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Taking Advantage of Design Process Models

Tirer profit de modèles du processus de la conception

Ausnützung von Entwurfsprozessmodellen

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SUMMARY

This paper describes explicit representations of design processes for improving knowledge acquisition, implementation and user-interface design. A model for conceptual design of bridges uses assumptions and physical principles as well as design criteria and design strategies for incorporating several starting points, directed trial-and-error and multiple solution traces. The implementation is non-monotonic and uses the constraint-propagation paradigm. Through integrating attributes of other models and several processes, an extended maze provides an intuitive mapping of reasoning and knowledge for conceptual structural design.

RÉSUMÉ

Cet article présente une description explicite du processus de la conception pour faciliter l'acquisition de la connaissance, l'implantation informatique et la conception de l'interface utilisateur. Le modèle retenu traite la conception préliminaire des ponts et est fondé sur des hypothèses et des principes physiques, ainsi que sur des critères et des stratégies de conception pour incorporer différents points de départ ainsi que des cheminements de solution multiples. L'implantation est non-monotone et s'appuie sur le paradigme de la propagation des contraintes. En assimilant des attributs propres à d'autres modèles et à plusieurs processus, un labyrinthe étendu permet un rapprochement plus intuitif du raisonnement et de la connaissance utilisés lors de la conception des ouvrages.

ZUSAMMENFASSUNG

Dieser Artikel beschreibt explizite Repräsentationen des Entwurfsprozesses mit dem Ziel der Verbesserung der Wissenserfassung, der Implementierung und der Benutzerschnittstellen. Ein Modell für den Vorentwurf von Brücken benützt neben Annahmen und physikalischen Prinzipien ebenso Entwurfskriterien und -strategien zur Behandlung von verschiedenen Ausgangssituationen, gerichtetem "trial-and-error" sowie alternativen Lösungswegen. Die Implementierung erfolgt nichtmonoton und benutzt das Fortpflanzungsparadigma für Nebenbedingungen. Durch Anpassung der Eigenschaften weiterer Modelle und Einbeziehung von Produkt- und Prozessmodellen entsteht ein Labyrinth aus intuitiven Uberlegungs- und Wissensmustern für den Vorentwurf von Bauwerken.

1 Introduction

No two artifacts are designed in the same way and therefore it is difficult to develop useful models of design. Different assumptions are made in light of incomplete information. When decisions regarding the refinement and the direction of the design are made and when conflicts occur, they are resolved using different criteria and strategies.

Given the complexity of design tasks, models of design processes often propose a procession from general to specific, little support for incomplete information, a rigid structure for conflict resolution, and few possibilities for deviating from a global plan. The need for more realistic models has been recognised for many years (Simon, 1981, Gero, 1993, Fenves, 1992, Holgate, 1986), and many computational models have been proposed which partially support such characteristics. Ganeshan, Finger and Garrett (1991) provide an environment for capturing the intent of a decision. Sause and Powell (1991) maintain two levels for the development of design steps. Many researchers have recognised the need to incorporate more than one paradigm : Bañares-Alcántara's (1992) two hypotheses, Bowen and Bahler's (1992) multiple perspectives, Tong and Tueni's (1990) control and domain levels, Soo and Wang's (1992) qualitative and quantitative reasoning, and Zhao and Maher's (1992) analogy and mutation.

Our goal is not to automate conceptual design but to augment human designers' creativity and to provide an explanatory trace of their steps. Representation in design is knowledge-intensive and reasoning is dynamic and temporarily inconsistent (Gero, 1993). We begin by observing experts during sketching in order to extract a set of desirable features for recognising various starting points, trial-and-error approaches, and end points during conceptual design of bridges. We propose traces of solutions with multiple uses of design knowledge, applying design models as conceptual frameworks and including explicit representation of assumptions, design criteria and design strategies for developing alternatives and for resolving conflicts. Thus we aim to provide support for design exploration as proposed by other researchers (Petrie, Cutowsky and Park, 1994, Logan, Corne and Smithers, 1992, Brazier, van Langen, Ruttkay and Treur, 1994). We emphasise the desirability of working with a model, as distinct from am implementation version of it, see Figure 1. Models become the focal point for the iterative process used during development, providing a common platform for interacting with experts (a) and the implementation team (b) and for integrating the user-interface (c). A model can be very different than the cognitive map of an expert's mind and also different than the implementation.

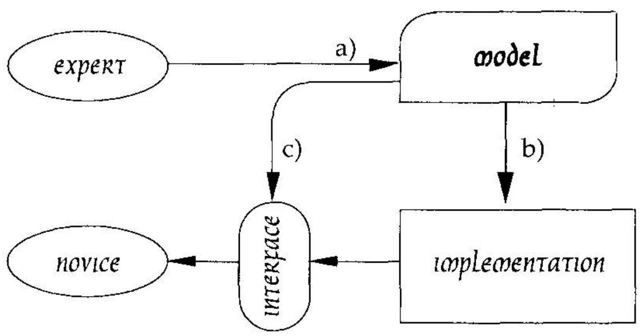

Figure 1 — The role of design models during development. A model should assist knowledge acquisition (a), system implementation (b), and user interface design (c). A model acts as a focal point for interacting with experts and the implementation team, and provides the basis for development of the user interface.

2 Models of design processes

A model, in our context, is a non-exhaustive description of key elements of the design process and provides a framework of important design aspects in order to facilitate knowledge acquisition, implementation and interface design. Models of design processes help capture initial conditions, state transformations and final specifications. Transformation implies a change from one state to another, such as from function to structure, from abstract to concrete concepts, and from qualitative to quantitative attributes. Models represent problem solving, search, decision-making and exploration which englobe major design tasks. A global environment needs to provide multiple opportunities for advancing the design. In Figure 2, several models are presented, linear, tree and semi-lattice models as well as more complex network and maze models.

A **linear model** assumes that a design problem can be segregated into successive tasks resulting into one set of specifications. Initial models of the design process were mostly linear. It presupposes the existence of the one-best-solution. However, that idea is incompatible with many design tasks where a high number of solutions are plausible. Designers use *satisficing* methods (Simon, 1981) which cannot be embraced by a linear model. Since in design, an interdependency of parameters meshes quickly during exploration, the linear model cannot be used to represent a global design process.

A **tree model** is an improvement since more than one alternative can be elaborated. It allows the solution space to be decomposed into subgoals and provides an environment for the 'generate-and-test' method. It is commonly used to represent decision nodes. The tree model typifies conventional decomposition methods or hierarchical approaches provided that weak interactions exist (Stefik, 1981, Maher, 1989, Mittal and Araya, 1990, Topping and Kumar, 1989). They may also represent AND/OR graphs (Sause and Powell, 1991, Bédard and Ravi, 1991). The **semi-lattice** is an enlargement of the tree model as it offers accommodation for dependent subgoals. During her analysis of empirical design studies, Visser (1991) observed that design activities deviated so regularly from a decomposition approach that it could not be representative of a global design control strategy.

A **network** is another improvement as it can model interdependencies between subgoals and provide support for backtracking to previous decisions. Non-monotonic systems can partially be modelled with networks. Many researchers have included the network as a successful representation. Zhao and Maher (1992) use a network-based prototype where the links represent dependencies as well as domain-independent relations such as qualitative, quantitative, and inequality relations while global operations consist of a blend of mutation and analogical reasoning. Garcia and Howard's (1992) ADD (Augmented Design Documentation) is based on design and decision network models. The design network model provides local (or microlevel) relations which consist of activities such as : generate, constrain, evaluate and select while the decision network model provide global relations such as sequencing, composition and dependency. Network models have evolved significantly to the point where they have become a preferred model for many researchers as they offer a better support for exploration.

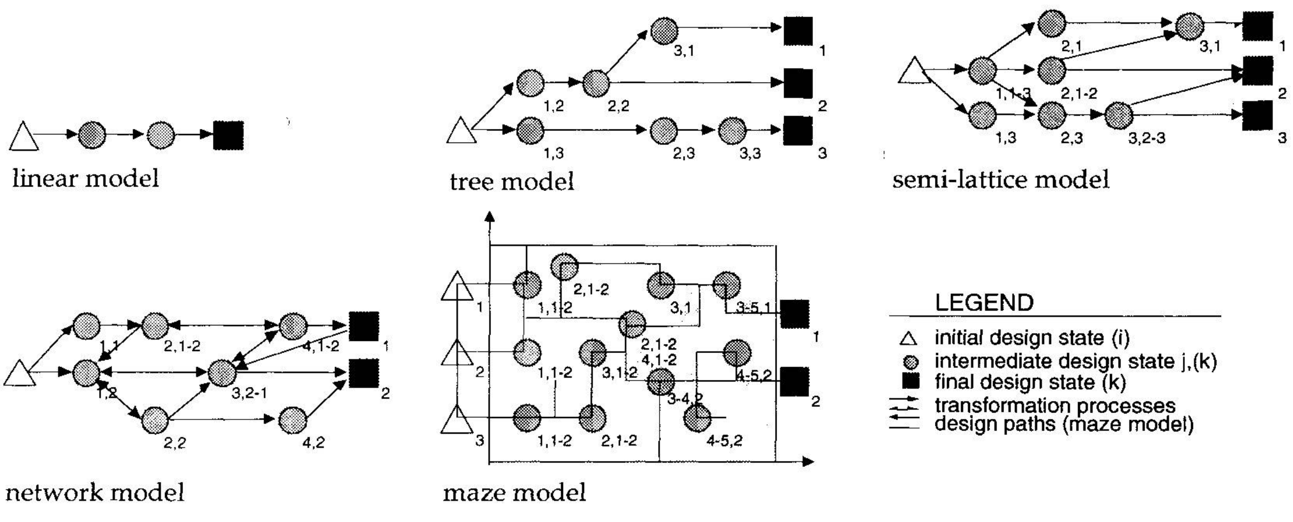

Figure 2 — Design process models inspired from Holgate (1981) and Bañares-Alcántara (1991)

The **network** and the **tree** models are often used to model *and* implement design systems. Their implementation strengths are not questioned. However, as Gardiner (1987) points out, strict hierarchical conceptualizations may be convenient for mimicking human performance but there are important problems associated with them for explaining and for describing human performance. These models, she claims, tend to assume too much knowledge on the part of the human. On the other hand, it is difficult to imagine a model which is completely hierarchy-free. A compromise for a model would be to represent a product loosely and redundantly, and allow a dynamic and fluid creation of the design path. The maze model is proposed to help satisfy these requirements.

A **maze** facilitates the integration of typical design tasks such as imitating false-starts, backtracking, lateral searches, the presence of more than one point of entry and exit, and the strong influence of the selection of the starting point on the end result (Holgate, 1986). Newell and Simon (1972) describe the GPS (General Problem Solver) for selectively searching through a large environment as moving through a large maze and reducing it to manageable proportions. In the maze, Visser's (1991) concept of *cognitive cost*, that is, as soon as other actions are more interesting, the engineer deviates from a global plan in favour of these actions, can be integrated. The maze then, appears suitable for representing a global control process, with the possibility of introducing local plans which may take on the form of another maze, a network, a tree or a linear model. Another distinction is the presence of axes; for example, the horizontal axis may represent parameters while the vertical axis indicates the range of each parameter. The dynamic creation of the path makes it less inhibiting for designers to proceed. The intricacy of the paths, in a maze, models more realistically exploration and multiple models of design processes.

3 Observations from conceptual design sketching

Sketching provides a rich medium for observing processes and collecting knowledge, and hence it was used as the basis for prescribing model requirements. Sketching is an effective informal method for starting, developing and communicating a design. Sketching is dynamic and constraint-free. Although imprecise, sketching is both concise and realistic. Some researchers have recognised sketching as such an important activity during conceptual design that computer-support is under development. For example, Jenkins and Martin (1993) have partially completed a system for automatic sketch input, called Easel. Gross and Zimring (1994) are adding a link between diagrams in Archie III, a case based design aid, and an 'electronic cocktail napkin' program which tags a designer's conceptual sketch, in order to explore alternatives quickly.

For illustration purposes, a small sample of sketches produced by four experienced Swiss engineers is presented in Figure 3. The four resulting products for spanning a 300 m long and 70 m deep unsymetrical valley are very different. Expert 1) used constant-depth beams and focused on shorter (economical) spans, while adding aesthically pleasing diminishing spans up the long slope on the right of the valley. This complicates construction as launching is more practical when all spans are equal. Expert 2) indicates a preference for cantilevered construction and longer spans, and provides haunched beams which have a higher aesthetic rating. The light diagonals drawn indicate an evaluation of the spaces enclosed which he found satisfying. In a symmetrical environment, an even number of spans would not be recommended. Expert 3) is not influenced by the complexity of the foundations for such an arch, and exploited the strong effect of the long span and symmetry of the arch. Cost was not his first concern. Expert 4) is highly influenced by his area of expertise which is cable-stayed bridges. This environment, as other experts have noted, does not initially lend itself to this bridge type. His first reaction was also to provide a symmetrical bridge, as experts 2) and 3) did, but was dissuaded after a second glance. A non-symmetrical single-mast cable-stayed bridge pleased him, as this reduced the height of the mast and provided a dominant span.

In summary, two aspects of the processes used during design stand out. First, experts can distinguish many **levels of importance** and attribute different priorities and values to parameters, criteria and strategies in order to help them refine designs. Second, they are able to manage **change**, prevalent during sketching, by deciding when to iterate, when to use intelligent trial-and-error, and when to compromise. Although additional sketches and calculations performed on the side are not shown in Figure 3, they provided a strong indication that experts rarely followed a strict hierarchical approach and felt strained to describe a precise plan of their tasks (Gruber, 1991). They adapt as they design. Visser's (1991) detailed study of programmers confirms this informal observation. In those side sketches, one expert would dwell on a cross-section, thinking of a good transfer between pier and beam, one would dabble on a construction sequence to reduce doubt on its feasibility, or one would look at a mast more closely in order to make it more slender and discrete. An opportunistic approach (Hayes-Roth and Hayes-Roth, 1979) is a partial explanation. However, other factors have influence : each expert responds uniquely to incomplete and competing information in order to fill the gap between specifications and product description; they each have their own priorities regarding cost and aesthetics; each one is lightly or heavily influenced by previous designs; and at least one prefers generating many partial solutions rather than commit quickly to a more detailed solution.

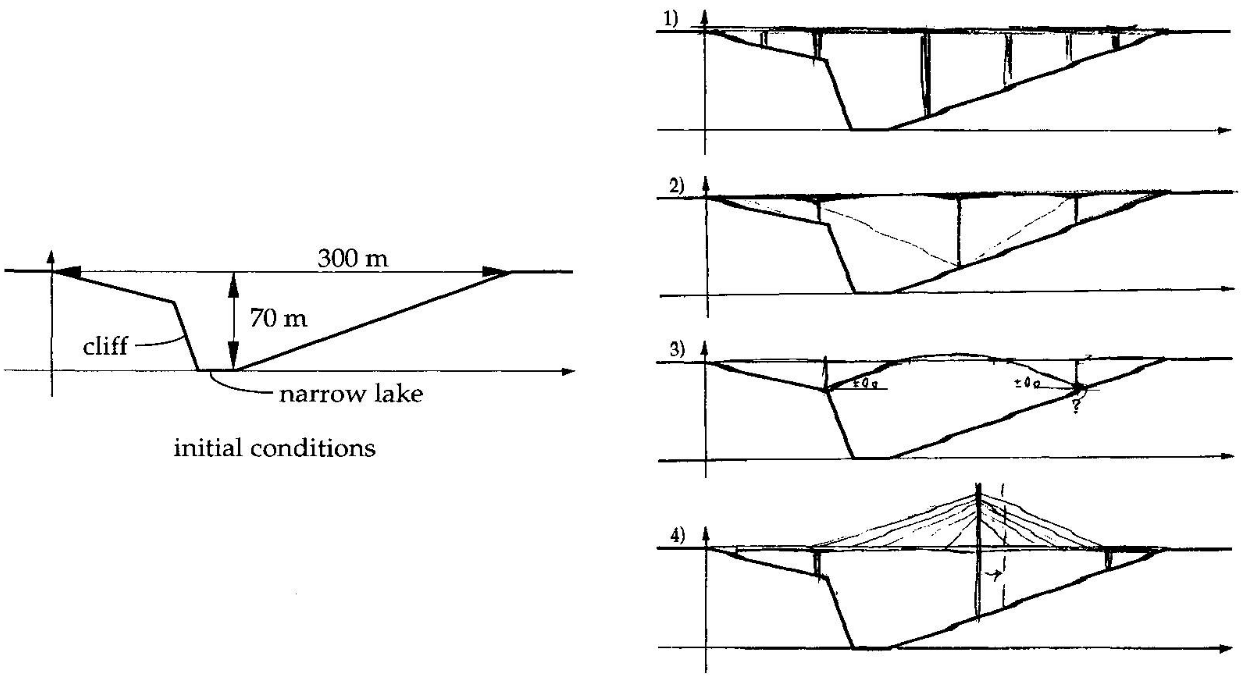

Figure 3 — Sketches from four experts based on same initial conditions

4 Adoption and adaptation of the maze model as a framework

An extended maze is presented in Figure 4 for meeting the design flow requirements observed during sketching sessions with experts. More specifically, the extended maze comprises three features which support the three activities mentioned in Figure 1. The primary task of assignment and refinement of parameters is modelled with *assumptions and physical principles;* the main maze (middle maze of Figure 4). It delimits and classifies the search environment. In general, assumptions act as magnetised zones of positive or negative intensities within the maze while physical principles indicate rigid barriers against penetration for a particular context. *Design criteria* represent factors such as social acceptance, viability, feasibility and economics of an artifact. These criteria influence exploration of the design space in order to reflect an order of importance and an order of use of knowledge. Different orders change the development of a solution set by allowing the designer to alter the emphases of the criteria on the sub-goals and final specifications. *Design strategies* deal with the problem-solving approaches of designers. Four modes enclosing eight strategies are used. They are described in more detail later. Essentially, a designer starts at a more abstract level and proceeds to the specifications. Designers employ these strategies to suit their style and switch from one strategy to another during the search of a suitable alternative. The three mazes are linked in a three-dimensional diagram to provide an interaction schema. The design criteria maze and design strategies maze behave as exploration guides for assisting the identification of design spaces, expressed in terms of parameters and their range of feasible values.

Constraints related to *assumptions and physical principles* are the founding labels of a design space. Assumptions are context-dependent and defeasible whereas physical principles must be satisfied in a final alternative. In structural design, assumptions are made continuously from the initial conception and during the iterative and refinement processes, since hypotheses are needed in the absence of complete and exact information. In fact, the ability to determine reasonable boundaries in situations of incomplete knowledge is one of the most valuable assets of experienced engineers ; an asset which distinguishes experts from novices who are accustomed to viewing design problems in closed worlds.

Design criteria indicate the many facets a product must satisfy before it is considered an acceptable alternative. It is always tempting to generalise domain-dependent features in knowledge-based systems in order to provide a "generic design procedure" applicable to most domains. Although this approach presents advantages, a completely domain-independent approach holds unrealistic expectations. An encompassing

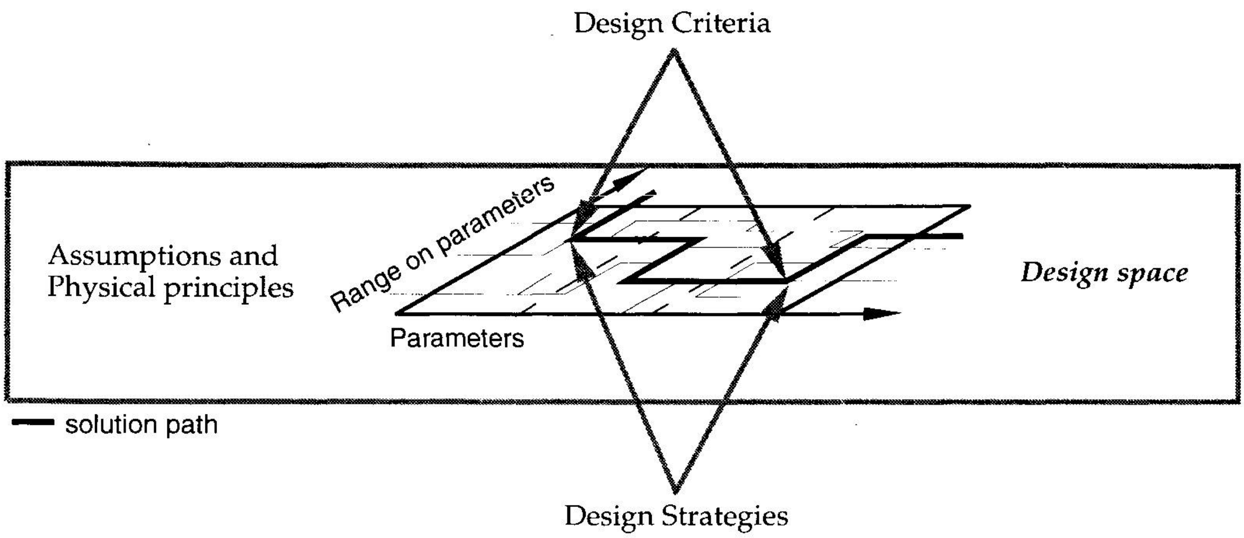

Figure 4 — Design criteria and strategies guiding search through the design space

procedure for designing electronic boards and urban bridges is not feasible, especially given their significantly different lifespans. An intermediate approach is to consider general design criteria labels which characterise a project, such as feasibility and then apply it locally to a domain, such as construction for bridge design, and manufacturing for board design.

Definition of general design crieria —

social acceptance :	how will the artifact integrate into its environment ?
viability :	how will it withstand its environment ?
feasibility :	how will it be assembled and from which sub-assemblies ?
economics :	how much will it cost initially and during its lifespan ?

General design criteria applied to bridge design —

I social acceptance :	**aesthetics** (harmony, accessibility, integration)
II viability :	**resistance** (statics, strength, stability, fatigue, serviceability, durability)
III feasibility :	**construction** (fabrication, transportation, erection)
IV economics :	**cost** (material, labour, maintenance)

Designers rarely consider one criterion only but attribute different importance to each one, which may differ at each main phase of design. For example, the alternating importance might affect whether they simplify construction by compromising on aesthetics, or whether they provide minimum resistance in order to save on short-term cost.

A model of multiple *design strategies* makes explicit knowledge assimilation processes and decision-making skills employed during synthesis. The motivation for the development of multiple design modes stems from informal observations of a dozen experienced (expert) engineers over the course of five years. Designers' activities are described according to four modes. Within each mode, engineers can apply two strategies. Examples of each strategy are provided below.

Modes and strategies employed by designers —

I paradigms :	**derivers and retrievers**
II granularities :	**generalisers and detailers**
III medias :	**visualisers and verbalisers**
IV metaphors :	**lateral thinkers and extrapolaters**

Designers are rarely in one mode exclusively. However, one mode more than another dominates for a particular sub-space of the solution. Also, these modes are not entirely independent and they are grouped according to types of strategies. Altering dominant modes affects the elaboration and commitment to different solution paths thereby creating a complex web of possibilities which can be captured in a maze environment.

6 Comparison of the model with the design of an existing bridge

The simulation example is based on a constructed bridge in Germany: the Kochertal viaduct in Geislingen (Figure 5). The topology consists of a 1128 metre long gap, with a maximum depth of 185 metres. The slopes are relatively gentle and the surroundings are a peaceful blend of farm land and scattered forests. During the bidding process, many solutions were proposed. Three are schematised in Figure 5.

The basis for deciding on number-of-spans and span-distribution is rarely recorded . However, such considerations have an important influence on the remainder of the design, including details. An Italian bridge design system reduces this aspect by a harsher categorisation of span distribution (Cauvin, 1992) because of the complexity represented by geometrical interpretation of the surroundings and the subjectivity of the knowledge associated to this phase. A Japanese bridge system (Nishido, Maeda and Nomura, 1990) also simplifies this problem by limiting their system to simple river-crossing bridges although they still dedicate more than half of their rule-base to "geometry".

This example is limited to initial decisions regarding number-of-spans, span-distribution, beam and pier types and cross-sections, and erection-methods (Figure 5). Initially, coordinates for valley-profile and bridge-alignment are specified. There is then an enrichment of this environment with terms such as V-shaped profile, symmetrical-distribution and viaduct-use. Since there is a small river, a large and deep valley, and a gentle slope, a beam bridge is selected. Aspect-ratios, design-ratios and static-limits help choose satisficing systems. Member dimensions are attributed opportunistically during design. Three alternatives are obtained with the same knowledge by varying the emphasis on design criteria, and hence their order of importance and order of introduction during a session.

Alternative 1) :	1) cost; 2) constructability; 3) statics; 4) aesthetics
Alternative 2) :	1) aesthetics; 2) cost; 3) statics; 4) constructability
Alternative 3) :	1) aesthetics; 2) constructability; 3) statics; 4) cost

Global evaluations of each alternative are summarised for aesthetics and cost criteria. The heaviness of alternative 1) and the high cost of alternative 3) tilted the decision towards alternative 2). The latter alternative is retained for further investigation. Figure 6 provides a design simulation of alternative 2), in Figure 5. It is illustrated by the dark line (the solution path) in the maze and thirteen numbered nodes. Each node represents a decision which is guided by design criteria and/or design strategies when assumptions and physical principles do not constrain the design space sufficiently. Decisions involve refining parameter ranges, selecting other parameters or managing conflicts. It is an explicit application of the design space maze in Figure 4 with implicit reference made to the criteria and strategies. The navigation between parameters, criteria and strategies show deviations from a hierarchical plan.

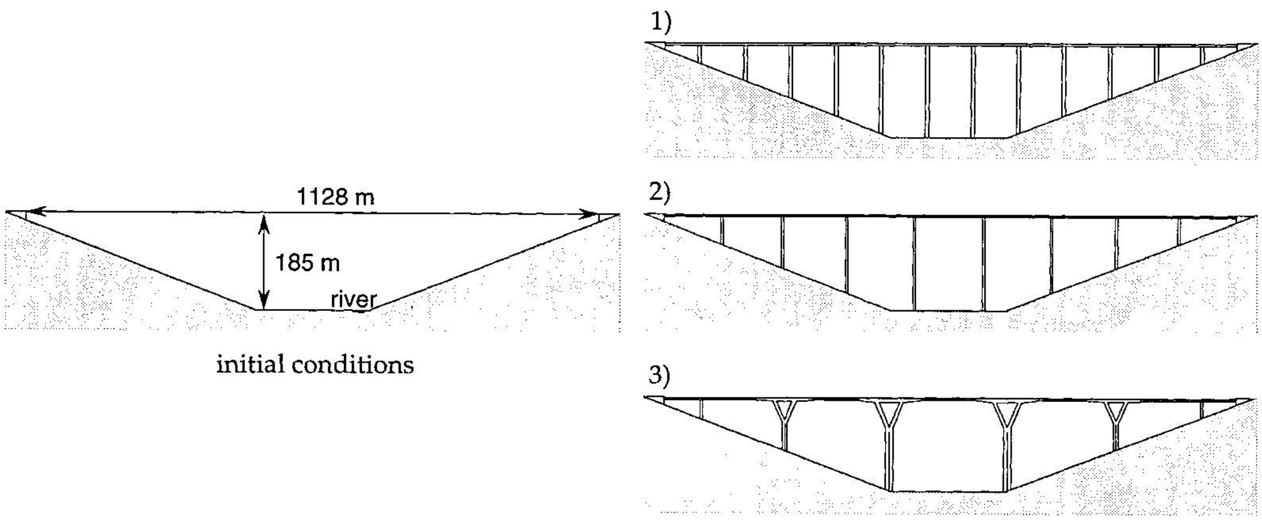

Figure 5 — Three bridge proposals inspired from Kochertal viaduct in Leonhardt (1986)

The entry into the maze (**node 0**) begins with 6 spans (bridge-length/valley-depth). Other possible entry points contain initial attributes such as equal-spacing, constant-depth I-beam, rectangular wall piers and erection by-crane. An aesthetic rule for that valley-type, suggests an odd number-of-spans (**node 1**) for avoiding placement of a pier in the middle of the valley. This rule is introduced early because of its ranking importance. It expands exploration with the generaliser mode and is based on the deriver mode i.e. it is not directly inspired by specific projects. Number-of-spans 6 is overridden by a set of odd numbers from 1 to 19. This set is reduced to {7, 9, 11}(**node 2**) by physical principles and a design-ratio reflecting reasonable pier-to-span distribution. The design continues with 7 spans (**node 3**) and retains equal-spacing and constant-depth I-beam (**node 4**) for cost reasons although a local evaluation based on the retrieval of other projects with equal-spacing reveals low-aesthetic quality. Since a static-consideration indicates that a span-limit is exceeded, the I-beam is replaced by a box-girder. After applying equal-spacing in more detail (**node 5**), the importance of aesthetics, previously evaluated as low, surfaces and causes a switch to graduated-spacing. A graduated-spacing, or a gradual decrease in span values, is especially recommended by experts in the presence of long, gentle slopes. This means that the central (main) span increases and the end spans decrease. A more comfortable number-of-spans (**node 6**) to satisfy the requirements of the longer span is 9. Graduated-spacing is then reapplied in more detail (**node 7**), as well, a plain girder is replaced by a reinforced girder to increase slenderness and cantilever resistance. Piers change from a wall-type (**node 8**), after retrieving examples of other projects, to a column-type to increase compatibility with beam slenderness. A rectangular cross-section is initially accepted (**node 9**), the erection-method is overridden from crane to launching (**node 10**) given the depth of the valley. Additional aesthetic refinement propose inclined, slightly-curved piers (**node 11**). The design session terminates (**node 12**).

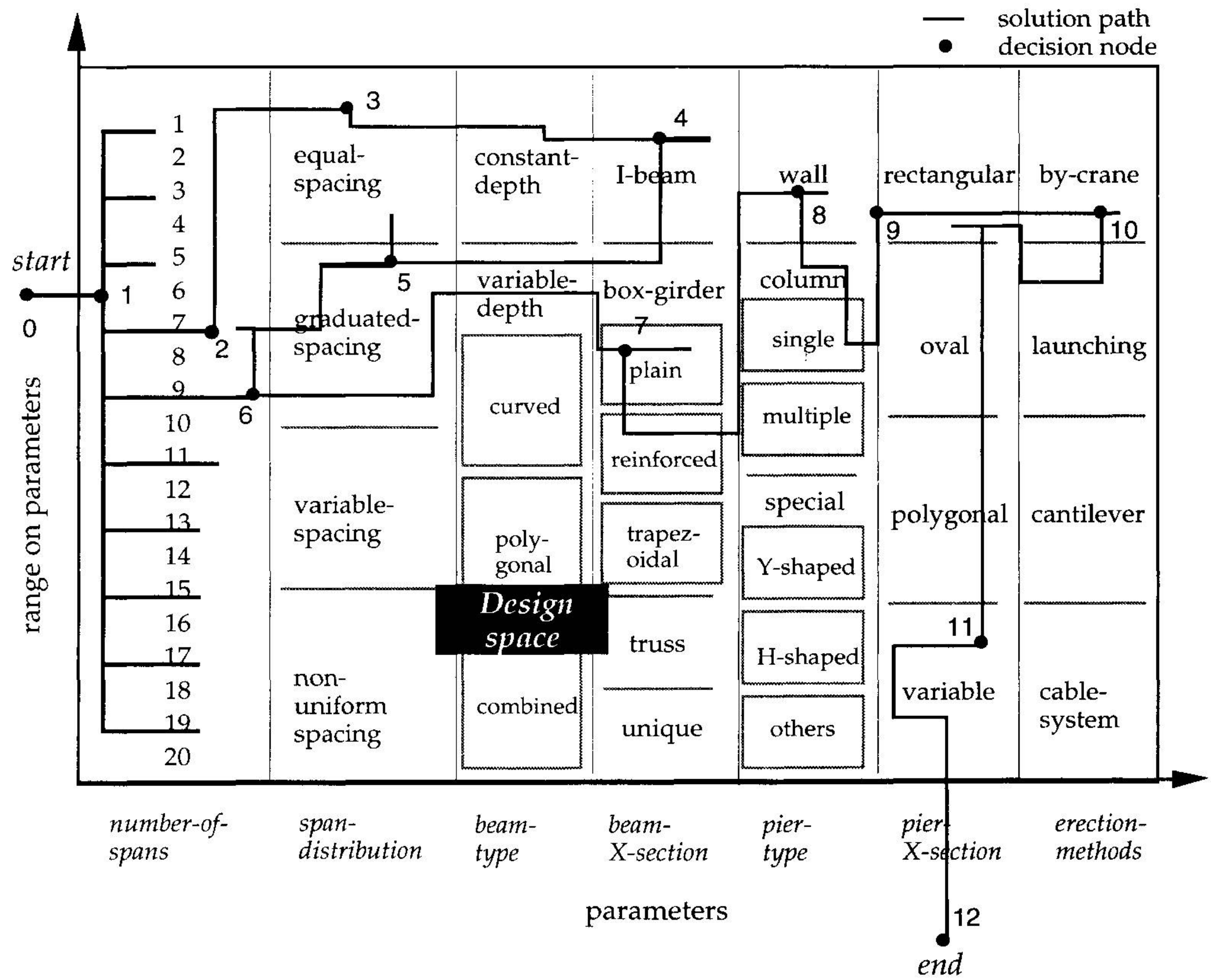

Figure 6 — Possible design path for alternative 2) in Figure 5, using schema of Figure 4

5 Overview of implementation in PRELIM

Some of the concepts described in earlier sections are implemented. The maze model provides a framework for making control knowledge explicit, thereby assisting system developers during implementation.

For processing knowledge, PRELIM incorporates a forward chaining rule engine for activating constraints, a justification-based truth maintenance system, a constraint processing framework for checking consistency and a conflict resolution module. The system can treat symbolic knowledge as well as continuous variables. These are represented as intervals indicating a range of feasible solutions. During constraint propagation each new interval inferred is justified by the justification-based truth maintenance system label expliciting links between design variables and constraints.

Conflict resolution is handled non-monotonically by overriding a default, weakening a preference or backtracking. Weakening preferences is a type of partial backtracking allowing retraction and reinstatement of previous decisions. Other domain-dependent and variable-oriented information contribute secondary help for conflict resolution. More details are provided by Haroud, Boulanger and Smith (1994). The algorithms treating the process explicitly in PRELIM are written in LISP, on Sunworkstations.

For representing knowledge, PRELIM uses assumptions (defaults and preferences) and physical principles (rigid rules), design criteria and design strategies to label rules. Objects represent physical, conceptual and relational properties. Internally knowledge about the artifact is represented in a flat structure as a constraint network enabling consistency checks. ICAD, an intelligentCAD system, provides the user-interface with graphical representation and a product model written in IDL, the object-oriented language of ICAD.

Assumptions have labels which are used to guide instanciation and assign values. They are further divided into defaults and preferences. Defaults can be included in objects as an attribute or in rules. Defaults impact on the initial stages of design, i.e. the entrance into the maze, and are highly defeasible. A context which consists of defaults is most probably inconsistent as each parameter evaluated via a default is set according to different contexts. As the design space progresses,these inconsistencies may dissipate without a formal mechanism. Preferences represent "expert" knowledge and are directly recognizable heuristics. They are the most difficult to manipulate, particularly in conflicting situations. The labels on preferences and the activity of weakening together supply a form of redundancy as unexplored paths are maintained in the objects and retrieved when a temporary impasse during the exploration occurs. A thorough treatment of explicit representations of assumptions in PRELIM can be found in Smith and Boulanger (1994).

Limits of the current implementation

Navigation within the maze model is partially influenced by the order in which rules are introduced in the system. In our implementation the user can fix rule order by manipulating design criteria before the session is started. Dynamic reordering during the session is not possible. Different strategies reflecting the user's way of tackling conception are not yet implemented. Although the system behaves non-monotonically, controlling weakening and backtracking interactively with the user is not yet stable. For constraint satisfaction, we are currently developing methods to improve reliability and ensure consistency of constraint sets that include both equalities and inequalities.

7 Conclusions

Although several researchers currently propose a network model for design, a maze description provides additional modelling potential; for *representing key expert behaviour* including exploration of several design paths from several starting points, for *specifying implementation requirements* such as non-monotonicity, decision networks and temporarily inconsistent contexts, and for *developing user interfaces* by distinguishing between different types of information. Observations from sketching assisted the selection of a maze model. The basic maze structure is extended for representing design criteria and design strategies. The maze is the design space containing information related to parameters and ranges on parameters. Two additional elements, formulated using design criteria and design strategies, provide control methods for directing search and for conflict management. A system for preliminary design of bridges uses these descriptions as a conceptual framework for design process support.

8 Acknowledgement

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