A model of aesthetic judgment in design

Yoram Reich
Engineering Design Research Center
Carnegie Mellon University
Pittsburgh, PA 15213
yoram@cs.cmu.edu

18 September, 1992

Artificial Intelligence in Engineering, 8 (2) : 141-153, 1993

Keywords: aesthetic judgment, rationalism, romanticism, computational model, design adaptation, machine learning, bridge design.

Running head: Aesthetic judgment in design

Abstract

Aesthetics plays a major role in real design. To date, aesthetics is mostly ignored in studies dealing with computational design support systems. Probably, the main reason for this omission is that aesthetics is tightly associated with art which is perceived to be beyond the capabilities of computational techniques. The paper outlines a model for the incorporation of aesthetic judgment in design. It shows how important aesthetic criteria that follow the rationalistic and the romanticist movements of aesthetics, can be represented, refined, and used in design. BRIDGER, a system that assists in the preliminary design of cable-stayed bridges, implements a preliminary version of this model. Several examples of designs generated by BRIDGER are discussed for demonstrating the scope and potential of the model.

The most significant investigations in bridge aesthetics deal primarily with fundamental philosophical and psychological problems or direct aesthetic analysis of existing bridges, providing relatively few basic concepts for use in design. (Menn, 1991, p. 177)

1 Introduction

Design research usually concentrates on the generation of descriptions of artifacts that satisfy some functional requirements. This emphasis leaves out additional concerns that influence the quality of artifacts. In particular, it is indisputable that designs that are aesthetically pleasing, besides being functionally adequate, have a higher chance of being commercially successful. Many engineers will even state, whether correctly or not, that *designs that are not aesthetic are probably functionally inadequate.*

Aesthetics is usually associated with art. Since it is not clear how computers can be made artistic, it is not clear how aesthetic principles can be captured and used in computer-aided design

systems. Nevertheless, although aesthetics *per se* is rarely addressed in design research, the common view of design that emphasizes functionality does not completely ignore aesthetics. Aesthetic criteria are embedded in designers' expertise and their use is manifested in existing designs. Thus, design support systems based solely on functionality, that use knowledge extracted from experts or from existing designs, will implicitly capture some aesthetic judgment. This, however, is not sufficient to support all aesthetic concerns in design.

Three proposals for the incorporation of aesthetic criteria in computational tools were proposed by Stiny and Gips (1978), Makkuni (1987), and Minai (1989). A review of these proposals reveals that they are limited to one view of aesthetic judgment. A view that will be referred to as *rationalism*.

This paper proposes a model of design that extends the support for aesthetic judgment in two ways. First, it adds another perspective of aesthetics, referred to as *romanticism*, and combines it with rationalism. In doing so, the model breaks away from the either-or dichotomy of rationalism-romanticism and demonstrates their necessary synergistic relationship. Second, the model argues that there are no generally "objective" or fixed aesthetic criteria. Rather, aesthetic appreciation is culturally dependent and evolves in time; therefore, static or imposed aesthetic criteria are inadequate as a basis for computational models that support aesthetic judgment. An appropriate model must rely on the continuous acquisition and adaptation of aesthetic criteria. These two extensions are the major improvements of this work upon the three aforementioned computational models of aesthetics.

This paper demonstrates the proposed model for a small, but important, set of aesthetic criteria of cable-stayed bridge design. The model is implemented in BRIDGER, a system that learns to assist designers in the preliminary design of cable-stayed bridges. The system allows designers to explore several alternatives that have initial good aesthetic appeal while leaving to designers the responsibility over the design process, leading to its successful realization in an aesthetic form.

The remainder of this paper is organized as follows. Section 2 briefly summarizes two views of aesthetics: rationalism and romanticism. It starts by providing their traditional interpretations and then discusses their *reconstructed* interpretations. Section 3 discusses these views in the context of bridge design. Section 4 outlines a model of aesthetic judgment based on the reconstructed interpretations. It also compares the proposed model with three other models and briefly outlines how aesthetic criteria can be used in several traditional computational models of design. Section 5 describes BRIDGER, the system that implements the model of aesthetic judgment for cable-stayed bridge design. Section 6 discusses the aesthetic aspects of design revealed in four design scenarios with BRIDGER. Section 7 evaluates the model and its implementation and Section 8 summarizes the paper.

2 An overview of aesthetics

Aesthetics is the study of beauty (Britannica, 1979; Mahshavot, 1990). The name *aesthetics* was given to this study by Alexander Baumgarten in his book *Reflection on Poetry* (1735). Baumgarten noticed that sensations and perceptions, the sources of aesthetic experiences, are neglected as subjects of study in the rationalistic school of philosophy. In accordance with his rationalistic

background, Baumgarten embarked on a mathematical study of aesthetics. The rationalistic view of aesthetics persisted over the years and additional views emerged, many whose origins date back at least to the Greeks.

Today, there are many views of how aesthetics is subdivided into different areas of inquiry. These views differ considerably; for example, see the differences in the discussions on aesthetics in the 1979 and the 1989 prints of the 15th edition of The Encyclopaedia Britannica. In this paper we focus on two major views of aesthetics that seem to play a major role in design: the *rationalistic* and the *romanticist*. As Lesnikowski (1982) said, the "struggle between intellect and emotion, reason and instinct, rationalism and romanticism is the fundamental creative force behind Western (and maybe universal) cultures." (p. ix) Similar ideas about the role of these two views in design are expressed elsewhere (Minai, 1989; Smith, 1987).

Before reviewing the rationalistic and the romanticist views, it is useful to address briefly whether beauty is a quality of objects themselves or whether it solely exists in the mind of the observer. The rationalists will tend to favor the former and the romanticists the latter. Although no solution can be found to this question, it is offered that any study of beauty really deals with the ideas of the observer. As Santayana (1988; first edition in 1896) said, our ideas about an object are the residuum of our encounters with this object. Our experience is subjective although it refers to an object. Ideas of people from different cultures and at different times may be completely different.

Rationalistic view.

The rationalists view aesthetics as the *science* of beauty. Thus, it is not enough to appreciate an artifact, it is also mandatory to understand why, explain, and evaluate the origins of this appreciation. Aesthetic experience is built up of elementary sensory pleasures by associations; thus, general rules of aesthetics can be easily formulated. In doing so, the limited attention-span of perception of humans has a considerable impact on aesthetic laws and must be taken into account in the study of aesthetics. For example, one rule may state that compositional forms should avoid *monotony* since monotony can cause fatigue. The prevention of fatigue can be achieved by adhering to laws of *contrast* that introduce novelty and complexity. Another example of an important aesthetic principle that supports easy perception is the concept of *order* (e.g., symmetry or coherence).

The two aspects, contrast and order, contradict each other and cause tension that may distort the aesthetic experience; nevertheless, some aesthetisticians claim that this tension is the essence of the aesthetic experience. Some of the principles that control this tension include: organization and harmony. The aesthetic laws that primarily realize these principles are the laws of *proportioning* whose use dates back to ancient times and still persists today. For instance, Pythagoras discussed proportions in relation to sound and form perceptions; Vitruvius discussed it in relation to architecture; and the architects Palladio and Le Corbusier used proportioning laws in their designs. Two well known proportion principles involve the use of the *Golden Mean* and the *Fibonacci series* as means for generating aesthetic figures.

Aesthetic laws derived from the rationalistic view can be used in *generative* processes since they address the relationships between elementary aspects of objects or forms. Therefore, an object can be generated incrementally and aesthetic criteria can be used at each generation step.

Romanticist view.

The romanticists object to the stipulation of laws that can solely account for aesthetic creation and judgment. Artistic aesthetic acts cannot be captured by laws since some perceptions cannot be explained by appealing to elementary impressions. The main principle used in romanticism is that some partial objects have the tendency to 'complete' themselves by closure. An object generated from these partial objects has properties that cannot be summarized from the properties of its building blocks. This fuzzy notion is translated into aesthetic principles such as balance, redundancy, and unity of form.

The aesthetic principles derived from the romanticist view can apply in *classification* or *overall evaluation* processes since complete forms are required to verify whether they hold. These principles can also generate complete designs similar to previous designs through associations.

Reconstructed interpretations of rationalism and romanticism.

The traditional rationalistic view assumes that *reason* is the source of judgment. It opposes empiricism which argues that aesthetic judgment is developed through learning from experience. In spite of this difference, both rationalism and empiricism accept a reductionist (or structuralist) view of aesthetics, namely, the aesthetic appeal of objects is determined by the various explicit relationships between the objects' components, whether obtained through reason or learning. The *reconstructed* interpretation of rationalism reconciles these views. Henceforth, the term rationalism will refer to the reductionist view of aesthetics.

The idea that aesthetic judgment can be learned applies to romanticism; in fact, it is natural to romanticism. The application of the closure principle of romanticism can result in wholes that are learned from experience, and most probably, through social construction based on community experience.[1]

The type.

Rationalism and romanticism are not mutually exclusive. In fact, there is a spectrum of views ranging from the extreme rationalist to the extreme romanticist. One example of an aesthetic organization that can be viewed as borrowing from both rationalism and romanticism is the *type* (Santayana, 1988). A type is generated through learning during adjustment to the social and physical environment. A type is a psychological concept based on a group of features that are recognizable as a whole by perception and senses. Types have an organizational power. The aesthetic pleasure created from observing an object can be derived from the appreciation of the way the object fulfills the function of a previously generated type. Since this pleasure depends on knowledge, it is sometimes called *intellectual beauty*. Two important categories of types are: (1) *types of utility* that are derived from the recognition of how objects ought to function for maximum utility; and (2) *types of technique* that are derived from the knowledge of the skills needed for producing an artifact.

[1] As reconstructed, rationalism and romanticism have some similarities to psychological schools of thoughts: rationalism corresponds to the Constructivist or Structuralist school of psychology and romanticism corresponds to the Gestalt school of psychology.

3 Bridge aesthetics.

This section illustrates the abstract ideas discussed in the previous section using concepts from bridge design. Before discussing the details of bridge aesthetics, it is important to be familiarized with the specific type used in this paper: cable-stayed bridges.

Figure 1 shows the main components and dimensions of a cable-stayed bridge. A cable-stayed bridge is composed of a superstructure and a substructure. The superstructure is composed of a deck, towers, and stays that are attached to the towers and support the deck. The figure shows some of the properties used to describe a cable-stayed bridge; additional properties include: `SPAN-N`, the number of spans of the bridge; and `DECK-A`, `TOWER-A`, and `STAY-A`, the cross-sectional areas of the deck, tower, and stays respectively.

Put figure 1 about here

In a design scenario the requirements are expressed as a set of specification property-value pairs (e.g., the required length of the bridge and its horizontal clearance requirement). Subsequently, design progresses by making design choices as assignments of design-description property-value pairs (e.g., `SPAN-M`=500 m, `STAY-N`=20).

In general, bridges are examples of artifacts whose aesthetics is a major evaluation criteria. By their very nature, bridges are displayed for everyone to see, use, and appreciate. An extensive number of publications on bridge aesthetics have been published to date. Two recent titles of collections of papers on bridge aesthetics are *Esthetics in Concrete Bridge Design* (Watson and Hurd, 1990) and *Bridge Aesthetics Around the World* (Committee on General Structures, 1991). A reading of these two books, as well as others references, some from the extensive bibliography in the latter, reveals several patterns. First, there is a large variety of views on bridge aesthetics including the rationalist and the romanticist views.

Second, there is a significant controversy about how aesthetic bridges can be designed. This is best illustrated by four citations from the collection *Bridge Aesthetics Around the World*, discussing the relationships between optimal functionality and aesthetics quality.

(1) "Yet there can be no doubt that any manmade product of great efficiency will also be aesthetically satisfying." (De Miranda, 1991, p. 92)

(2) "Greater aesthetic requirements normally result in more space under the structure, especially thinner superstructures, longer spans, fewer piers, wider deck overhangs, and smaller piers. These requirements often lead to an increase in cost." (Von Olnhausen, 1991, p. 197)

(3) "No greater mistake could be made than to subordinate beauty to technical aspects or to think that a perfectly functional bridge is necessarily beautiful." (Fernández Ordóñez, 1991, p. 206)

(4) "Any technological action should be efficient. As a rule, we want our work to be technically correct and economical. The tendency toward cool rationalization may lead, in an extreme case, to a product that does not fit human needs and aspirations." (Glomb, 1991, p. 96)

The differences between these views demonstrate the tension between rationalism (functionalism) and the romanticism in bridge design.

While it is expected that romanticism is subjective, rationalism is often proclaimed to be objective by its supporters. Nevertheless, there is a significant variation in the interpretations of rationalism in bridge design. "Most of the authors who have suggested guidelines or rules are [...] generally in agreement on the most important aspects [such as unity of form or harmony]. However, it is not always easy to differentiate between the generally accepted principles and what may be mere working rules." (Liebenberg, 1991, p. 4)

One prevalent factor that influences aesthetic judgment is cultural background. It is manifested by different views on bridge aesthetics, such as those from China, India, and Italy, appearing in *Bridge Aesthetics Around the World*. The dependency upon cultural background further downplays any appeal to objectivity in aesthetic judgment.

Examples of the rationalist and the romanticist viewpoints as they appear in publications on bridge aesthetics are elaborated below.

Rationalistic view of bridge aesthetics.

The rationalist view relies on the use of laws relating various components of the bridge to each other. In particular, good proportions between the various parts of the bridge (e.g., $\texttt{MSL}-\texttt{RATIO} = \frac{\texttt{SPAN-M}}{\texttt{CROSS-L}}$, $\texttt{ST}-\texttt{RATIO} = \frac{\texttt{TOWER-H}}{\texttt{SPAN-M}}$, $\texttt{SSDD}-\texttt{RATIO} = \frac{\texttt{SPAN-SPD}}{\texttt{DECK-D}}$, $\texttt{SAM}-\texttt{RATIO} = \frac{\texttt{SPAN-SA}}{\texttt{SPAN-M}}$, $\texttt{FMM}-\texttt{RATIO} = \frac{\texttt{FMM}}{\texttt{STAY-SPD}}$, and $\texttt{FIM}-\texttt{RATIO} = \frac{\texttt{FIM}}{\texttt{STAY-SPD}}$, shown in Figure 1) are viewed as conveying an impression of harmony. Order is achieved by the use of symmetry (e.g., stay arrangement in both sides of a tower is symmetrical if possible) and the avoidance from abrupt changes in forms of bridge components (e.g., the form of the deck is maintained along the entire bridge, especially in long bridges with several spans).

Two examples illustrate the rationalistic view. An extreme rationalistic position is manifested by Lee (1990), who argued that "all that need be referred to [...] is that what looks well can generally be mathematically tested." (Lee, 1990, p. 103) Lee provided two examples of using proportions to design the cross section of a bridge and the overall configuration of a cable-stayed bridge. In another example, a utilization of two aesthetic principles, order and contrast in the design of Chinese bridges was discussed by Tang (1991). Tang also discussed the evaluation of bridges through the use of the Golden Mean proportion.

There are additional rationalistic aesthetic considerations. For example, certain stay arrangements may be viewed as superior since they do not cause crossing of the stay-lines from any perspective they can be viewed (Buckland, 1990), therefore, they are preferred to other configurations.

The above laws and considerations provide guidelines for synthesizing new bridges since they contain information about the generation or selection of alternatives. Nevertheless, the fulfillment of all the rules does not guarantee the generation of a bridge that is aesthetically appealing as a whole. Furthermore, the rules are never detailed to the level of precise procedures, they are left as general guidelines that leave much room for the exercise of subjective judgment.

Romanticist view of bridge aesthetics.

The bridge as a whole is the final determinant of aesthetic judgment. Considerations such as balance, redundancy, and unity of form play important roles in this judgment. The very nature of romanticism makes it difficult to explicate what is the cause of an aesthetic pleasure or to provide rules for designing an aesthetic bridge. However, examples of ideas about it do exist.

To illustrate, Ohta, Takahashi, and Yamane (1987) explained the use of cultural motifs and their transformations into forms of bridge towers. The transformation are not discussed and the abstracted forms of the towers, can remind, only in an associative holistic sense, of the original motifs. It is this association that gives the forms of the towers a new aesthetic meaning. It is clear, therefore, that this aesthetic appreciation is predicated on familiarity with the cultural motifs and therefore is culture and time dependent.

The manifestation of romanticism in evaluation is more significant. It is enough to look at bridges, appreciate them and then read the reconstructed explanation that writers on bridge aesthetics provide. These descriptions are abstract and assume that the readers fill in most of the details between the abstract explanations and their aesthetic pleasure. Undoubtedly, this activity itself is based on romanticism.

The type.

A major contribution to the aesthetic experience with a bridge arise from the fulfillment of the type function discussed before. As Gustav Eiffel stated: "the first principle of architectural beauty is that the essential lines of a construction be determined by a perfect appropriateness to it use." (cited in Billington, 1991, p. 67) Here, the type is the concept generated from experience of a good bridge. For example, a cable-stayed bridge is recognized as an aesthetic type of utility when (1) it is evident how forces flow from the deck through the stays to the tower; (2) the relative sizes of the components convey a feeling that the material used to carry the loads is adequate; and (3) each part of the bridge is equally supported. In addition, some aesthetic experience can be generated by the fulfillment of a type of technique if it is transparent how such a bridge can be naturally built.

Buckland (1990) argued through an example that aesthetic qualities arise from the practical issues of bridge design. As demonstrated by his example, a significant part of type appreciation requires having knowledge about structural engineering. But even this is not sufficient to arrive at a consensus about aesthetic qualities as exemplified earlier by the four contradicting views on the relation between functionality and aesthetics.

4 A model of aesthetic judgment

We have seen that aesthetic judgment, as discussed in philosophy and by bridge designers and researchers, has several important properties: (1) some abstract principles such as order, proportions, and harmony influence on aesthetics, (2) general holistic appreciation affects the aesthetic quality of objects, (3) no agreement exists about the specific nature of the first two properties including whether any of them is more important, and (4) there are significant evidences that different appreciations of bridges stem from different experiental backgrounds.

The proposed model.

This paper proposes a model that relies on the rationalistic and the romanticist views of aes-

thetics. As an integral part, it assumes that aesthetic criteria arise in cultural context and change through learning. The model argues that design is an iterative process composed of *romanticist generations* followed by *rationalist adaptations* (see Figure 2).

Put figure 2 about here

In synthesis, a specification, abstract or concrete, associatively reminds of previous design scenarios or designs. These associations embed implicit aesthetic criteria. Subsequently, the design scenarios or designs are adapted to fit relevant rationalistic rules. Analysis and redesign that apply after synthesis can be also accommodated into this framework. Analysis is a holistic evaluation and redesign involves local adaptations.

No design knowledge is fixed *a priori*. In contrast, knowledge, including that of aesthetic judgment, evolves continually. This evolution is manifested by the addition of new romanticist associations, as well as, by the modification of rationalistic rules and parameters. For example, the proportions of the Golden Mean can only be maintained as guidelines for creating aesthetic designs if they are used extensively in producing designs that prove to be aesthetic, otherwise, different proportions that were found aesthetically pleasing in the past will be used. Care is taken not to "stiffen the taste" through extensive use of experience by providing means for (1) exploring variations on previous designs and (2) maintaining the designer in control of the design process, thereby allowing the introduction of new perspectives.

The model proposed is very general and simple, aiming at conveying its fundamental principle: the synergy between romanticism and rationalism in aesthetics. The model contends that associative generation and local adaptation are necessary complementary processes for achieving an overall aesthetic appeal of artifacts. While associative generation can create complete artifacts, it can only approximate the desired functionality. Similarly, while local adaptation can operate on existing structures and modify them locally to satisfy given requirements, it can hardly satisfy any holistic requirement.

Incorporation of aesthetics in design.

The new model extends several computational models of aesthetics in design that have been previously proposed, of which three are briefly reviewed.

Stiny and Gips (1978) implemented an architecture that supports a rationalistic aesthetic judgment. Their approach was based on a grammatical representation of designs. They proposed that the aesthetic value of an object could be based on the object's entropy, where entropy is defined as the length of a computer program that is capable of reconstructing the object. This definition limits the model to rely strictly on simplicity and order as the guiding aesthetic principles. While the model is strictly rationalistic, its quantitative aspect depends on subjectively imposed parameters. Therefore, this model does not escape the need to rely on principles other than rationalism, principles that are unaccounted for by the model.

Makkuni (1987) implemented a system for designing Chinese temples based on the rationalistic view of aesthetics. In this system, a design consists of several intertwined processes: vocabulary definition and generation, vocabulary manipulation, the exploration of topologies generated by the

vocabulary, and the realization of the topologies by rules that specify the dependencies between design components. The system only provides facilities for easy generation and manipulation of designs. It is the responsibility of the designer engaged in the dynamic interaction with the system to provide the aesthetic judgment. The generative part of design supported by this model is strictly rationalistic. Nevertheless, the model allows the designer to exercise both forms of aesthetic judgment independently of the model.

Minai (1989) shared the same concerns for supporting both views of aesthetic judgment as expressed in this paper. He also criticized Stiny and Gips' model for lacking the holistic aspect of creation. Minai proposed that design is optimizing the communication between various opposing views, such as the rationalistic and the romanticist. Nevertheless, his two models of design: entropy and design games, are equally based on mathematical or formal principles as the model he criticized.

In addition to the three proposed models, aesthetic judgment can be augmented to various existing computational models of design.

(1) *Refinement + constraint satisfaction (Steinberg, 1987).* This model refines an artifact description while generating, propagating and solving constraints representing dependencies between the components. This model can potentially consider rationalistic aesthetic criteria in each refinement step. An example of using simple aesthetic criteria for bridge design with this model was reported by Hua, Faltings, Haroud, Kimberley, and Smith (1990) . Similar treatment of aesthetics can be accommodated into Brown and Chandrasekaran's (1986) generic task model of design.
(2) *Grammar expansion (Stiny, 1975):* This model generates candidate designs using grammar rules that can embed rationalistic aesthetic criteria. The correspondence between the behavior of an artifact and its specification is determined after generation. While one of the criteria for accepting a candidate design may be its romanticist aesthetic quality, the generation can only be guided by rationalistic concerns. Stiny and Gips' work exemplifies this model.
(3) *Generate and test (Simmons and Davis, 1987):* This model follows three steps: generation, analysis, and redesign. It can naturally be used to implement the model of aesthetics discussed in this paper.

The first two computational models follow the *rationalistic* view by trying to capture aesthetics in elementary aspects of artifacts or in explicit aesthetic rules. While the rationalistic view is used in the generative part, romanticist criteria can be used as evaluation after generation takes place. Such roles for the two views of aesthetics are different from the roles presented in the new model. The third computational model is specified very abstractly. It can implement the proposed model if generative processes based on romanticism are used, otherwise, this model leaves aesthetic judgment as an evaluation to the end of design. This can potentially cause the expenditure of considerable effort on generating designs that are obviously aesthetically inappropriate.

In summary, the proposed model differs with several existing computational models of aesthetics in design and is based on (1) modifying the roles of romanticism and rationalism to perform generation and adaptation, respectively; and (2) evolving the details of these activities through learning.

5 BRIDGER

BRIDGER implements the model of aesthetic judgment in the preliminary design of cable-stayed bridges. The details of the implementation follow certain principles (Reich, 1991), but they are orthogonal to the model of aesthetics which is the focus of this paper. Therefore, only details necessary for understanding the implementation of aesthetic judgment are discussed. For additional information on BRIDGER, see (Reich, 1991).

Overview.

BRIDGER is a system developed to explore the way in which machine learning techniques can support the development of design support systems. BRIDGER intended domain is the preliminary design of cable-stayed bridges. Figure 3 shows the architecture of the system consisting of two main sub-systems: synthesis and redesign.

Put figure 3 about here

The synthesis sub-system integrates learning and problem solving. Learning incrementally builds synthesis knowledge from design examples. Examples of designs for the knowledge construction process can be obtained from two sources: descriptions of existing designs (denoted by arrow (1) in Figure 3) or design scenarios (arrow (9)). The complete learning process is denoted by arrows (1) and (2). The synthesis knowledge is used to synthesize candidate bridges for new specifications (arrows (3), (4), and (5)). Since the knowledge created is heuristic, candidate designs are usually inadequate in some aspects; they might violate constraints or be inefficient in some manner. The redesign sub-system resolves these problems. Candidate designs are given to a critic that analyzes them and submits them to a redesign module, if necessary. The iteration through analysis and redesign (arrows (6) and (7)) results in acceptable designs (arrow (8)).

Synthesis in BRIDGER.

The learning part of the synthesis sub-system creates two hierarchical knowledge structures from bridge examples. A hierarchy contains the examples as its leaf nodes and intermediate nodes that are generalizations of the examples below them. Learning groups similar designs under the same intermediate node while dissimilar designs are stored in different branches of the hierarchy. The first hierarchy is built out of the properties explicit in bridge descriptions and is called the *synthesis hierarchy* or *synthesis knowledge-base*. This hierarchy is used to generate candidate designs by various synthesis methods. As an illustration, the simplest synthesis method retrieves a set of previous designs that are highly similar to the present design context by successively descending through the hierarchy while searching for designs that are highly relevant to the present design context. This synthesis method follows the romanticist view of aesthetics since it creates candidates by holistically associating previous aesthetic designs (or their generalizations) with the present design context. The second hierarchy is generated from 'artificial' examples; each example is composed of the specification properties and several *derived* properties and is called the *derived hierarchy* or *derived knowledge-base*. Several derived properties were mentioned in Section 3. Partial descriptions of a bridge example and the artificial example generated from it are given in Table 1.

Table 1: An original description and 'artificial' bridge examples

	An original bridge example			**An 'artificial' example**	
	Property	Value		Property	Value
Specification properties	LENGTH	475.79		LENGTH	475.79
	CLEAR-H	115		CLEAR-H	115
Design description properties	SPAN-M	259.99	Derived properties	MSL-RATIO	0.55
	SPAN-SA	107.90		ST-RATIO	0.15
	SPAN-N	3		SAM-RATIO	0.41
	TOWER-A	0.3		FMM-RATIO	3.02
	TOWER-B	5.0		STAY-IN	0.58
	TOWER-H	39.93			
	STAY-SPD	35.97			
	STAY-N	3			
	CABLE-A	0.08			
	DECK-D	3.20			
	DECK-A	0.59			

As mentioned in Section 3, the derived properties encapsulate domain knowledge about aesthetic judgment. These properties capture the rationalistic view of aesthetics since they specify relationships between bridge components irrespective of the aesthetic appeal of the bridge as a whole. If BRIDGER was capable of performing constructive induction (Reich, 1990; Rendell, 1988) or discovery (Langley et al., 1987), it would have generated these interesting derived properties itself.

BRIDGER uses several synthesis methods to generate a set of candidate designs. A synthesized candidate will never fit exactly the specification. The candidate serves as raw data, or a prototype, for a new candidate that satisfies the specification. Figure 4 shows a new specification (4a) described by three properties: the minimum horizontal (CLEAR-H) and vertical clearance (CLEAR-V) requirements and the required length of the bridge (LENGTH). One of the designs retrieved is shown in Figure 4b. This candidate does not satisfy the vertical clearance and length requirements; in addition, its main span is too large, potentially resulting in sub-optimal bridge configuration. Therefore, this design must be modified to match the new specification. A simple modification starts with the reduction of the middle span (SPAN-M) until it reaches the horizontal clearance requirement. This action also reduces the length of the bridge. Any excess length is further reduced by shrinking the side spans (SPAN-SA). For satisfying the vertical clearance requirement (CLEAR-V), the height of the tower (TOWER-B) is increased. The resulting candidate is shown in Figure 4c. This candidate is not only inadequate but it is also inconsistent since the outer stays are not connected to the deck.

Put figure 4 about here

The modifications described do not necessarily produce an aesthetic structure; a better process, called *adaptation*, is devised to carry out proportioning actions that create an aesthetic bridge. Adaptation uses derived properties from the derived hierarchy, implementing the rationalistic part of the model. For each given specification, BRIDGER retrieves a set of derived property-value pairs

from the derived hierarchy, using the same methods that are used for synthesis, i.e., successively descending through the derived hierarchy searching for a collection of derived properties that is highly relevant to the present design context. This retrieval is independent of the synthesis from the synthesis hierarchy. The derived properties are then satisfied in a pre-specified order. First, MSL-RATIO ($\frac{\text{SPAN-M}}{\text{CROSS-L}}$) is used to calculate SPAN-M. If SPAN-M is less then the required CLEAR-H, its value is set to CLEAR-H. CLEAR-V is assigned to TOWER-B and SPAN-SA is calculated from LENGTH (or CROSS-L), SPAN-M, the number of spans (SPAN-N), and SAM-RATIO ($\frac{\text{SPAN-SA}}{\text{SPAN-M}}$). This leads to a candidate similar to the one in Figure 4c. Thereafter, FMM-RATIO ($\frac{\text{FMM}}{\text{STAY-SPD}}$), FIM-RATIO ($\frac{\text{FIM}}{\text{STAY-SPD}}$), STAY-N and STAY-SPD are used to determine the length of the new stay spacings (STAY-SPD). Finally, the stay inclination (STAY-IN) and ST-RATIO ($\frac{\text{TOWER-H}}{\text{SPAN-M}}$) are used to calculate the new tower height (TOWER-H), leading to the candidate shown in Figure 4d.

Four observations about the adaptation process are important. First, the adaptation process uses a collection of proportions that was retrieved through associations. Therefore, it may seem that adaptation also follows the romanticist view. Nevertheless, the fundamental part of the adaptation process—the use of the proportions to modify the design—is purely rationalistic since adaptations are performed without taking into account the bridge geometry as a whole.

Second, there are no generally fixed *a priori* derived values; rather, they are context dependent. The current context, which is the specification of a new design, is used to access derived values in the derived hierarchy. Derived values also evolve in time when derived properties of new bridges are assimilated into the derived hierarchy.

Third, constraints such as minimum horizontal clearance may override aesthetic considerations initially. However, this is not definite since the final design is also evaluated aesthetically; therefore, aesthetically bad designs can be discarded. Furthermore, since derived properties created from aesthetic designs are expected to refine the derived hierarchy continuously, previous pitfalls that led to the initial creation of unaesthetic designs will be eliminated gradually.

Fourth, currently, there is an imposed ordering on the use of derived properties for modifying candidate bridges. This ordering can be also the subject of future learning since it involves domain knowledge. For example, reducing the tower height in Figure 4c using constraints on the stays and then calculating the new STAY-IN from aesthetic criteria may decrease the support of the deck compared to the one obtained by changing the stay inclination and then modifying the tower height due to aesthetic criteria.

In summary, the synthesis sub-system implements the model of aesthetics as a romanticist generation and rationalist adaptation, where both use context sensitive aesthetic criteria, and both allow for the evolution of these criteria.

Analysis-redesign iterations.

The product of the adaptation process is a bridge description that is analyzed by a finite-element program. The analysis results are used to devise redesign modifications that are executed until the bridge satisfies the requirements and the governing design codes (arrows (6) and (7) in Figure 3). After each redesign modification, the bridge is again geometrically adapted using the derived properties.

Evaluation.

In the evaluation stage, candidate designs are presented to the users in a graphical (see the next four figures) and a tabular form. The users can select a partial set as the product of the preliminary design phase based on their subjective aesthetic judgment. Furthermore, the users can submit this set to the synthesis sub-system for further training (arrow (9)). The users selection constitutes feedback that primarily is based on a romanticist aesthetic experience generated by the graphic display of the candidates. This evaluation and the subsequent training from the selected candidates support the learning of romanticist aesthetic criteria (arrows (8) and (9) in Figure 3).

6 Examples

This section provides four examples of the use of aesthetic judgment in BRIDGER. The statements regarding the aesthetic appeal of the bridges presented are subjective, the arguments supporting them can be challenged by the reader.

Example 1.

The specification of this design is:

```
LENGTH = 550.0 m, CLEAR-H = 350.0 m, CLEAR-V = 20.0 m.
```

Four candidates are generated by BRIDGER.[2] The original and adapted candidates are shown in Figure 5. The derived proportion properties retrieved are based on the description of candidate 3. Apparently, its derived properties are most appropriate for the current context as determined by the design specification.

Put figure 5 about here

Candidate 1 and 2 are close to satisfying the geometric requirements; they are only slightly changed in the adaptation process. In this case, the aesthetic appearance of the bridges is guaranteed since the original candidates are existing, hopefully aesthetic, bridges. The main span (`SPAN-M`) of candidate 3 needs to be increased slightly. This causes (1) stretching the spacing between the stays (`STAY-SPD`) to maintain the values of `FMM-RATIO` and `FIM-RATIO`, and (2) increasing the height of the towers (`TOWER-H`) to compensate for the change in `ST-RATIO`. Candidate 4 is changed slightly. Its main span is increased and the height of its towers is increased as well. In general, all the adapted candidates look aesthetic, mostly, due to the success of the initial romanticist associations.

Example 2.

The specification of this design is:

```
CROSS-L = 800.0 m, CLEAR-H = 450.0 m, CLEAR-V = 20.0 m.
```

The crossing length and the horizontal clearance specified are larger than most existing bridges used to create BRIDGER's knowledge hierarchies. The original and adapted designs are shown in Figure 6.

[2]This number was selected for display purpose only and can be modified easily.

Put figure 6 about here

The derived proportions retrieved were not generated from any of the four candidates, but rather from another bridge. For example, `STAY-IN` is different from the values[3] in the four candidates, and `SAM-RATIO` is only similar to the values in three candidates (1, 2, and 3).

Except for candidate 1, which almost satisfies the specification, all the other candidates are far shorter than required: the scaling of their crossing length (`CROSS-L`) ranges from 1.11 to 1.52, and the scaling of their main span (`SPAN-M`) ranges from 1.18 to 1.64.

Candidate 4 may pose difficulties since it is a two-span bridge. In a two-span bridge the ratio of the tower height to the main span reflects a relationship between the tower and the *whole span*; whereas in the three-span bridge, the aesthetic impression is based on the proportion of the height of the tower to *half* the main span. This difference may cause the towers of candidate 4 to be too high. Nevertheless, the adaptation process takes care of this difference and results in an aesthetically pleasing form. This success demonstrates the beneficial synergy between the two views of aesthetics. When additional bridges are learned, candidates with dimensions closer to the design specifications will be synthesized, reducing the need to add spans or perform significant adaptations. Consequently, the influence of adaptation will be reduced, while the contribution of the original designs towards aesthetic solutions will be more significant.

Candidates 1 and 3 are good designs considering their weight and analysis results (not shown). Candidate 1 slightly outperforms candidate 3, an expected result since it was initially closer to satisfying the specification. Nevertheless, candidate 1 is less aesthetic than candidate 3 since its stays' layout conveys a sense of instability in the flow of forces from the deck to a single point at the tower.

Example 3.

The specification of this design is:

```
LENGTH = 400.0 m, CROSS-L = 350.0 m, CLEAR-H = 250.0 m,
CLEAR-V = 20.0 m.
```

The original and adapted designs are shown in Figure 7. A large variety of original candidates is generated for this specification and the derived properties are generated, yet, from another bridge. Two candidates gain an additional span in the adaptation process.

Put figure 7 about here

As in example 2, the adaptation is responsible for adding a span to candidates 1 and 2 while verifying that the product is aesthetically pleasing. The major modification impacts the quality of these candidates; although they almost satisfy all the analysis constraints they are overly heavy. In contrast, both candidates 3 and 4 are good designs, their improvement can be pursued further in analysis-redesign iterations. While both these candidates are aesthetic, candidate 4 will probably

[3]The values of the properties mentioned in this paragraph as well as other appearing in the other examples are not provided.

be inadequate after detailed analysis is performed since its unsupported span portions are too long and slender to withstand bending and compression. This impression is conveyed as a less aesthetically appealing design. This is precisely how the interplay between domain knowledge and artifact form, as manifested in the concept of *bridge type*, affects aesthetic judgment.

Example 4.

The specification of this design is:

```
LENGTH = 450.0 m, CROSS-L = 375.0 m, CLEAR-H = 100.0 m,
CLEAR-V 2.0 m.
```

The original and adapted designs are shown in Figure 8.

Put figure 8 about here

In this specification, the horizontal clearance requirement is smaller than in most existing bridges used to train BRIDGER. Therefore, the original candidates need to be scaled down. Since the `CLEAR-H` is only 26% of the total `CROSS-L`, the bridges generated have `SPAN-M` much larger than the `CLEAR-H` constraint. The aesthetic proportioning does not reduce the span to the minimum required, but leaves it to be about 1.75 of the required clearance. This incurs an additional cost on the bridges since the weight of a bridge structure is highly dependent on the length of its main span. This choice exemplifies an explicit tradeoff between a low cost and functionally adequate design and a more costly, but aesthetically appealing, design.

7 Discussion

Scope of the implementation.

The scope of BRIDGER is limited in several ways. These limitations, however, are major contributors to its success. First, design is restricted to the generation of artifacts with fixed topologies that can be represented by lists of property-value pairs. This restriction can be relaxed to designing with structured objects (Thompson and Langley, 1991). Precisely this restricted language allows for easy learning from the complete artifact descriptions, enabling the acquisition of romanticist aesthetic criteria. When the state-of-the-art of machine learning advances such that more complex representations can be effectively learned, the overall aesthetic criteria of more complex artifacts can be studied with an architecture similar to BRIDGER.

The second limitation is that explicit aesthetic laws are captured by a pre-defined set of derived property-value pairs. This requires a careful analysis of the domain to understand which properties may be potential good proportioning properties. Discovery or constructive induction methods can assist in the automatic generation of such properties. Furthermore, the proportions retrieved for a particular design scenario can act as constraints to be satisfied by constraint solution techniques, thereby allowing the exercise of ordering more dynamic than the fixed order of satisfaction imposed currently.

BRIDGER only uses proportions in its rationalistic adaptation. In may be questioned whether

proportion properties, which seem trivial, can account for an interesting part of rationalism. The answer is yes, as discussed in the review of aesthetics. To illustrate, proportions can be used to model additional aesthetic concerns not discussed here such as symmetry. For example, symmetry can be modeled by insisting on proportions that are close to 1 between two or more dimensions used to describe an object (see Figure 9). Nevertheless, it must be acknowledged that there may be rationalistic concerns that cannot be modeled by proportions and must be treated in a modified adaptation procedure.

Put figure 9 about here

Scope of the model.

While BRIDGER has several limitations, the model it implements is more general. The model proposes that romanticist associations and rationalistic adaptations are necessary complementary parts in any model that supports aesthetic judgment. And, as was demonstrated by the four examples, none of the views alone can support aesthetic judgment fully.

A major criticism can be raised against the model's interpretation of romanticism. It can be argued that romanticism and computational modeling are two contradicting concepts. Any computer model of romanticism involves coding a whole as a set of properties which, is principle, is reductionistic. We can offer two partial responses. First, the model can only approximate a romanticist view, it can only adapt to a romanticist view implicit in existing designs or users' feedback, but cannot represent it precisely. Second, the model can be further refined to work with other association schemes, such as those that operate on images of bridges, rather than on their property-value list representations. Such association schemes can increase the richness of the model but again cannot remove the difficulty.

The model cannot be perfect, therefore, it is not intended to be implemented as an automated tool, but rather, as an assistant. The designers are the final judges about aesthetics and their judgment can be captured for future reference.

The model insists that aesthetic judgment is acquired through experience and evolves continually. It is not possible to study aesthetics without learning. Learning creates romanticist associations, establishes important rationalistic relations, and develops aesthetic types. Both the romanticist and the rationalistic criteria are context dependent principles developed through experience.

8 Conclusions

The incorporation of limited aesthetic judgment in BRIDGER reveals several aspects of using aesthetics in design.

Partial aesthetic concerns can be supported by current artificial intelligence technology. This paper shows how aesthetic criteria can be used not only in a final evaluation of candidates, but also in their generation. Nevertheless, the inherent limitations in modeling aesthetic judgment, requires

keeping designers in control over the design process.

Aesthetic criteria are the function of experience. They evolve as experience grows. Therefore, studying aesthetic judgment in conjunction with learning is mandatory.

Aesthetic criteria are context dependent. Different design scenarios give rise to different governing aesthetic criteria. This is definitely exemplified by the existence of different aesthetic criteria in different cultures.

Aesthetic design is more than the achievement of functionality. Aesthetic concerns have a considerable influence on the choice of solutions for real problems and they cannot be addressed by optimizing functionality. In contrast, functionality and aesthetic appeal may be conflicting.

Acknowledgments

This research has been supported in part by the Engineering Design Research Center, a National Science Foundation Engineering Research Center, and the Sun Company Grant for Engineering Design Research. I would like to thank Steven J. Fenves for his support and invaluable discussions on BRIDGER, to Shoulamit Milch-Reich for her comments on a draft of this paper, and to the reviewers for their constructive remarks.

References

Billington, D. P. (1991). Bridges and the new art of structural engineering. In *Bridge Aesthetics Around The World*, pages 67–79, Washington, DC. Transportation Research Board, National Research Council.

Britannica (1979). Aesthetics. In *The New Encyclopeddia Britannica, 15th Edition*, pages 149–163. Encyclopedia Britannica.

Brown, D. C. and Chandrasekaran, B. (1986). Knowledge and control for a mechanical design expert system. *Ieee Computer*, 19(7):92–100.

Buckland, P. G. (1990). The inherent beauty of cable-stayed bridges. In Watson, S. C. and Hurd, M. K., editors, *Esthetics In Concrete Bridge Design*, pages 233–246, Detroit, MI. American Concrete Institute.

Committee on General Structures (1991). *Bridge Aesthetics Around The World.* Transportation Research Board, National Research Council, Washington, DC.

de Miranda, F. (1991). The three mentalities if successful bridge design. In *Bridge Aesthetics Around The World*, pages 89–94, Washington, DC. Transportation Research Board, National Research Council.

Fernández Ordóñez, J. A. (1991). Spanish bridges: aesthetics, history, and nature. In *Bridge Aesthetics Around The World*, pages 205–214, Washington, DC. Transportation Research Board, National Research Council.

Glomb, J. (1991). Aesthetics aspects of contemporary bridge design. In *Bridge Aesthetics Around The World*, pages 95–104, Washington, DC. Transportation Research Board, National Research Council.

Hua, K., Faltings, B., Haroud, D., Kimberley, G., and Smith, I. (1990). Dynamic constraint satisfaction in a bridge design system. In Gottlob, G. and Nejdl, W., editors, *Expert Systems in Engineering, Principles and Applications, International Workshop*, Lecture Notes in Artificial Intelligence, pages 217–232, Vienna, Austria. Springer-Verlag.

Langley, P., Simon, H. A., Bradshaw, G. L., and Zytkow, J. M. (1987). *Scientific Discovery: Computational Explorations of the Creative Processes*. MIT Press, Cambridge, MA.

Lee, D. (1990). Bridging the artistic gulf. In Watson, S. C. and Hurd, M. K., editors, *Esthetics In Concrete Bridge Design*, pages 101–108, Detroit, MI. American Concrete Institute.

Lesnikowski, W. G. (1982). *Rationalism and Romanticism in Architecture*. McGraw-Hill, New York, NY.

Liebenberg, A. C. (1991). Aesthetic evaluation of bridges. In *Bridge Aesthetics Around The World*, pages 1–9, Washington, DC. Transportation Research Board, National Research Council.

Mahshavot (1990). *On The Beauty in Science and Art*. Ibm Israel, Tel Aviv, Israel. (In Hebrew).

Makkuni, R. (1987). A gestural representation of the process of composing Chinese temples. *Ieee Computer Graphics and Applications*, 7(12):45–61.

Menn, C. (1991). Aesthetics in bridge design. In *Bridge Aesthetics Around The World*, pages 177–188, Washington, DC. Transportation Research Board, National Research Council.

Minai, A. T. (1989). *Design as Aesthetic Communication*. Peter Lang, New York.

Ohta, T., Takahashi, N., and Yamane, T. (1987). Aesthetic design method for bridges. *Journal of Structural Engineering, ASCE*, 113(8):1678–1687.

Reich, Y. (1990). Constructive induction by incremental concept formation. In Feldman, Y. A. and Bruckstein, A., editors, *Proceedings of the Seventh Israeli Symposium on Artificial Intelligence and Computer Vision (Ramat-Gan)*, pages 195–208, Amsterdam. Elsevier Science Publishers.

Reich, Y. (1991). *Building and Improving Design Systems: A Machine Learning Approach*. PhD thesis, Department of Civil Engineering, Carnegie Mellon University, Pittsburgh, PA. (Available as Technical Report EDRC 02-16-91).

Rendell, L. (1988). Learning hard concepts. In Sleeman, D., editor, *Procedings of the Third European Working Session on Learning*, pages 177–200, Aberdeen. Pitman.

Santayana, G. (1988). *The Sense of Beauty. Critical Edition* Edited by W. G. Holzberger and H. J. Saatkamp, Jr. MIT Press, New York, NY.

Simmons, R. and Davis, R. (1987). Generate, test and debug: combining associational rules and causal models. In *Proceedings of the Tenth International Joint Conference on Artificial Intelligence*, Milan, Italy. Morgan Kaufmann.

Smith, P. F. (1987). *Architecture and the Principle of Harmony.* RIBA Publications, London, UK.

Steinberg, L. I. (1987). Design as refinement plus constraint propagation: The Vexed experience. In *Proceedings of Aaai-87, Seattle, Wa*, pages 830–835, San Mateo, CA. Morgan Kaufmann.

Stiny, G. (1975). *Pictorial and Formal Aspects of Shape and Shape Grammars.* Birkhauser, Basel.

Stiny, G. and Gips, J. (1978). *Algorithmic Aesthetics: Computer Models For Criticism and Design in The Arts.* University of CAlifornia Press, Berkeley, CA.

Tang, H. C. (1991). Philosophical basis for Chinese bridge aesthetics. In *Bridge Aesthetics Around The World*, pages 167–176, Washington, DC. Transportation Research Board, National Research Council.

Thompson, K. and Langley, P. (1991). Managing components in object concept formation. In Fisher, D. and Pazzani, M., editors, *Concept Formation: Knowledge and Experience in Unsupervised Learning*, Los Altos, CA. Morgan Kaufmann.

Von Olhausen, W. (1991). Bridges in Sweden: should we do more about aesthetics? In *Bridge Aesthetics Around The World*, pages 197–204, Washington, DC. Transportation Research Board, National Research Council.

Watson, S. C. and Hurd, M. K., editors (1990). *Esthetics In Concrete Bridge Design.* American Concrete Institute, Detroit, MI.

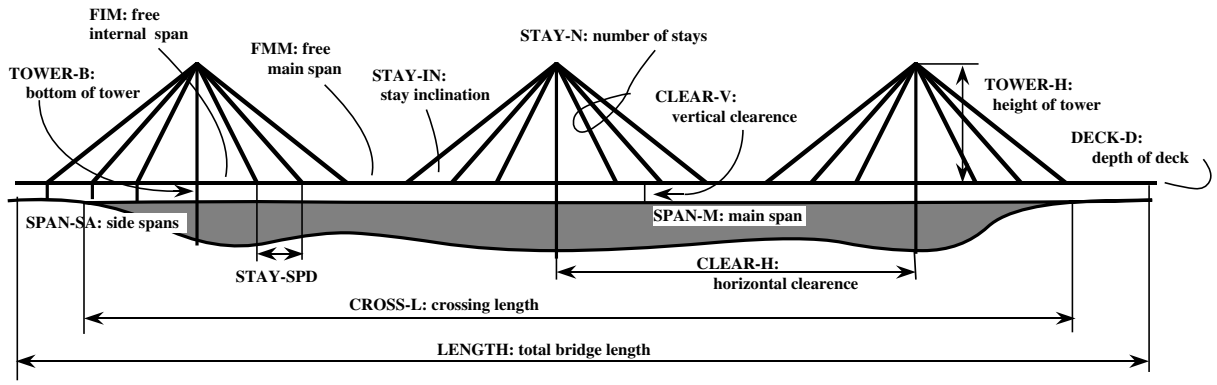


Figure 1: Bridge description

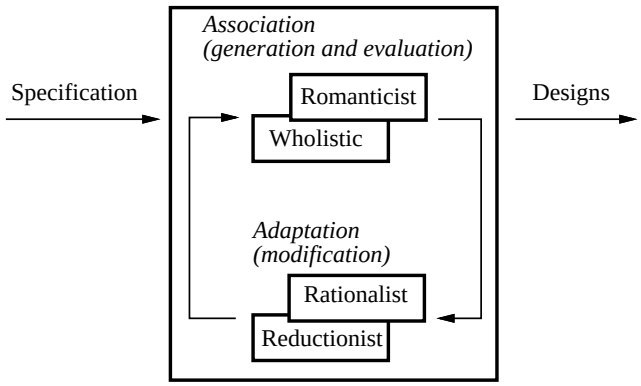


Figure 2: A model of aesthetic judgment

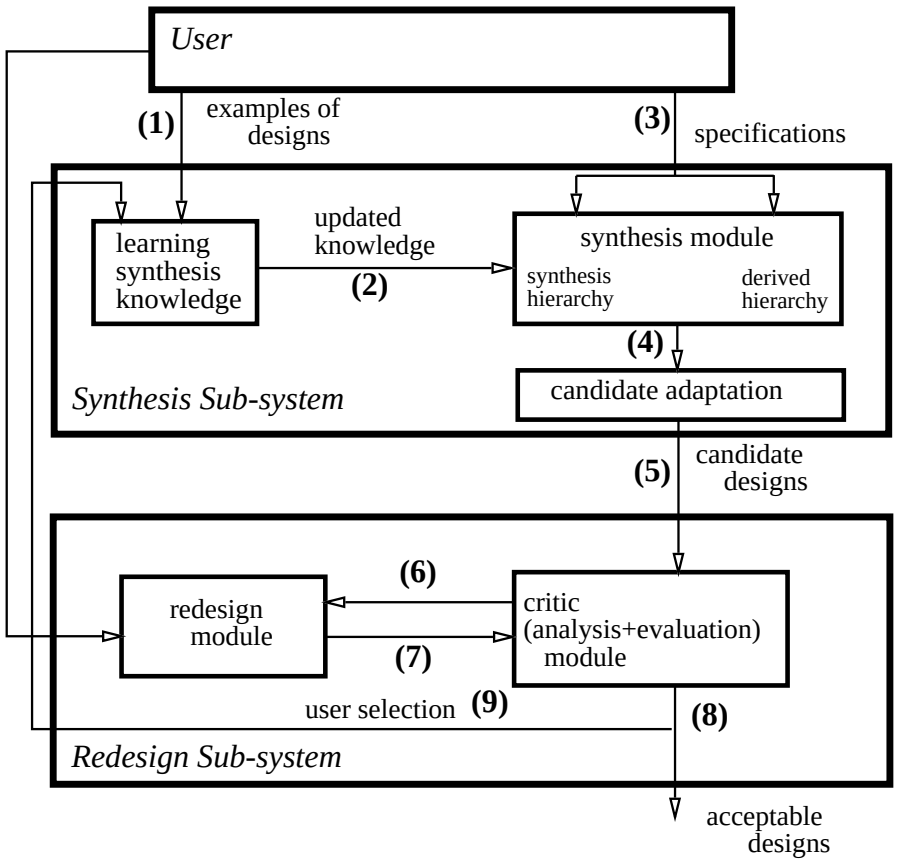


Figure 3: BRIDGER's architecture

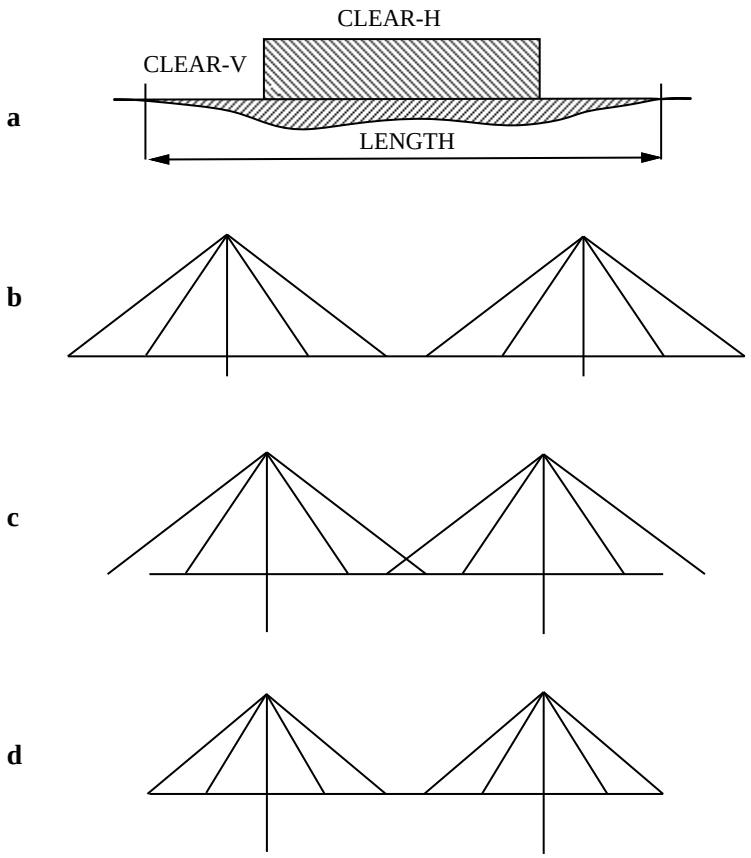


Figure 4: Adapting an old design to new specifications

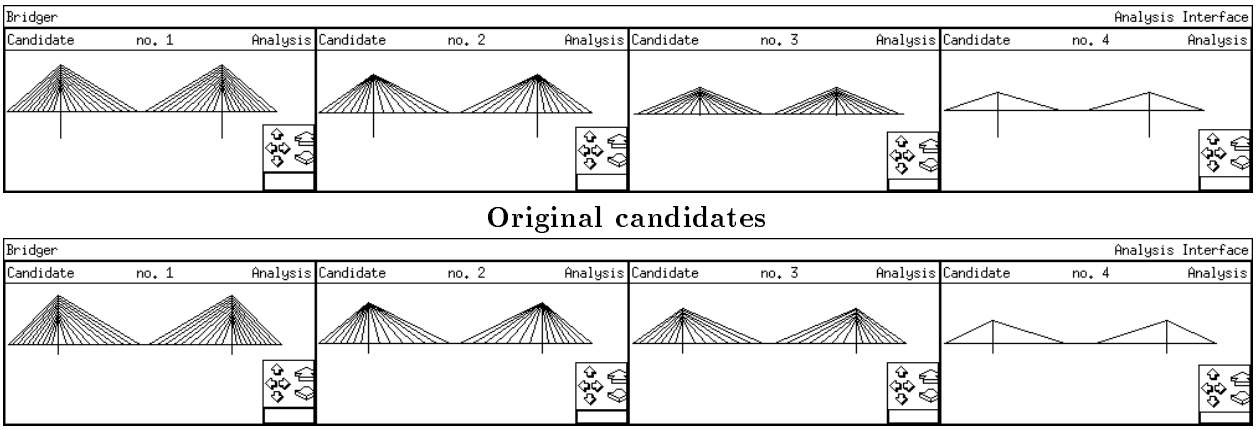
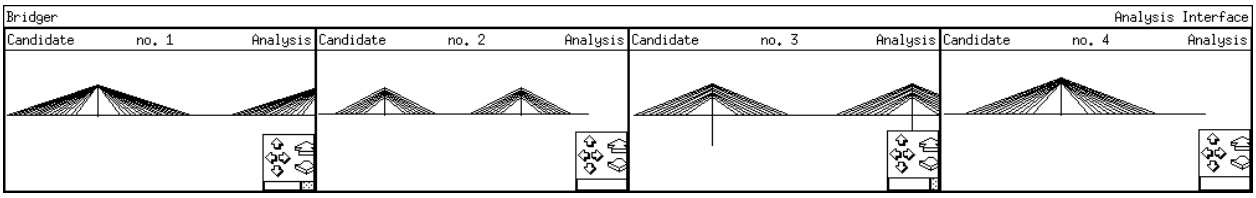
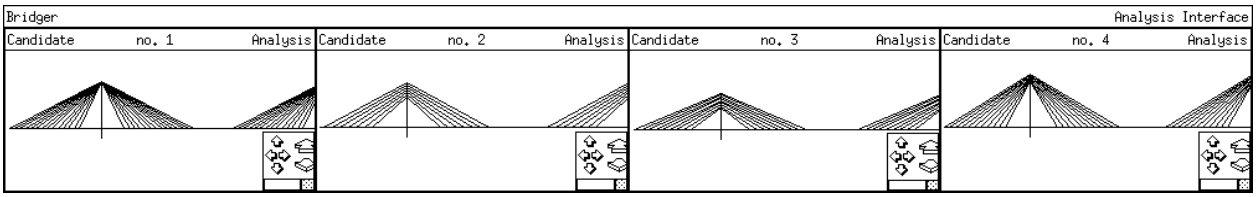


Figure 5: Original and adapted candidates: example 1



Original candidates



Adapted candidates

Figure 6: Original and adapted candidates: example 2

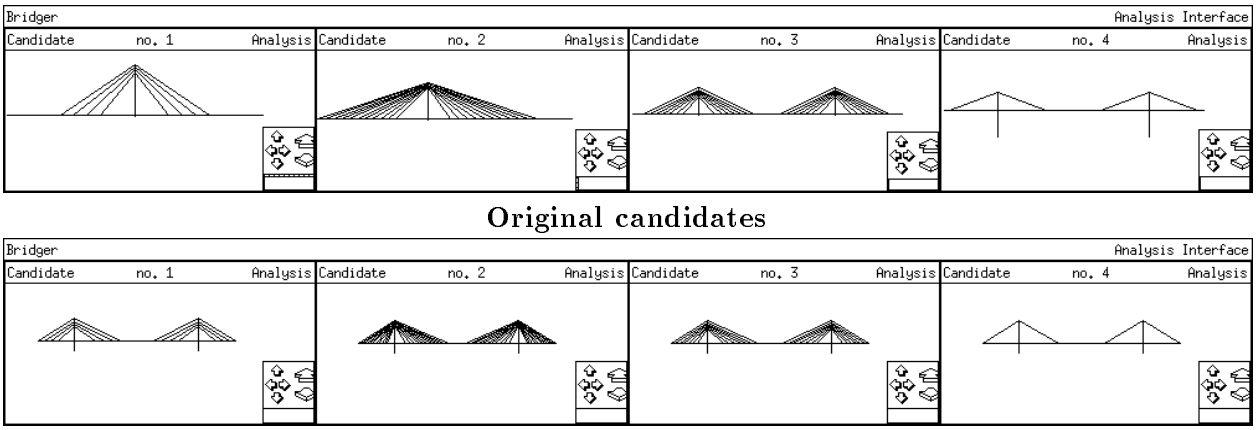


Figure 7: Original and adapted candidates: example 3

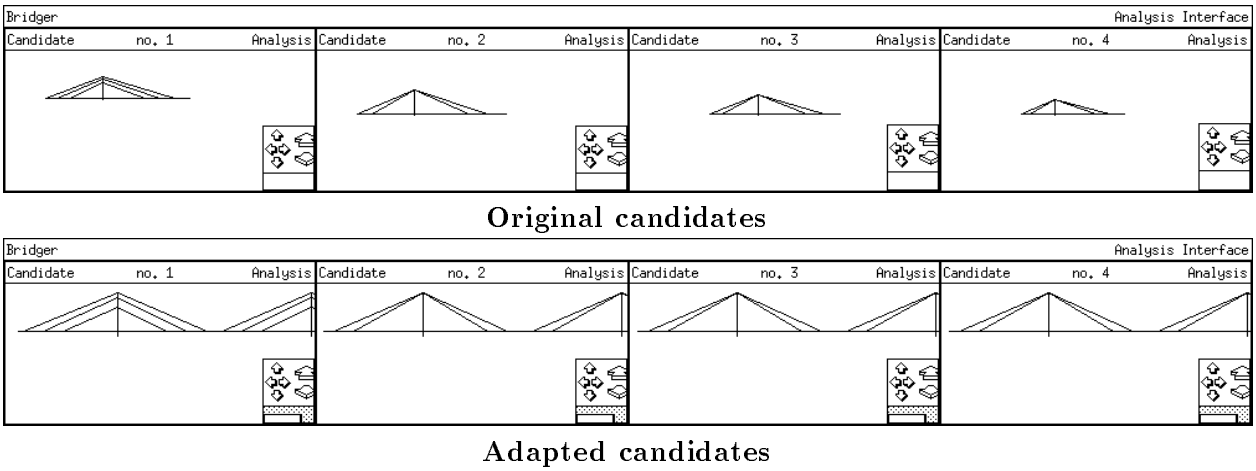


Figure 8: Original and adapted candidates: example 4

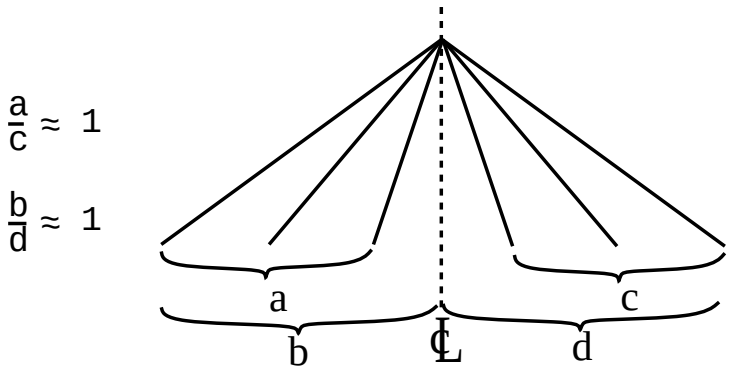


Figure 9: Modeling symmetry with proportions