ACQUISITION AND MODELING OF CONCEPTUAL STRUCTURAL DESIGN KNOWLEDGE

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ABSTRACT

The goal of this research is to provide knowledge-based computer support for conceptual structural design through design suggestions and alternative evaluations. Rules-of-thumb from experience and generalized heuristic knowledge are mainly used. A knowledge acquisition process was performed from available literature and through interviews with two experienced structural engineers. For the interviews, design situations were simulated in which the engineers were videotaped while designing and thinking aloud. From these interviews, rules-of-thumb were obtained and a conceptual design process, established in advance, was validated. Additional knowledge, not available in the literature, was obtained through direct questions to engineers. The knowledge modeling is based on the technology nodes paradigm by which the engineer controls the design process and is allowed to backtrack to previously made decisions. Interaction is provided with a component called StAr (Structure-Architecture) that supports conceptual structural design through geometrical reasoning, based on a representation model that integrates architectural and structural entities. This interaction will permit the engineer to combine knowledge with geometric and functional architectural and structural concerns. A knowledge-based prototype will be implemented in Java. An envisioned interface for this prototype is presented in this paper.

KEY WORDS

Conceptual design, Knowledge acquisition, Computer support, Building design, Structural design.

INTRODUCTION

Computer programs are currently used by engineers for performing analysis that predict the behavior of the structure. However, before using these programs engineers must first produce preliminary structural models element by element (bottom-up approach) during conceptual design. This model generation approach assumes that the engineer has already selected structural materials, types and locations of structural subsystems, etc. Conceptual structural design is the design phase that has more impact on the costs of a project. Poor conceptual design decisions cannot be compensated by good detailed design ones (Dekker 2000).

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At the present, there are no computer programs available to assist engineers in producing preliminary design solutions to be used by structural analysis packages. Engineers must rely on their own experience to make conceptual design decisions. Several researchers have proposed approaches to assist engineers during conceptual structural design. However, the resulting prototypes often underestimate interactions with the engineer in favor of automation. In addition, these prototypes tend to replace the engineer in many conceptual design tasks.

This research proposes a computer system to assist engineers during conceptual design, while giving him/her control of the process and respecting the process that s/he usually follows to make preliminary decisions. The paper presents a literature review, followed by a description of the methods that have been used for knowledge acquisition and organization. Then, the proposed paradigm for knowledge-modeling is presented. Finally, an example of knowledge modeling is used to illustrate the envisioned support.

LITERATURE REVIEW

A considerable amount of research has been carried out to date in computer-assisted conceptual structural design. However, nowadays the trend in computer-assisted design is towards the use of advanced analysis tools and detailed three-dimensional building modeling packages.

DEFINITION OF CONCEPTUAL STRUCTURAL DESIGN

During conceptual design, major decisions are made concerning the type of building, the space layouts, and the shape, dimensions and type of the structural system. Several alternatives can be generated and evaluated roughly (Rivard et al. 1995). The structural engineer determines the structural material and the structural layout, carries out a preliminary dimensioning of structural elements and determines their position. Decisions are made based on information such as: the height of the building, the type of building, the typical live loads, the wind speed, the seismic load, the fundamental period of vibration of the building, the ground acceleration, maximum lateral deflection, the spans, the floor height, and other requirements from the client (Soibelman and Peña-Mora 2000).

LACK OF SUPPORT FOR CONCEPTUAL STRUCTURAL DESIGN IN ANALYSIS PACKAGES CURRENTLY USED BY PRACTITIONERS

Only to mention some well known commercial analysis and design packages, Computer and Structures Inc. provides a set of modules (SAFE, ETABS, DETAILER) for design modeling, detailed analysis and the production of construction/fabrication drawings. VisualDesign by Civil Design Inc. is very popular in Canada particularly for seismic analysis. These packages rely on three-dimensional (3D) modeling and a bottom-up approach for most design modeling. Once designed, the internal stresses in the structure are obtained depending on the particular analysis performed.

However, these packages are limited in terms of supporting conceptual structural design: they do not assist the engineer in carrying conceptual design decisions as described in the previous section, and they support a bottom-up approach for structural model generation by which structural elements are generated first to obtain a complete model of the structure. However, engineers are more used to make overall/general decisions first followed by local/specific decisions, i.e. a top-down design approach. It would also be advisable that architects include structural considerations in their initial design explorations. This cannot be achieved with the existing packages because they require producing a complete model of the building for performing structural evaluations.

PROTOTYPES TO SUPPORT CONCEPTUAL DESIGN

Different methods and techniques have been proposed to support conceptual structural design. However, none of these have been commercialized so far.

Expert systems

These systems rely on heuristics for performing tasks that are carried out normally by an expert. Heuristics are rules-of-thumb based on expert's advice. Expert systems were extensively studied during the end of the 1980s and beginning of the 1990s. For example, HI-RISE (Maher 1985) and TALL-D (Ravi 1998) assist the design of tall buildings. However, due to an inherent lack of extensibility and interactivity, expert systems were found ineffective for supporting conceptual structural design. Nevertheless, some new expert systems have been developed lately, for example, to design concrete buildings subject to seismic loads (Berrais 2005).

Case-based reasoning systems

Case-based reasoning is the process of recalling solutions from previous cases similar to a case at hand, comparing those cases with the new case, and using their solutions (Kolodner 1993). In actual practice, previous projects are filed and rarely used again. However, practitioners have found it useful to facilitate the access to previous projects (Kumar and Raphael 1997). Several research prototypes have been proposed that rely on this knowledge-based technique, for example SEED-Config (Rivard and Fenves 2000).

Integrated design environments

Integrated design environments attempt to facilitate the communications between professionals involved in the early building design process. For example, SEED (Software Environment to support the Early phases of building Design) (Fenves et al. 2000) and IBDE (Integrated Building Design Environment) (Fenves et al. 2000) propose specialized modules for structural design support that consider interactions with the architecture. The user-interaction level in IBDE can be set to automatic or interactive. However, user-interaction is limited to the input of some parameters by the designer and selection of solutions generated by the system.

Other approaches

Several approaches have been proposed to support conceptual structural design, namely: logic-based systems that rely on formal logic to make decisions, systems based on physical laws, genetic algorithms (that attempt to optimize the structure), generative systems (similar to expert systems but based on grammars), and hybrid systems combining two or more of the above techniques. These systems are not explored further in this research.

Research justification and introduction to the project

It is not possible to claim to support conceptual design when no assistance is given to an engineer in making conceptual design decisions, even if evaluations are performed after a structure is generated. Sometimes, systems that aim at supporting designers indirectly attempt to replaced them (Kumar and Raphael 1997). The prototype proposed by Berrais (2005) supports the conceptual design of shear walls to resist seismic loads. However, the prototype does not verify what proposal is valid for a particular situation and does not cover other lateral-load resisting subsystems.

This research attempts to support conceptual design decisions such as the choice of structural materials and structural subsystems and their location within the building. The quick exploration of design solutions should also be supported. Preliminary dimensioning of elements is part of this exploration because these dimensions help in finding alternative subsystem choices. To acknowledge the relationship with the architecture, close interaction is provided with the geometrical reasoning component StAr.

KNOWLEDGE IDENTIFICATION AND ORGANIZATION

Available references for students, architects and junior engineers address the general principles of conceptual design. Tables present feasible and economical floor spans with approximate floor depths given as a function of the span (Schodek 2004). The guides from manufacturers of prefabricated elements provide general strategies to facilitate the selection of feasible element sections. In addition, the literature for the detailed design of structural elements provides general guidelines for conceptual design. The codes provided by the wood, steel and concrete materials associations are also a good source of information. However, the literature is sometimes contradictory and incomplete, mainly that concerning the lateral-load resisting elements. Therefore, it becomes necessary to rely on experts to complement these sources.

EXPERT INTERVIEWS

The goal of the interviews was to validate a conceptual design process that was established in advance, and to obtain missing knowledge that is not provided in the literature. The interviews consisted of two parts: (1) the observation of an expert while designing (45 min), (2) direct questions to period (15 min).

Observation of experts while designing

Several previous research projects have acquired knowledge from experts and in some of those projects experts have been observed while designing (Lecomte 2003, Meniru et al. 2003). In this research, initial architectural sketches of a projected university pavilion were given to the expert engineers. They were videotaped while designing from those sketches and thinking aloud. Similarities were observed between the design method of engineers and the design process that was established before the interviews (see Figure 1).

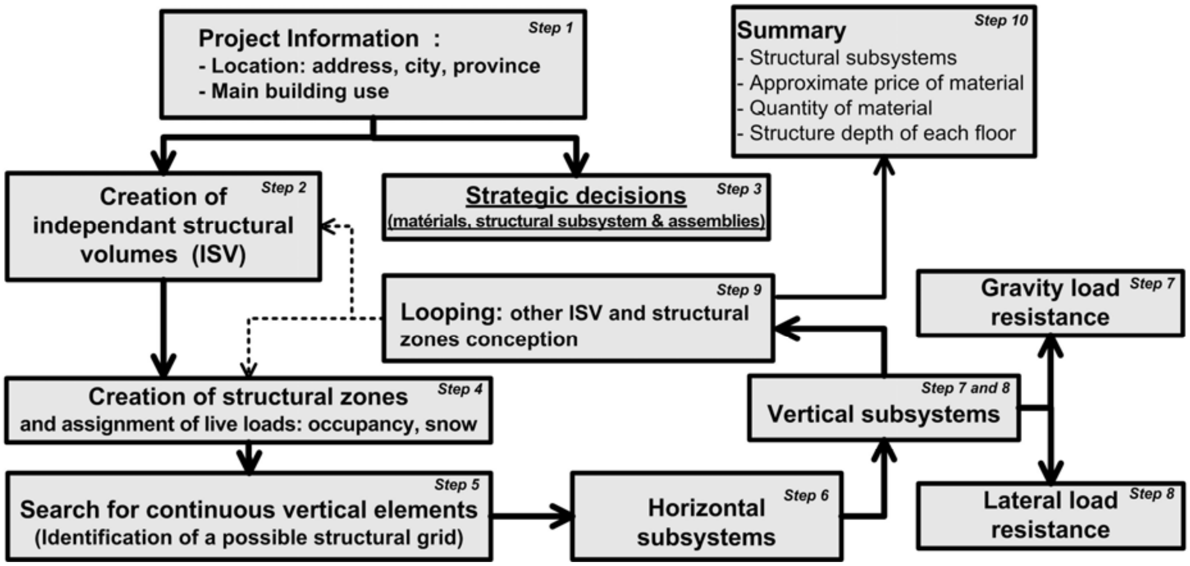

Figure 1. Conceptual design process validated by observing experts while designing

Explanation of the conceptual design process

The conceptual design process has been established from the literature and the authors' own experience. It is described in ten steps. In the first step, overall project information is gathered and organized, such as the building location and height restriction. It is assumed that at this step only minimum architectural information is available, for example and architectural sketch or preliminary plans. In the second step, independent structural volumes (ISV) are created. ISVs are used whenever it is required to divide the structure into independent systems. For example, it is advisable to divide the structure of a large L-shaped building into two independent structures for improved seismic performance. The second and third steps are carried out in parallel. In the third step it is assumed that the engineer often makes strategic decisions, based on her/his experience, on the types of structures usually used as a function of the type of building type, the availability of materials, the speed of construction, etc. In this way, the engineer can makes these strategic decisions at any time that limit the search for design solutions (solution space). In the fourth step, structural zones are created while assigning live loads for each zone based on default values that the engineer can change. The purpose of the structural zones is to group spaces having the same structural conditions such as: applied live load, nearly uniform bay dimensions and allowable floor depth, etc. In the fifth step, a search for continuous vertical elements takes place to guarantee load paths down to the foundation. In this step, the engineer determines tentative structural grids, while keeping in mind the locations of continuous vertical elements and the spaces that could accept additional vertical structural elements. Then, the engineer defines the structural subsystems in steps six through eight (i.e. horizontal, vertical gravity, and vertical lateral). In the sixth step, the horizontal subsystem is designed. Based on the structural grids that have been tentatively determined, the engineer can evaluate several subsystem alternatives. In the seventh and eighth steps vertical structural subsystems are designed, which largely depends on the horizontal subsystems' own weight. Finally, in the ninth step a loop is required for other structural zones and independent structural volumes.

Validation of the conceptual design process with the observations to experts

It would be required to carry out multiple interviews and use different building cases to have a complete validation of the conceptual design process as described above. However, from the observations in the interviews the steps and their order in the process could be confirmed. Nevertheless, this part of the interview was limited due to the conditions imposed to the designers. Firstly, there was no communication between the engineers interviewed and the architects who developed the sketches. Therefore, the interviewer had to answer architectural questions instead of the architect. Secondly, the plans obtained from the architect were in a different scale to the one typically used by engineers (1:100). Thirdly, the plans were not detailed enough to clearly identify the layout of partitions for placing walls and columns. Finally, the plans did not provide a complete description of the building. Only one isometric view was available to describe the building façade; other views would have been required to locate structural walls in the envelope.

Direct questions

Previous research projects have already used direct questions to address the gaps identified in the literature, for example: Fischer (1993) and Meniru et al. (2003). In our research, new knowledge was identified in this part of the interview. For example, seven important factors have been identified that affect the selection of structural material: the material that is used more often for the type of building being designed, the material proposed by the architect, the restriction on the height of the building, the total building cost, the technical feasibility, the soil conditions, and finally the shape of the building. Regarding the orientation of repetitive elements (e.g. joists) in a rectangular bay, it seems more convenient to orient these elements in the long span direction. However, in some situations it could be more advantageous to use the short direction, for example to facilitate the passage of mechanical ducts.

MODELIZATION PARADIGM: KNOWLEDGE REPRESENTATION AND REASONING

Knowledge representation is central to any approach that aims at supporting conceptual design. However, such an approach must guarantee that the knowledge is transparent to the user so that s/he can judge its applicability in a given design situation. The knowledge representation paradigm that is used in this research is inspired in the technology nodes (or design options) developed in the BENT "Building Entity and Technology" model (Fenves et al. 2000, Gomez 1998). A technology node represents the knowledge required to implement one design step in the top-down design process (Figure 1) utilizing a specific construction system or component. Nodes are organized into a hierarchy ranging from nodes dealing with abstract concepts (e.g. a structural subsystem) to those dealing with specific building entities (e.g. a reinforced concrete beam). The application of a technology node to a building entity can be interpreted as making one decision about a design solution. This approach supports reasoning at different abstraction levels, as required during conceptual design: ISV, structural zones, structural subsystems, structural assemblies, and structural elements level. An example of a decision tree, in the form of a circle, for the design of the horizontal subsystem is shown in Figure 2.

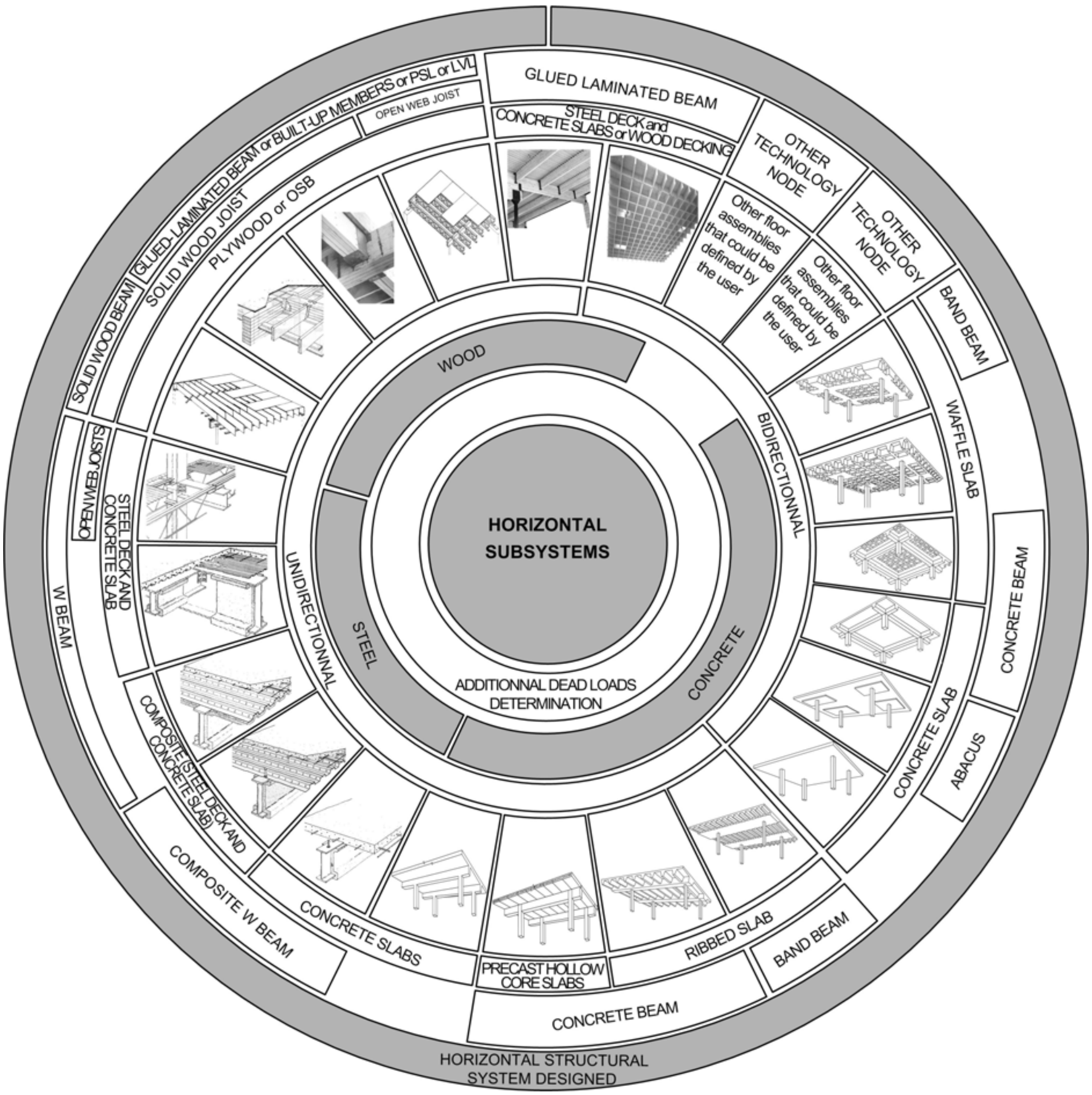

Figure 2. Example of a decision tree for the design of the horizontal structural subsystem

From the center of the circle towards the exterior, the engineer must first determine, with knowledge-assistance, additional dead loads to the structure’s own weight. Then, if floor assemblies are not determined yet, the engineer selects among the floor assemblies presented in the circle that have been pre-selected by the computer with the use knowledge. For example, Schodek (2004) provides tables with economically feasible floor systems as a function of bay dimensions, type and use of building, etc. Then, just by passing the mouse on top of a floor assembly image in the circle, the engineer can check why a technology node (in this case representing the knowledge that makes floor assembly viable) for a floor assembly is active or not (e.g. "flat slabs are not economically viable for the bay dimensions provided (Schodek 2004)"). For the viable floor assemblies, evaluation is provided based on costs per square feet as a function of the bay dimensions and applied loads (so that the engineer will be aware of the conditions for evaluating the costs), as well as a comparison of the required floor depths. Then, the engineer selects a floor assembly and proceeds to design its structural elements. For example, for a floor assembly consisting of a concrete slab on a steel deck, supported by open-web joists on W beams, once the engineer has selected this floor assembly, s/he must select the thickness of the concrete slab, the type of steel deck, the depth of the joists as a function of their spacing, and the W-beam section. Each of these selections needs knowledge support.

Thus, the knowledge-based reasoning process depends on the choices made by the engineer, and computer assistance is provided in the form of suggestions and evaluations. This approach provides the confidence to the engineer to make decisions that could involve not taking into consideration the suggestions and evaluations performed by the computer. These decisions are made at different levels of structural abstraction. Using decision trees for reasoning facilitates backtracking so that new design choices can be made at different abstraction levels, while preserving the decisions made at higher levels in the tree. In Figure 2, a technology node contains the information of a structural assembly. It is therefore possible to add new assemblies without making changes to existing nodes. This facilitates adding new technologies and knowledge.

EXAMPLE OF THE APPROACH FOR KNOWLEDGE MODELING

A prototype knowledge-based system called design knowledge manager (DKM) will be implemented in Java. The envisioned interface works in two main modes: the DKM mode and the StAr mode (see Figure 3). With the interface, the engineer can switch between these modes at will. In this paper the focus in on the DKM mode. The envisioned DKM interface will consist of five main windows. The design process itself (Figure 1) is presented in an interactive window that enables the engineer to have support for any design step on demand. The subsystems tab presents the engineer with an interactive image such as the one illustrated in Figure 2 so that the engineer can make subsystem choices and elaborate them into assemblies. The base elements tab enables further elaboration of assemblies into base structural elements. The dialogue window informs the engineer about actions to be taken and other important guidelines required to proceed with the process. An image of the 3D model, accessible in the StAr mode, is shown for visual support to the engineer while using the DKM. The history of the design is a list of decisions made during the design. It is used to the engineer to come back to decisions already made. Finally, the window of suggestions based on knowledge displays suggestions, generated by the DKM, that remain present even at the StAr mode so that the engineer will have permanent access to these suggestions. For example, this window could be useful for the generation of the structural grid by the engineer, while considering the economic spans for the systems made out of wood, steel and concrete. Once implemented, the prototype will be validated by experts.

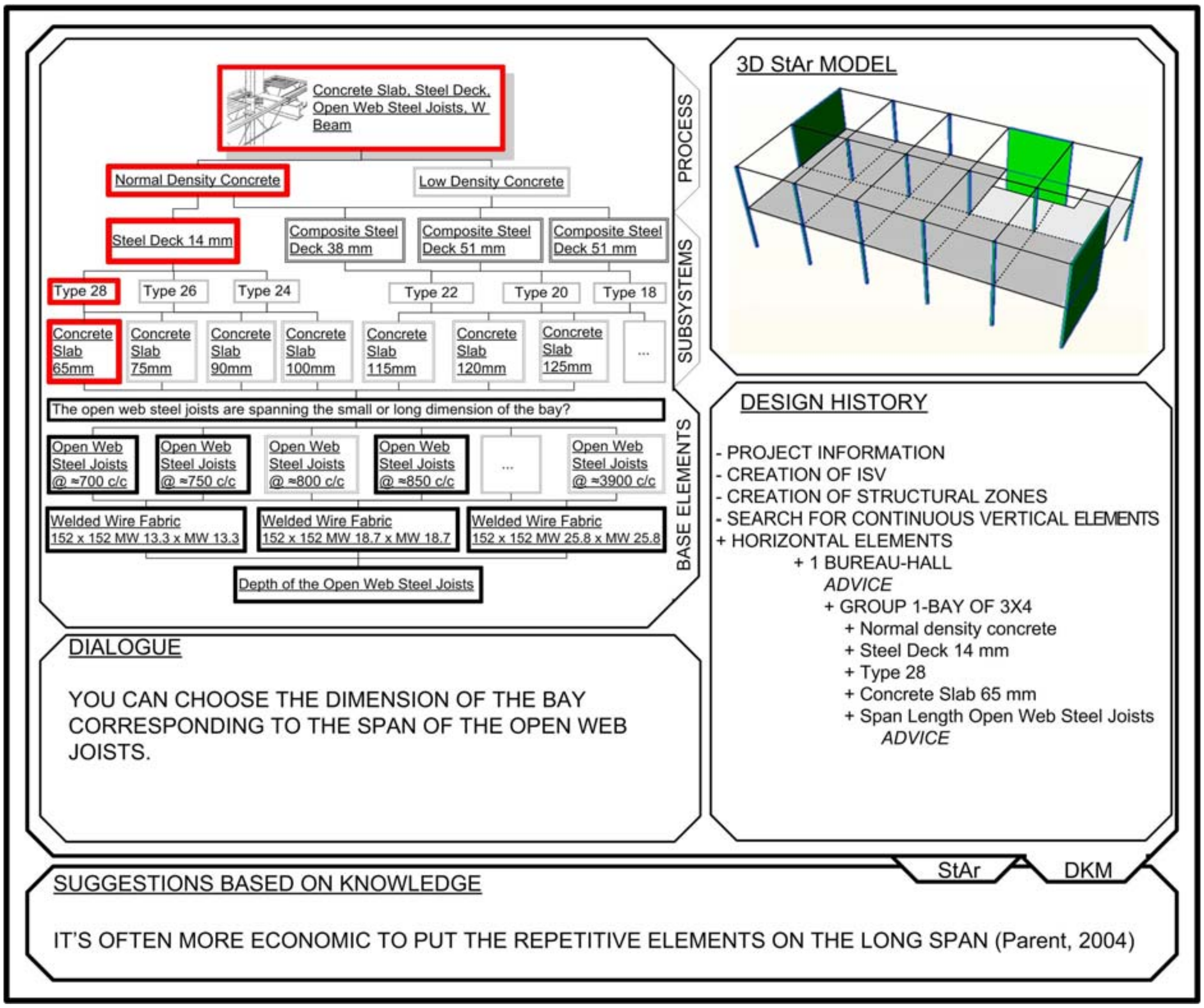

Figure 3. The envisioned user interface

CONCLUSION

This paper proposes a knowledge-based approach to conceptual structural design. The approach combines a design-knowledge manager that assists the engineer based on knowledge, and a geometrical reasoning component (already implemented), called StAr. The focus of this paper is on the design-knowledge manager. It is proposed that knowledge-based assistance to the engineer follows a top-down approach, which as validated with practitioners, is closer to the actual engineer's reasoning process than the bottom-up approach supported by commercial applications. Knowledge-based suggestions and advice can be given to the engineer at different abstraction levels. The consequences of selecting any proposed structural sub-system are presented to the engineer through possible solution paths in the decision tree. A software prototype will be implemented in Java.

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