International Journal of Architectural Engineering & Urban Planning

Architectural

Desirability-based architectural design of forms

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Abstract

The decisions and personal preferences of the designer are vital for all aspects and stages of the design. To elaborate, the designer has the central role in creation, development, detailing and construction of the built forms. Also, the scientific/engineering evaluations of the design models are carried out under the directions and decisions of the designer. The paper explores the concept of 'desirability factor' as a method for incorporating the decisions and preferences of the designers within the digital design media. Desirability factors are assigned to the models and explicitly express the views of the designer on the level of desirability of various aspects of the design. The desirability factors direct the process of selection of design variants (that are obtained from the sole scientific/engineering analyses) in the direction favoured by the designer. The examples in the paper illustrate the methods of definition and application of desirability factors to architectural design. The concept may be used for various engineering disciplines encountered in architectural design.

Keywords: *Desirability factor, Digital design, Architectural design, Design model, Design automation.*

1. Introduction

The advent of high technologies, availability of materials with diverse properties, and sustainability issues require sophisticated analyses and evaluations of the architectural forms. Physical objects can now be captured into digital models and vice versa (B Khoshnevis 2004).

The scientific/engineering analyses include energy analysis, study of circulation and access pattern, lighting, ventilation and heating, as well as acoustic and aesthetic considerations. Furthermore, the environmental performance of forms regarding the effects of sun, wind, snow… are to be investigated. A single digital model could collect information for diverse design aspects and disciplines. The paper shows that the personal preferences of the designer may also be included in the design model of the architectural form by the use of 'desirability factors' (M Heristchian 2010). To explain further, consider the following example:

Figure 1, shows an aerial view of a gymnasium in Japan during its construction stage (Tomoe Corporation). The dome belongs to the class of domes that are called scallop domes.

A scallop dome consists of a number of arched sectors (H Nooshin et al 1997, H Nooshin and P Disney 2000-2002). The dome of Fig 1 has eight sectors. Figure 2 shows four scallop domes with six sectors. The central rise of the outer edge arch of a sector is referred to as the amplitude (the parameter h of dome 'd' on the right).

In the domes of Fig 2, the amplitude varies from zero in dome 'a', to a maximum of h=0.5R, in dome 'd', where R is half of the span of the domes. Dome 'a', is the base on which scalloping has taken place.

Changing an aspect of a form, in general, will have different consequences and implications and it can be looked upon from various points of views. For instance, changing the amplitude of a scallop dome will affect:

The geometric particulars of the dome such as the length and the 'approach' angle of the elements (that is, the angle of an element relative to the connection), the occupied volume, ...

The self-weight, the response to environmental loads such as wind, snow, rain, temperature change ...

The acoustic response, the response to natural (day) light, sun shading,...

The cladding details, connection details, the architectural details,...

The functionality and visual impact,...

The structural response such as natural frequencies, strength, stiffness, support reactions,...

The construction methods,...

The maintenance requirements,...

The economy,...

The items listed above are only a few examples, and in general, an architectural form may have much wider and more diverse range of aspects. It should be noted that, the architectural form is the enveloping form and, normally, the structural form responds to an architectural form (A W Charleson 2005). Also, architecture is responsible for the built environment's social (mostly non-measurable) performance and engineering is responsible for its technical performance (P Schumacher 2014).

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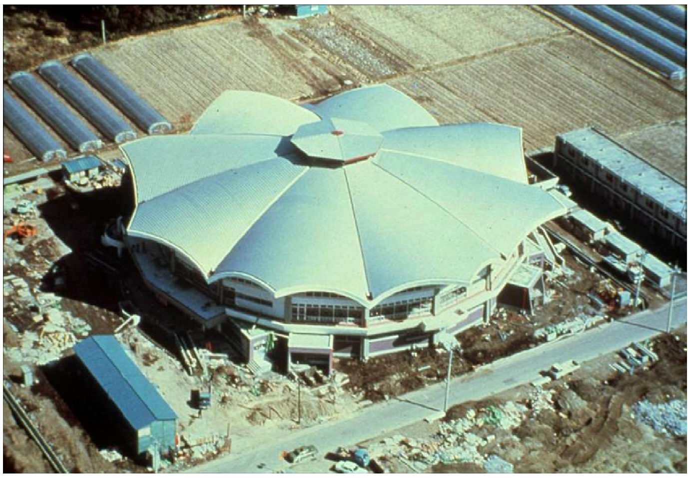

Fig. 1. An aerial view of a gymnasium, Japan (Tomoe Corporation)

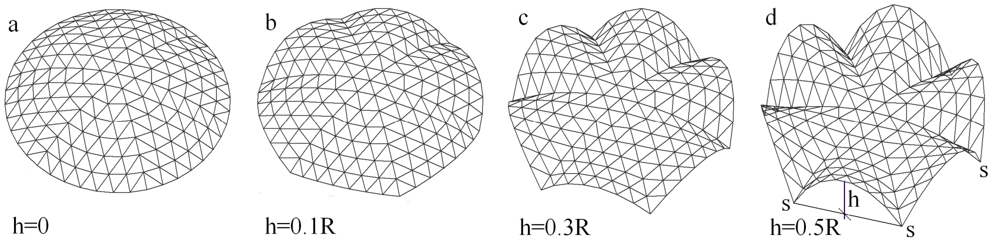

Fig. 2. Scallop domes with various amplitudes

Now, suppose that a designer has to select a dome from the set of domes of Fig 2. What are her/his criteria for this selection? Some of these criteria relate to measurable engineering aspects such as safety, strength and economy. In addition to the engineering criteria, an aspect such as visual impact of a dome could be the selection criteria. Visual impact is a non-measurable (and not easily definable) architectural aspect of a form. The selection is, in general, based on the two-fold criteria of engineering and non-engineering (subjective) considerations. But, both of these classes of criteria have their roots in desirability.

The opinion on the desirability of an entity of the form are expressed with phrases such as ‘excellent’, ‘very good’ ... ‘not good’ and the like. Suppose that the domes of Fig 2 are to be classified with such conventional phrases regarding their degree of desirability. Then, regarding the domes of Fig 2, one may say, for instance:

{[a, is ‘good’], [b, is ‘very good’], [c, is ‘the best’], [d, is ‘not good’]}.

With this type of description, it is very difficult -if not impossible- to carry out useful and further manipulations. It is possible, however, to express the degree of desirability of every aspect of the form numerically, and this type of expression is more useful in design considerations.

To express the level of desirability regarding the visual impact of the domes, one can use various numerical scales. For instance, the scale of 0 to 1 can be used for this purpose. Thus, any number between 0 and 1, referred to as a ‘desirability factor’, will represent a degree of desirability. Within this scale, let the number, ‘1’ represent ‘the highest degree of desirability’ and ‘0’ represent ‘the complete absence of desirability’.

A desirability factor, explicitly defines the level of preference. For the set of four domes of Fig 2, let the following list of desirability factors be assigned:

f = {0.5, 0.75, 0.9, 0.4},

where, the numbers 0.5, 0.75, 0.9 and 0.4 are associated with the domes a to d, respectively. Thus, dome c, has been given the relative highest desirability factor of 0.9, and dome d has been given the lowest desirability.

Now that the degree of desirability of a design aspect is expressed numerically, the question is how it can be useful in the design process?

Suppose that the domes of Fig 2 are the models to be evaluated in a design process, and suppose that the criteria of evaluation of the models relate to the realm of structural engineering. The domes have the same diameter, are single-layer lattice type with moment resistant connections, and each dome has six supports at the valley points ‘s’, as shown in Fig 2d. The members of the domes may assume a section from a list of steel square hollow sections and can be proportioned according to a design code of practice in the most economical way for a gravitational load uniformly applied all over the domes.

For a numerical example, a measure of the structural behaviour of the domes is given as:

K= {18.7, 3.1, 53.9, 100},

where, K is the normalised stiffness of the node at the crown of domes a to d of Fig 2. Here, dome d has the highest stiffness and possibly the most desired one from a purely engineering point of view. The desirability factors associated with the visual impact of the dome are already given as:

f = {0.5, 0.75, 0.9, 0.4},

To combine the engineering results and the visual desirability, the elements of the list K_m are obtained by multiplying the elements of the list K and the corresponding elements of f, as follows:

$K_m = f \times K = \{9.35, 2.33, 48.51, 40\}$,

The logic of multiplying the desirability factors with the engineering preferences is that here, one is encountered with two different classifications of preferences and the desirability factors can act as multipliers to combine the effects of the two classifications.

Thus, according to the list K_m dome c, has the highest score, and is therefore, the most suitable dome from both architectural and structural engineering points of view.

In cases where, the minimum value of a design criterion is sought, the above mentioned approach which applies to the maximum value criteria has to be slightly changed. As an example, suppose that, W is the normalised list of the weights of the domes, with the weight of the heaviest dome being considered as 100:

$W = \{90.1, 78.1, 83.2, 100\}$

Minimum weight of structures could be a design goal, therefore, dome b with the least weight of 78.1, is the most preferred dome. In order to find the effect of the desirability factor f on the weight list W, first a list M is obtained by finding the inverse of the elements of W:

$M = \{11.1, 12.8, 12, 10\} \times \frac{1}{1000}$

All numbers of list M have the common multiplier ($\frac{1}{1000}$). Now, the problem of minimising W has changed to the problem of maximising of M. The maximum value of list M, 12.8 corresponds to the minimum value of the list W, that is, 78.1 which is the relative weight related to dome b. Multiplying the desirability factor f by list M, in the same way that it was done for the list K, will modify the weight list W, as follows:

$W_m = f \times M = \{5.55, 9.6, 10.8, 4\} \times \frac{1}{1000}$

According to the modified weight list W_m, 10.8 is the maximum and corresponds to dome c, and is the most desirable dome by the combination of the desirability list f and the analytical results.

Having introduced the concept of desirability factor, some important points need to be elaborated upon as follows:

If all of the desirability factors in a list f are equal, then, these factors will have ‘no effect’ on the outcome. In such a case the design decisions are made only on the analytical results. For instance, the desirability list $f = \{0.5, 0.5, 0.5, 0.5\}$, will give rise to the choice of domes d and b, according to the stiffness criteria (K) and the weight criteria (W), respectively.

In the example under consideration, there was only one desirability list defined and all other decisions were left to the engineering considerations. Also, only one area of engineering, namely, the structural engineering was considered. The members of the domes were structurally proportioned based on a selected list of hollow square sections. But, many other structural sections could be used instead, based on the personal attitude of the designer. Additionally, a criterion such as ‘W’, that is, the weight of the domes was used as the engineering measure for comparison of the domes. It may happen that for another designer other criteria, say, the length of construction time to be more important than the weight criterion. The discussion reveals the fact that all design decisions (on measurable or non-measurable aspects) involves the personal preference of the designer. The same applies to optimisation processes as well (for instance, S Fujita and M Ohasaki 2010). It does not undermine the science and engineering advice available in a very wide range of areas and aspects of form, but it emphasises the twofold nature of any design decision: **desirability + engineering**.

Some design aspects have complicated nature. For instance, degrees of ‘comfort’ and ‘pleasantness’ of architectural spaces are not easily definable (C Alexander 1974). Also, temperature, humidity (M Tahbaz 2011and 2013) and sound, are among the measurable aspects, but their ‘acceptable and pleasant’ ranges could be different for different people. Aspects such as ‘privacy’ of living spaces, has dissimilar meanings and interpretations in different cultures and societies (G Safdarian and F Habib 2014). The aspect of ‘circulation path’ has different values for an exhibition hall, an air terminal, a school, a library and an office from the point of view of different architects. Interior decoration of houses, offices,... has to rely mainly on the personal preferences. As an example, suppose that in an office a number of desks and plant/flower boxes are to be arranged. There are many complicated aspects to be considered. For instance, circulation path, degree of occupancy of the area, privacy of each person, allergy of persons to plants, the natural draught/artificial ventilation, type of the duties of the persons and the required minimum area, the required light, the noise, ...

Considering the above given discussions, it is essential that the preferences of the designer regarding various aspects of the form, to be associated with the models within the digital design media.

2. Methods of Defining Desirability Factors

There are various methods for defining a desirability factor. The methods, in general, may involve lists (as discussed previously), mathematical expressions, diagrams, as well as, interactive definitions based on the analytical results.

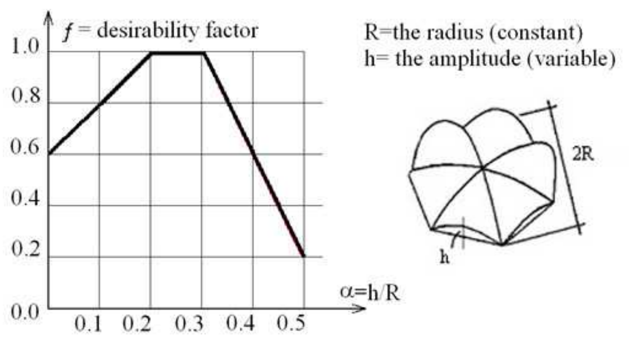

Fig. 3. A desirability diagram

- Figure 3 defines the desirability factor f as a function of the ratio $\alpha = h/R$, for a family of scallop domes.

The amplitude of the domes can assume any value in the range [0, 0.5R]. The figure shows that f=1, for α=0.2 to 0.3, and f=0.2, for α= 0.5. Here, the desirability factor is defined as a diagram instead of a numerical list. The desirability diagram of Fig 3, also, defines the allowable range of variable α. The desirability diagrams are useful for cases where there are numerous variants.

- Figure 4 shows the plan and side views of a pedestrian bridge over a valley in a wooded region. In addition to its role as a pedestrian bridge, the particular plan shape of the deck is to provide a suitable platform for an uninterrupted pleasant panoramic view of the surroundings of the bridge. The deck is supported by three columns at points A, C, D, and a pylon OP as shown in the side views of the bridge. The pylon at point P supports a main cable APB which is connected to a number of hanging stay cables. The deck of the footbridge is suspended from these stay cables at the inner side of the loop ASBR of the bridge deck. This type of supporting of the bridge deck from the inner side of the deck is similar to the idea of an S-shape footbridge, at Bochum, designed by J Schlaich and R Bergermann, 2003 (A Bögle et al 2005).

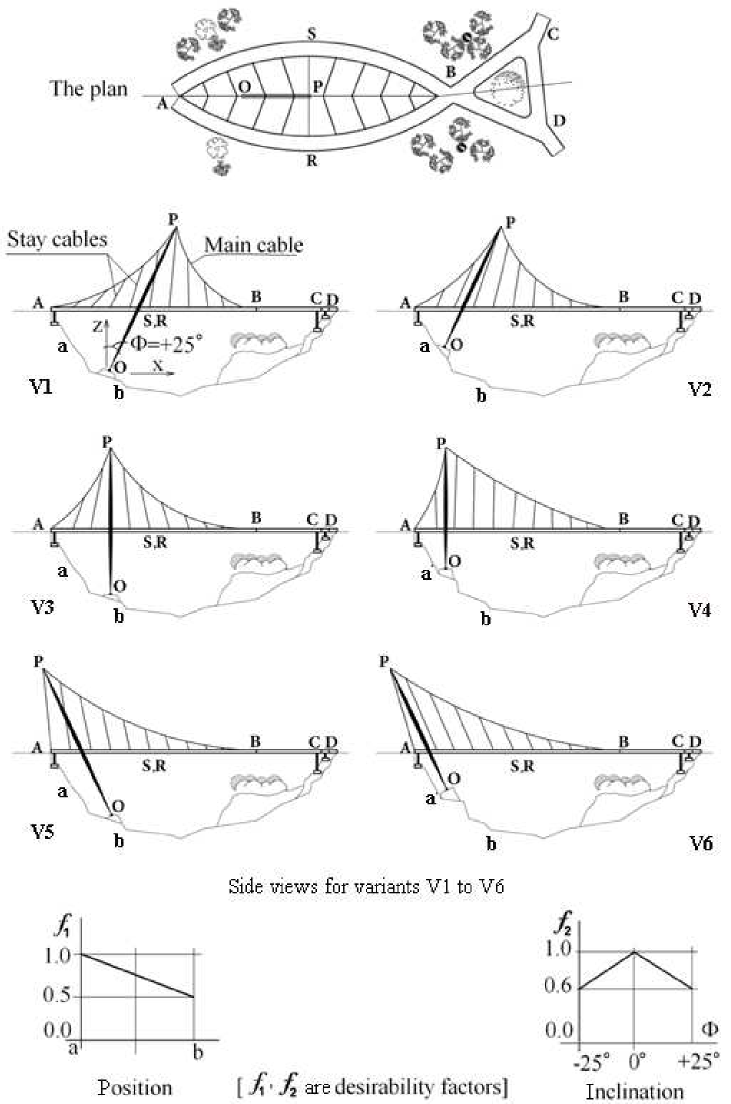

Fig. 4. Use of desirability diagrams for a pedestrian bridge

In designing the details of the bridge of Fig 4, it is intended to investigate the effects of the variation of the position of pylon OP. This investigation is to cover both the effects from an engineering point of view as well as those regarding the visual impact of the bridge. Regarding the base O of the pylon, the shape of the valley provides a region along the curve ab that suits the positioning of the foundation of the pylon. The choice of a point along ab for the foundation would of course affect the position of the pylon. The pylon's position is also altered by the angle Φ between the axis of the pylon and the z-coordinate axis (see the top left side view in Fig 4). A number of variations concerning the position of the pylon are shown in Fig 4, where the height of the top point of the pylon (that is, z-coordinates of point P) is kept constant.

The desirability diagrams f_1 and f_2 of Fig 4 are associated with the pylon OP of the bridge. In the desirability diagram f_1, point a, is the most preferred position of the base point of the pylon. Also, in the desirability diagram f_2, the inclination of 0° (with respect to the vertical axis z) is the ideal value of angle Φ.

The effects of the variations of the position of the pylon may be investigated from many different points of view. However, for this particular example, the investigation is limited to the horizontal movement of point P of the pylon in the x-direction, and the vertical deflection of point B of the deck of the bridge. These parameters are, in effect, measures of the stiffness of the footbridge. To investigate the structure, six variants of the bridge v_1 to v_6 whose longitudinal side views are shown in Fig 4 are analysed. The displacements of points P and B under the gravitational dead and live loads, for an assumed geometry of the bridge are obtained respectively, as

$D_P = \{149, 195, 78, 138, 33, 186\}$,

$D_B = \{116, 244, 161, 299, 402, 542\}$,

The displacements are in mm, and they are related to the following positions of the base point O and the angle Φ of the pylon.

C= {b, a, b, a, b, a},

Φ= {+25°, +25°, 0°, 0°, -25°, -25°},

respectively. The lists C, Φ, D_P and D_B, given above, contain the data and the output of the analysis for the variants v_1 to v_6 of Fig 4. Thus, for v_1 and v_4, one has [b, +25°, 149, 116], and [a, 0°, 138, 299], respectively.

The desirability factors for variants v_1 to v_6, extracted from the desirability diagrams of Fig 4, are

f_1= {0.5, 1, 0.5, 1, 0.5, 1} and

f_2= {0.6, 0.6, 1, 1, 0.6, 0.6}

In the case of present example, applying the desirability factors to the results of analysis, is not as straightforward as the example of Section one. The two desirability factors f_1 and f_2 have to be 'combined'. If it is assumed that the parameters C and Φ, have the same 'value' for the designer, then, their corresponding desirability factors f_1 and f_2 will have identical values as well. Therefore, the operation of averaging can be used to combine the two desirability factors

f= {0.55, 0.8, 0.75, 1, 0.55, 0.8}

Now, the rest of the process can proceed as before, by assuming that a smaller value of displacement is more favourable from the engineering point of view. Then, the inverses of D_p and D_B are multiplied by the desirability factor f, as explained in Section one,

$D_{pm}= \{3.69, 4.1, 9.62, 7.25, 16.67, 4.3\} \times \frac{1}{1000}$,

$D_{Bm}= \{4.74, 3.28, 4.66, 3.34, 1.37, 1.48\} \times \frac{1}{1000}$

According to the modified displacement lists, D_{pm} and D_{Bm}, the variant v_5 and v_1, have, respectively the highest stiffness and are the preferred variants from the point of view of the analytical measures combined with the desirability values.

The averaging of the desirability factors as applied above, assumes that all the participating aspects have the same importance. However, if the considered aspects of a form, have different levels of importance for the designer, then, a multiplier $0<\lambda\leq 1.0$, could be applied to the desirability factors associated with them according to their degree of importance. Otherwise, λ=1, is assumed for all the aspects.

The same type of combined desirability factors may be obtained, where several persons suggest different desirability factors for the same aspect of a form. The multiplier λ could also be applied in this case to consider the difference in ranks of the participants in the suggestions of the desirability factors.

The details of the combining the desirability factors may vary in different cases. For instance, for the example of the pedestrian bridge, suppose that an additional desirability factor f_3, reflecting the constructional experience of the designer is expressed in terms of the inclination angle Φ of the pylon. Then, the combined (=effective) desirability factor may be obtained as $f=\frac{1}{2}(f_1+\frac{1}{2}(f_2+f_3))$ or $f=\frac{1}{3}(f_1+f_2+f_3)$.

- Desirability factors can be assigned to any varying aspect of a form. To exemplify this, consider another type of variation for the footbridge of Fig 4, as shown in Fig 5a. The figure shows the plan of the centreline of the loop ASBR of the bridge of Fig 4. Here, it is assumed that the positions of points A and B are fixed. But, the shape of the bridge deck could change with respect to its initially assumed centreline of Fig 5a.

To elaborate, suppose that the hatched area of Fig 5b defines the region in which the geometry of the plan of the bridge deck can change. In other words, the hatched area defines the 'extent' or the 'tolerance' area for the base arc ('zero-arc', which means, the initially given geometry) of the bridge. There are infinitely many possibilities for the definition of the variants of the bridge deck within the hatched area. Here, a simple method is suggested for generating the variants of the bridge deck based on its initial geometry, that is, the looped arc ASBR. In order to explain the method of generating the variants of a given base arc, consider Fig 5c and suppose that the initially defined arc is jk. Now, let points j and k move to new positions (j_1, k_1) in the direction (side) 1, and (j_2, k_2) in the direction (side) 2, respectively. Furthermore, assume that the steps of movement jj1, kk_1, jj_2 and kk_2, are normal to the base arc jk.

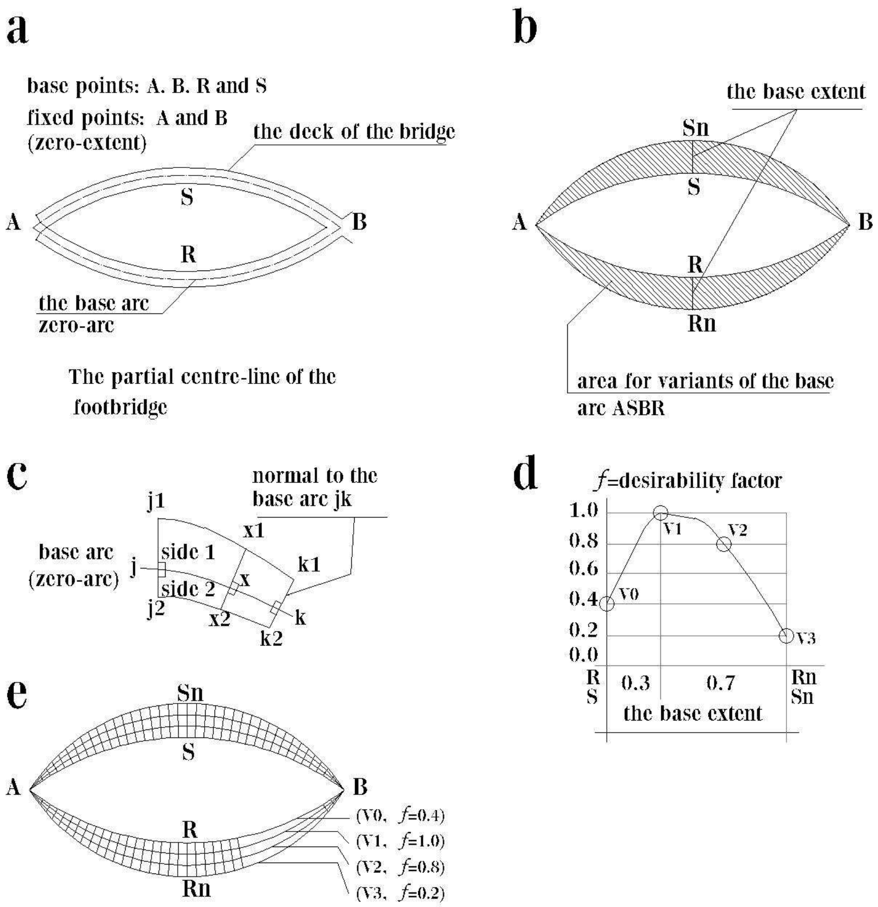

Fig. 5. Defining desirability diagram in terms of the shape of an arc

With these assumptions, the points x_1 and x_2, are the new positions of a typical point x, of the arc jk, on the sides (in the directions) 1and 2, respectively. Where,

$$\mathrm{xx}_1 = \mathrm{jj}_1 + (\mathrm{kk}_1 - \mathrm{jj}_1)\frac{\text{arc length(jx)}}{\text{arc length(jk)}}$$
$$\mathrm{xx}_2 = \mathrm{jj}_2 + (\mathrm{kk}_2 - \mathrm{jj}_2)\frac{\text{arc length(jx)}}{\text{arc length(jk)}}$$

Thus, the new position of a point x, is obtained by linear interpolations of movements of j and k. The arcs $j_1x_1k_1$ and $j_2x_2k_2$ are considered as two variants of the base arc jxk. For the arc jk, the points j and k, with known extents (steps of movements), are referred to as the 'base points'. Here, it is assumed that the arc jxk does not have 'sharp and abrupt' changes. For the loop ASBR of the bridge, the points A, B, R and S are assumed to be the base points. There could be several base points for an arc. The points A and B have a zero extent, and the extent of the points R and S, in the outside direction of the loop are RRn and SSn, respectively (Fig 5b). Then, the new position of any point x of the arc segments ASB and ARB could be obtained in terms of the movement of its base points. Thus, the variants of arc ASBR could be generated within the hatched area of Fig 5b. For instance, Fig 5e, shows four variants v_0 to v_3 of the base arc ASBR (including itself), together with the associated desirability factors extracted from the assumed desirability diagram of Fig 5d. In obtaining a variant, the steps of movement are assumed to be normal to the previously obtained (or neighbouring) variant (rather than the initial base arc). In a manner, similar to the outward direction, the variants of the inward direction of the loop ASBR could be obtained.

3. Desirability Factors and Initial Sketches

Architects use sketches as a tool to approach their projects and to give shape to the image they have in mind. The aim is to record the most significant features of the form to be built. The use of sketches is clearly an important part of the natural process and stages of designing (N Cross 1999 and 2008, C Paredes 2009). As a rule, the initial sketch lacks the detailed design information. The change from the initial sketch to the final design occurs by the evolutionary process of design. The initial sketch has to be refined according to the architectural, structural, mechanical and other requirements to come up with the final design. For example, consider Figs 6 to 8, which show the initial sketches and the final designs for Terminal 5 of Heathrow Airport (N Grimshaw 1991, The realised design of Terminal 5 differs from the design under consideration), a section of the roof of the main terminal of Kansai Airport, Osaka Japan (Renzo Piano, Building Workshop 1989) and the California Academy of Sciences (Renzo Piano), respectively.

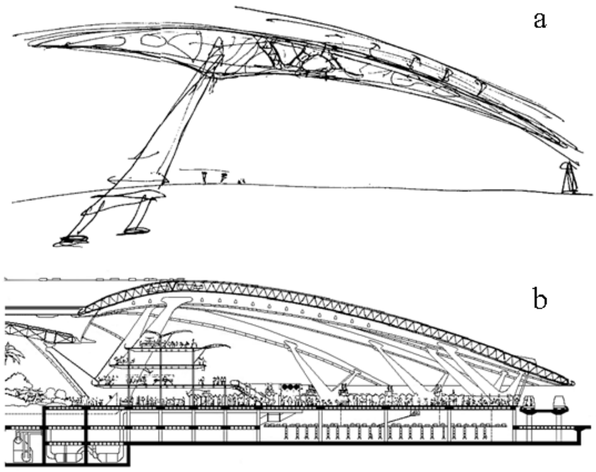

Fig. 6. Initial (a, top) and finalised (b, bottom) proposal for Heathrow Terminal 5 Nicolas Grimshaw exhibited at Venice Biennale 1991 (B Edwards 1998)

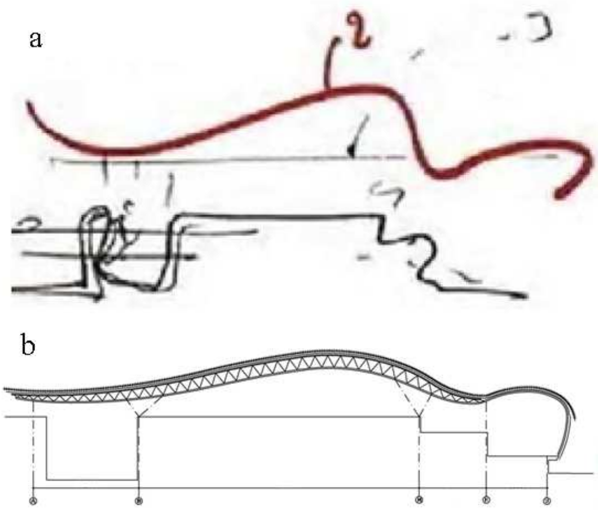

Fig 7. a (top) Part of the initial sketch, b (bottom) the finalised section, The main terminal of the Kansai Airport, Osaka, Japan, Renzo Piano Building Workshop (renzopiano.com), Ove Arup Consulting Engineers

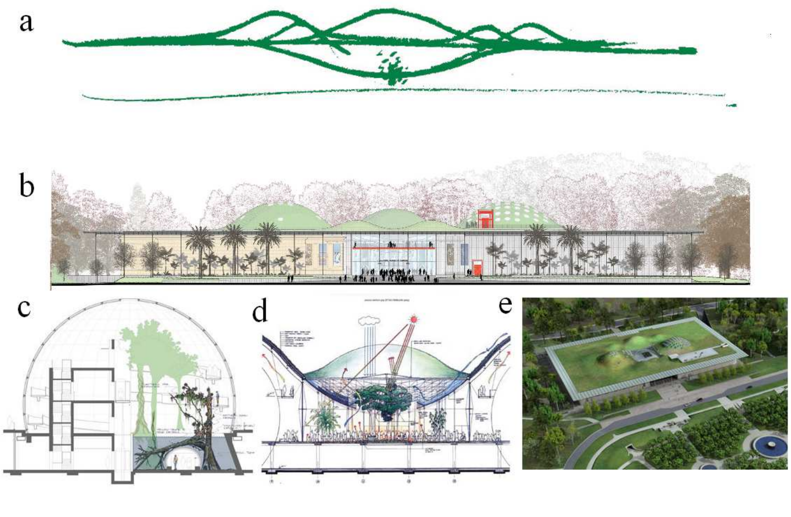

Fig. 8. a The initial sketch (basic idea), b to d development of the basic idea, e a view of the final structure, California Academy of Sciences, Renzo Piano Building Workshop and Arup Consulting Engineers

The way that the form of the initial sketch and the related data are interpreted in design process, does not follow a well-defined simple approach. However, it is clear that a sort of optimisation is involved in this transformation. The degree of change of an aspect of the initial sketch compared to the final design, somehow, is inversely related to the degree of 'desirability' of that aspect of the initial form. Thus, a 'low' degree of change of a feature, may, indicate that the feature has had a high desirability level. On the other hand, a high degree of change indicates that it has had a low level of desirability. Fuzziness is an inherent nature of the geometry of a sketch. Therefore, a desirability factor given to a sketch, intriguingly, is related to its degree of fuzziness as well. Phrases such as 'not sure', 'pretty sure', 'absolutely sure' that are customary and meaningfully used in relation to initial forms, reflect the degree of certainty of the designer regarding various aspects of the design. By comparing the forms of the initial and the final design, one could classify the degree of the changes that occurred as, say, low, moderate and high and so on. Here, the 'degree of change' rather than the 'reason for change' is the point in mind.

If the process of refinement of an initial sketch is to be carried out by computer, then, the digital media should receive information on the parts that are preferred to be left untouched, the parts that could be changed freely and so on. In other words, the steps for transformation of the initial sketch as the basis for the shape of the final design in a digital media, should take into account the personal preferences and the approach of the designer. And, this needs high-level conceptual tools that guide shape manipulations. The first step in this process is to input the hand-drawn sketch into the digital media, by appropriate devices such as scanners. Most of the digitised free-hand sketches cannot be used for engineering purposes directly, because either they have ambiguities or they do not have enough information such as scale and dimensions. Therefore, they have to be refined and synthesised. The next step consists of filtering graphic noises and removing ambiguities, classifying line thickness and colour, scaling and dimensioning of sketch and identifying the boundaries (fixed points). The attention, here, is focused on the general geometry as the main message of the sketch and the other data conveyed by the sketch is ignored. The end product of this step is referred to as a 'zero-sketch'. The geometry of the zero-sketch is clearly known and could be used for engineering purposes. A zero-sketch, normally, is a clue to the definition of a 'family' of geometric shapes rather than a single unique geometry. The acceptable ranges of deviations from the geometry of the zero-sketch are defined by 'tolerance space', which allows for the creation of geometries 'similar' to the geometry of the zero-sketch.

Then, by a method similar to the method used in Fig 5, variants of a zero-sketch could be generated. In this way, the hand drawn initial sketches could be used within the digital media for generating of the variants. With sufficient data, the idea could be extended to the three dimensional geometries.

4. Concluding Remarks

Architectural design is engaged with complex freeform geometries (P Zellner 1999) and a designer may imagine many interconnected hierarchy of patterns for a built environment (C Alexander et al 1977). As such, the architectural design is a multi-facet complicated process, in which the decisions and personal preferences of the designer are essential in shaping of the form. Existence of a measurable basis for an aspect of design, naturally, increases the rationality of the decision, but does not exclude human personal inclinations. Also, the absence of scientific measures in an area strengthens reliance on the experience, insight and judgment of the designers.

The paper shows that the personal desirability of the designer can be assigned with the design models, and can be combined with the results obtained from various engineering disciplines. The method is general and could be applied to any aspect for architectural design of form. However, for the practical application of the concept of desirability factor within the automated design media, devising suitable software is required.

Acknowledgements: During development of the concept of desirability factors, the author had many long discussions with Professor Hoshyar Nooshin of the University of Surrey, UK and received valuable comments from him.

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