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

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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 façades 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 (\textit{IEQ}) to occupants’ response. From this, an ‘ambient-performance’ relationship is established to quantify the relationship between \textit{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 demonstrated with a simple application.

INDOOR ENVIRONMENTAL QUALITY AND OCCUPANTS’ PRODUCTIVITY

Literature review
The performance or productivity of occupants is affected by façade-related \textit{IEQ} parameters in a complex manner. Figure 1 illustrates this relationship.

Visual comfort
Thermal comfort
Aural comfort
Air quality
Personal control
Vibration

IEQ

Vision, mood, hearing, motivation, etc.

Health

Performance

Reduced absence
Reduced health care costs

Economic benefit

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 \textit{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, CO2 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 \( \varphi_1 \) to \( \varphi_4 \) are the acceptance indices of thermal comfort, air quality, aural comfort and light level.

\[
k_i = \begin{cases} -15.02 & i = 1 \\ 6.09 & i = 0, \ldots, 4. \\ 4.88 & \end{cases} \quad (2)
\]

where \( k_1 \) to \( k_4 \) represent the relative importance of the four factors. \( \varphi_1 \) to \( \varphi_4 \) 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);

\[
\varphi_2 = \frac{1}{2} \left( \frac{1}{1 + \exp(3.118 - 0.00215 \zeta_i)} \right) - \frac{1}{1 + \exp(3.230 - 0.00117 \zeta_i)} \quad (4)
\]

where \( \zeta_i \) denotes the CO2 concentration (ppm);

\[
\varphi_3 = \frac{1}{2} \left( \frac{1}{1 + \exp(9.540 - 0.134 \zeta_i)} \right) ; (45 \leq \zeta_i \leq 72) \quad (5)
\]

where \( \zeta_i \) denotes the equivalent noise level (dBA);

\[
\varphi_4 = \frac{1}{2} \left( \frac{1}{1 + \exp(-1.017 + 0.0055 \zeta_i)} \right) ; (200 \leq \zeta_i \leq 1600) \quad (6)
\]

where \( \zeta_i \) 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 CO2 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:

\[
SP = 15.097 \cdot IES + 75.466 \quad (-1 \leq IES \leq 1) \quad (7)
\]
Table 1 Estimated potential productivity gains in 1996 $US (Fisk, 2000)

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

Table 2 Environmental conditions tested in Kawamura et al, 2007

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Air Temperature (°C)</th>
<th>Operative Temperature (°C)</th>
<th>Relative Humidity (%)</th>
<th>Equivalent sound level (dBA)</th>
<th>Illuminance (lx)</th>
<th>CO₂ (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>28.3</td>
<td>28.5</td>
<td>44</td>
<td>63</td>
<td>405</td>
<td>941</td>
</tr>
<tr>
<td>T</td>
<td>25.2</td>
<td>25.2</td>
<td>44</td>
<td>64</td>
<td>404</td>
<td>875</td>
</tr>
<tr>
<td>N</td>
<td>27.4</td>
<td>27.9</td>
<td>43</td>
<td>51</td>
<td>401</td>
<td>825</td>
</tr>
<tr>
<td>L</td>
<td>27.9</td>
<td>28.2</td>
<td>41</td>
<td>64</td>
<td>773</td>
<td>825</td>
</tr>
<tr>
<td>TN</td>
<td>25.6</td>
<td>25.7</td>
<td>43</td>
<td>51</td>
<td>401</td>
<td>792</td>
</tr>
<tr>
<td>TL</td>
<td>25.1</td>
<td>25.1</td>
<td>44</td>
<td>64</td>
<td>772</td>
<td>862</td>
</tr>
<tr>
<td>NL</td>
<td>27.7</td>
<td>28.0</td>
<td>42</td>
<td>51</td>
<td>757</td>
<td>798</td>
</tr>
<tr>
<td>TNL</td>
<td>26.1</td>
<td>26.4</td>
<td>42</td>
<td>51</td>
<td>752</td>
<td>963</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>CURVES</th>
<th>BEST-FIT OF</th>
<th>EQUATION</th>
<th>R²-VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filtered 1</td>
<td>all data points</td>
<td>$IEA = 0.95 \exp\left[-0.0279\exp\left[1.8038\left(-I_EA\right)\right]\right]$</td>
<td>0.6732</td>
</tr>
<tr>
<td>Filtered 2</td>
<td>all data points except Point TL and L</td>
<td>$IEA = 0.95 \exp\left[-0.0225\exp\left[2.1948\left(-I_EA\right)\right]\right]$</td>
<td>0.9144</td>
</tr>
<tr>
<td>Filtered 3</td>
<td>all data points except Point TL and Control</td>
<td>$IEA = 0.95 \exp\left[-0.0312\exp\left[1.7568\left(-I_EA\right)\right]\right]$</td>
<td>0.9603</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>WWR (%)</th>
<th>GLAZING TYPE NO.</th>
<th>$U_e$ (W/m²K)</th>
<th>$g$ (%)</th>
<th>$T_v$ (%)</th>
<th>NET ECONOMIC COST (£x10⁴)</th>
<th>IEQ ACCEPTANCE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>67</td>
<td>0.7</td>
<td>13</td>
<td>23</td>
<td>-5.49</td>
<td>97.3</td>
</tr>
<tr>
<td>70</td>
<td>67</td>
<td>0.7</td>
<td>13</td>
<td>23</td>
<td>-13.0</td>
<td>97.1</td>
</tr>
<tr>
<td>25</td>
<td>54</td>
<td>1.1</td>
<td>17</td>
<td>30</td>
<td>-0.162</td>
<td>97.4</td>
</tr>
<tr>
<td>60</td>
<td>54</td>
<td>1.1</td>
<td>17</td>
<td>30</td>
<td>-9.88</td>
<td>97.2</td>
</tr>
<tr>
<td>70</td>
<td>54</td>
<td>1.1</td>
<td>17</td>
<td>30</td>
<td>-13.0</td>
<td>97.1</td>
</tr>
<tr>
<td>25</td>
<td>53</td>
<td>1.1</td>
<td>15</td>
<td>24</td>
<td>-0.162</td>
<td>97.4</td>
</tr>
<tr>
<td>60</td>
<td>53</td>
<td>1.1</td>
<td>15</td>
<td>24</td>
<td>-9.88</td>
<td>97.2</td>
</tr>
<tr>
<td>70</td>
<td>53</td>
<td>1.1</td>
<td>15</td>
<td>24</td>
<td>-13.0</td>
<td>97.1</td>
</tr>
</tbody>
</table>

Table 7 The optimal solutions for IEA vs. net GWP

<table>
<thead>
<tr>
<th>WWR (%)</th>
<th>GLAZING TYPE NO.</th>
<th>$U_e$ (W/m²K)</th>
<th>$g$ (%)</th>
<th>$T_v$ (%)</th>
<th>IEQ ACCEPTANCE (%)</th>
<th>NET GWP (kg CO₂ x10⁴)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>67</td>
<td>0.7</td>
<td>13</td>
<td>23</td>
<td>97.4</td>
<td>-1.17</td>
</tr>
<tr>
<td>50</td>
<td>67</td>
<td>0.7</td>
<td>13</td>
<td>23</td>
<td>97.3</td>
<td>-2.05</td>
</tr>
<tr>
<td>60</td>
<td>67</td>
<td>0.7</td>
<td>13</td>
<td>23</td>
<td>97.2</td>
<td>-2.33</td>
</tr>
<tr>
<td>70</td>
<td>67</td>
<td>0.7</td>
<td>13</td>
<td>23</td>
<td>97.1</td>
<td>-2.56</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>WWR (%)</th>
<th>GLAZING TYPE NO.</th>
<th>$U_e$ (W/m²K)</th>
<th>$g$ (%)</th>
<th>$T_v$ (%)</th>
<th>NET ECONOMIC COST (£x10⁴)</th>
<th>NET GWP (kg CO₂ x10⁴)</th>
</tr>
</thead>
<tbody>
<tr>
<td>70</td>
<td>67</td>
<td>0.7</td>
<td>13</td>
<td>23</td>
<td>-13.0</td>
<td>-2.56</td>
</tr>
</tbody>
</table>

An ‘ambient-performance’ relationship

The \( I_{EA} \) calculated according to Wong represents the percentage of occupants who will vote ‘acceptable’ for a specific indoor environment quality. In comparison, the \( I_{ES} \) in Kawamura’s experiment denotes the mean score ranging from -1 to 1. However, the relationship between \( I_{EA} \) and \( I_{ES} \) is unknown, consequently, the relationship between measurable \( I_{EQ} \) variables and performance of occupants cannot be established directly. Therefore, an attempt was made to establish one.

Firstly, \( I_{EA} \)s 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). \( I_{ES} \) was obtained from Kawamura’s experimental results.

Secondly, \( I_{EA} \)s and \( I_{ES} \) 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 \( I_{EA} \) and \( I_{ES} \), respectively. Therefore, the extended Fanger’s model was established as follows. In Fanger’s model, \( PPD \) is calculated as:

\[
PPD = 100 - 95 \exp \left[ -0.03353PMV^4 + 0.2179PMV^{-2} \right]
\]  

(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 \( I_{ES} \). ‘PMV = 0’ (thermal neutral) was equivalent to ‘\( I_{ES} = 1 \) (clearly satisfied)’, and ‘PMV = -2’ (very cold) was equivalent to ‘\( I_{ES} = -1 \) (clearly dissatisfied)’. \( I_{ES} \) could then be expressed as:

\[
I_{ES} = PMV + 1
\]  

(9)

It was assumed that there was a linear relationship between \( PPD \) and \( I_{EA} \) as:

\[
I_{EA} = 1 - \frac{PPD}{100}
\]  

(10)

A possible relationship between \( I_{EA} \) and \( I_{ES} \) derived from Fanger’s model gives:

\[
I_{EA} = 0.95 \exp \left[ -0.03353 \left( I_{ES} - 1 \right)^4 + 0.2179 \left( I_{ES} - 1 \right)^2 \right]
\]  

(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 \( I_{EA} \) and \( I_{ES} \). Compared to Points \( T \), \( N \), \( NL \), and \( TN \), Point \( TL \) either overestimated \( I_{EA} \) or underestimated \( I_{ES} \). 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-\( I_{ES} \)) and \( I_{ES} \) 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 \( I_{EA} \) (Wong) and \( I_{ES} \) (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 \( I_{EA} \) and \( I_{ES} \). The ‘ambient-performance’ relationship that could be used to convert \( I_{EQ} \) into the productivity of occupants is summarised in Figure 3. However, it should be noted that further investigation is required to validate the \( I_{EQ} \) vs. \( I_{ES} \) 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 × 3 × 4 m². 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 found in Jin and Overend, 2011.

![Figure 4: A typical office room in London](image)

The two variables for this optimisation problem were window-to-wall ratio (WWR) and glazing type. WWRs 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](image)

**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 1 less that of the reference case (Type 1):

\[
NC_i = C_i - C_1
\]  

\( \text{Table 4: Indicative cost data for double and triple glazing for UK application (Thompson, 2011)} \)

<table>
<thead>
<tr>
<th>GLAZING TYPES</th>
<th>INDICATIVE COST (£/m²)</th>
<th>MEAN (£/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double glazing unit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clear</td>
<td>125-135</td>
<td>130</td>
</tr>
<tr>
<td>Clear with low-e coating</td>
<td>135-150</td>
<td>142.5</td>
</tr>
<tr>
<td>Clear with high performance solar control and low-e coating</td>
<td>175-200</td>
<td>187.5</td>
</tr>
<tr>
<td>Triple glazing unit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clear</td>
<td>180-195</td>
<td>187.5</td>
</tr>
<tr>
<td>Clear with low-e coating</td>
<td>195-215</td>
<td>205</td>
</tr>
<tr>
<td>Clear with high performance solar control and low-e coating</td>
<td>235-255</td>
<td>245</td>
</tr>
</tbody>
</table>

The net operating cost was calculated as follows. Firstly, the annual total energy demand, which consisted of annual heating energy demand \( AED_{h,i} \), annual cooling energy demand \( AED_{c,i} \) and annual lighting energy demand \( AED_{l,i} \) 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:

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

The net energy demand of glazing Type \( i \) \( NED_i \) is:

\[
NED_i = TED_i - NED_{ref}
\]

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 & Atmospheric 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 \( C_{CO2} \) and level light \( LL \) were calculated as follows:

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

\[
\text{weighted annual average } C_{CO2} = \sum_{h=0}^{h=8760} w_h C_{CO2,h} \quad (13)
\]

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

where \( w_h \) is the weights of the occupancy in Hour \( h \).

The objective function \( F_2 \) is:

\[
F_2 = NC_i + TED_i + NED_i
\]
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 \( C_{\text{NED}} \) (£) for 25 years is:

\[
C_{\text{NED}} = NED_i \sum_{n=1}^{25} \frac{0.15}{(1 + 0.0435)^n}
\]

In order to evaluate the monetary value of IEQ, the ‘performance-ambient’ relationship proposed in the preceding 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:

\[
CPL_i = \sum_{n=1}^{\infty} \frac{\text{Maximum productivity of employee for Type } i - \text{Maximum productivity of employee for Type 1}}{\text{productivity of employee for Type 1}} \times 724,846
\]

where \( n_e \) is number of employee.

Finally, the economic cost \( F_2 \) is:

\[
F_2 = NC_i + C_{\text{NED}} + CPL_i
\]

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.

\[
\text{Table 5 GWP and density of coated and uncoated glazing (Kellenberger et al., 2008)}
\]

<table>
<thead>
<tr>
<th>GLAZING TYPES</th>
<th>IPCC 2007 GWP (kg CO2 eq)</th>
<th>DENSITY (kg/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glazing uncoated</td>
<td>0.971</td>
<td>2.5</td>
</tr>
<tr>
<td>Glazing coated</td>
<td>1.13</td>
<td></td>
</tr>
</tbody>
</table>

To account for the operating CO₂ 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 0.54055 kg CO₂/kWh was used (DEFRA, 2009).

Therefore, the net operating global warming potential of the office room with Glazing Type \( i \) \( \text{OGWP}_{\text{net},i} \) can be calculated as:

\[
\text{OGWP}_{\text{net},i} = 0.54055 \cdot NED_i
\]

Finally, the net GWP \( F_3 \) is calculated as:

\[
F_3 = IGWP_i - IGWP_1 + \text{OGWP}_{\text{net},i}
\]

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 25,631 kg CO₂, 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.
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.

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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REFERENCES


NOMENCLATURE

PPD - Predicted percentage of dissatisfied (%)
th - Weight of the occupancy in Hour
h
CCO2h - Average CO2 concentration in Hour h (ppm)
C1 - Initial capital cost of Glazing Type i (£)
NC - Net initial capital cost of Glazing Type i (£)
TED - Total energy demand of the office with Glazing Type i for 25 years (kWh)
AEDh - Annual heating energy demand (kWh)
AEDc - Annual cooling energy demand (kWh)
AEDl - Annual lighting energy demand (kWh)
NED - Net energy demand of glazing Type i (kWh)
CPL - Net cost of employee for Glazing Type i (£)
IEA - Acceptance of indoor environmental quality (%) 
IEQ - Satisfaction of indoor environmental quality
E2 - the CO2 concentration (ppm);
E1 - the equivalent noise level (dBA);
E3 - the illumination (lux) at working plane.
q1 - the acceptance of thermal comfort (%) 
q2 - the acceptance of air quality (%) 
q3 - the acceptance of aural comfort (%) 
q4 - the acceptance of light level (%) 
k1 - the relative importance of thermal comfort 
k2 - the relative importance of air quality 
k3 - the relative importance of aural comfort 
k4 - the relative importance of light level 
PMV - Predicted mean vote (%) 
WWR - Window-to-wall ratio (%) 
IGWPi - Initial global warming potential for glazing type i 
OGWP - Operating global warming potential for glazing type 
LL - light level at a specific point (lux)