APPRAISAL OF BUILDING ENVELOPE ALTERNATIVES IN TERMS OF OVERALL PHYSICAL PERFORMANCE

M Aygun

Faculty of Architecture, Istanbul Technical University, Turkey

ABSTRACT

The envelope as functional building element acts as a filter intended to regulate energy and mass flows. The overall performance of the envelope is ascertained by the combined effects of the functional components. Thus a methodical approach is required for the comparative appraisal of envelope alternatives in terms of multiple performance requirements and identification of the best overall performer. While some requirements pertaining to the same or different physical quantities are in accordance with each other, others are mutually exclusive. One requirement may also affect any number of components. Conversely, each component may involve any number of requirements. Representation of each alternative is achieved by means of a conceptual element model. Performance indicators are applied for quantitative measurement of the extent to which requirements are fulfilled and are expressed as functions of element attributes. An application of the method is carried out on a set of generic alternatives.

INTRODUCTION

The indoor environment is expected to attain satisfactory performance levels in various domains. Within the context of this paper the domains of concern are health, comfort, energy and ecology. The implicated environmental parameters are air and surface temperatures, relative air humidity, air velocity, purity, light and heat. These parameters are influenced by diverse exogenous and endogenous design factors that can be further categorized as external (*i.e.* climate, outdoor air quality, urban pattern, location, orientation and building form) and internal (*i.e.* building envelope, mechanical services, spatial disposition, occupancy and user attributes). The relationships between these factors and the previous parameters, which are functions of the factors, can be expressed by means of an interaction matrix (Table 1).

Table 1. Interaction of design factors (DF), environmental parameters (EP) and domains (D)

DF	D_1			D_2		
	EP_{11}	EP_{12}	...	EP_{21}	EP_{22}	...
DF_1						
DF_2						
...						

Among the factors mentioned above, the building envelope is the subject matter of this paper. The envelope as functional building element acts as a filter enclosing the indoor environment and is intended to regulate energy and mass flows between the exterior and interior. The overall performance of the envelope is ascertained by the combined effects of the functional components as constituent parts of the envelope. At present many materials and assemblies are available for configuring the building envelope, yielding different values for the multiple performances with different units of measurement. Consequently identification of the most appropriate configuration among all the viable alternatives becomes a challenge. Thus a methodical approach is required for the comparative appraisal of alternatives in terms of multiple performance requirements and subsequent selection of the best overall performer. There are two strategies to adopt for solving the problem of conflicting or varying requirements. The first is to design a responsive (interactive) envelope that is adaptable dynamically to the changes in environmental conditions by means of physio-chemical transformations. The second, being the *genius loci* herein, involves the selection or development of a compromised solution that fulfills the requirements to an acceptable degree at any given time.

A brief overview of the relevant works is presented as follows. BS 8200 provides guidelines on the physical performance specification of design and production of external vertical enclosures [1]. Rivard *et al* describe an envelope design process based on functional analysis of principal design requirements [2]. Vanier *et al* propose a product model for representing user requirements as a complete data structure [3]. Harris and Cowan suggest the consideration of a more interactive envelope design approach in which heat and light can be manipulated as and when required [4]. Aygun presents a method for quantifying the effects of various energy and mass flows on the relative environmental performance of buildings [5].

ENVELOPE REQUIREMENTS

The building envelope is anticipated to fulfill certain functional requirements expressing the stipulations on mass and flows through this element. The requirements as the *raison d'être* of components are measured by performance indicators as explicated later. During the occupancy phase of the envelope lifecycle the physical quantities involved are heat, water, air, light, sound, fire and emissions. These quantities can be tabulated in conjunction with the pertinent requirements and functional components for each domain as dependent and independent variables (Table 2). One requirement *per se* may affect any number of components. Conversely, each component may involve any number of requirements.

Table 2. Relationships between dependent and independent variables

Domain (D)	Physical Quantity (PQ)	Functional Requirement (FR)	Component (C)
D_1	PQ_1	FR_1	C_3, C_5, ...
...	...	...	...

While some of the requirements pertaining to the same or different physical quantities are in accordance with each other, *e.g.* thermal capacity and sound reduction (or air infiltration and water penetration), others are in conflict (mutually exclusive), *e.g.* thermal transmittance and capacity. There may also be no correlation in-between, *e.g.* light transmittance and air infiltration. These relationships can be represented by means of an interaction matrix, as denoted by the signs of +, - and 0 (Table 3). Consequently any satisfactory envelope alternative is anticipated to strike a balance between all the performance indicators of these requirements, thus providing a compromised or optimal solution.

Table 3. The interaction matrix of functional requirements

FR_2	+		
FR_3	0	+	
FR_4	-	0	-
	FR_1	FR_2	FR_3

Beside the negative interactions of functional requirements, evaluation of envelope alternatives is further confounded by the *laissez-faire* entities of domains, environmental conditions, user physiology and envelope components, as listed below together with their instances.

Domains: Health, Comfort, Energy, Ecology; Environmental Conditions: Cycle (Seasonal, Diurnal), Thermal (Heating, Cooling), Moisture (Humid, Dry); User physiology: Age, Sex; Envelope components: Opaque, Transparent.

The instances of any one of these entities may impose stipulations contrary to one or more of the other instances of the same entity. A different set of requirements is amenable to each instance due to distinctions arising from attributes. While some requirements may be shared by more than one set, others may be unique to a certain set.

ENVELOPE MODEL

The representation of each envelope alternative is achieved by means of a conceptual object *cum* element model based on an object oriented approach. The alternatives are presented as instances of the object model for the purposes of physical performance appraisal. The object hierarchy allows any sub-types (descendants) derived from the main types (ancestors) to inherit the embedded attributes while retaining their idiosyncratic attributes. Instances of these objects are obtained when actual values are assigned to these attributes as independent variables of the element concept. The synopsis of the model description is presented below:

Element
Location: External (Below -, Above -, Partly above ground), Internal, Semi-enclosed.
Inclination: Horizontal, Vertical, Inclined.
Order of Components (Layers in the context of the building envelope):
- External finish or layer (Surface characteristics)
- Vented Cavity
- Thermal insulator and Vapour barrier
- Waterproofing
- Core and/or Carrier
- Supplementary Layer (e.g. filter or drain sheet)

Component
Geometry (Form, Dimension, Position)
Texture and Colour
Intra- / Inter-component Joints
Material (Chemical, Physical and Biological description)
Structural (Self-supporting, Supporting other component of same element / other element)
Restraint/Support/ Attachment / Fixing

PERFORMANCE INDICATORS

Performance indicators are applied for quantitative measurement of the extent to which performance requirements are fulfilled and are expressed as functions of the element attributes. Those salient indicators are stated below as perceived within the scope of the subsequent demonstrative application of the proposed appraisal method for building envelopes during the occupancy phase. While some of them apply to both opaque and transparent components, e.g. thermal transmittance, others apply to only one, *e.g.* light transmittance. There are also those amenable to joints between components, *e.g.* water penetration. The range of values for each indicator in the demonstration are presented in parentheses.

Thermal Transmittance (TT= 0.4-1.2 W/m^2C) expresses the overall rate of heat energy loss through the unit area of the building envelope obtained as a weighed average according to the surface area covered by the opaque and the transparent components.
Thermal Capacity (TC= 200-2000 J/m^2C) states the amount of heat required to elevate the temperature of a unit area of the internal surface by one degree. In conjunction with the preceding thermal transmittance this parameter significantly influences the thermal behaviour of the envelope.
Water Penetration (WP=0.004-0.012 m^3/h @ 2500 Pa) denotes the rate of water volume ingressing through the joints between the components per unit length instigated by wind driven rain at the specified air pressure. Water through any cracks or porous material is excluded.
Condensation Risk (CR=0.1-0.7) is indicated *ad hoc* herein by the simple ratio of the inner to outer thermal resistances of the pertinent layers, sustained by the argument that the risk is greater when the outer resistance is smaller in relation to the inner.
Solar Heat Factor (SH= 3-12%) expresses the proportion of the heat transmitted through the envelope due to solar radiation to the total radiation incident on the external surface. This parameter is a function of the thermal transmittance, solar absorbtivity and conductance of the external surface. The effect of any vented cavity is also to be considered.
Light Transmittance (LT= 60-95%) states the ratio of the visible solar radiation transmitted through the transparent component to the total incident visible radiation. Reflective coatings on glass tend to change the quality of natural light.
Air Infiltration (AI= 0.006-0.014 kg/h @ 2500 Pa) conveys the mass of air entering through the joints per unit length at a certain air pressure induced by wind.
Mean Sound Reduction Index (SR= 18-52 dB) specifies the ratio of the incident to the transmitted airborne sound energy, thereby representing the sound insulation property of the envelope. This measure is significantly influenced by any gaps between components.

QUANTITATIVE PROCEDURE

Prior to the appraisal process, envelope alternatives can be generated by the combination of principal component alternatives according to formal taxonomy so as to achieve exhaustive enumeration. The combination process contains the following three variables: 1.Number of components in the envelope, 2.Arrangement of components, 3.Component alternatives. Those alternatives with any incompatible components are eliminated. Furthermore, the alternatives failing to attain above-average values for any one indicator may be precluded from appraisal, thus reducing the total number of alternatives included.

The quantitative procedure as the *modus operandi* of the appraisal consists of two consecutive parts employing the same procedure into which the sets of environmental and statistical indicators are substituted respectively. In the first part, before the actual evaluation is undertaken, the actual values of each indicator are converted through standardization, acting as the *deus ex mashina* to non-dimensional relative values. Then utility functions and relative indicator weights are applied as required. In the second part, the conventional aggregation process is enhanced by incorporating the supplementary statistical parameters of standard deviation and coefficient of variation beside the mean for any array of relative values. Thus the distribution of indicator values for each alternative is accounted for. Subsequently standardization is re-applied to all three statistical parameter values, yielding a single overall performance indicator for that set of values allowing element alternatives to be rank-ordered.

APPLICATION

A demonstrative application of the comparative appraisal method is carried out on a set of 21 generic alternatives (A_1-A_{21}) of an hypothetical envelope as represented by the functional element model with 8 environmental performance indicators (PI_1-PI_8) described above. All utility functions implemented on indicators are deemed to be linear and relative weights equal. Table 4 displays the actual physical indicator values of alternatives providing input data for the subsequent appraisal process. The actual values are then standardized. Table 5 presents the actual and relative statistical indicators of arithmetic mean, standard deviation and variation coefficient. In the final column of this table the overall performance values are provided according to which alternatives can be rank-ordered.

Table 4. Actual values of physical performance indicators for envelope alternatives

	TT W/m^{2}C	TC J/m^{2}C	WP m^3/h	CR --	SH %	LT %	AI kg/h	SR dB
A1	0.8	1100	0.006	0.4	3	95	0.006	36
A2	0.4	200	0.008	0.1	8	78	0.008	18
A3	1.0	2000	0.004	0.7	12	60	0.012	45
...	...	...	...	...	...	...	...	...
A19	0.4	2000	0.004	0.1	8	60	0.010	18
A20	1.2	650	0.012	0.2	5	72	0.012	52
A21	0.8	200	0.006	0.1	3	78	0.006	18

Table 5. Actual and relative statistical values

	Actual			Relative			
	Mean	Sta.Dev.	Var. Coe.	Mean	Sta.Dev.	Var. Coe.	Overall
A1	7.24	2.27	3.19	8.79	9.54	9.33	9.22
A2	5.26	3.64	1.45	4.74	2.63	2.33	3.23
A3	4.45	4.16	1.07	3.08	0.00	0.80	1.29
...	...	...	...	...	...	...	...
A19	7.83	2.33	3.36	10.00	9.24	10.00	9.75
A20	4.31	3.62	1.19	2.79	2.73	1.29	2.27
A21	5.96	3.94	1.51	6.17	1.11	2.57	3.28

DISCUSSION

The suggested envelope appraisal process on the basis of the functional element model allows alternative designs to be compared in terms of their overall physical performance. Hence the best overall performer, *i.e. primus inter pares*, among the viable alternatives providing a well synthesized solution that can be identified under fluctuating climatic and occupancy conditions. Furthermore the effect can be investigated of any individual envelope attribute on the overall performance of that alternative. The implementation of this method is anticipated to achieve a more satisfactory indoor environment through the most appropriate building envelope. The method is intended primarily for the benefit of researchers and practitioners involved in the design of building fabric and also indoor spaces. However the process is *de facto* confounded to a certain extent by the complexity of user preferences in performance requirements that vary according to human factors such as physiology and psychology. This situation is exacerbated by the indeterminate nature of the exoclimate that undergoes a gradual change due to global pollution. Therefore further research is called for in the field of performance requirements of building enclosures for achieving sufficient quality in the artificial environment.

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