DECISION MAKING OF INNOVATIVE BUILDING FAÇADE USE IN SINGAPORE

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ABSTRACT

Façades of office buildings conventionally consist of predominantly opaque walls or translucent glass panels. Due to recent economic and environmental concerns, innovative building façades, such as translucent concrete panels or double skin façades with green concrete, have started to be developed. These façade systems have considerable benefits in reducing energy consumption due to artificial electrical lighting and heating/cooling loads. However, initial costs associated with these emerging technologies are higher than their conventional counterparts. In this paper, a powerful decision making framework is used to evaluate the performance of innovative and conventional façades for a typical room of a representative building in Singapore, by taking into account lighting and thermal energy consumptions and initial cost. The adopted decision making framework is based on a recently extended version of multi-criteria decision analysis coupled with performance-based engineering methodology. The study shows that the performance of the innovative façade, despite its high initial cost, is comparable to glass façades.

KEYWORDS

Decision tool, Innovative façade, Multi-criteria, Performance-based engineering, Utility.

INTRODUCTION

Façades of high-rise buildings conventionally consist of predominantly opaque walls or translucent glass panels. Due to recent economic and environmental concerns, innovative building façades, such as translucent concrete panels (TCPs) or double skin façades with green concrete, have started to be developed. While these façade systems have considerable benefits in reducing the energy expenditures and CO₂ emissions due to artificial lighting and heating/cooling systems, initial costs associated with these emerging technologies are higher than those of conventional façades. Therefore, a combined use of innovative façade systems and conventional ones can lead to an optimal solution in terms of a widespread range of indicators, namely cost, energy expenditure, CO₂ emission, and human comfort.

A preliminary investigation of the combined use of innovative and conventional façade systems is conducted in this study using a probabilistic decision framework, which is based on a recently extended version of multi-criteria decision analysis (MCDA) and performance-based engineering (PBE) (Mosalam et al. 2015). Three alternatives are considered by altering one of the walls for a typical room of a representative building in Singapore, while keeping the other three walls unchanged. These alternatives are defined by using: a) an opaque wall, b) a glass panel, and c) an innovative façade consisting of TCPs. Two of the unchanged walls are opaque with the third wall having a window opening. Probability of exceedance (POE) and expected value of the utilities are computed for the three alternatives considering the light and thermal energy consumptions and the initial cost as the indicators.

METHODOLOGY: PBE-MCDA

MCDA is considered as an essential tool to select the best solution amongst various alternatives. There are many MCDA methods applied to many problems. In general, they are classified into three categories (Wang et al. 2009):
1) Elementary, e.g. weighted sum method (WSM) and weighted product method (WPM);

2) Outranking, e.g. elimination of choice translating reality (ELECTRE) method and preference ranking organization method for enrichment evaluation (PROMETHEE);

3) Unique synthesizing criteria, e.g. analytic hierarchy process (AHP), technique for order of preference by similarity to ideal solution (TOPSIS), simple multi-attribute rating technique (SMART), MCDA combined fuzzy method, and multi-attribute utility/value theory (MAUT/MAVT).

There are other methods which are not included in the above categories, e.g. novel approach to imprecise assessment and decision environments (NAIADE), measuring attractiveness by a categorical-based evaluation technique (MACBETH), and preference assessment by imprecise ratio statements (PAIRS). Among the MCDA methods mentioned above, AHP, SMART, and MAUT/MAVT are closely related. In particular, SMART and MAUT/MAVT are widely used in the utility or value function-based assessment. The main difference between them is the linearity of the utility/value functions, which is required in SMART. Some MCDA methods derived from the ones mentioned above address the environmental aspects of a building design, e.g. integrated value model for sustainable assessment (MIVES) (Lombera and Aprea 2010; Pons and Aguado 2012). They deal with conflicts arising among environmental indicators (Gustavsson and Sathre 2006). In this study, a version of MAUT, recently enhanced to take into account uncertainties of indicators, is used for investigation of different façade configurations.

The MAUT, developed by Keeney and Raiffa (1993), provides an analytical framework to deal with decision problems that involve multiple criteria (Mosalam et al. 2015). In this framework, each alternative receives a single-attribute value function for each indicator, and these scores are combined into an overall value by the assignment of weights to each indicator. Table 1 lists considered indicators and corresponding weights in this investigation.

Table 1. Indicators and corresponding weights for the considered room.

<table>
<thead>
<tr>
<th>Indicator</th>
<th>( w_{\text{ind}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light energy consumption (LE)</td>
<td>0.2</td>
</tr>
<tr>
<td>Thermal energy consumption (TE)</td>
<td>0.3</td>
</tr>
<tr>
<td>Initial cost (IC)</td>
<td>0.5</td>
</tr>
</tbody>
</table>

The objective of the MAUT is to determine the most sustainable design alternative out of the three considered ones using the indicators listed in Table 1. Eq. 1 constitutes the simplest form to be used by the MAUT for this decision. The utility functions, \( u_{\text{LE}} \), \( u_{\text{TE}} \), and \( u_{\text{IC}} \) transform the response of each indicator into a normalized value (between 0 and 1) to allow consideration of heterogeneous indicators with different units. The corresponding weights, \( w_{\text{LE}}, w_{\text{TE}}, \) and \( w_{\text{IC}} \), are assigned to these utility functions where their sum is 1.0. Accordingly, the combined utility function, \( U(a, b, c) \), can be interpreted as the weighted average of the utility functions of the individual indicators.

\[
U(a, b, c) = w_{\text{LE}}u_{\text{LE}}(a) + w_{\text{TE}}u_{\text{TE}}(b) + w_{\text{IC}}u_{\text{IC}}(c)
\]  

Eq. 1 is mainly valid for deterministic indicators. However, considered indicators possess inherent uncertainties. The uncertainty in light and thermal energy consumptions are attributed to that in the outside weather conditions, while the variability of the market prices causes the initial cost uncertainty. Accordingly, considered indicators are not defined by deterministic values, rather each particular value of each indicator has a certain probability of occurrence defined by a distribution given in terms of a probability density function (PDF), \( f \), as shown in Eq. 2. For mutually independent indicators, as the case in this investigation, \( f(LE, TE, IC) \) is simply calculated by Eq. 3.

\[
f(LE, TE, IC) = f(LE) \times f(TE | LE) \times f(IC | TE, LE)
\]

\[
f(LE, TE, IC) = f(LE) \times f(TE) \times f(IC)
\]  

Incorporation of Eq. 2 or Eq. 3 and the consequent involvement of uncertainty quantification and probabilistic computations transform the classical MAUT methodology to the PBE domain, where the resulting decision making tool is designated as PBE-MAUT in the remainder of this paper. Developing the PDFs in PBE-MAUT gives the decision maker the opportunity to stochastically evaluate the considered alternatives. A decision maker
can determine a central utility metric by calculating expected value of utility for each alternative, Eq. 4. Analogues to Eq. 1, Eq. 4 represents a weighted average of each possible value of the combined utility, where the weights are defined by the corresponding probabilities. Moreover, by calculating the POE values, the decision maker can take decisions according to his/her risk preference. In this study, two POE-related metrics are defined: 1) $U_{50}$ determined as the utility value with POE of 0.5 and 2) $U_{90}$ determined as the utility value with POE of 0.9. $U_{50}$ and $U_{90}$ represent metrics that would be likely used by decision makers who are risk-neutral and risk-averse, respectively. Figure 1 outlines the application of PBE-MAUT for the investigation of the combined use of innovative and conventional façade systems in this study.

$$E(U) = \int \int \int U(LE,TE,IC) f(LE,TE,IC) \, dLE \, dTE \, dIC$$

Figure 1. Outline of the application of PBE-MAUT for the investigation of different façade systems.

**CASE STUDY**

**Setup**

A case study is designed to evaluate the performance of different façade systems using the decision-making tool PBE-MAUT. In this problem, the decision maker needs to decide between using conventional facades like opaque and glass facades or choosing an innovative façade. Thus, the decision space consists of three façade alternatives: Opaque, Glass, or Innovative. For this investigation, a one room ($4.5m \times 3.65m$) office space in Singapore, with all opaque walls except a south-facing window, is modeled. The room has two desk spaces: one near the window (A) and the other at the farthest corner (B) of the window, Figure 2. Considered alternatives in the study and shown in Figure 3 are defined by setting the west facing façade ($A_f = 11.14m^2$) as concrete block wall (Opaque), double glazed glass (Glass), or TCPs (Innovative).

For the opaque façade, a concrete block wall is considered with plasters on both sides (thickness $d=150mm$ and thermal conductivity $k=0.8$ W/m-K). For the translucent façade, a double pane glass façade (solar heat gain coefficient, $SHGC=0.8$ and visible transmittance, $VT=0.7$) has been considered. TCPs represent an innovative façade system with optical fibers inserted in concrete panels to transmit daylight (Ahuja et al. 2014) and consequently reduces the usage of artificial lighting systems. Recently, the light energy savings objective of TCPs has been combined with a thermal energy savings objective, by employing ultra-light weight cement composites (ULCC) as the concrete mix. ULCC has significantly low thermal conductivity, $k=0.43$ W/m-K, compared to conventional concrete, $k=1.98$ W/m-K (Wu et al. 2015). The TCPs, produced recently at UC Berkeley with ULCC, are considered as the innovative façade alternative with thickness $d = 50$ mm.
Probability Distribution of the indicators

An ideal way to develop the probability distribution of the indicators would be to obtain thermal and lighting consumption data experimentally for multiple years. Since such data are not available, simulation tools currently used in design processes are employed herein.

Thermal Energy Consumption

In order to determine the PDF for annual thermal energy (TE) consumption, \( f(TE) \), selected material properties are used. Outside dry bulb temperature, \( T_{\text{out}} \), and hourly incident solar radiation, \( IR \), are determined from the weather file of Singapore Airport Weather station. Using such data, hourly cooling load \( Et \) for a year is calculated from Eq. 5 as the sum of conductive, convective, and radiative energy contributions, assuming an indoor temperature, \( T_{\text{in}} = 25^\circ \text{C} \), corresponding to comfortable indoor conditions in Singapore. While calculating this energy exchange, it was assumed that internal gains and infiltration losses are same for all three alternatives and therefore are not included.

\[
Et = (k/d + h) \times A_f \times (T_{\text{out}} - T_{\text{in}}) + U_w \times A_w \times (T_{\text{out}} - T_{\text{in}}) + SHGC \times IR \times A_w
\]

where \( h \) is the air film conductance, \( U_w \) is taken as 2.82 W/m\(^2\)-K for the \( U \)-value of the glass window and is taken as 2.92 W/m\(^2\)-K for the \( U \)-value of the optical fibers in the TCPs (about 2.57% of the surface area represent the optical fiber density), and \( A_w \) is the window area with window to walls ratio (WWR) of 0.043 and 0.270 for the opaque and glass alternatives, respectively.

Hourly TE consumption is plotted in Figure 4 for the 365 days of a representative year for the three alternatives, together with mean values from 365 days indicated with large open circles. Figure 4 shows that, as the temperature gradually rises during the midday, thermal energy consumption also rises for all three alternatives. For opaque and innovative façades, this rise reaches 0.17 and 0.23 kWh, respectively, whereas for the glass façade, TE consumption peaks at 3.8 kWh indicating that glass façade would be the least suitable alternative if only TE consumption was considered in the decision making. The mean and standard deviation of TE are calculated for each hour from the 365 days data. By using these mean and standard deviation values for the hourly TE consumption, Monte Carlo simulation is performed to extend the data to obtain the TE for all days of 30 years (total of 365 × 30 × 24 TE values), where 30 years represents the design life of the typical buildings in Singapore. Summing the 365 × 24 values, annual TE consumption is determined for the 30 years. Probability distribution for TE consumption, \( f(TE) \), is assumed as a normal distribution with parameters obtained as the mean and standard
deviation of the 30 annual TE values for all three alternatives. Flowchart of the devised algorithm and the resulting probability distributions are shown in Figures 5 and 8, respectively.

**a. Opaque**

![Chart showing TE consumption for Opaque]

**b. Glass**

![Chart showing TE consumption for Glass]

**c. TCP**

![Chart showing TE consumption for TCP]

Figure 4. Hourly TE consumption for a representative year for all alternatives (Table reports the multiplier of the TE consumption on the vertical axis for the different alternatives).

<table>
<thead>
<tr>
<th>Alternatives</th>
<th>Scale Factor (SF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opaque</td>
<td>0.20</td>
</tr>
<tr>
<td>Glass</td>
<td>4.00</td>
</tr>
<tr>
<td>TCP</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Figure 5. Algorithm devised to obtain the PDF for the annual TE consumption.

**Light Energy Consumption**

For determination of the light energy (LE) consumption PDF, $f(LE)$, the room is modeled in Ecotect (2011) with respective visual transmittance properties and illuminance value is calculated at both desks by exporting the model to RADIANCE (2014) and using the daylight data obtained from the weather file. In an office, the minimum amount of light on the working plane enforced by the building code (Section 9, ASRAE Standard 90.1.2007) is 400 Lux. It is assumed that the lights (three sets of three T8 tubes) are on if light level is below this recommended 400 Lux in any of the two working desks. Figure 6 shows that mean hourly illuminance level at desk B does not exceed the 400 Lux level for opaque façade but frequently exceeds that for the innovative façade and always exceeds that for the glass façade. Accordingly, glass façade outperforms the opaque and innovative façades when LE is considered. From hourly mean and standard deviation values, annual LE consumption for 30 years have been calculated and $f(LE)$ distributions have been developed in similar manner to the $f(TE)$ as shown in Figure 8. Figure 7 presents the algorithm devised to calculate the PDF of the LE consumption.

**Initial Cost**

Data for cost which include material and labor costs have been obtained from market survey in the US. Material and labor cost for the opaque façade is the least ($150/m^2$). Use of optical fiber and unconventional manufacturing process make the innovative façade the most expensive alternative among the three ($950/m^2$). However, installation cost for double glazed façade ranges from $200$ to $300/m^2$ making this double glazed façade a moderately expensive alternative. Although, price of constructing the investigated façades may be different in
Singapore compared to US, it is assumed that the ratio of the mean cost will be almost the same in both countries. Figure 8 shows the assumed distributions of the initial cost \( f(IC) \) for all three alternatives.

<table>
<thead>
<tr>
<th>Alternatives</th>
<th>Scale Factor (SF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opaque</td>
<td>800</td>
</tr>
<tr>
<td>Glass</td>
<td>45000</td>
</tr>
<tr>
<td>TCP</td>
<td>800</td>
</tr>
</tbody>
</table>

![Figure 6. Hourly illuminance level for a representative year for all alternatives (Table reports the multiplier of the illuminance level on the vertical axis for the different alternatives).](image)

![Figure 7. Algorithm devised to obtain the PDF for annual LE consumption.](image)

**Utility Functions**

In a decision problem like the one presented here, most often, different attributes will yield best consequences. Hence, an objective function is required to rank the consequences taking into account risk preference of the decision maker (Keeney 1982). In decision analysis, these objective functions are referred to as utility functions \( u(x) \). These utility functions also transform values of each indicator to a normalized value between 0 and 1 in order to consider response of indicators with different units, i.e. heterogeneous indicators.

In this study, risk neutral (linear) utility functions, defined by Eq. 6 and plotted in Figure 9, are used for the indicators. For LE consumption, the case when lights are never and always on have utility values of 1 and 0, which correspond to the annual LE consumptions of \( LE_a = 0 \) and \( LE_b = 1,261 \) kWh, respectively. For TE consumption, the case when no artificial energy is required to maintain comfortable indoor condition has a utility of 1 and the case where there is no façade to stop heat from escaping outside has utility of 0. These two cases correspond to the annual TE consumptions of \( TE_a = 0 \) and \( TE_b = 10,000 \) kWh, respectively. For cost, utility of 1 indicates no cost associated with façade construction (i.e. \( IC_a = 0 \)) and utility of 0 refers to the maximum amount the decision maker can possibly spend on a façade, assumed to be \( IC_b = $1400/m^2 \) in this study.
\[ u(x) = \begin{cases} 
\frac{1}{x_b - x_a} & x \leq x_a \\
1 - \frac{x - x_a}{x_b - x_a} & x_a \leq x \leq x_b \\
0 & x \geq x_b 
\end{cases} \] 

Figure 8. PDFs for three indicators of all three alternatives.

Figure 9. Utility functions of the three alternatives.

**Weight of the Indicators**

Weights of the indicators depend on the preferences and priorities of a decision maker. If there are multiple decision makers, the weights will be decided according to their mutual agreement. In this study, weights are approximated by referring to the preferences in similar projects and energy use data. Initial cost has always been the primary decisive factor in many construction projects. For this reason, \( IC \) corresponds to 50% weight of this decision problem (\( w_{IC} = 0.5 \)). Energy consumption breakdown of commercial buildings show that heating and cooling load include about 30% to 35% of the total energy consumption whereas lighting load is about 20% (DOE 2012). Accordingly, \( w_{TE} \) and \( w_{LE} \) are considered to be 0.3 and 0.2, respectively.
RESULTS AND DISCUSSION

After developing the PDFs, defining utility functions and assigning appropriate weights for each indicator, different metrics, listed in Table 2, can be used to evaluate the performance of each façade alternative. This study shows that, in Singapore, opaque façade has the highest probability of being the “Best” alternative. From Figure 10, it is also observed that the opaque façade stochastically dominates the glass and innovative façades. Thus, a risk neutral or a risk averse decision maker will most likely choose the opaque façade over the innovative one.

Innovative façade can achieve 92% annual \( TE \) consumption reduction when compared to the glass façade. On the other hand, it can reduce \( LE \) consumption by 40% compared to an opaque façade. This energy savings are negated by its high \( IC \) when compared to an opaque façade which has almost 10 times lower \( IC \). However, innovative façade is performing comparably to glass façade despite its higher \( IC \). This indicates that some design modification of the innovative façade to enhance its energy savings or adapting to a more cost efficient manufacturing process will make it a superior candidate to glass and possibly opaque façades.

<table>
<thead>
<tr>
<th>Alternative</th>
<th>( E(U_f) )</th>
<th>( U_{50} )</th>
<th>( U_{90} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opaque</td>
<td>0.76</td>
<td>0.76</td>
<td>0.74</td>
</tr>
<tr>
<td>Glass</td>
<td>0.55</td>
<td>0.55</td>
<td>0.50</td>
</tr>
<tr>
<td>Innovative</td>
<td>0.54</td>
<td>0.54</td>
<td>0.49</td>
</tr>
</tbody>
</table>

Figure 10. POE of the utilities for the three alternatives.

CONCLUDING REMARKS AND FUTURE EXTENSIONS

The goal of performance-based engineering is to provide a design that will deliver best performance using an approach that considers various design aspects and the priorities of various stakeholders in a holistic manner. The decision tool PBE-MAUT presented here allows the decision makers to consider the whole life cycle and all components of a building together with the associated uncertainties.

In this paper, PBE-MAUT methodology was applied to investigate the performance of different façade systems. This study presented a scenario where each alternative is superior to others in one aspect. As a result, choosing the “Best” alternative was not straightforward for a decision maker. The PBE-MAUT decision making framework provided the decision maker a robust quantitative tool to consider multiple attributes with different measuring units while making the decision. Results of the study showed that the opaque façade is suited for office spaces in Singapore if energy consumption and initial cost is considered. The result could be different if several other indicators such as maintenance cost, constructions safety, and human comfort were considered or if the current indicators were employed with different weights.
This decision tool PBE-MAUT can also be utilized as an important design tool. In this study, innovative façade is
the least preferred choice but changing façade parameters, reducing cost, or a combination of these two issues is
likely to improve its performance. However, this study is conducted for a typical office room in Singapore. The
conclusions inferred from this study are likely to change when a study is conducted for the building scale with
more indicators. Moreover, the assumption of the ratio of initial cost of the different alternatives being the same
in Singapore and the US may not hold due to lack of availability of raw materials in Singapore. Future research
will be conducted by taking into account more representative cost information and considering other important
indicators on a building scale.

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REFERENCES

Concrete Panels.”, Journal of Architectural Engineering, 21(2).
Department of Energy, Washington, DC.
Concrete Building Materials.”, Building and Environment, 41(7),940–51.
Keeney, Ralph L. and Raiffa, Howard. (1993). Decisions with Multiple Objectives: Preferences and Value
Trade-Offs. Cambridge University Press.
Technologies Used to Build Schools in Catalonia, Spain.”, Building and Environment, 53,49–58.
Decision Analysis Aid in Sustainable Energy Decision-Making.”, Renewable and Sustainable Energy
Reviews, 13(9),2263–78.
Lightweight Cement Composites with Low Thermal Conductivity and High Specific Strength for Energy