Shapes, Numbers, Perception: Aspects and Dimensions of the Design-Performance Space

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ABSTRACT

The design-performance space denotes a virtual space that can be constructed based on discretized design variables and performance indicators. For an n-dimensional design-performance space, n = d + p, whereby d = the number of discrete design variables, and p = the number of discrete performance indicators. Once constructed, this space can be visualized and used by the designer to explore the relationship between design variables and corresponding performance attributes. We present, for the building design domain, an approach to generation and exploration of the design-performance space. In this approach, an initial design is used to generate a set of alternative designs that collectively constitute the design space. One way of doing this relies on the "scalarization" of design variables. The scalarization leads to the representation of a building as a point in a *d*-dimensional design space. Each coordinate of such a space accommodates a salient (semantic or geometric) design variable. Subsequently, the entire corpus of design alternatives is subjected to performance modeling. Based on the modeling results, an *n*-dimensional design-performance space is constructed. We specifically address the potential for and limitations of describing building geometry in terms of a continuous scalar dimension of the design space. We introduce the concept of "Relative Compactness", which is derived by comparing the volume to surface area ratio of a shape to that of a (compact) reference shape with the same volume. We present the results of an empirical study, which shows a significant correlation between the numeric values of relative compactness and the subjective evaluation of the compactness of architectural shapes.

Keywords: Buildings, design, performance, simulation, geometry

1 SUPPOSITIONS

Upfront, we would like to explicate certain suppositions behind this paper:

The building design process typically involves the iterative generation of multiple drafts. Alternatives may be generated for the design as a whole, or for parts of the design. Acts of comparison and evaluation accompany the process of convergence toward the end product. Evaluative acts should also address the performance of the building in view of its habitability and sustainability. Comparison and evaluation of design alternatives based on their predicted performance may benefit from specific (compact, abstract) forms of building design and performance representation. One such *formalism involves the representation of designs and their performance in a multi-dimensional design-performance space. The various dimensions of this space can represent salient design variables and relevant performance indicators. Despite the loss of some design information resulting from such representational formalisms, they could be effective in exploring the general performance implications of alternative designs.*

While the full significance of the paper's arguments depends on the validity of these suppositions, the work presented may still be of interest to those who do not share them.

2 MOTIVATION

Computational building performance assessment tools have been generally believed to have the potential of improving building designs. Accordingly, a large number of such tools have been (and are being developed). Yet the application of such tools in (and thus their impact on) the building delivery process has been rather limited. One possible contributing factor may be the circumstance that, while performance simulation tools can generate large amounts of data, there is not sufficient support for exploring, organizing, visualizing, and making sense of such data. Put in other terms, one could postulate that the navigation process in the "design-performance space" is not effectively supported.

3 THE PROPOSED APPROACH

In a previous publication we outlined a general computational process involving: *i)* generation of alternative designs based on parametric variations of the variables of an initial design; *ii)* making the resulting corpus of design alternative subject to systematic building performance simulation; *iii)* representation of the resulting information in terms of a landscape in the design-performance space; *iv)* interactive exploration of this landscape towards the identification of designs with preferable levels of performance (Mahdavi and Gurtekin 2001).

A typical instance of this process can be best described following a demonstrative system operation sequence:

a) The initial architectural design is entered into the system by the user.

b) This design is represented as a point in a d-dimensional design space. Each coordinate of such a space accommodates a salient (semantic or geometric) design variable.

c) Design alternatives are generated based on consideration of a region of the design space defined by selected ranges of the constitutive design variables.

d) The entire corpus of design alternatives is subjected to performance modeling (e.g. using neural network copies of simulation programs).

e) Based on the modeling results, an n-dimensional design-performance space is constructed (n = d + p, whereby d = the number of discrete design variables, and p = the number of discrete performance indicators).

f) User can navigate through the design-performance space (e.g. using computational data visualization tools).

g) Preferred designs in the design-performance space can be mapped back to geometrically specified designs by the user.

The selection of the essential design variables and their numeric definition is a critical part of the proposed approach. Various candidate design variables must be tested in view of their "expressive" potential and the most expressive ones could be used during the alternative design generation phase. In this paper we specifically explore the potential for the representation of certain aspects of building geometry in terms of a continuous dimension of the design space.

4 DESIGN VARIABLES

4.1 **Semantic design variables**

Building design variables typically capture either geometric or non-geometric (semantic) information of the building. Table 1 lists a few examples of common semantic design variables.

Table 1: **Examples of commonly used semantic design variables**

Semantic design variables	Unit
U	$W \cdot m^{-2} \cdot K^{-1}$
Thermal Mass	$kg \cdot m^{-2}$
Shading Coefficient	-
Visible Transmittance	-
Internal Load	$W \cdot m^{-2}$

4.2 **Geometric design variables**

4.2.1 *Introduction*

While most semantic design variables are scalar in nature, geometric design information is more difficult to express in terms of scalar values. Some familiar scalar indicators of building geometry are: The ratio of a building's length to its width (plan aspect ratio), the floor-to-floor height, the ratio of a space's height to its depth, the ratio of glazing area to the facade area, and the ratio of the glazing area to floor area (for rooms). Most of these indicators are rather limited in their scope and applicability. This implies the need for improved aggregate descriptors of building geometry.

4.2.2 *Characteristic Length and Ratio of Change*

There have been some attempts to describe the compactness of building shapes in terms of the relation between a building's volume and total surface area. One common example is "Characteristic Length" (l_c = V. A^{-1} [m]), which is simply the ratio of a building's volume (V) to its envelope area (A) (Mahdavi et al. 1996).

In another effort toward numeric characterization of building shapes, the relation between volume and area is explored as related to building's fabric heat loss (Markus and Morris 1980). In order to compare the surface area to volume ratios of buildings with different shapes, the volumes must be equal. It has been stated that cube has the least surface area to volume ratio as compared to other shapes with the same volume. Therefore, the "Ratio of Change" (ROC) has been calculated by comparing the surface area to volume ratio of a building to that of a cube with the same volume (Markus and Morris 1980).

4.2.3 *Relative Compactness*

In an effort to develop better aggregate descriptors of building geometry, we used the concepts of characteristic length and the ratio of change to derive the geometric variable "Relative Compactness" (RC). The Relative Compactness of a shape is derived by comparing its volume to surface area ratio to that of the most compact shape with the same volume. The most compact shape in geometry is the sphere. Therefore, when the volume to surface area ratio of another shape is compared with the sphere's, the following relationship can be established:

$$RC_{sphere} \cong 4.84 \times V^{2/3} \cdot A^{-1} \qquad \text{(Equation 1)}$$

Even though sphere is the most compact shape, it is perhaps not the ideal reference, as most buildings have orthogonal polyhedronal shapes. Using cube (the most compact polyhedron) as the reference shape, we obtain:

$$RC_{cube} = 6 \times V^{2/3} \cdot A^{-1} \qquad \text{(Equation 2)}$$

4.2.4 *Relational and Contextual Variables*

The relational and contextual variables of a design also affect the way it performs. The contextual variables are the ones related with the surrounding environment. The relational variables specify the connection between the design and its context. The orientation of a building within a site or the relative height of the ground floor of a building represents some common relational variables. The relational variables can be integrated into design variables. Climate is the major contextual variable affecting a building. The elevation and density of the surrounding buildings and vegetation, and the topographical properties of the site constitute further contextual variables.

5 THE PERCEPTUAL RELEVANCE OF RELATIVE COMPACTNESS

5.1 **The problem**

In principle, one can think of many different descriptors of building geometry. An important question is, however, if a proposed indicator is of perceptual relevance. A designer may be told that increasing or decreasing the value of a design variable would affect the performance of a building in this or that way. But this information would be of little use, if the designer cannot relate the numeric values of the variable to some intuitively accessible feature of the design. Hypothetically, the notion of compactness of a geometric shape is something that a designer could intuitively relate to. But it is not known *a priori*, if the subjective judgments of the degree of the compactness of shapes are reproducible. Neither can we claim *ex cathedra*, that the proposed Relative Compactness is a reliable correlate of such subjective evaluation.

5.2 **A pilot study**

5.2.1 *Overview*

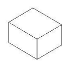
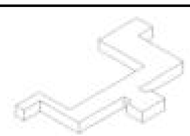
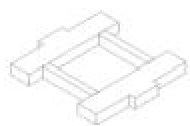
We performed an empirical pilot study to explore the degree to which the Relative Compactness correlates with the subjective assessments of the compactness of building shapes. The study involved the following general steps:

a) Based on multiple sources, a sample of 14 different building shapes was selected (one and two-story residential buildings).
b) A sample of 48 test participants (mostly students of Architecture) evaluated these shapes in terms of their compactness using two different procedures.
c) The subjective evaluations were compared with the numeric values of Relative Compactness.

5.2.2 *Building shapes*

Using multiple sources and documentations of residential buildings, a sample of 14 building shapes was established. These one and two-story buildings were represented in terms of axonometric line drawings (cp. table 2). For each building shape, the value of the Relative Compactness was calculated according to equation 2. As it can be seen from table 2, these values cover the range between 0.49 and 0.98.

Table 2: **Sample building shapes with volume (V) and Relative Compactness (RC) information**

Shape	V [m3]	RC	Shape	V [m3]	RC
	323	0.98		855	0.70
	507	0.94		723	0.68
	673	0.92		507	0.67
	428	0.89		795	0.63
	416	0.85		679	0.58
	517	0.80		1207	0.52
	528	0.78		1319	0.49

5.2.3 *Subjective assessment*

A group of 48 people participated in the subjective evaluation of the compactness of the shapes. Two methods of presentation were used. In the first case, five randomly selected sets of four shapes each were presented to the test participants (figure 1 shows an example of such a set). For each set, the participants were asked to arrange the four shapes from least to most compact. We compared these arrangements with the one resulting from the numeric values of the Relative Compactness. We expressed the degree of agreement between the subjective evaluation and the numeric values as follows. We ranked the four shapes according to their Relative Compactness values from the least to the most compact. We then compared this order with the corresponding compactness rankings by the students. To represent the degree of matching (agreement) numerically, we assigned 100% to identical ranking and 0% to most divergent ranking. For each set of four shapes the matching (M) was calculated as a function of displacement (D), whereby for each comparison the total displacement (of subjective rankings as compared to the RC-based order) would be 8 for the most divergent ranking. Thus:

$$M = (1 - \Sigma D \cdot 8^{-1}) \cdot 100 \qquad [\%] \qquad \text{(Equation 3)}$$

In the second case, we asked the test participants to evaluate each shape (presented in a random sequence) separately based on a semantic differential (cp. Figure 2), whereby they were to assign a numeric value (from 1 to 7) to each shape according to its (subjectively perceived) level of compactness.

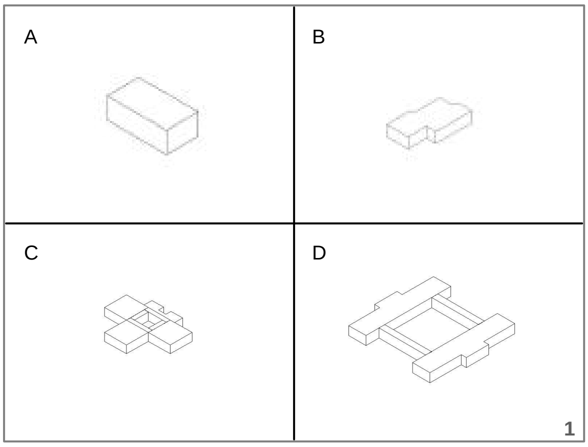


Figure 1: **Example of a set of four (randomly selected) shapes**

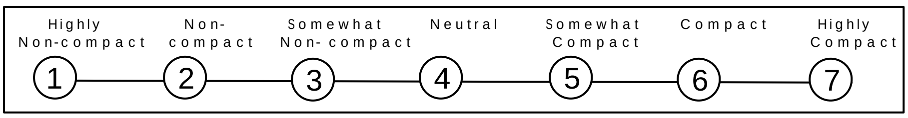


Figure 2: **Semantic differential for the subjective evaluation of the compactness of shapes**

5.2.4 *Results*

Both evaluation methods displayed good agreement between Relative Compactness values and subjective judgments. In the first case the overall level of agreement or matching (M according to equation 3) averaged over all five sets of four shapes and all test participants was 89.5%.

For the second case, figure 3 shows for all 14 shapes the relationship between the subjective evaluation marks (averaged over all test participants) and the corresponding numeric values of the Relative Compactness (R^2 = 0.965).

As a comparison, we also explored the relationship between subjective compactness evaluations and the numeric values of Characteristic Length. As figure 4 illustrates, in this case the correlation is much less impressive (R^2 = 0.663).

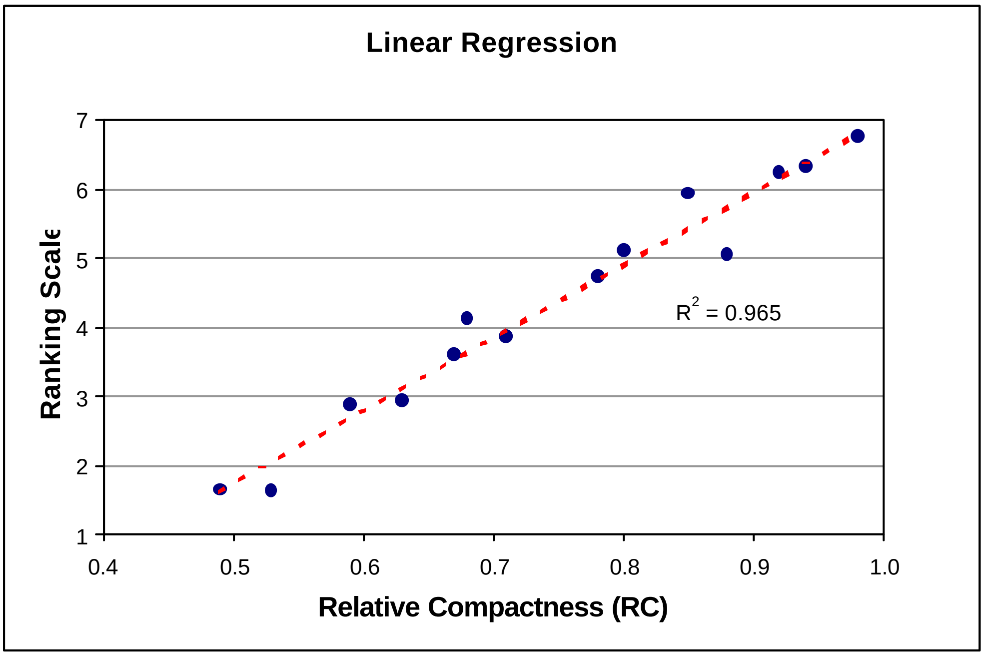


Figure 3: **Relative compactness of 14 shapes versus their subjective ranking**

5.2.5 *Limitations*

Despite the good agreement demonstrated in our pilot study, we do not claim that Relative Compactness is an unquestionably valid correlate for a designer's subjective sense of the compactness of an architectural object. Our study involved many abstractions and simplifications. For example, both the sample of shapes and the sample of test participants were limited. Moreover, shapes were presented from singular (axonometric) viewpoints and without architectural details, color, and texture. Nonetheless, the results do appear to suggest that certain reductive formalisms to capture building geometry can facilitate the representation of certain intuitively meaningful geometric features of buildings along a design dimension of a design-performance space.

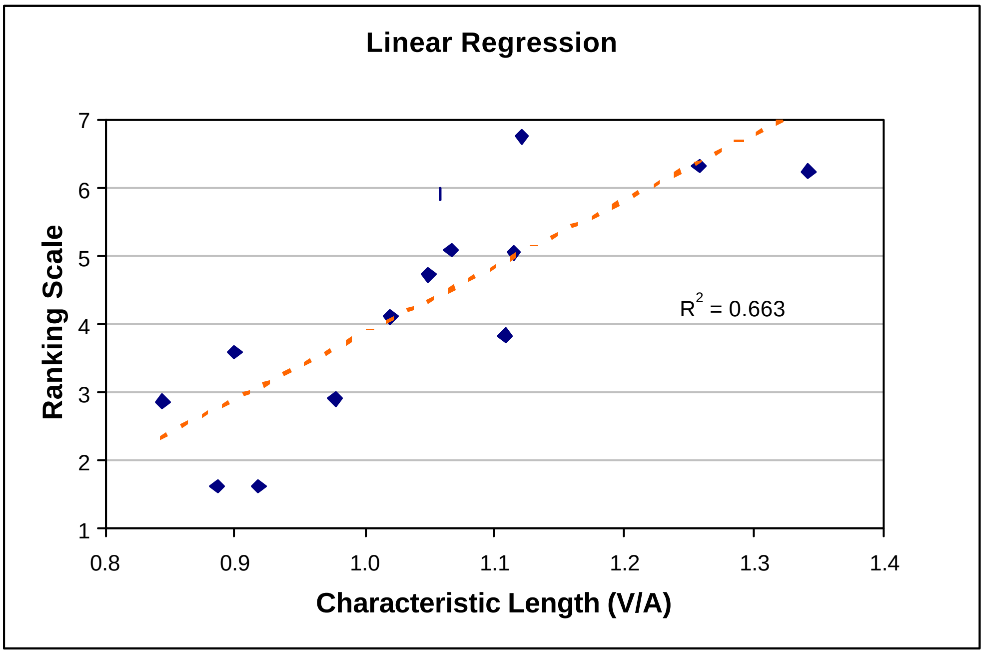


Figure 4: **Characteristic length of 14 shapes versus their subjective ranking**

6 CONSTRUCTING AND NAVIGATING THE DESIGN-PERFORMANCE SPACE

Given a well-specified design-performance space, an initial design can be used to generate a large number of variations. In a previous study, we demonstrated that such large sets can be made subject to rapid performance assessment using neural network copies of simulation programs (Mahdavi and Gurtekin 2002). In neural network modeling, a mathematical model that represents the relationship between design variables and the performance attributes is constructed. To obtain sample data needed for this model, parametric performance analyses can be applied to a design. These base case buildings are used for extensive parametric analysis and generation of a mathematical building performance model. It is envisioned that a series of these mathematical models could be constructed in order to cover a reasonably wide range of possible designs. These models can be categorized according to one or more parameters (e.g. climate, site, building type and size).

Given the variations of the initial design and their corresponding performance attributes, a design-performance space can be constructed. This space can be explored using data visualization tools. Thus, the designer can visualize various views of the solution space and is able to study the relationship between design variables and corresponding performance attributes. By visually marking the initial design's performance value in the design-performance "landscape", the designer can understand where the initial design stands within the overall n-dimensional design-performance space) could be mapped back to a concrete design. Thus, necessary changes to the design variables can be identified, resulting in designs with improved performance.

7 REFERENCES

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