A system that learns to design cable-stayed bridges

Yoram Reich[1] and Steven J. Fenves[2], Honorary Member, ASCE

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Abstract: The critical design decisions in bridge design are made at the preliminary design stage. This stage depends on the expertise of the designer, built up from extensive experience. Experience is difficult to acquire, and may be entirely lacking when new technology is introduced. As a result, there is little shareable and transferable collective design knowledge within the profession.

This paper explores how preliminary design knowledge may be generated, updated and used, utilizing techniques of machine learning from the field of artificial intelligence. A model of the preliminary design process is first presented as a sequence of five tasks and then specialized to the design of cable-stayed bridges. A computer tool serving as a design support system is described whose design follows the model of the preliminary design process, and a design example using the tool is presented. The key property of the system is its adaptive nature: it acquires knowledge from information on existing bridges as well as from designs generated with the system, thereby continuously improving its performance. Future enhancements to the tool breadth and depth are offered.

Key words: preliminary design, cable-stayed bridges, decision-support system, knowledge acquisition, machine learning, synthesis.

1 Introduction

In bridge design, the preliminary design stage has the largest effect on the bridge's performance, cost, esthetics, constructibility, and maintainability. Yet, this important stage of design is not formalized and relies entirely on the designer's expertise. Expertise based on considerable experience is a scarce commodity, which may simply not be available when new technologies are introduced. This paper presents an exploration of how "experience" in preliminary design may be generated using techniques of machine learning from the field of artificial intelligence.

[1]Senior Lecturer, Department of Solid Mechanics, Materials, and Structures, Faculty of Engineering, Tel Aviv University, Tel Aviv 69978, Israel

[2]Sun Company University Professor, Department of Civil Engineering, Carnegie Mellon University, Pittsburgh, PA 15213, USA

Engineering design is the process of generating the description of an artifact that satisfies a set of objectives, requirements, and constraints; we denote this set as the artifact's *specification*. This paper concentrates on the first stage of design – preliminary design, which can be approximately decomposed into the tasks of problem analysis, synthesis, analysis, redesign, and evaluation. *Problem analysis* augments the problem statement with additional information and formulates a better basis for generating candidate designs. *Synthesis* involves the generation of candidate designs that are expected to satisfy the design specification. Invariably, in real design problems these candidates will partially violate some functional requirements (also called behavioral or performance requirements) or constraints of the specification. These violations are detected by *analysis*, a functional simulation of the behavior of a candidate design. *Redesign* is the task of modifying a candidate so as to satisfy its specification and is directed by the discrepancies between the required behavior stated in the specification and the derived behavior revealed by analysis. *Evaluation* is the final task that selects the design(s) for further detailed design from the set of candidates that satisfy the specification.

The major unstructured task in bridge design is the synthesis of candidates in the preliminary design stage. Good synthesis knowledge is hard to obtain, in contrast to analysis, which is well developed in all engineering disciplines. As an example, books and summaries on cable-stayed bridge design (ASCE, 1992; Podolny and Scalzi, 1986; Troitsky, 1988) typically contain only general discussions about possible configurations with few abstract guidelines for selecting among them. The lack of synthesis knowledge, coupled with the need for this knowledge, leads to a search for ways to *generate* bridge synthesis knowledge.

The paper focuses on the preliminary synthesis of large cable-stayed bridges. It describes a research project that explores the use of new techniques of machine learning from artificial intelligence to build a computational support tool for bridge design. The experimental system developed in this research, called BRIDGER, demonstrates how design knowledge can be acquired from an evolving database of existing designs and designer interactions with the design support system.

2 Model of preliminary bridge design process

The process of preliminary bridge design has to be modeled as a collection of well-defined tasks, if it is to be a basis for building a computational support tool. This section describes a model of the preliminary design of cable-stayed bridges based on the five tasks previously discussed.

Problem analysis. Books on the design of cable-stayed bridges (Podolny and Scalzi, 1986; Troitsky, 1988) provide some results of simplified problem analyzes consisting of: (1) a typology – a set of properties with their possible values; (2) analysis procedures; and (3) design standards.

Tables 1 and 2 provide a partial list of the properties and their acronyms used in this study for describing cable-stayed bridges. The tables contain four groups of properties: specification, design description, derived, and design performance properties. The specification properties define the input for preliminary design, while the design description properties define a candidate design in terms of its physical form and material. The distinction between specification and design description properties is flexible, since a design may be specified by a subset of the specification properties, or it may be constrained by enforcing a subset of the design description properties (e.g., local conditions may dictate that the deck and tower material properties have the value of "concrete").

Derived properties are calculated from the design description properties, frequently in the form of ratios. Several derived properties are illustrated in Figure 1. Values of some of these properties are perceived by many designers to influence the esthetics of a bridge (Committee on General Structures, 1991).

Design performance properties describe the performance of the bridge in terms of structural behavior and weight. The structural behavior properties consist of the performance measures sufficient for evaluating the behavior in the preliminary design stage.

We recognize that for completeness, particularly for cable-stayed bridges, three additional groups of properties are needed: construction process properties describing the methods of fabrication and erection; final construction cost properties; and in-service performance properties. These properties have been excluded from the present study largely because of the scarcity of information.

Synthesis. Since cable-stayed bridges represent a relatively new technology and experience does not accumulate and disseminate rapidly, one cannot expect to find a formalized synthesis procedure. Indeed, there is no synthesis theory for cable-stayed bridges, or for large modern bridges in general.

There are fragments of synthesis knowledge in the form of general comparative studies that evaluate the relative weight or cost of different types of bridges. One example of synthesis information can be a sketch depicting the weight of various types of steel bridges as a function of the span. Another form of synthesis information, also derived from limited experience, is rules such as (Troitsky, 1988, p. 236-237):

```
PREFER a stay inclination of 45°;
```

or

```
IF the main span is in the range of 450-490 ft (140-150 m),
THEN PREFER a panel length of 65 ft (20 m).
```

Both types of recommendations, based on past experience and using fixed values, may become obsolete as technology improves. Since the recommendations are presented as general guidelines, abstracted from the design contexts from which they were generated, they cannot be easily corrected to accommodate change. By contrast, if the design contexts out of which the recommendations arose are stored in the form of a database of previous designs, the recommendations can be updated and reprocessed to facilitate timely modifications of the synthesis knowledge, as new designs, reflecting new knowledge, construction techniques and materials are incorporated in the database.

Analysis. This task is the best understood and formalized aspect of bridge design. The role of analysis is to verify that the bridge satisfies the applicable limit states on stresses, deflections, vibrations, stability, fatigue, etc.. Available analysis procedures range from approximate techniques suitable for preliminary design to "exact" techniques appropriate for the detailed design stage. Analysis involves considerable judgment in modeling the bridge and its loading, and in interpreting the results. For long-span bridges there are only recommendations such as the guidelines for cable-stayed bridge structures (ASCE, 1992) that can be altered based on the designer's judgment or the owner's criteria.

Redesign. Analysis can show that a candidate design violates certain design requirements. Redesign knowledge determine the appropriate design modifications for removing these violations. For the case of continuous properties, such as the cross section of elements, traditional techniques of sensitivity analysis can be used. For discrete properties a different sensitivity approach must be used. These techniques, however, are costly since they involve the execution of many analyzes. As a result, redesign remains a heuristic, unformalized task.

Knowledge that may reduce the number of analyzes by focusing on promising design modifications can be identified in the form of cause-and-effect or influence relationships. Often these influences are described in a textual form but can be translated into rules such as (Troitsky, 1988, p. 231):

```
IF rigidity of girder (DECK-MI) is reduced,
THEN the stay stress (CABLE-ST-OUT-M) is increased.
```

A set of such rules can be represented by a causal model.

The difficulties of using purely analytical procedures or symbolic cause-and-effect relations force designers to exercise their judgment and rely on their experience in making redesign decisions. Experience results in the development of heuristics that can be applied to new redesign situations.

Evaluation. After redesign has been successfully completed, two sets of criteria are typically used to assess the quality of candidate designs: an objective quantitative calculation of the estimated cost and a subjective qualitative evaluation of additional considerations. The nature of this evaluation suggests that: (1) for a large range of spans, several alternatives will always be available for consideration; and (2) the major decision will be based on subjective criteria and experience, as much as on estimated cost alone.

Figure 2 illustrates the refinement of the design task analysis from an abstract description of the five tasks, discussed in the introduction and shown in Figure 2(a), to the type of knowledge used in each of the tasks based on the particular characteristics of cable-stayed bridge design, discussed in this section and shown in Figure 2(b): problem analysis results in a typology for describing bridges; there is little or no systematic synthesis knowledge; analysis knowledge consists of procedures based on a strong theory (we neglect the subjective aspects of modeling and interpretation associated with analysis); redesign uses cause and effect relationships between description properties and performance properties; and evaluation is mostly subjective.

3 Computational support for bridge design

Computer tools are extensively used in the practice of bridge design, primarily for analysis, drafting, and the visualization of spatial models. Designers retain full responsibility for generating and interpreting these models. Therefore, such tools only incidentally support synthesis.

Progress in analysis includes procedures based on new theoretical developments that can help replacing costly scale model testing which presented a bottleneck in the design process. New modeling and analysis techniques shorten the design cycle by providing more rapid feedback on design decisions in the form of analysis results.

Recent advances in computer tools can provide additional support for modeling and analysis. Computer tools can aid in systematically generating numeric models from physical descriptions (Dale, 1991; Turkiyyah and Fenves, 1990). There are many tools that can assess whether structural components conform to design standards, and others to proportion or size components subject to the constraints in the design standards. In one case, the designer, or a small expert system, may explicitly specify the limit state(s) likely to control the behavior of the component (Garrett and Fenves, 1989). All such tools ease the analysis task, allowing more attention to be spent on the synthesis and redesign tasks.

In contrast to analysis support tools, there has been virtually no development of intelligent design aids that can assume some of the responsibility for synthesis. Some recent studies deal with the optimization of various design properties such as member sizes and cable prestressing forces (Bhatti and Nasir Raza, 1985). These studies assume a fixed bridge configuration and only affect local decisions.

The selection of the bridge configuration is critical to the quality of the design. Due to the complexity of a major bridge, this selection cannot be optimized, it can only be made to satisfy the given specification and design constraints, including qualitative evaluation criteria. The methodology that dominates recent studies on computational support tools for bridge synthesis is that of expert systems. The studies differ in the specific methods employed: a simple selection mechanism (Spencer et al, 1989), constraint satisfaction (Hua et al, 1990), or fuzzy sets (Leelawat et al, 1990).

In a system for bridge design developed in Japan (Nishido et al, 1989), the expert system approach is practically turned into an algorithm: the selection of bridge description properties is performed in a fixed order; and the final design is chosen from the alternatives generated by the expert system using rules based on subjective judgment. Such a system can automate almost the entire design process, where the process has been completely formalized and restricted by very tight design rules relevant to Japan and applicable to short-span bridges only.

In contrast to the fixed and limited nature of the knowledge encoded in the above system, techniques intended to create knowledge relevant to the situation in which the knowledge is expected to be used are being developed in artificial intelligence research and are called *machine learning techniques*. A subset of these techniques can incrementally and continually acquire knowledge and adapt it to changing situations.

In contrast to the above studies, this paper describes an approach for the *continuous acquisition and improvement* of bridge design knowledge, with the focus on the acquisition of synthesis knowledge.

4 Acquisition and organization of design knowledge

Many traditional tools based on statistics, as well as new tools originating from artificial intelligence, are available for the acquisition of knowledge from data. Since different methods are appropriate for different purposes, it is important to select the appropriate technique for a practical knowledge acquisition problem. Following a particular method (Reich, 1991) leads to the selection of two existing learning programs,COBWEB (Fisher, 1987) and PROTOS (Bareiss, 1989), for the acquisition of synthesis and redesign knowledge, as shown in column (c) of Figure 2. These two systems were enhanced to better suit their intended learning tasks; the enhanced systems are called ECOBWEB (Reich and Fenves, 1992) and EPROTOS, respectively.

The system that integrates ECOBWEB and EPROTOS is called BRIDGER. The architecture and flow of control of BRIDGER is illustrated in Figure 3. BRIDGER consists of two main subsystems: synthesis and redesign. ECOBWEB and EPROTOS implement parts of these systems as shown by the dashed rectangles in Figure 3. While ECOBWEB and EPROTOS use mechanisms that are independent of bridge design and can be used in other design support systems, the remaining parts of BRIDGER were built specifically for cable-stayed bridge design.

The synthesis sub-system is responsible for synthesizing several candidates for a given specification (branches 3, 4, and 5 in Figure 3). Synthesis knowledge is generated by learning from existing designs (branch 1) and from successful design examples that are selected by the designer in the regular course of using the system (branch 11). Since the knowledge created is heuristic by nature, synthesized designs (branch 4) will generally violate some geometric or functional constraints. Geometric constraint violations in the candidates are remedied by the candidate adaptation module; in the present system, no learning of the type or order of these improvements takes place, although their magnitude is learned. The result of the candidate adaptation module are candidates with acceptable dimensions (branch 5). The potential functional constraint violations are then corrected by the redesign sub-system. Since the redesign sub-system filters out erroneous solutions, the performance of the synthesis sub-system need not be perfect; rather, it is expected to improve over time through updated synthesis knowledge (branch 2).

In the redesign sub-system, candidate designs are analyzed by the analysis module and submitted to the redesign module, if necessary (branch 6). This module retrieves the most suitable redesign modifications for the problem at hand (branch 7). The designer can override the module's recommended redesign modifications and supply explanations (branch 9) that enhance the redesign knowledge (branch 8). The process of analysis and redesign iterates until the candidate designs satisfy the functional requirements, after which they are called *acceptable* designs and become candidates for evaluation.

4.1 Synthesis sub-system

The structure of synthesis knowledge. Synthesis knowledge is acquired from descriptions of bridges and is internally organized into a hierarchical classification tree. A class in the hierarchy represents a collection of bridges whose properties are similar within that class and different from bridges in other classes at the same level.

The hierarchy is created incrementally. A description of an existing bridge example is classified into the hierarchy starting from its top, or root, node until it reaches a bottom, or leaf, node. There, it is accommodated into the hierarchy. The classification is guided by a statistical similarity function and progresses down the tree, the path determined by how similar the new description is to the classes encountered at each level of the hierarchy. In this process, the existing hierarchy may undergo two changes to produce an organization that better accommodates the new bridge description: merging of two similar nodes into one, or splitting a heterogeneous node into its more homogeneous sub-nodes.

A hierarchical classification tree was created from data on 96 cable-stayed bridges erected between 1955 and 1987. This set comprises all the bridges for which sufficient information was available to define or approximate the specification and design description properties. Since some properties (e.g., cable areas, deck and tower section properties) were missing, and particularly since the bridges were designed at different times and with different design loads, the 96 initial examples were redesigned, using the redesign subsystem described below, until they met the design criteria used throughout the rest of the study.

Synthesis of candidate designs. The synthesis knowledge described above can be used to synthesize candidate designs. Candidates are created by using a mechanism similar to the one used for creating the synthesis classification hierarchy from the descriptions of existing bridges. In synthesis, the set of specification properties, considered to be a partial description of a new bridge, is classified with the hierarchy, but with no change in the hierarchy permitted. During this classification, characteristic property values of classes visited augment the partial description of the new bridge until a leaf node is reached. Once the description of the new bridge reaches a leaf node, the properties missing from its description are completed from that leaf as well as from several adjacent nodes, each completion resulting in a candidate, until a pre-defined number of candidates is constructed. As a result of this process, the candidates synthesized often do not match any one of the existing examples. BRIDGER provides several additional ways to synthesize candidate designs (Reich, 1991; Reich and Fenves, 1992). One of the simpler synthesis methods that is used in the example (Section 5) and the evaluation (Section 6), follows the same above steps without assigning the characteristic property values.

Candidate adaptation. The candidate designs generated by ECOBWEB generally do not satisfy important geometric constraints of the specification, such as length and clearances, and must be adapted. This adaptation uses a second hierarchy, called the *derived hierarchy*, created by ECOBWEB from artificial examples composed of the specification properties and the *derived* properties shown in Table 1. For example, one derived property is: $\texttt{ST-RATIO} = \frac{\texttt{TOWER-H}}{\texttt{SPAN-M}}$. The derived properties are known to encapsulate domain knowledge and were pre-selected as part of the problem analysis task. The hierarchy generated with these properties is used by the synthesis sub-system in the adaptation.

As an example, consider a problem where the specification properties are: the horizontal and vertical clearance requirements and the required length of the bridge. A synthesized candidate may not satisfy the vertical clearance and length requirements; in addition, its main span may be too large, potentially resulting in a sub-optimal bridge configuration.

The adaptation proceeds as follows. First, the `MSL-RATIO` is used to adjust the main span (`SPAN-M`). Similarly, the `SAM-RATIO` is used to adjust the side spans (`SPAN-SA`), the `ST-RATIO` is used to adjust the tower height (`TOWER-H`), and the `SD-RATIO` is used to adjust the stay spacing (`STAY-SPD`). The vertical clearance (`CLEAR-V`) is assigned to `TOWER-B`. This leads to a still incomplete layout where stays from two towers may overlap. Thereafter, the `FMM-RATIO` is used to determine the length of the free main span, potentially re-adjusting the stay spacing and the tower height. Finally, the stay spacing of the side spans is determined.

4.2 Redesign sub-system

Analysis. Presently, a two-dimensional, linear analysis model is implemented in BRIDGER. It is considered sufficiently accurate for preliminary design. Stability or large deflections are not considered, nor are torsional effects. The towers are only modeled in the longitudinal direction. No prestressing of the deck or tower, if built of concrete, is calculated; this necessitates the use of an artificially large deck moment of inertia. The cables are assigned a uniform prestressing force. No lateral or longitudinal analysis for wind loads is performed. The addition of these modeling and analysis considerations, as well as others, would involve only coding them in the analysis module and incorporating redesign knowledge that can remedy violations of constraints related to these effects. Such additions, however, would not impact the issues discussed in this paper.

The analysis is performed as follows. First, the stiffness matrix of the bridge is assembled and factored to allow fast calculations of influence lines for the stay forces, tower moments at the connections to the deck and at the base, and deck moments at the panel points. The influence lines are displayed to the designer for qualitative evaluation that may assist in redesign. The influence lines are used to calculate the maximum moments and forces at each point due to live loads. The moments and forces due to the dead load are also calculated and added to the live loads. The live and dead loads for the above calculations are based on the AASHTO guidelines (AASHTO, 1983) and the loading recommendations for large bridges (Ivy et al, 1954).

Instead of displaying the complete set of analysis results, only 12 key design performance properties, sufficient for preliminary design purposes, are generated. Table 1 provides their descriptions and acronyms.

Redesign. An acceptable design must satisfy all design criteria; in BRIDGER, this means limits on the 12 design performance properties. Candidate designs that violate some of the design criteria are subject to redesign. Redesign is a collaborative process between the designer and the redesign sub-system. The redesign sub-system proposes design modifications and the designer executes them, or overrides them with other modifications. In the latter case, redesign knowledge refinement may be initiated by the redesign sub-system.

The structure of redesign knowledge. Redesign knowledge is built from two knowledge sources: a model of the bridge and its behavior, and cases and explanations of redesign actions solicited on-line from the designer. Each source has a distinct function.

The bridge model contains the possible influences between the design description properties and the performance properties. Redesign cases contain descriptions and explanations or redesign heuristics that relate the remedial actions selected to the redesign case. The purpose of this source is to adjust the importance of the influences in the first source and to add redesign heuristics that elaborate the model.

A partial bridge model is shown in Figures 4 and 5. In these figures, the design description properties are denoted by typeface font and the mediating properties are denoted by small letters.

The basic source of information in the bridge model is the structural decomposition of the bridge shown in Figure 4(a). It provides the basis for all the influences between the design description properties and the performance properties. For example, the functional hierarchy shown in Figure 4(b) inherits the relationships between the stiffnesses of the components from the structural hierarchy, and only the leaf nodes that connect to design description properties are represented explicitly. Similar inheritance is manifest in the behavior and load hierarchies shown in Figure 4(c) and (d), respectively. Each hierarchy, other than the structural decomposition hierarchy, is rooted in an abstract concept and is detailed such that its leaves are design description properties.

The connection between the structural, functional, load, and behavior hierarchies is represented by two types of relations shown in Figure 5: global and local. The global relations describe qualitatively the system of equations modeled numerically in the analysis model, while the local relations reflect the force-deflection relations for each substructure.

To illustrate, the influence between the main span length (`SPAN-M`) and the midspan deflection (`MAIN-S-DEFL`) can be traced in the following way. First, Figure 4(b) shows that an increase in `SPAN-M` decreases the stiffness of the stays, and therefore, decreases the stiffness of the bridge (the "increase" or "decrease" terms do not appear in the figure). It also decreases the stiffness of the deck, thus further decreasing the stiffness of the bridge. The stiffness of the bridge influences, through the global relations (Figure 5(a)), the deflections of the bridge. Furthermore, the total load is also increased through the addition of both live and dead loads (Figure 4(d)). The deflection of the bridge is connected to the midspan deflection through one of the behavior hierarchies (Figure 4(c)). This long chain of influences determines a connection between the two variables `SPAN-M` and `MAIN-S-DEFL`.

The hierarchies and causal relations discussed present a forward influence network from design description to design behavior. EPROTOS supports a backward influence direction that is further strengthened by redesign cases and explanations.

Redesign cases are complete descriptions of bridge examples appended with their analysis results and with one additional property, the best redesign modification that applies to that particular case. A particular case is an *exemplar* of the redesign modification selected for correcting it.

The structure of redesign actions follows immediately from the hierarchies and causal relations. Each design description property gives rise to several possible redesign recommendations. A continuous design description property generates two possible recommendations: *increase property* and *decrease property*. A nominal property generates a number of possible recommendations equal to the number of values the property has. Abstract remedial actions, such as `INCREASE BRIDGE STIFFNESS`, correspond to mediating properties in the bridge model.

Redesign cases are assigned to specific redesign recommendations. To illustrate, a redesign case where increasing the tower height corrected a constraint violation will be assigned to the recommendation `INCREASE TOWER-H`. In addition to redesign cases, redesign heuristics are incrementally introduced by the designer based on his/her judgment. These heuristics can be generally acceptable or subjectively discovered during the designer's interaction with the redesign sub-system. Examples of such heuristics include:

```
IF    internal stay stress (CABLE-ST-INS-M) is too high
THEN  increase deck moment of inertia (DECK-MI)
      (to better distribute the loads)

IF    DECK-M = concrete
THEN  maintain CABLE-PRE * CABLE-A approximately constant
```

Additional redesign knowledge is continuously accumulated from redesign interactions. First, redesign interactions update the strength of influences in the network based on credit and blame assignments. Second, new explanations can elaborate the influence network with additional relations between the properties describing the bridge behavior and those describing the remedial redesign modifications.

Retrieval of remedial design modifications. The input to the redesign sub-system is a complete bridge description, including the analysis results. The properties in the description remind EPROTOS of existing recommendations. EPROTOS combines the evidence and forms a hypothesis about the potential remedial actions. EPROTOS next attempts to locate an exemplar for each potential recommendation and match it to the new case. Finally, EPROTOS orders the recommendations based on the above matches and outputs an ordered list of recommended redesign modifications.

Design modification. After the identification of the remedial design modification directions, the magnitude of the modifications for properties having continuous values needs to be determined by the designer. If the modification involves geometric properties, the resulting description is checked for geometric consistency, as after synthesis. Since only small modifications can occur, a consistent bridge geometry can be maintained. The modifications entered by the designer remain fixed and are not modified. At this stage, additional side constraints on the sizes of components are enforced. If the stay area is determined to be less than 0.0005 m^2, it is adjusted to this minimum. Similarly, the deck and tower cross sectional areas, or the deck and tower cross sectional moment of inertia cannot be smaller than 0.05 m^2 or 0.05 m^4, respectively.

The analysis and redesign tasks discussed above are executed iteratively until a set of candidates that satisfy all the design criteria and any designer preferences is obtained.

4.3 Support for evaluation

Acceptable designs resulting from successful redesign are presented to the designer for evaluation. Two mechanisms are provided for displaying data for designer evaluation: graphical and tabular. The graphical representation of four candidates is shown later in Figure 7. Each display contains the configuration of the bridge and the influence lines calculated in the analysis task. For symmetric bridges only half of the influence lines are displayed. A tabular description of the properties of the four candidates is also provided. Each complete description contains the list of properties describing the design, the analysis results and the weights.

The designer can use the configuration of the bridge, the shape of the influence lines, and the summary of design descriptions to select the subset of acceptable designs. This subset is the product of the preliminary design stage. The designer can also select a partial set of the acceptable designs and submit it to the synthesis module for further training. Such training eventually adapts the synthesis knowledge to the designer's preferences.

5 A design example

This section provides a detailed design scenario with Bridger, demonstrating its capabilities as a design system.

5.1 The synthesis task

The following design specification is posed to Bridger:

```
CROSSING-LENGTH      = 434.8  m
BRIDGE-LENGTH        = 920.9  m
BRIDGE-WIDTH         =  30.2  m
HORIZONTAL-CLEARANCE = 244.0  m
VERTICAL-CLEARANCE   =  23.0  m
```

The list specifies that the length of the crossing is 434.8 m, the overall length of the bridge is to be 920.9 m, the width of the bridge is to be 30.2 m, and the horizontal and vertical clearances be at least 244.0 m and 23.0 m, respectively.

Synthesis of candidate designs. Bridger is asked to retrieve four candidate designs. Each candidate contains a set of specification and design description properties.

Table 3 and Figure 6 show the four candidates retrieved; they roughly match the specification. In particular, the ratios of the required horizontal clearance, 244 m, to the main span of the four candidates is 0.95, 0.89, 0.84, and 0.8, respectively; thus, the candidate designs match the horizontal clearance requirement reasonably closely. The designs vary considerably: the number of spans, the layout and number of stays, as well as the height of the towers are quite different among the four candidates. The weights of the cables and structural steel (in kN) of the four candidates, given in Table 3, are also different. These differences cannot be accounted for by differences in the bridge length only. (Candidate 1 may seem to have excessively heavy cables; nevertheless, it is an acceptable design. It can be redesigned such that the weight of cables is reduced by 55%, at the expense of increasing the steel weight by 15%.)

Candidate adaptation. Candidate adaptation modifies the four candidate designs to satisfy the geometric specification. This is done in several steps. Candidate 4 will be used to illustrate the process, since it undergoes the most significant modification. The following list describes the sequence of adaptations:

(1) The height of the tower below the deck (`TOWER-B`) is reduced from 54.8 m to 23.0 m to match the vertical clearance requirement.
(2) The main span (`SPAN-M`) is scaled down from 304.8 m to 244.0 m to match the horizontal clearance requirement. This assumes that there are no ground obstacles preventing the relocation of the towers.
(3) The tower height above deck (`TOWER-H`) is scaled up from 38.1 m to 45.2 m to maintain the proportions with the derived values retrieved from the derived hierarchy. These values are based on a retrieved previous example similar to candidate 4. Note that although the original main span was scaled down, the tower is scaled up since the retrieved value of `ST-RATIO` is 0.185 ($0.185 \times 244.0 = 45.2$).
(4) The stay spacing on the main deck (`STAY-SPD`) is reduced from 42.2 m to 40.1 m to account for the retrieved values of the free main span (`FMM-RATIO` = 1.61) and free internal span (`FIM-RATIO` = 1.36) ratios.
(5) The stay inclination (`STAY-IN`) is assigned the value of 0.478 based on the previous dimensions.
(6) The properties related to the side spans are similarly adjusted.

The four adapted candidate designs are shown in Figure 7. A partial listing of their properties and weights is given in Table 4.

The proportions of the four candidates shown in Figure 7 are reasonable, although the stay inclination of candidates 1 and 3 is slightly low. This is the result of using derived values from a three-span bridge to scale two-span bridges. The inclusion of additional design examples through learning would provide knowledge capable of synthesizing more appropriate proportions. The bridge weights presented in Table 4 suggest that candidates 1, 2, and 4 have a potential of becoming good designs.

5.2 The analysis and redesign tasks

The analysis results of the four candidates are given in Table 5. In the Table, the 12 design performance properties, introduced in Table 1, are expressed on a qualitative scale, where the values: `UNDER`, `SERVICE`, `LIMIT`, and `EXCESSIVE` denote: below 60%, 60-90%, 90-100%, and above 100% of the specified performance limit, respectively. In the Figure, the flat segments of the influence lines to the left of the tower in candidate 1 indicate that this span has a support under each stay connection (`SIDE-S` = 1). The nature of the influence lines for candidate 2 and 3 suggests that the deck moment of inertia is too small to contribute to the distribution of moments into several adjacent segments. As for candidate 4, it is hard to imagine a bridge with a main span of 244 m with one stay. The fact that this candidate satisfies all the performance requirements is directly determined by its small deck cross-section area, which exerts only minimal dead load. Such a small deck area is possible since axial loading and stability are not considered. If, however, they were to be considered, analysis would detect that the axial stresses superimposed on the flexural stresses are larger than the stress limit, therefore requiring an increase in the deck area.

The influence lines and the analysis results are the starting point of the analysis-redesign iterations. The analysis results of candidate 3, in addition to its very high relative weight, suggest that it is a bad starting point for redesign; therefore, only candidates 1, 2, and 4 are considered in subsequent redesign and analysis iterations. Two redesigns, manual and semi-automatic, are performed with the assistance of the redesign module. For both, we only describe the redesign of candidate 2.

Manual redesign. The first consideration in redesigning candidate 2 is to increase the deck moment of inertia so as to distribute moments to additional stays. This permits a reduction of the stay area, even though the stays are currently overstressed. The modifications

```
new value of CABLE-A        = original value * 0.8
new value of CABLE-SA-RATIO = original value * 0.9
new value of DECK-MI        = original value * 3.0
```

reduce the stay stresses but still maintain the high tower stresses. A reduction of the stay spacing in the tower to 0, (in effect changing `STAY-L` from `Fan` to `Radial`,) a further reduction of the stay area ratio, and a change in the connection of the tower to the deck

```
new value of STAY-SPT       = 0.0
new value of CABLE-SA-RATIO = original value * 0.8
new value of TD-CON         = Roller
```

reduce the tower stresses below the acceptable limit. These modifications, however, increases the stay stresses.

To remedy the problem of the high stay stresses, the previous reductions are slightly reversed. In addition, the tower is made stiffer in bending while its area is reduced so as to make it more fully stressed. The following modifications

```
new value of CABLE-A        = original value * 0.9
new value of TOWER-A        = original value * 0.6
new value of TOWER-MI       = original value * 2.0
new value of CABLE-SA-RATIO = original value * 0.9
```

reduce the stay stresses to almost the limit. A slight modification of the stay area completes the redesign process. The final weights of candidate 2 are:

```
WEIGHT-CABLES:    628 kN
WEIGHT-STEEL:   4,003 kN
```

Compared to the property values of the candidates after adaptation and before redesign (Table 4), these values show a reduction of 16% in cable weight and a reduction of 7% in steel weight.

Semi-automatic redesign. A brief illustration of the current status of the redesign sub-system is illustrated by submitting candidate 2 to semi-automatic redesign. The first set of recommendations generated by the redesign sub-system is:

Recommendation	Strength
decrease CABLE-A	2.27
decrease CABLE-SA-RATIO	1.40
set TD-CON to Roller	0.41
increase TOWER-A	0.36
increase DECK-MI	0.32

The recommendations are ranked in descending order of strength. The strength is based on the way the current case matches redesign cases that have previously undergone the corresponding redesign modifications. A high ranking suggests that the recommendation may be more relevant to the current case, whereas a low ranking suggests that the recommendation is spurious.

All of the above recommendations are executed with a magnitude of change that roughly corresponds to their relative ranking. The redesign modifications

```
new value of CABLE-A        = original value * 0.9
new value of CABLE-SA-RATIO = original value * 0.95
new value of TD-CON         = Roller
new value of TOWER-A        = original value * 1.05
new value of DECK-MI        = original value * 1.05
```

slightly reduce the tower stresses but increase the stay stresses. A second redesign iteration generates the recommendations:

Recommendation	Strength
decrease CABLE-A	0.87
decrease CABLE-SA-RATIO	0.64
decrease STAY-SPT	0.54
set TD-CON to Roller	0.41
increase DECK-MI	0.30

Again, all the redesign recommendations are executed. The knowledge that `DECK-MI` directly influences the deck stress leads to increasing it further than suggested by its low strength. The redesign recommendations

```
new value of CABLE-A        = original value * 0.85
new value of CABLE-SA-RATIO = original value * 0.925
new value of STAY-SPT       = original value * 0.9
new value of DECK-MI        = original value * 1.5
```

further reduce the tower stresses but maintain the stay stresses above the limit. The third redesign generates recommendations similar to those of the second iteration and the resulting redesign modifications

```
new value of CABLE-A        = original value * 0.8
new value of CABLE-SA-RATIO = original value * 0.9
new value of STAY-SPT       = original value * 0.8
new value of DECK-MI        = original value * 3.0
```

further reduce the stresses. Instead of continuing with the same redesign strategy in which the magnitude of actions is influenced by the strength of the recommendations, knowledge that the `STAY-SPT` property has a more significant impact than currently suggested by the sub-system is used. Therefore, the next modification (which in effect changes `STAY-L` to `Radial`)

```
new value of STAY-SPT       = 0.0
```

is executed and reduces the tower stresses below the limit and further reduces the stay stresses. The most obvious decision is to perform a local adjustment of the stay area even though this recommendation is not selected by the redesign sub-system. The execution of the redesign modifications

```
new value of CABLE-A        = original value * 0.95
new value of CABLE-SA-RATIO = original value * 0.95
```

reduces all the stresses below the limits. The weights of the final configuration are

```
WEIGHT-CABLES:      685 kN
WEIGHT-STEEL:     4,324 kN
```

The steel weight can be easily reduced further by reducing the area of the tower.

5.3 The evaluation task

After redesign, candidates 1, 2, and 4 are evaluated. Table 6 provides a summary of the weights of the the candidates after manual redesign. Candidates 2 and 4 are better than 1; their cables weight is substantially lower.

It is worthwhile to evaluate the candidates by the following criteria.

(1) *Background knowledge.* An experienced designer will know when a certain design property value is likely to cause violation of constraints to be verified in later design

stages. Simple approximations of these constraints can help rank the alternatives. Candidate 2 is better than candidate 4 along this criterion since the deck cross-sectional area of candidate 4 will not be sufficient in the detailed design stage.

(2) *Esthetics.* Of the four criteria, this is the most subjective one and is highly dependent on experience. Candidate 2 is preferred to candidate 4 as it induces a better feeling that its components perform their intended task. (For an elaboration on the issue of esthetics in BRIDGER see Reich (1993).)

(3) *Level of analysis measures.* The final analysis results of each candidate provide an adequate margin of available capacity for the detail design stage. The higher this margin, the more flexible is the design in accommodating local changes in the detailed design stage. The two candidates are similar except that candidate 2 has a larger margin in its deck and in its overall stiffness (exemplified in the `MAIN-S-DEFL` property).

(4) *Weight.* The overall weight of candidates 2 and 4 are quite similar but candidate 2 is slightly lighter.

Evaluation is a multi-criterion process. Candidate 2 ranks better that candidate 4 along the four criteria and is therefore considered here as the best product of the preliminary design stage. Subsequently, the designer can use candidate 2 to train and enhance the synthesis and derived hierarchies.

6 Statistical evaluation

This section provides an evaluation of BRIDGER's synthesis knowledge as it develops through learning. No such evaluation was performed with the redesign knowledge for several reasons: first, the redesign module was not the focus of the work; second, it did not contain sufficient knowledge; and third, it was not possible to separate the human interaction aspect from the semi-automatic redesign.

The evaluation of the synthesis knowledge was performed as follows. Three synthesis hierarchies, K_1, K_2, and K_3, were generated by training BRIDGER with examples of bridge descriptions. Hierarchy K_1 was generated from the set of 96 bridge examples after their analysis and redesign by BRIDGER. Thus, K_1 consists of examples that have all been analyzed and redesigned using the same design criteria. Hierarchies K_2 and K_3 were generated from 144 (48 in addition to the 96 in K_1) and 192 (48 in addition to the 144 in K_2) examples, respectively, where all additional examples were generated by BRIDGER.

The experiment evaluated the design performance of BRIDGER while synthesizing candidates for 48 test specifications selected to span a range of problems, some of which were outside the scope of the training examples used to create the synthesis knowledge. Since the power of BRIDGER's synthesis process comes from (1) the retrieval of designs closely related to the new specification, and (2) the adaptation of candidates by scaling, the evaluation included both.

The retrieval process is evaluated by the `Scaling` factor that calculates the ratio of the specified crossing length to the length of the retrieved bridge (main plus side spans); it measures approximately how close the retrieved design (before adaptation) is to fulfilling the dimensional specification. A value 1 of the `Scaling` measure indicates a perfect match. The combination of retrieval and adaptation is tested by measuring the `Quality` of the candidate designs after their adaptation, but before any redesign took place. The `Quality` measure is the summation of the deviation of 12 design performance properties shown in Table 1 from their specified limits, penalizing the properties that exceed their respective limits more severely than those which are below the limit. A value 0 of the Quality measure indicates a design that is perfectly in compliance with the performance constraints.

Table 7 provides the mean values of the Scaling needed to adapt the candidates to the bridge length specifications of the 48 test problems, and the Quality of the designs synthesized.

A MANOVA (Hays, 1988) analysis was performed to assess the statistical significance of the differences in the performance levels observed. Based on the power law of practice governing learning, which suggests that performance varies as a power function of the number of examples, the logarithm of the number of examples is the independent variable and the logarithm of the performance levels are the dependent variables in the statistical analysis.

The results of the Scaling were: $K_1, K_2 >_{0.01} K_3$; where the $>_{0.01}$ indicates that candidate designs generated with K_3 were closer to satisfying the specification than those generated with K_1 or K_2 with statistical significance at the $p < 0.01$ level. Therefore, *the more knowledge* BRIDGER *has, the closer to the geometric specifications are the retrieved candidates.* The Quality values satisfy: $K_1 >_{0.01} K_2 >_{0.01} K_3$; therefore *the more knowledge* BRIDGER *has, the better the quality of candidates it generates*; therefore, each design would require fewer redesign cycles. Further, the first result should have been expected since Scaling measurement is based on properties existing in retrieved bridge descriptions. In contrast, the second result involves testing the Quality measure which is calculated from results of analysis and, hence, is not straightforward.

7 Summary and conclusions

An approach for building a computational support system for the preliminary design of cable-stayed bridges has been presented. The system extracts knowledge from previous designs and designer interactions. BRIDGER operates by accepting a bridge specification and, with limited designer guidance, terminates with a list of candidate designs. Currently, the support that BRIDGER provides for design is limited since many considerations are not addressed, such as alignment, cost, and constructibility. In addition, the system only employs a 2D linear analysis model.

BRIDGER continuously learns from experience, as demonstrated in the previous section. This fact has been established through statistical experiments and analyzes of the synthesis sub-system. We have not performed similar experiments for the redesign sub-system. However, it is the synthesis part, rather than redesign, that constitutes the most difficult task in the preliminary design process.

The mechanisms that accumulate knowledge may potentially support the adaptation of that knowledge to new technologies, specific countries, and styles of particular designers. This potential is predicated upon future experimental testing and demonstration. In general, however, the ability to learn and adapt is perceived as a crucial aspect of design systems in an environment with rapidly changing technology.

Future enhancements will include increasing the role of the designer in both the learning and design activities, by enhancing the interactive nature of the system and allowing for designer intervention at each step of the two activities. Other enhancements include increasing the depth and breadth of the system.

Depth can be enhanced in at least two ways. First, bridge description properties can be elaborated. For instance, the representation of the deck as a prismatic section can be replaced by the representation of a variable cross-section. In order that these enhancements be meaningful, analysis procedures that evaluate these more detailed bridge descriptions are necessary. Second, the addition of 3D visualization can help designers in the evaluation process.

Breadth can be enhanced by extending BRIDGER to support the design of other types of bridges. This involves the collection of data on existing bridges and training the synthesis module with them. More importantly, BRIDGER can be extended to incorporate concerns other than the preliminary design stage. For example, service performance and maintenance data entered as additional bridge description properties could be used to improve future designs. G. F. Fox stated in an interview that:

> "we should be developing databases, or knowledge bases, as well. Unit cost, technical data, historical costs, and failures could be put into these databases. Right now designers aren't able to get to the information that's out there" (Spector and Gifford, 1986).

We believe that the approach explored through BRIDGER goes beyond Fox's expectations. BRIDGER presents a way to organize past and future experience and use it for assisting in designing future bridges.

8 Acknowledgments

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Appendix I. References

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Table captions

1. Bridge description: Specification and derived properties
2. Bridge description: Design and performance properties
3. Summary of candidates retrieved from the hierarchy
4. Tabular summary of adapted candidates
5. Analysis results of adapted candidates
6. Weights of candidates after manual redesign
7. Scaling and quality statistics of candidates

Table 1: Bridge description: Specification and derived properties

Property	Acronym	Property	Acronym
Specification properties		**Derived properties**	
date bridge was opened	OPENED	inclination of outer stay	STAY-IN
vertical clearance	CLEAR-V	SPAN-M to DECK-D ratio	SD-RATIO
horizontal clearance	CLEAR-H	SPAN-M to CROSS-L ratio	MSL-RATIO
total width	WIDTH-T	TOWER-H to SPAN-M ratio	ST-RATIO
number of lanes	LANES	free main span to STAY-SPD ratio	FMM-RATIO
purpose	PURPOSE	free internal span to STAY-SPD ratio	FIM-RATIO
crossing length	CROSS-L	SPAN-SA to SPAN-M ratio	SAM-RATIO
total length of bridge	LENGTH		

Table 2: Bridge description: Design and performance properties

Property	Acronym	Property	Acronym
Design description properties		**Design performance properties**	
width of the bridge	`WIDTH`	midspan deflection	`MAIN-S-DEFL`
number of spans	`SPAN-N`	tower tip deflection	`TOWER-TIP-DEFL`
length of main span	`SPAN-M`	cable stress, outer side span	`CABLE-ST-OUT-S`
are side spans supported by piers	`SIDE-S`	cable stress, middle side span	`CABLE-ST-MID-S`
layout of stays	`STAY-L`	cable stress, inner side span	`CABLE-ST-INS-S`
number of stays	`STAY-N`	cable stress, outer main span	`CABLE-ST-OUT-M`
spacing of stays on main span	`STAY-SPD`	cable stress, middle main span	`CABLE-ST-MID-M`
area of cables	`CABLE-A`	cable stress, inner main span	`CABLE-ST-INS-M`
depth of deck	`DECK-D`	deck stress at midspan	`DECK-ST-M`
material of deck	`DECK-M`	deck stress at outer cable	`DECK-ST-O-CABLE`
moment of inertia of deck	`DECK-MI`	deck stress at inner cable	`DECK-ST-I-CABLE`
area of deck	`DECK-A`	tower bottom stress	`TOWER-ST-BOT`
material of tower	`TOWER-M`	total weight of steel	`WEIGHT-STEEL`
moment of inertia of tower	`TOWER-MI`	total weight of concrete	`WEIGHT-CONCRETE`
area of tower	`TOWER-A`	total weight of cables	`WEIGHT-CABLES`
tower height above deck	`TOWER-H`		
connection between tower and deck	`TD-CON`		
connection of tower to foundations	`TB-CON`		
connection of deck to abutments	`DA-CON`		

Table 3: Summary of candidates retrieved from the hierarchy

CANDIDATE:	1	2	3	4	
OPENED:	1968	1971	1971	1971	
LENGTH:	890	542	565	1,321	m
SPAN-M:	257	274	291	304	m
WEIGHT-CABLES:	6,135	846	1,906	1,866	kN
WEIGHT-STEEL:	4,751	2,749	9,905	6,455	kN

Table 4: Tabular summary of adapted candidates

Property	Cand. 1	Cand. 2	Cand. 3	Cand. 4
Design description properties				
CABLE-A:	0.047	0.012	0.007	0.052 m^2
CABLE-M:	Steel	Steel	Steel	Steel
CABLE-PRE:	0.0	0.0	0.0	0.0
CABLE-SA-RATIO:	1.0	0.48	1.0	1.0
DA-CON:	Hinged	Fixed	Fixed	Hinged
DECK-A:	0.05	0.05	0.05	0.05 m^2
DECK-D:	3.66	2.23	3.62	3.23 m
DECK-M:	Steel	Steel	Steel	Steel
DECK-MI:	0.069	0.05	0.05	0.05 m^4
SIDE-S:	Supported	Unsupported	Unsupported	Unsupported
SPAN-M:	244.0	244.0	244.0	254.0 m
SPAN-N:	2	3	2	3
STAY-L:	Harp	Fan	Radial	Single
STAY-N:	4	7	11	1
STAY-SPD:	40.84	14.94	18.81	40.10 m
TB-CON:	Hinged	Fixed	Fixed	Hinged
TD-CON:	Hinged	Fixed	Roller	Roller
TOWER-A:	0.161	0.153	1.288	0.197 m^2
TOWER-H:	45.21	45.21	45.21	45.21 m
TOWER-M:	Steel	Steel	Steel	Steel
TOWER-MI:	0.379	0.124	5.910	0.361 m^4
WIDTH:	30.2	30.2	30.2	30.2 m
Design performance properties				
WEIGHT-CABLES:	3,589	746	1,599	1,654 kN
WEIGHT-STEEL:	4,365	4,324	10,250	4,551 kN
WEIGHT-CONCRETE:	0	0	0	0 kN

Table 5: Analysis results of adapted candidates

Property	Cand. 1	Cand. 2	Cand. 3	Cand. 4
MAIN-SPAN-DEFLECTION:	SERVICE	UNDER	SERVICE	UNDER
TOWER-TIP-DEFLECTION:	UNDER	UNDER	UNDER	UNDER
CABLES-STRESS-OUT-SIDE-SPAN:	UNDER	EXCESSIVE	EXCESSIVE	UNDER
CABLES-STRESS-MID-SIDE-SPAN:	UNDER	EXCESSIVE	EXCESSIVE	UNDER
CABLES-STRESS-INS-SIDE-SPAN:	UNDER	EXCESSIVE	EXCESSIVE	UNDER
CABLES-STRESS-OUT-MAIN-SPAN:	EXCESSIVE	SERVICE	EXCESSIVE	UNDER
CABLES-STRESS-MID-MAIN-SPAN:	LIMIT	UNDER	EXCESSIVE	UNDER
CABLES-STRESS-INS-MAIN-SPAN:	SERVICE	UNDER	EXCESSIVE	UNDER
DECK-STRESS-MAIN-SPAN:	UNDER	UNDER	SERVICE	UNDER
DECK-STRESS-OUTER-CABLE:	UNDER	UNDER	UNDER	UNDER
DECK-STRESS-INNER-CABLE:	UNDER	UNDER	UNDER	UNDER
TOWER-STRESS-BOTTOM:	EXCESSIVE	EXCESSIVE	UNDER	UNDER

Table 6: Weights of candidates after manual redesign

CANDIDATE:	1	2	4
WEIGHT-CABLES:	2,958	628	777 kN
WEIGHT-STEEL:	4,534	4,003	3,975 kN

Table 7: Scaling and quality statistics of candidates

Hierarchy	No. of examples	`Scaling`	`Quality`
K_1	96	2.154	50.19
K_2	144	2.092	2.89
K_3	192	1.325	1.20

Figure captions

1. A subset of derived properties and their relationships to some design description properties
2. Model of preliminary bridge design process
3. The architecture of BRIDGER
4. Hierarchies in the bridge model
5. Causal relations in the bridge model
6. Retrieved candidates
7. Adapted candidates

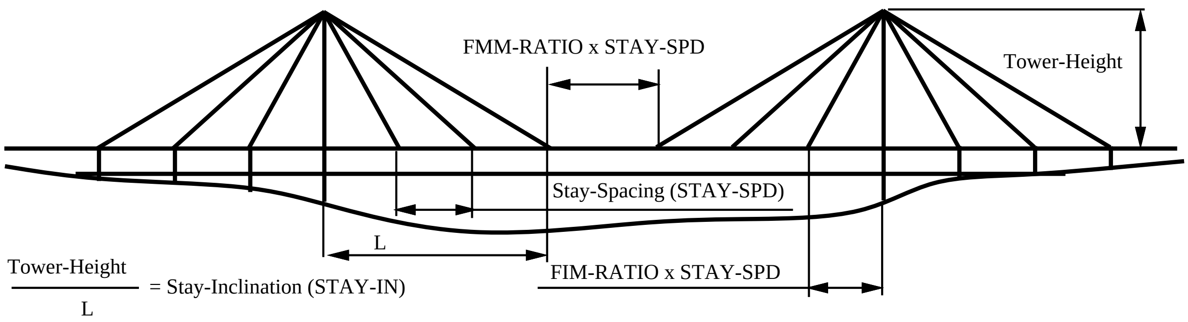


Figure 1: A subset of derived properties and their relationships to some design description properties

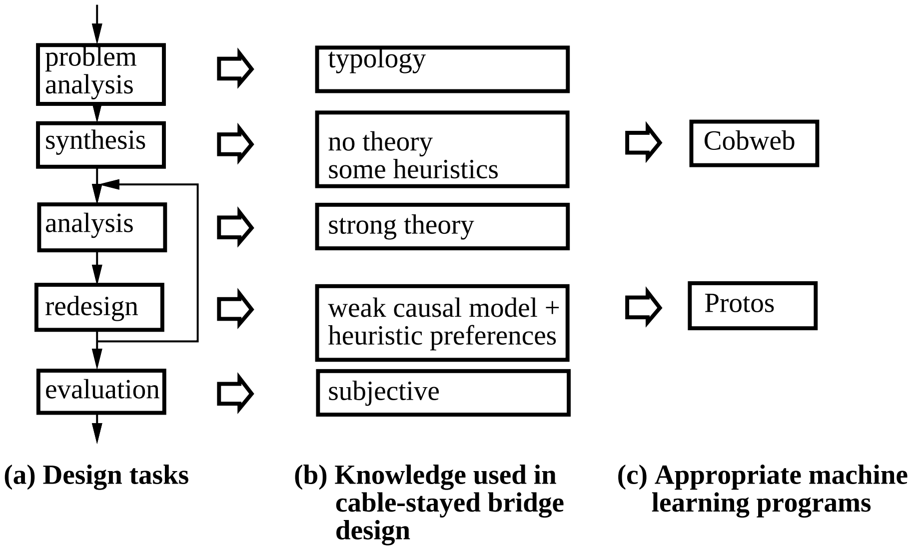


Figure 2: Mapping design tasks to machine learning programs

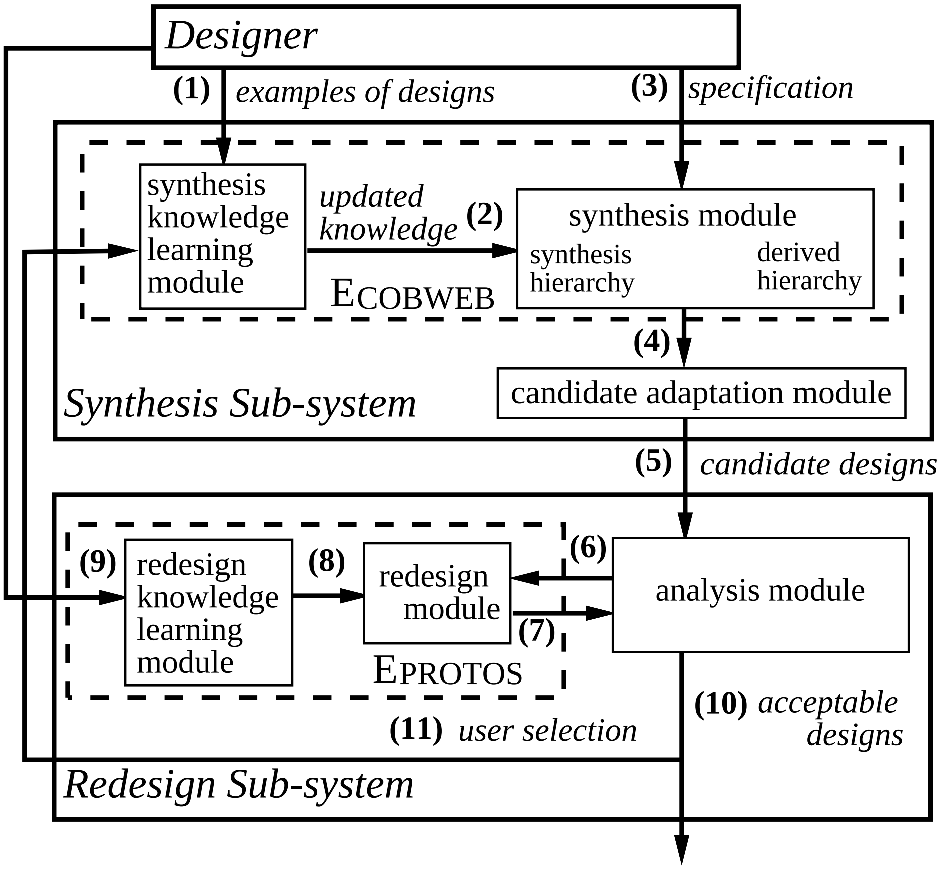


Figure 3: The architecture of BRIDGER

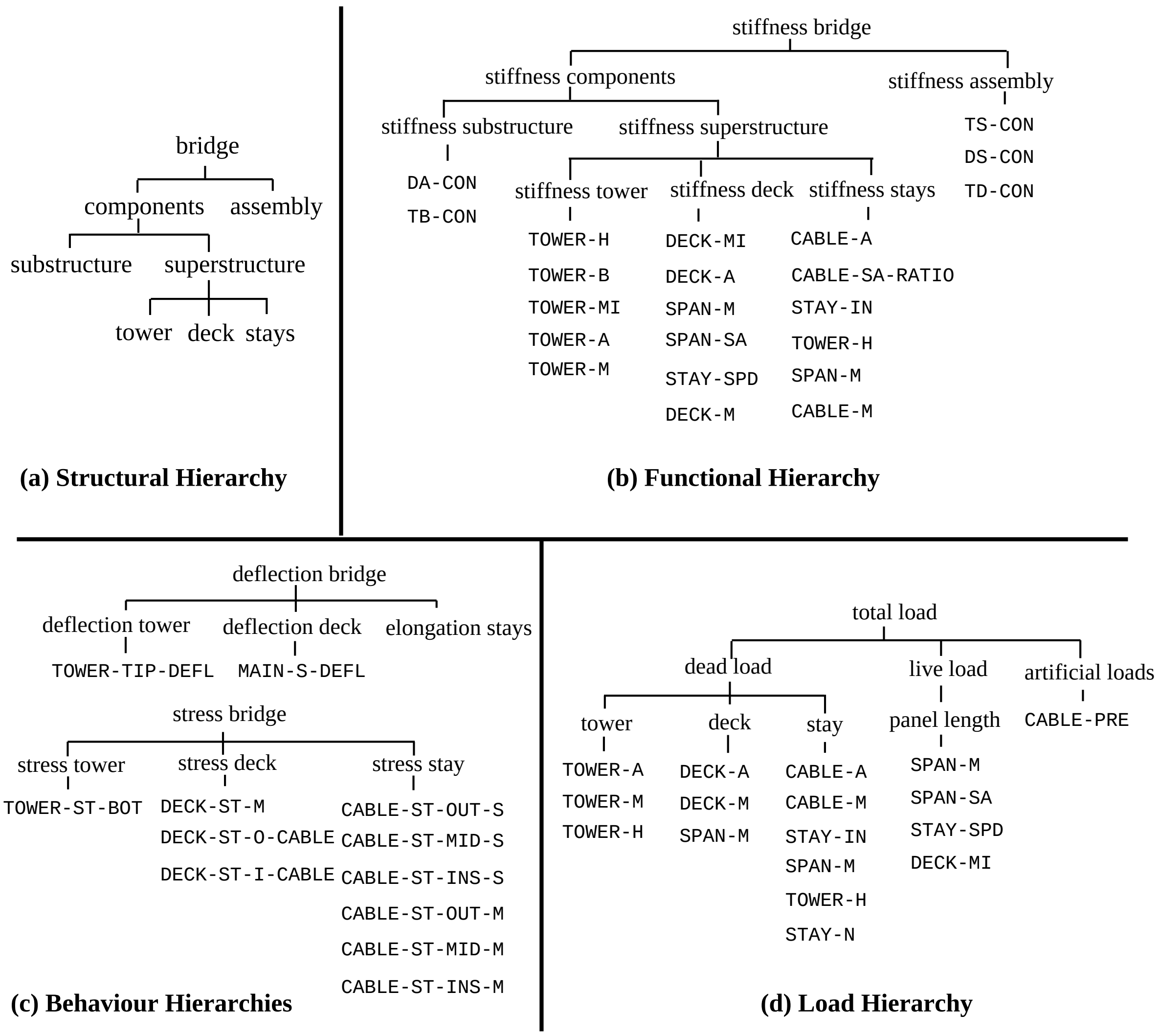
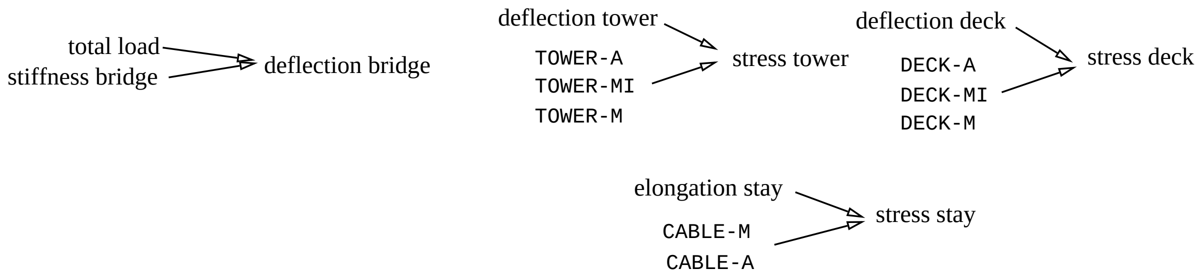


Figure 4: Hierarchies in the bridge model



(a) Global Relations **(b) Local Relations**

Figure 5: Causal relations in the bridge model

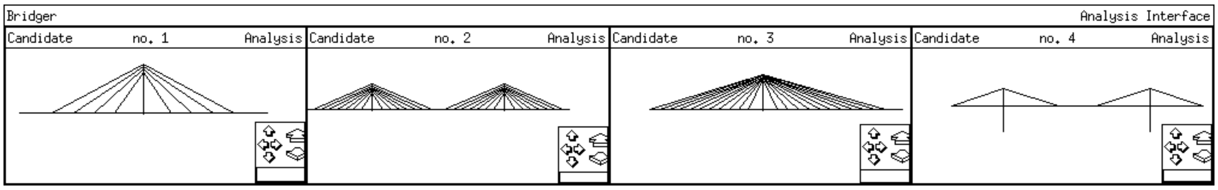


Figure 6: Retrieved candidates

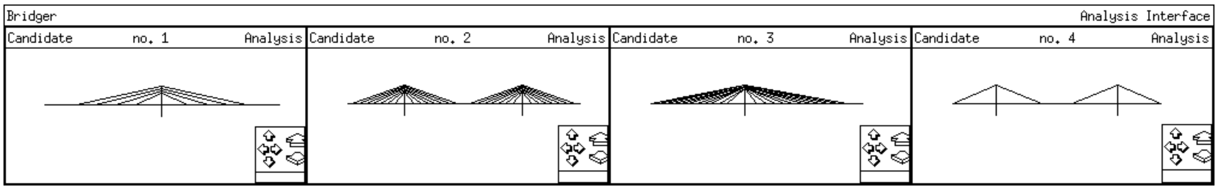


Figure 7: Adapted candidates