions for IEQ acceptance *vs.* net GWP.

WWR (%)	**GLAZING TYPE NO.**	**U_g (W/m^{2}K)**	**g (%)**	**T_v (%)**	**IEQ ACCEPTANCE (%)**	**NET GWP (kg CO_2 x10^4)**
35	67	0.7	13	23	97.4	-2.46
65	67	0.7	13	23	97.3	-3.63
85	67	0.7	13	23	97.2	-4.42
95	67	0.7	13	23	97.1	-4.49

Table 4.6**:** The optimal solutions for Net economic cost *vs.* net GWP.

WWR (%)	**GLAZING TYPE NO.**	**U_g (W/m^{2}K)**	**g (%)**	**T_v (%)**	**NET ECONOMIC COST (£x10^4)**	**NET GWP (kg CO_2 x10^4)**
95	67	0.7	13	23	-13.330	-2.59
95	54	1.1	17	30	-13.335	-2.48

4.6 Exhaustive search

In order to examine the performance of different glazing in more detail, the net energy demand and net GWP for every glazing type when WWRs are 25%, 50% and 75% were extracted from the exhaustive search performed in Section 4.4. The performance properties for each glazing type are plotted in Figure 4.6, and the results are plotted in Figure 4.7. In Figure 4.6, the GWP curves generally follow the trend of the net energy demand curves. This is because in most cases, the initial GWP is no more than 10% of the net operating GWP. Therefore, it is potentially more beneficial to produce a high-performance glazing with higher embedded CO_2 than a low-performance glazing with lower embedded CO_2.

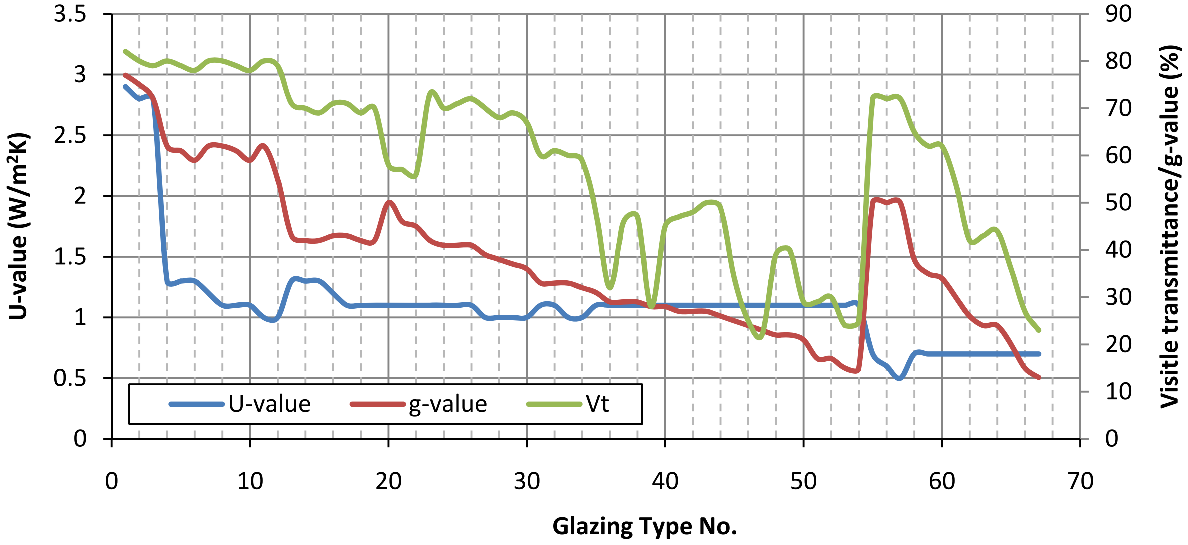


Figure 4.6: Performance properties for each glazing type.

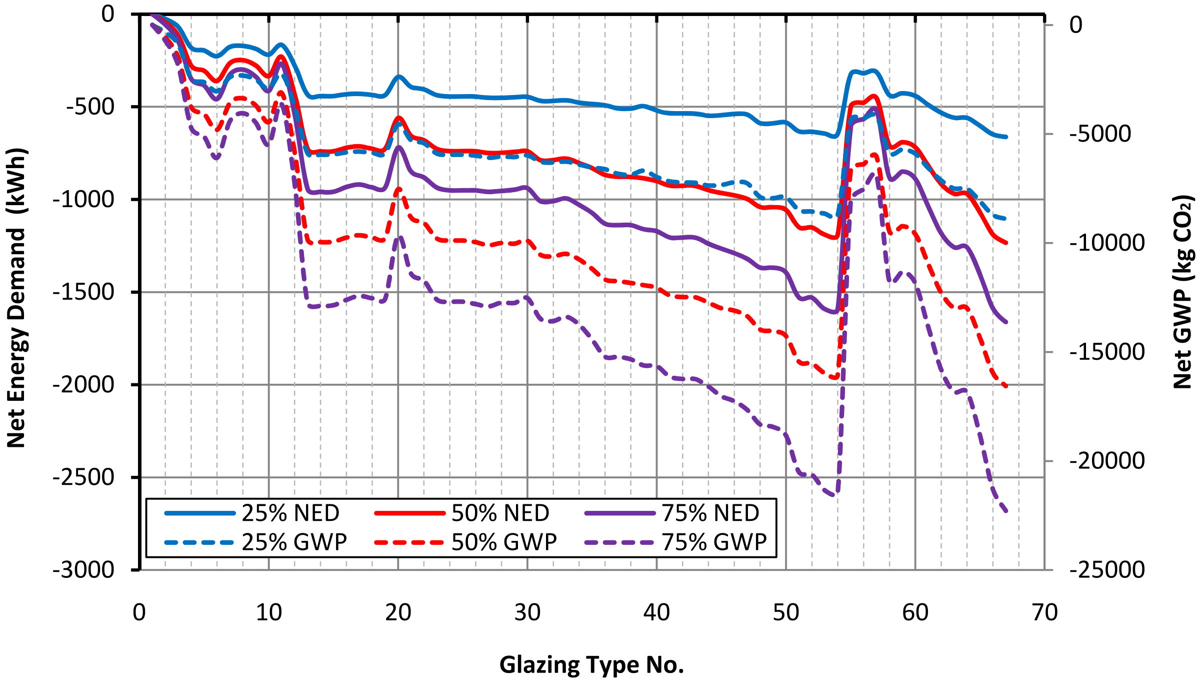


Figure 4.7: Net energy demand and GWP for each glazing type when window-to-wall ratio ranges from 25% to 75%.

Some interesting observations can be drawn from Figure 4.6 and Figure 4.7.

Firstly, Interpane’s products outperform the traditional double glazing (Type 1, 2, 3) for all the three window-to-wall ratios. This is the combined result of improvement in *U*-value, *g*-value and T_v. In general, a lower *U*-value and a higher T_v are more desirable. A higher and lower *g*-value is preferrable for the heating and cooling season, respectively.

Secondly, a ‘jump’ at Type 20 is observed for all the three WWRs, but with different variations. Let us compare Type 19 and Type 20 (refer to Appendix 1 for detailed properties). With the same U-value, Type 20 has an 8% higher *g*-value but a 12% lower T_v than Type 19. The higher *g*-value leads to higher solar heat gain and therefore increases/decreases the cooling/heating load. A lower T_v requires more lighting energy, and consequently increases/decreases the heating/cooling load. On the other hand, Type 21 has a 1% lower T_v and the same *U*-value. The 4% lower *g*-value helps to reduce the energy demand for WWR=75%. Therefore, for an office in London facing south, when *U*-value is kept constant, it is the *g*-value that dominates the total energy demand, while T_v has much less effect.

Thirdly, glazing Type 55, 56, 57 provide a measure of the effect of *U*-values. The three glazing types have the same *g*-value and T_v, but the *U*-values are different (Table 4.7). For a lower window-to-wall ratio (25% to 44%), lower *U*-values are beneficial, as heat loss is reduced. However, when the window-to-wall ratio is high (75%), a lower *U*-value is not necessarily preferable. For example, when *g*-value and T_v are all equal, Type 55 (*U*-value = 0.5 W/m^{2}K) requires the largest amount of energy while Type 57 (*U*-value = 0.7 W/m^{2}K) demands the least amount of energy This is because: (1) the cooling energy is dominating, and (2) when the window is large, solar heat gain builds up quickly and the room becomes overheated, but the lower *U*-value reduces the desirable heat loss thereby increasing the cooling load. It is therefore important to find an optimal *U*-value, which is low enough to preserve the room temperature but not too low to retain unwanted heat.

Table 4.7: performance properties Type 55-57.

Glazing Type No.	**T_v [%]**	***g*-value [%]**	***U*-value [W/m^{2}K]**
55	72	50	0.7
56	72	50	0.6
57	72	50	0.5

In addition, these glazing types have higher *g*-values than their neighbours. By comparing the total energy demand, it is concluded that a high g-value is desirable when the window to wall ratio is low and vice versa. When window-to-wall ratio is low, it is more efficient to achieve a lower *U*-value. When window-to-wall ratio is high, main efforts should be made to reduce *g*-value. This is proved by the decreasing trend of the WWR=75% curve between Type 35 to 54, where *U*-values are the same while *g*-values decrease from 31% to 15%.

4.7 Conclusions

The multi-objective optimisation model is sufficiently robust to identify the global minima with respect to each of the three objectives, and the Pareto-fronts as trade-offs between the objectives. NSGA-II is suitable for this problem. The only shortcoming of the application used in this report is that the dimension of the problem is small. Therefore, the capability of handling more complex problems should be investigated in future research. 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, window-to-wall ratio, framing, etc), the automated optimisation process provides an efficient way of product design

Several important conclusions can be drawn from the optimisation results. Firstly, the operational CO_2 emission of a particular glazing type is an order of magnitude larger than the embodied CO_2 of that glazing. From a whole-life point of view, it is worth producing a high-performance glazing with higher embedded CO_2 to reduce the future operating CO_2 emission, and therefore to increase the whole-life value. Secondly, for facades with high percentage glazing, it is essential to reduce the g-value in order to reduce overheating; for facades with lower window-to-wall ratios, it is more important to increase U-value in order to reduce heat loss. A lower U-value is not necessarily the best option. For largely glazed facades with high g-value, too low a U-value would exacerbate the over-heating problem. Finally, it should be noted the data that are used for the analysis, e.g., initial global warming potential and average employer cost of people were approximate.

Some future work has been identified. Firstly, the model should be modified to include the effects of facades frames. Secondly, the optimisation algorithm will be further improved for handling problems of large dimensions with better convergence. Thirdly, further efforts will be made to obtain the latest and more accurate data for life-cycle analysis and whole-life costing analysis.

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