SPATIAL COGNITION SUPPORT FOR EXPLORING
THE DESIGN MECHANICS OF BUILDING STRUCTURES

Abstract

A web-based tool for visualizing the simulated structural behavior of building models was developed to support the teaching of structural design to architecture and engineering students by activating their spatial cognition capabilities. The main didactic issues involved establishing a consistent and complete three-dimensional vocabulary throughout a base collection of structural system diagrams that is as related to familiar 2D conventions and as intuitively “legible” for architecture students as possible. To this end, the visualization techniques used in a number of structural simulation programs for engineers were assessed according to didactic criteria in the context of the architecture curriculum at two levels: semantic initial assessment for preliminary user-interface design and explorative learning effectiveness based on prototype implementations. The results suggest generalized criteria for modeling multidimensional constructivist learning resources aimed at higher education in the architecture, engineering, and construction (AEC) domain.
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The three professional fields comprising the “AEC domain” – architecture, engineering, and construction – are closely related in practice by virtue of their common focus on the built environment. Yet there are fundamental differences in the respective working methods and immediate design concerns of each field, which are reflected in distinct styles of academic training.

Spatial thinking and modeling skills are central to the qualification of architects, whose education traditionally revolves around simulating the building design process in the form of so-called “design studios.” Comprising over half of the curriculum in typical architecture programs, such studio teaching is inherently constructivist in approach, engaging students in the three-dimensional modeling of physical relationships – the outward shape – as a means of grasping and developing complex solutions to building design tasks. In contrast, classic training of civil engineers focuses on describing the quantitative relationships between mechanical and material properties (“working with the numbers”); qualitative geometric and time-dependant patterns are of secondary concern in reaching a design solution.

Both these “angles on the building” are, of course, closely interdependent subject views on facets of the same physical construction in space and time. With an aim to better bridge this design-concern gap between architecture and engineering, our e-learning development work focuses on the interdisciplinary subject matter of advanced structural design and construction methods, and builds on a strong foundation of computer skills that both architecture and engineering students bring to their studies. Given the fact that nearly all AEC students at the
authors’ university are computer literate, electronically well-equipped, media savvy and highly motivated to employ sophisticated digital means in their everyday learning work, an integrated project titled “archistructura: Knowledge Construction Site for Building Science and Structural Design” has been initiated to encompass the following three main application areas:

- **design aids** – design support for architects and engineers,
- **study aids** – courseware and accompanying learning resources, as well as
- **buildings** – a database of documented design precedents with integrated case studies.

Working versions of the various components are being provided to students in a web-publishing framework on a running basis, targeting content needs as they arise in conjunction with the current curriculum for both architecture and engineering programs (Pfeiffer-Rudy & Jaksch, 2004).¹

The following article reports on a recent, substantial enhancement to the **study aid** applications of archistructura: the tool “3D Visualiser” (3Dvis) as a standalone application or web-based embedded applet, for visualizing the mechanical properties of three-dimensional simulation models through learner-driven exploration of their structural behavior. The primary objective of this tool development has been to activate the strong cognitive capabilities of architecture students in understanding spatial relationships so that they may better and more deeply grasp the mechanical principles underlying structural design and engineering.

Over the past three years, several intermediate assessments of varying scope were performed in stages to refine the concept and establish a working definition of what, concretely, such **spatial cognition support** should and can be in application as an interactive learning resource. The results (and limitations) of some of these studies are related and discussed in conjunction with the issues treated in relevant sections of the article.
Didactic Approaches to Structural Design for Architects

The largely engineering-based subject matter behind structural design, statics and strength of materials, is generally quite unpopular with architects, a “necessary evil” that is often viewed as more likely to hamper their creativity than to improve the quality of what they should be learning to design competently: buildings with a projected physical reality beyond the digital visualization, subject to physical forces (“loads” such as gravity, wind and weather, etc.) that may or may not immediately impact formal qualities (visual-psychological effect). The architectural fascination is further limited by the simple fact that well-engineered structures aim to be as geometrically static as possible, in equilibrium with the forces acting upon them over a decidedly long period of time (design lifecycle of 50+ years, i.e. spanning generations).

Nonetheless, understanding the principles of mechanical behavior is essential to designing buildings that shall actually one day remain standing and appreciated in the real world (cf., Alexander, 1979), so fostering students’ natural curiosity by bringing such invisible phenomena to the fore of their visual cognition should be the principle objective of new learning resources in this area.

A look at what architecture students “bring to the table” reveals a discrepancy in comprehension levels between spatial and mathematical cognition, which is often neglected in the teaching of basic mechanics aimed at building design. In a manner more appropriate for engineering candidates, the calculation methods for statics and strength of materials are presented incrementally in a sequence of increasing mathematical complexity, meaning the concepts presented first are those that can be most simply described in fundamental equations. Other, more advanced concepts are not addressed until the math can follow suit – too late for most architects (whose math prerequisites are relatively minimal), with the result that the
cognitive connection between structural behavior and design relevance is hardly achieved before the boredom sets in and all interest in the integral subject matter is lost for good.

Though not necessarily fluent in reading mathematical equations, architecture students do, however, show highly developed skills in recognizing spatial patterns and reasoning by analogy across multiple dimensions. It appears obvious that these skills should already be used at an introductory level, as a point of entry to understanding where and how the math may be necessary to get the “hard numbers” needed when developing a building design to construction-ready maturity. Even if architects rarely calculate such numbers themselves in practice, it is important to understand what, exactly, the structural engineer contributes and how both sides of the design process can communicate better on the way to an improved realized result in the built environment we all share.

**Establishing the Universe of Discourse**

When talking about long-standing teaching traditions in the AEC domain, a “literal” understanding of modern learning philosophies (such as constructivist approach, scaffolding, etc.) becomes quite apparent: the distinction between the object of study (building design task as learning object) and the cognitive process of studying it blurs to the point where a metaphorical usage of the cognitive learning terminology can hardly be distinguished from its literal application. This is to say that much of what has been tested and proven in the education of architects and engineers may, indeed, serve well in other domains by analogy, much like the architecturally grounded “pattern language” of Alexander et al. (Alexander, Ishikawa, & Silverstein, 1977) has found its greatest impact in informatics and artificial intelligence, outside of the architecture profession. In order for others to better draw valid analogies we must first spell out the semantic foundation of our originating arena, that is, the nature and morphology of
building structures. This process of establishing the terminology in a field of reference, a common ground for talking about the inherently non-verbal “things” instructors try to convey to their students, is also fundamental to a solid didactic approach for teaching principles of structural design to architects. Structural taxonomies and descriptive models based on morphological characteristics are very useful as a point of departure for drawing analogies at an abstract, pattern-based level that both architects and engineers can relate to (cf., Büttner & Hampe, 1985; Engel, 1997). Such disciplined hierarchical vocabularies, which have been developed and refined over the years as metadata to organize building design resources, constitutes our *universe of discourse*, that is, the set which, with reference to our particular context, contains all possible elements having the same characteristics and from which sets can be formed (cf., Rajasekaran & V. Pai, 2004). It implicitly contains a substantial amount of essential structural information, knowledge that is shared with students in the form of so-called “pictionaries” (Figure 1) and accompanying explorative resources.

![Figure 1](archistructura.png)

*Figure 1.* Screenshot of the “pictionary” for load-bearing structural systems in *archistructura*: hierarchical taxonomy as a base ontology derived from structural classifications of generic elements.
With the aim of internationalizing as much *archistructura* content as possible, the pictionaries are currently being generated and presented in both German and English versions. Of course, a number of the original German expressions cannot be exactly matched to equivalent expressions in other languages, which inherently makes such unified taxonomies less “natural” than they would be if kept within the semantics of a single spoken language. Such linguistic discrepancies are visually resolved to a certain extent through the hierarchical structure of the terminology and other non-verbal information contained in supporting media (such as icons, movies, and models).

Beyond the taxonomic representation, the characterizing sets of terms can also be expressed mathematically (crisp sets of tuples), as well as diagrammed with a theoretically unlimited number of semantic dimensions (*k*-cubes; cf., Bondy & Murty, 1976). Given the spatial understanding of building designers, it makes cognitive sense to support the interpretation of up to three dimensions by visual analogy to the x/y/z/-coordinates of space (Figure 2). Correlative comparisons of different buildings with similar formal characteristics and recurring structural features can thus reveal generalized relationships between architectural and structural principles (Rudy, 2005).
Figure 2. Morphological characterization of generic element types by structural properties (organized in a $k$-cube diagram).

**Graphic Conventions in Architecture and Engineering**

The graphic standards and conventions familiar to architects (cf., Ramsey et al., 2000) were established primarily to convey relationships between spaces and outward shapes at the global level (floor plans, sections, elevations), as well as between materials configured to separate spaces at the detail level (construction details). By comparison, diagrams relating the mechanical properties of a building’s load-bearing components (e.g., the system diagram of a static calculation model or finite element analysis of material stress patterns) are considerably more abstract and not as immediately accessible to the architecturally trained eye.

Translating the *universe of discourse* described above into symbolic representations led to the development of a three-dimensional graphic vocabulary for rendering a structural model in semantic terms common to both mechanical (engineering) and morphological (architectural)
understandings of structural behavior. Referred to as the “function model,” it conveys structural components by their most characteristic role in the overall context of typical load-bearing configurations. This generic information is what actually “explains” the structure and is, therefore, particularly valuable for didactic purposes (Figure 3). Since such terms are not originally contained in the data sets comprising mechanical simulation models, they must be added in a separate stage of instructional enhancement (see also last section “Summary and Prospects”).

Figure 3. Four different views of the same structural behavior model: system (static calculation model), function (semantic definition of elements in generic terms), design (material and geometry) without loads and with stress texture (load case with deformed geometry).
Particular difficulties are posed by the problem of characterizing the nodes of simulation models using graphic symbols, which must carry a highly complex set of mechanical information in a relatively small region of the visualization. Especially the specification of bearing nodes in all six degrees of freedom is of critical importance to the overall structural behavior of the simulation model and should be related as faithfully and completely as possible. A comparative analysis of graphic engineering standards (cf., EUROCODE) and a wide variety of simulation programs showed that, at present, no consistent concepts exist for rendering bearing nodes in spatial visualizations. Our proposal is a compromise: the conventions for symbolizing nodes in pairs of two-dimensional diagrams are combined orthogonally (Figure 4), whereby two degrees of freedom are sacrificed for the sake of visual simplicity (such invisible information can still be revealed in a separate detailed description of the node properties). Specialized rendering forms can be used to graphically integrate more node information, but these are generally difficult to read and may obscure more than they illuminate at the first stages of comprehending a simulation model.

*Figure 4.* A complex support situation visualized as the bearing node of a structural behavior model: standard 2D view set and alternative 3D views (simplified and specialized proposals).

“And finally, the things which seem like elements dissolve, and leave a fabric of relationships behind which is the stuff that actually repeats itself, and gives the structure to a building ...” (Alexander, 1979, p. 89).
Development of a 3D Visualization Tool

The experiences gained in teaching structural design to architecture students determined
the need for a tool that makes what is mechanically invisible and static, visible and dynamic, by
activating a sense of both time and space in cognitive exploration (cf., Gershon, 1994).
Competing visualization concepts were initially developed and tested in the context of an
introductory course in structural design (see below), and later validated in the framework of a set
of advanced courses in structural logic targeting both architects and engineers (see next section:
“Evaluation of Effectiveness and Usability”). Aside from programming the concrete
visualization tool, it was also necessary to develop a consistent base collection of simulation
models, i.e. create the actual content to be viewed and tested, hand-in-hand with the user-
interface design. At present, approximately 100 basic and composite systems, as well as some
50+ models based on real-world buildings are available as a foundation for using the so-called
“3D Visualiser” (*3Dvis*).

Initial Learner Assessment

The first level of assessment focused on establishing a graphic vocabulary for the
semantic terms used to explain building structures at the introductory level. In the process of
registering for the compulsory course “Structural Design” (approximately in the middle of the
core curriculum for the architecture program), students were required to fill out an online
questionnaire asking them to (a) identify six three-dimensionally represented structural elements
by selecting an appropriate term for each from a drop-down list and (b) select the subjectively
more understandable representation (from a choice of two) for three different, increasingly
complex structural bearing situations.
The restricted vocabulary provided in the drop-down list for the first part had been defined to enable the combined testing of two didactic aspects: correctness of element recognition and preferred terminology. For each displayed element, there were at least three essentially correct answers available in the list, which contained near synonyms from three related semantic sub-domains (“world views”): mechanical, structural, and architectural (Figure 5). It should be noted here that the structural sub-domain, which communicates functional characteristics as described in the previous section, can be expressed compactly in German with common terminology that is clearly distinct from the mechanical and architectural sub-domains. The same tripartite distinction does not, however, translate directly into entirely equivalent sets of English terms (architectural terminology is generally used when talking about structural design in English).

In total, 378 students (188 females and 190 males) participated in the assessment at the beginning of the project in 2004. Beyond helping us establish where the students were coming from verbally on their way into their first major compulsory course in structural design (Figure 6), the results of the poll were used to fine-tune the geometric proportions of generic
representations in order to improve the clarity of function model visualizations, especially in those instances where the initially proposed representations were consistently misread across semantic sub-domains (Figure 7). Surprisingly to the authors, significant gender differences in comprehension could be ruled out with respect to both the preferred terminology and the ability to read 3D representations in structural terms.

**Figure 6.** Preferred vocabulary (semantic sub-domain) of participating students in response to element representations, differentiated by gender.

**Figure 7.** Distribution of correct and incorrect responses for element representations by semantic sub-domain.
The second part of the questionnaire included text descriptions of three, increasingly complex bearing node situations with different configurations for structural degrees of freedom. Two alternative graphics corresponding to our proposed visualization styles were provided for each case: “simplified” and “specialized” (as previously described in “Graphic Conventions in Architecture and Engineering” and illustrated in Figure 4) and the students were requested to select the option that they felt more clearly/correctly represented the related case. The results showed that half of the participants overall did not choose any of the specialized representations, whereby occasional preferences for this more complicated style (or the willingness to read it at all) was slightly more pronounced among female than male participants (Table 1). Given these results, it was decided to focus development on implementing the simplified bearing node representation in the first prototype, and plan on adding the specialized style as an advanced view option in later versions.

Table 1. Preferred visualization styles selected for different bearing node situations (see also Figure 4).

<table>
<thead>
<tr>
<th>Selected visualization style</th>
<th>All</th>
<th>Male</th>
<th>Female</th>
</tr>
</thead>
<tbody>
<tr>
<td>simplified only</td>
<td>50%</td>
<td>53%</td>
<td>47%</td>
</tr>
<tr>
<td>specialized only</td>
<td>12%</td>
<td>8%</td>
<td>15%</td>
</tr>
<tr>
<td>mixed selection</td>
<td>38%</td>
<td>39%</td>
<td>38%</td>
</tr>
</tbody>
</table>

**Interface Design and Implementation Considerations**

Since the visualization tool is aimed at a wide range of target users, its technical implementation required technologies that operate on different platforms and ensure web-based applicability in subsequent programming generations. As an intermediate format, the extensible mark-up language (XML) was originally chosen for structuring model data because it is
especially flexible, well-suited for a number of well-documented reasons (Davies, Fensel, & van Harmelen, 2003), and can be expected to remain a viable format for some time to come in the future. To maximize compatibility with different platforms, it was decided to program the software in the object-oriented language Java with its cross-platform “virtual machine” concept and make use of a number of related technologies that work within this environment (e.g., Java-Swing for graphical user interfaces, Java3D to visualize three dimensional scenes, or JDom for interacting with XML-files).²

Based on the preceding conceptual analysis, a prototypical user-interface was developed and implemented with the following sets of toolbars organized around the main model window (Figure 8):

1. Primary controls along the top edge of the view window (beneath the menu bar) for selecting the model type to be viewed (design, system, or function), the color-coding scheme for the model surfaces (material, stress/force, function, or no textures) and basic rendering options (solid or wire frame, coordinate axes, etc.).

2. Secondary controls along the top and bottom edges for view toggling and scaling of system nodes symbols, load vectors, displacement and animation (visual exaggeration of the deformation).

3. A navigation control panel to the right of the model window for “homing” (squaring to global coordinate axes), panning, zooming, and rotating the current view.
Models can also be manipulated directly in the main window using standard drag-and-drop mouse functions. Popup dialogs appear wherever needed for immediately specifying view details, such as the selection of which stress/force texture should be displayed (with associated color scales in the legend, Figure 8). In extension to the embedded applet version of 3Dvis, the standalone application includes a menu bar at the top for accessing functions needed to navigate locally stored collections of simulation models offline (File, Structural Systems, and Load Cases). Finally, the language can easily be switched by selecting one of the integrated XML-based language sets, as well as values for a range of further view configuration parameters saved and managed as reusable settings in XML format (Parameter Manager).

**Evaluation and Discussion of Effectiveness**

Once the first versions of 3Dvis had been programmed and informally tested by the developers, a number of working hypotheses that had been assumed up to this point needed to be
validated by actually intended users, that is, by members of the target audience of structural
design students for whom it had been designed. As with all entirely voluntary assessments in an
academic setting, the motivation of students to participate in an engaged fashion is limited and
the results are hardly representative of typical software use. Moreover, the information yielded to
developers by such unobliged experiments is generally anecdotal and rarely provides evidence of
how – or even whether – students intellectually process the knowledge provided to them through
the new learning resource.

Fortunately, we were able to find a meaningful occasion for a first cycle study (i.e. suitable curricular setting) and could enlist a group of 27 representative students, who were willing and able to work with 3Dvis to explore the base collection of simulation models and receive credit for a course in advanced structural systems (fall/winter semester 2005/06). Instead of writing a regular examination to complete the course, these architecture students were ask to perform a structural system study in the form of an online questionnaire with embedded learning resources. The questions were designed to activate immediate use of the visualization tool in combination with other supporting archistructura resources (pictionaries, building collection), both in the applet version online and as an offline application.

The learning goals were assessed in three sets of comprehension questions corresponding to increasing levels of cognitive complexity (Figure 9) as described in the following.

1. **Comparison of basic systems under vertical and horizontal loads:**

   The question “Which system is more rigid?” for pairs of simple models (single selection from five pairs for vertical and four for horizontal load cases based on simple model exploration).
2. Recognition of subordinate and superordinate structural concepts in composite systems:
   The questions “Of which basic system elements is this structure composed?” (multiple answers for two models based on composite model exploration online and search of basic system terminology in the structures pictionary of archistuctura) and “With which basic system is the overall behavior of this structure most closely comparable?” (single answers for two models based on search of basic systems in the online model collection).

3. Direct and analogue recognition of building structures in the “real world:”
   The questions “What building has this load-bearing structure?” and “What other building has a corresponding structure?” with a short explanation of the latter choice (answer sets for four structural simulation models, “proof buildings,” based on complex model exploration offline and search in the building collection of archistuctura, Figure 10).

Figure 9. Comprehension assessment of load-bearing structural behavior: six sets of questions corresponding to three cognitive stages of visual perception.
The interactive sequencing of the question sets described above was similar to the study done in a second cycle a year later, which is illustrated in the next section, “Application in Next Developmental Stage” (Figures 12 and 13). Extended technical and editorial feedback is informally encouraged by providing free-form comment fields in association with each section of the questionnaire.

At the end of the first cycle study form, students were asked to summarily evaluate a series of usability aspects on a scale of 1 to 5 (with 1 = best mark, Table 1), in order to better clarify immediate development needs for the 3Dvis prototype. The results for technical issues
clearly showed a strong need to improve the performance and stability of the software (grades ranging from 1 to 5, median 3). Overall impression, ease of installation, clarity of user-interface, and the like were generally graded higher (range 1-4, median 2).

The last aspect – “learning effect through spatial rendering of structural behavior” – received relatively high marks overall (median 2), but with the broadest distribution (range 1-5). The lowest marks were given by students who expressed some degree of frustration with technical difficulties, in particular slow performance on their individual computers.

Table 2. Assessment results for user interface design criteria: 27 participants, scoring on a grade scale from 1 to 5.

<table>
<thead>
<tr>
<th>User Interface Design Criteria</th>
<th>Mean score</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installation of the necessary browser plug-ins</td>
<td>2.67</td>
<td>1.21</td>
</tr>
<tr>
<td>First impression upon opening the application</td>
<td>2.44</td>
<td>0.83</td>
</tr>
<tr>
<td>User friendliness of overall navigation controls</td>
<td>2.26</td>
<td>1.36</td>
</tr>
<tr>
<td>Mouse functions to navigate model in main window</td>
<td>2.30</td>
<td>1.05</td>
</tr>
<tr>
<td>Model navigation buttons to the right of main window</td>
<td>2.07</td>
<td>0.94</td>
</tr>
<tr>
<td>Clarity and meaningfulness of button icons</td>
<td>2.15</td>
<td>1.12</td>
</tr>
<tr>
<td>Performance during model loading and manipulation</td>
<td>3.07</td>
<td>1.39</td>
</tr>
<tr>
<td>Clarity of menu structure (standalone application only)</td>
<td>2.07</td>
<td>0.86</td>
</tr>
<tr>
<td>Learning effect through spatial rendering of structural behavior</td>
<td>2.15</td>
<td>1.51</td>
</tr>
</tbody>
</table>

Most of the comments, though critical of technical details, lauded the visualization tool as a highly effective learning resource: a positive subjective impression that is objectively corroborated by the largely correct and thoughtful answers given to the comprehension questions (Figure 11).
Application in Next Developmental Stage

A revised version of the study was developed for a new group of students currently participating in the next cycle of the same advanced structures course (fall/winter semester 2006/07). In the meanwhile, we were able to both significantly improve the 3Dvis prototype and substantially extend the model collection based on the experiences gained in both the first cycle study and continual application in seminar-style courses. Given this more reliable learning resource base, the comprehension questions of the second cycle study could be focused on higher level structural concepts, as described in the following and illustrated in Figures 12 and 13.

1. Recognition of mechanical behavior concepts in composite systems:

   Open questions specific to simulation models, e.g., “What type of loading causes tension forces in a column of this structure?” or “How could this relatively ‘soft’ structure be stabilized most effectively?” (multiple answers for four models based on composite model exploration and search of related systems in the model collection, Figure 12).
2. Direct and analogue recognition of real-world building structures:

Similar to this category in the first cycle, but without having to identify the proof building of the reference model (“What building has this load-bearing structure?”). In the second cycle, the students were provided with an extended and readily identifiable collection of building simulation models on CD-ROM and asked to find an arguable answer to “What other building has a corresponding structure?” (answers for four proof buildings, either via the offline model collection or by searching online in the full building information system of archistructura, Figure 13).

In addition to answering the comprehension questions, the students must fill out a “structural polarity profile” of 16 semantic differentials in conjunction with each reference model (total 4 composite systems and 4 building structures). The consideration of semantic differentials forms a separate type of learning activity in this context and serves as an accompanying means to activate exploration of structural behavior in formalized terms. This facet of the study is familiar to the participating students from a related context, their case study work, where architectural polarity profiles consisting of 46 perceptual semantic differentials are used to tap into further learning levels in connection with introductory research assignments and final documentation (Rudy, 2005).
Figure 12. (A) Question fields in a panel for a composite system, e.g., “Which basic system corresponds most closely to this truss grid in its overall behavior?” and “Which type of latticed system is more efficient in terms of weight performance for spanning the same area?” (with polarity profile accompanying the reference model). (B) Online applet window with the model loaded in 3Dvis, accessible via links in the question panel (view of design model with load case and stress texture). (C) Online model collection, organized analogously to “structures pictionary” in archistuctura and accessible via a link in the question panel (view of a space frame model with corresponding load case).
Figure 13. (A) Standalone 3Dvis application with the reference model loaded offline. (B) Question fields in a panel for a composite system: “What other building has a corresponding structure?” and text field for entering a short explanation of this choice (with polarity profile accompanying the reference model). (C) Online building information in archistuctura, detail view of proof building linked directly from the question panel. (D) Online building collection in archistuctura, accessible via a link in the question panel.

This second cycle study is still in progress, but preliminary results are available for the first 16 participants and related in Figure 14. Most notable is the clear rise in average scores for the questions on “mechanical behavior recognition,” which have a level of difficulty
corresponding more or less to the “structural concept recognition” questions of the first cycle study (set 2, Figure 11). The preliminary results at this incomplete stage of the study show no gains in average scores for “real-world analogy recognition,” perhaps due to the fact that in-depth exploration of such complex models is still a relatively tedious task, even with the improved standalone version of 3Dvis.

![Figure 14. Ranges of percentage scores on learning activities in the second cycle (16 participants).](image)

**Summary and Prospects**

The visualization tool as spatial cognition support that we set out to develop at the beginning of the project has, at this stage of development, proven to be even more successful than originally expected as a means for architecture students to gain a deeper understanding of structural design principles by exploring the mechanical behavior of simulation models. Intensifying the application in the training of civil engineers promises to yield findings that can significantly promote the common language needed to cooperate more effectively in the AEC domain, both educationally and professionally.
A range of functional extensions and additional features are awaiting their realization. At present, in experimental form, the functionality has been expanded to allow input that enhances the base models semantically (pick and editing tools). As such, the 3D Visualiser already functions as editorial support for adding attributes to existing structural models by coupling the semantic modeling layers with ontological descriptions stemming from other applications. A base collection of models is also serving as parametric templates for a range of common structural systems (beams, frames, arches, etc.) that are used to dynamically generate input files for an engineering-based structural analysis program. Recent developments include interactive mechanisms for combining such component models in a manner that enables model generation and explorative simulation of more complex building structures “on the fly” (Jaksch & Rudy, 2005).

With respect to future improvements, it became apparent in the course of programming and evaluation that a more efficient data structure than the XML standard is necessary to optimize and stabilize the software in order to make the handling of larger and more complex structural models technically feasible. Once a statistically relevant collection of manageable models has been established, the next goal will be to distill and translate their ontological rules into machine-readable criteria sets to create semantically “self-aware” building component models. These enhanced models shall ultimately serve as an advanced knowledge base for the kinds of fuzzy-set search operations (cf., Zadeh, 1987; Klir & Yuan, 1995; Rajasekaran & V. Pai, 2004) needed to guide multi-faceted decisions in the building design process.
References


Author Note

Concept and tool development for the archistructura precursor project Building Information Systems as Interactive Design Support were supported in the years 2003-2004 by a grant from the Austrian Science Fund (FWF).

Footnotes

1 General archistructura URL: http://www.archistructura.net (English and German); see also embedded version in department website (with access to extended student resources):
http://www.iti.tuwien.ac.at.


3 Applied boundary conditions are selected in the applet version (without a menu) from a drop-down list of simulated load cases below the main window.
Figure Captions

Figure 1. Screenshot of the “pictionary” for load-bearing structural systems in archistructura: hierarchical taxonomy as a base ontology derived from structural classifications of generic elements.

Figure 2. Morphological characterization of generic element types by structural properties (organized in a k-cube diagram).

Figure 3. Four different views of the same structural behavior model: system (static calculation model), function (semantic definition of elements in generic terms), design (material and geometry) without loads and with stress texture (load case with deformed geometry).

Figure 4. A complex support situation visualized as the bearing node of a structural behavior model: standard 2D view set and alternative 3D views (simplified and specialized proposals).

Figure 5. Restricted vocabulary to identify a series of simple structural elements, classified by semantic domain (assessment results in percentage of responses for each domain).

Figure 6. Preferred vocabulary (semantic sub-domain) of participating students in response to element representations, differentiated by gender.

Figure 7. Distribution of correct and incorrect responses for element representations by semantic sub-domain.

Figure 8. Screen shot of the user interface: design model view of a deformed bridge structure (color-coded texture options to reveal facets of mechanical behavior).

Figure 9. Comprehension assessment of load-bearing structural behavior: six sets of questions corresponding to three cognitive stages of visual perception.
Figure 10. Simulation modeling of real-world building structures: indoor riding arena in St. Gerold, Austria (case study and preliminary model: E.M. Streit; structural simulation model: S. Jaksch).

Figure 11. Ranges of percentage scores on comprehension questions to determine achievement of learning goals in the first cycle (27 participants).

Figure 12. (A) Question fields in a panel for a composite system, e.g., “Which basic system corresponds most closely to this truss grid in its overall behavior?” and “Which type of latticed system is more efficient in terms of weight performance for spanning the same area?” (with polarity profile accompanying the reference model). (B) Online applet window with the model loaded in 3Dvis, accessible via links in the question panel (view of design model with load case and stress texture). (C) Online model collection, organized analogously to “structures pictionary” in archistructura and accessible via a link in the question panel (view of a space frame model with corresponding load case).

Figure 13. (A) Standalone 3Dvis application with the reference model loaded offline. (B) Question fields in a panel for a composite system: “What other building has a corresponding structure?” and text field for entering a short explanation of this choice (with polarity profile accompanying the reference model). (C) Online building information in archistructura, detail view of proof building linked directly from the question panel. (D) Online building collection in archistructura, accessible via a link in the question panel.

Figure 14. Ranges of percentage scores on learning activities in the second cycle (16 participants).
Table Captions

Table 1. Preferred visualization styles selected for different bearing node situations (see also Figure 4).

Table 2. Assessment results for user interface design criteria: 27 participants, scoring on a grade scale from 1 to 5.