Sven Bertel, Thomas Barkowsky, Christian Freksa (2008). Mental model-centered design for built environments.
In Saif Haq, Christoph Hölscher, Sue Torgrude (Eds.),
Proc. of EDRAMOVE workshop on "Movement and orientation in built environments: evaluating design rationale and user cognition",
EDRA 39th Annual Conference, pp. 13–19, SFB/TR 8 Report No. 015-05/2008.

Mental Model-Centered Design for Built Environments

Sven Bertel, Thomas Barkowsky, and Christian Freksa

Cognitive Systems, FB3 – Informatics, Universität Bremen
& SFB/TR 8 Spatial Cognition,
Enrique-Schmidt-Straße 5, 28359 Bremen, Germany

{bertel, barkowsky, freksa}@sfbtr8.uni-bremen.de

Abstract: In this contribution, we argue that understanding model preferences in human mental spatial reasoning can eventually help improve both the design and the use of built environments. We present a design support tool prototype that interacts with the designer by checking for model preferences in the spatial instantiation of design constraints and suggests alternative placements where such are appropriate. We then discuss the applicability of the underlying methodology for supporting preferences in the spatial mental models which users of built environments exhibit when conceptualizing these environments. A framework is proposed for systematically evaluating designs with regard to how well users can conceptualize the corresponding built environments. We suggest that integrating this framework into the design process can lead to buildings for which correct mental conceptualizations are comparably easy to construct and maintain. Users may ultimately benefit from better building use and designers from being able to construct more usable buildings.

Keywords: Spatial mental models; mental preferences; design support systems; building use; cognitive factors in human-computer collaboration.

1 Introduction

Declarative knowledge about the spatial configuration of objects in a scene is often mentally integrated and processed in terms of spatial mental models (SMMs, Tversky, 1991). Such mental structures are, for example, useful for describing how spatial facts can be mentally inferred from a set of premises. They also may serve as modeling paradigms for shedding light on the working principles of the involved mental processes. It has been shown for several domains that general preferences exist in the construction of SMMs, that is to say, in the case of configuration problems with more than one valid solution not all of these solutions get constructed equally often. Some solution models are being preferred over others (Knauff et al., 1995; Schlieder, 1999). We have argued in the past that investigating such preferences holds formidable potential not only for understanding human problem solving in various domains (including architectural design, Bertel et al., 2007) but also for eventually creating human-computer interfaces that allow for a closer and more effective coupling of mental and computer-based reasoning processes (Bertel, 2007, 2005).

Sven Bertel, Thomas Barkowsky, Christian Freksa (2008). Mental model-centered design for built environments.
In Saif Haq, Christoph Hölscher, Sue Torgrude (Eds.),
Proc. of EDRAMOVE workshop on "Movement and orientation in built environments: evaluating design rationale and user cognition",
EDRA 39th Annual Conference, pp. 13–19, SFB/TR 8 Report No. 015-05/2008.

In the following, we will first show how results from a study on model preferences in mental spatial reasoning have influenced the creation of a design support tool prototype. The presented approach focuses on introducing preferences in the designer's mental representations of a built environment into the design process. Second, we will argue that the demonstrated methodology should be transferred to address in a similar fashion the mental representations which the user of a built environment constructs of it. The goal is to give the user's mental preferences in conceptualizing the built environment a proper place in the design process, thereby enabling the construction of buildings which are easier to understand, use, and describe. Third, we will present a set of starting points towards realizing these aims; in particular, we will describe a conceptual framework for systematically evaluating designs with regard to how well the built environments which they would entail could be conceptualized by users.

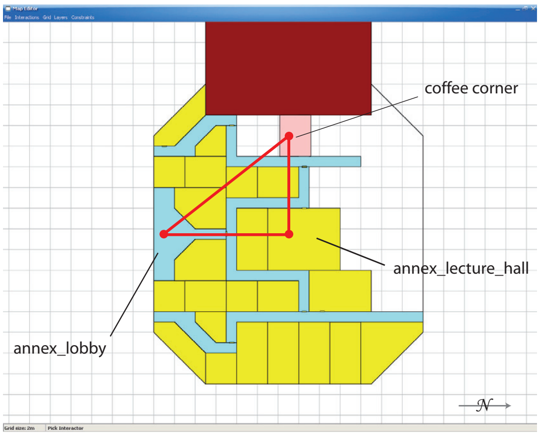


Fig. 1. An object placement (here '*coffee corner'*) is suggested by the design tool; the suggestion is based on the preferred direction model for configurations in which the relations *coffee corner northwest-of annex_lobby* and *annex_lecture_hall north-of annex_lobby* are given.

2 Designer's perspective: Mental models of spatial configurations

Part of the task of designing a built environment is to find a spatial model in which a set of spatial constraints can be instantiated to sufficient degrees (in particular: in a conflict-free manner). Often, such spatial constraints pertain to directional or distal requirements between parts in the structure to be designed, or they involve topological conditions. Figure 1 shows the result of an object placement in our design tool prototype.

Sven Bertel, Thomas Barkowsky, Christian Freksa (2008). Mental model-centered design for built environments.
In Saif Haq, Christoph Hölscher, Sue Torgrude (Eds.),
Proc. of EDRAMOVE workshop on "Movement and orientation in built environments: evaluating design rationale and user cognition", EDRA 39th Annual Conference, pp. 13–19, SFB/TR 8 Report No. 015-05/2008.

In a nutshell, during the design process the architect constructs SMMs of the overall layout of a built environment or parts of it in her head while sketching or drawing. Due to the nature of SMMs, in the designer's head mental spatial preferences will be effective in this construction process, for instance regarding the instantiation of direction or distance variables.

Although a trained architect usually will elaborate on various alternative design solutions to a given problem, the knowledge about the effects of spatial preferences in human mental model construction provides a fruitful basis for developing intelligent interactive assistance systems. Assistance systems of that kind, first, can help the designer overcome potential design biases imposed by her model preferences; second, they can inform a computational planning component about human design preferences (e.g. with respect to spatial configuration) in such a way that computationally generated design suggestions are constructed to be in line with human expectations based on such model preferences.

Our design support tool prototype interacts with the designer such that it permanently checks for model preferences in the spatial instantiation of design constraints. Based on the results of this check alternative placements of spatial entities are suggested. The presentation of potential alternatives is organized according to conceptual neighborhood structures (Freksa, 1992). That is, the system organizes alternative design solutions according to their conceptual similarity with respect to each other. By these means, the virtual space of possible solutions is explored in a systematic and mentally well conceivable manner (see Fig. 2).

3 User's perspective: Mental models in built environment usage

Although facilitating the process of design for the designer is a worthwhile endeavor in itself, the eventual goal of all building design is, of course, to create buildings which best fulfill their intended purposes. In the case of buildings that are intended to be used by people the degree to which their purposes can be fulfilled naturally depends on how well people can use them (i.e. how well they can navigate and orient in them, describe them, communicate about them, etc.). One crucial factor common to human performance across all such abilities is the degree of overlap between the SMM that a user constructs of a building (or, rather, of some part of it) and the building's actual structure: the higher this overlap, the higher the potential for good and unproblematic usage.

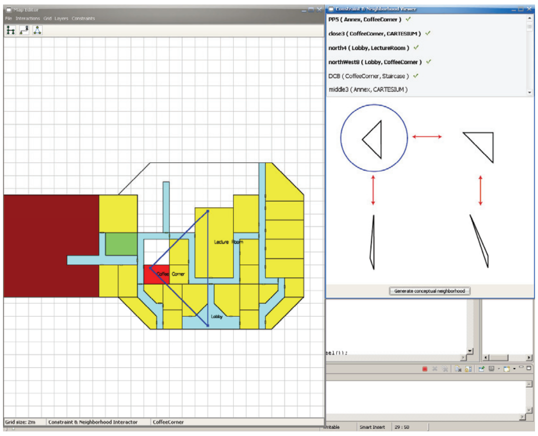
In the light of our previous discussion of preferences in SMM construction, we argue that preferences that exist on the part of a building's users should be considered for and influence planning decision already in early design stages. Two examples shall serve to illustrate our point:

First, imagine a human wayfinder who studies the map of a building which has been hung at the main entrance in order to establish a path between his current position and the location of a particular room. Depending on the complexity of the route, he may simply memorize in a verbal fashion a particular sequence of wayfinding decisions (e.g. *first left, straight, left*) or he may try to memorize a floor plan layout. Likely, during such actions he will read off a number of spatial facts from

Sven Bertel, Thomas Barkowsky, Christian Freksa (2008). Mental model-centered design for built environments.
In Saif Haq, Christoph Hölscher, Sue Torgrude (Eds.),
Proc. of EDRAMOVE workshop on "Movement and orientation in built environments: evaluating design rationale and user cognition",
EDRA 39th Annual Conference, pp. 13–19, SFB/TR 8 Report No. 015-05/2008.

the plan and integrate them more or less consistently into his mental representation of the building, i.e., into a SMM.

Any preferences in reading off such spatial information, in conceptualizing it and in integrating it into a model will then influence the structure of the resulting mental representation. Where this representation significantly differs from reality, building use will be impaired; where such differences are systematic one may have leverage to influence design processes so as to avoid constructing configurations that are easily misconceptualized. As an example, design methods may favor certain angles in corridor bends over others that have been shown to often lead to misjudgments with regard to the orientation of a building's main axes.



PP5 (Annex, CoffeeCorner) ✓
close3 (CoffeeCorner, CARTESIUM) ✓
north4 (Lobby, LectureRoom) ✓
northWest8 (Lobby, CoffeeCorner) ✓
DC8 (CoffeeCorner, Staircase) ✓
middle3 (Annex, CARTESIUM)

Fig. 2. Another view of the design tool. *center right:* A conceptual neighborhood for four different direction models; *center:* the object placement that corresponds to the currently selected model; *top right:* the results of an overall design check for certain spatial constraints.

Second, for a variation, imagine that instead of reading a map our wayfinder gets verbally instructed on his route by a second person. This process again entails the construction of SMMs with preferences playing a role in the model construction, and the story continues just as above…

We believe that the designer of a built environment should either be made aware of the configurations that are prone to later misconceptions by building users, or that design support tools should automatically avoid such configurations where possible. By this approach, building users may ultimately benefit from better building use and designers from being able to construct more usable buildings.

Sven Bertel, Thomas Barkowsky, Christian Freksa (2008). Mental model-centered design for built environments.
In Saif Haq, Christoph Hölscher, Sue Torgrude (Eds.),
Proc. of EDRAMOVE workshop on "Movement and orientation in built environments: evaluating design rationale and user cognition",
EDRA 39th Annual Conference, pp. 13–19, SFB/TR 8 Report No. 015-05/2008.

4 Model fit: Evaluation of expectations

The right question to ask now is – given that one already has sufficient knowledge about conceptualization and model construction preferences in a population of building users –: How can we make sure that these preferences are well appreciated in the design phase and that the resulting design does in fact avoid configurations which are easily misconceptualized? Here, a specific evaluation scheme for designs is needed. As movement in a built environment is at the core of how a user (e.g. a wayfinder) experiences it we see the necessity for suitable evaluation schemes to be similarly based on human movement patterns (i.e. on routes though the environment). Specifically, we propose that for each design to be evaluated a set of routes be defined that capture the most important (e.g. the most frequent) movement patterns in the environment. For these routes, qualitative descriptions are generated that include the necessary information on decisions to be made by a wayfinder who travels along a route from start to end. A standardized description process should be used for all routes; for performance issues, it should ideally be one that is capable of generating route descriptions which can be conceptualized as easily as possible, taking into account structural and functional issues of route and communication complexity (e.g. Richter, 2007).

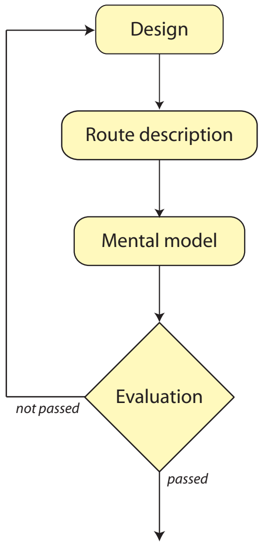


Fig. 3. The proposed evaluation scheme for designs.

Next, each route description is fed into a generative process that creates an SMM based on the spatial information contained in the route (or in route segments, in case of long or complicated route descriptions). This generative process is the one that takes into account the known human preferences in model construction: For each

Sven Bertel, Thomas Barkowsky, Christian Freksa (2008). Mental model-centered design for built environments.
In Saif Haq, Christoph Hölscher, Sue Torgrude (Eds.),
Proc. of EDRAMOVE workshop on "Movement and orientation in built environments: evaluating design rationale and user cognition",
EDRA 39th Annual Conference, pp. 13–19, SFB/TR 8 Report No. 015-05/2008.

route description only the preferred SMM is constructed so that a set of *n* route descriptions will eventually lead to the production of *n* SMMs.

As a next step, for each SMM, the spatial configuration specified by it is in turn compared to the spatial configuration specified by the design. The comparison process is qualitative in nature and it measures the degree of structural correspondence between the SMM and the design. It produces two main outputs: A value from applying the measure and a list of structural components that mismatch. After comparing the design to all generated SMMs, the individual correspondence measures are integrated and a global expectancy value is computed. This value signifies how well a design structurally corresponds to what a user can expect of it based on knowledge from route description and SMM construction processes that feature preference-based instantiations. A synopsis of structural mismatches can be used to identify critical parts in the design in case it needs to be modified. Fig. 3 gives an overview of the complete evaluation scheme.

On a general note, the proposed approach will likely not favor designs that lead to the simplest models or the shortest route descriptions. Rather, it will favor designs that lead to models whose construction and maintenance requires minimal cognitive effort.

5 Discussion and outlook

In this contribution we argue for considering preferences in spatial mental models both in the designer and in the user of a building right from the beginning of the design process. However, there are a number of open issues that need to be addressed towards realizing the described ideas in an intelligent interactive assistance system.

On the one hand, it is not completely understood (1) which spatial relations a potential user might use to construct a mental model and (2) how these relations refer to the constraints the architect has to consider during the design process. Some suitable kind of formal language is required to capture both, the specifications to be met in the resulting design and the constituents of the resulting spatial mental models in the user of the building. It seems that this issue has to be addressed in a joint interdisciplinary effort pursued by architects, cognitive scientists, and computer scientists.

On the other hand, we expect that the structure of the mental model constructed in a user's mind should vary depending on the task the user is confronted with. So, for instance, the task of reaching a specific location within the building vs. the task of describing a route to another person might lead to quite different spatial mental models.

Another issue to be addressed in the course of this research is how spatial mental models related to a given building vary between different individuals. Since it is known that mental spatial capabilities may be quite different in different people (e.g. Hegarty & Waller, 2006), we also expect that the grade of detail and the overall structure of spatial mental models should be different in people with different spatial abilities.

Acknowledgments. The authors gratefully acknowledge support by the *German Research Foundation* (DFG) through the project *R1-[ImageSpace]*, SFB/TR 8 *Spatial Cognition*. Fruitful collaboration with Kai-Florian Richter, Ben Weber, and Brett Bojduj on creating the design tool prototype as described in Section 2 is gratefully acknowledged.

References

Bertel, S. (2005). Show me how you act on a diagram and I'll tell you what you think. In: Reasoning with mental and external diagrams: Computational modeling and spatial assistance. Papers from the 2005 AAAI Spring Symposium (SS-05-06). Menlo Park, CA: AAAI Press.

Bertel, S. (2007). Towards attention-guided human-computer collaborative reasoning for spatial configuration and design. In Dylan D. Schmorrow and Leah M. Reeves (Eds.), Foundations of augmented cognition (Proc. of HCI International 2007, Beijing). Berlin: Springer, pp. 337–345.

Bertel, S., Vrachliotis, G. & Freksa, C. (2007). Aspect-oriented building design: Toward computer-aided approaches to solving spatial constraints in architecture. In Gary L. Allen (Ed.), Applied spatial cognition: From research to cognitive technology. Mahwah, NJ: Lawrence Erlbaum, pp. 75–102.

Freksa, C. (1992). Temporal reasoning based on semi-intervals. *Artificial Intelligence*, *54* (1), 199–227.

Hegarty, M. & Waller, D. (2006). Individual differences in spatial abilities. In P. Shah & A. Miyake (Eds.). Handbook of Visuospatial Thinking. Cambridge University Press, pp. 121-169.

Knauff, M., Rauh, R., & Schlieder, C. (1995). Preferred mental models in qualitative spatial reasoning: A cognitive assessment of Allen's calculus. Proceedings of the Seventeenth Annual Conference of the Cognitive Science Society (pp. 200-205). Mahwah, NJ: Lawrence Erlbaum.

Richter, K.-F. (2007). A uniform handling of different landmark types in route directions. In S. Winter, M. Duckham, L. Kulik, and B. Kuipers (Eds.), Spatial information theory (pp. 373-389). Berlin: Springer.

Schlieder, C. (1999). The construction of preferred mental models in reasoning with interval relations. In G. Rickheit and C. Habel (Eds.), Mental models in discourse processing and reasoning (pp. 333-357). Amsterdam: North-Holland.

Tversky, B. (1991). Spatial mental models. *The Psychology of Learning and Motivation, 27*, 109-145.