Computer Aided Architectural Design: Wayfinding Complexity Analysis

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Abstract

Design is a complex process often described as a collaboration between a designer and herself. In architectural design, a designer must consider the selection of a subset of actions from a set of possible actions while accounting for consequences on the overall design. Computer-based design tools enable humans to operate more efficiently in this process. We present CoSyCAD, a program that can be used to assist architects in the layout of a floor plan and to simultaneously analyze the cognitive complexity of routes through an indoor environment, thereby enabling direct feedback on a layout's usability. We provide a scenario that utilizes the program.

Keywords: Spatial Cognition, Computer-Aided Collaborative Design, Wayfinding, Spatial Representation.

1. Introduction

In our work, we have found it useful to take the following definition of design:

> Given a set of actions that can be applied to a concept, design is the process of selecting and applying one of the actions to the concept.

Thus, the process of design can be conceptualized as a selection of design actions out of a set of available possible design actions. Viewing design as a process of selection puts an emphasis on the need to make the correct decision when selecting which action to apply to a design.

Despite being bounded in their rationality [25], humans find ways to deal with the complexity of design in a satisfactory manner; they are able to accomplish many design tasks. One of the ways in which humans deal with the task's complexity is by externalizing portions of their design in the form of spatial representations, such as diagrams.

Spatial representations are a common way for humans to represent knowledge, as are sentential representations. Larkin and Simon [17] define sentential representations to be "sequential, like the propositions in a text," whereas they define spatial representations as "index[ed] by a location in a plane." Spatial representations typically must make explicit information that is only implicit in sentential representations. Spatial representations often require higher degrees of representational specificity and information integration than sentential ones [17]. Sentential and spatial knowledge representations can take two forms–internal and external. For internal knowledge representations, the knowledge is represented in a way that is only accessible from within the representational system. For humans, this is knowledge represented in our brain. It should be noted that even though these internal knowledge representations do not allow for explicit, direct access by external observers, one can often infer certain structural and procedural characteristics via indirect methods from the outside, as is typically done in cognitive science.

For external knowledge representations, the knowledge is represented in the physical world, allowing physical access to it. Representations might be, for example, charts, maps or diagrams (external spatial representations), or sentences or texts, such as this paper (external sentential representations). Unless specifically qualified with the word "internal," all representations discussed in this paper are assumed to be external.

For many tasks, humans can process information more efficiently if spatial representations, as opposed to sentential representations, are used [8, 26]. This is because spatial representations make information more readily understandable, saving considerable amount of computational cost, given that methods for decoding knowledge from the spatial representation are available. Webber and Feeney [27] demonstrated this observation when they created both sentential and spatial representations of the same information (see Figure 1 for the spatial representation).

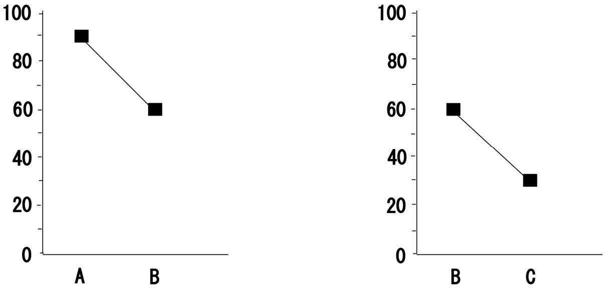

Figure 1. Diagrammatic representation of two spatial relations as used in the experiments of Webber and Feeney ([27], adapted).

In this case, the subjects' task is to compare the size of items A and C. This can be represented sententially as, "A is taller than C". To arrive at this conclusion using only the sentential representation, people must build representations of the connections between A and B, as well as between B and C, in their mind. They then must perform a unification of the two to reach the simplified conclusion, while keeping all the representations in their short-term memory. While this unification is not necessarily hard for a human, it does require time to process.

If, however, a spatial representation is presented, you can just look at the diagrams and read off the answer easily. This is a process that Shimojima [24] calls a "free ride." A "free ride" situation exists when the constraints of the spatial representation (in this case, the scales on the two axes) cause the realization of the conclusion, without any additional processing. This is a very efficient process and enables humans to offload a huge burden on their memory, as all the requisite information does not have to be stored in short-term memory but can be read from the spatial representation when needed. This allows more possibilities to be realized in more creative tasks. Webber and Feeney [27, 28] also suggest that humans are capable of developing analogous internal, spatial representations to diagrams. This suggests that humans have adapted well to spatial reasoning and thus can exploit it for many uses.

In this paper, we present work on exploiting the power of spatial representations in a collaborative tool for designing indoor spaces. The system, called CoSyCAD, checks topological, distance, and orientation constraints online while the human designer is making decisions and altering the design. It warns the designer of constraint violations and produces suggestions for improvement. We will briefly introduce the overall system and then explore a specific feature of the system: the analysis of a design's wayfinding complexity. The paper is structured as follows: in the next section we introduce some background on design and human-computer collaboration in design. Section 3 focuses on wayfinding complexity and its analysis. We then present CoSyCAD in Section 4, especially concentrating on the aspect of wayfinding complexity analysis. Finally, the functionality of the system is illustrated in an example scenario in Section 5.

2. Computer-Aided Design

Many of the representations that get created during an (architectural) design process are in a diagrammatic format, and hence spatial. The use of diagrams has a number of representational advantages for designing: for example, design problems are often complex in that they involve much information. Offloading some of that information to a diagram, integrating it into a coherent spatial model, and then being able to simply read off information from this model can effectively help to reduce the resultant complexity from too much information. In fact, the resulting dialectic relationship between a designer's mental reasoning processes and her actions on self-produced external (i.e. diagrammatic) representations often is so critical for the generation of design products that it becomes a quality of the design process and the degree of interaction between the mental and the external, as well as a measure of the designer's expertise (e.g., see [3, 9, 16]).

A step towards utilizing the power of spatial representations in human-computer interaction is the development of computer models that take into account how humans reason about and interact with spatial representations. In computer-based design tools such models can be employed to set how and when the tool takes over certain tasks in the design process, e.g. by explaining past and predicting future interactions (e.g., [2]).

Computer-aided design tools are nothing new. However, the emphasis has shifted from automation of design tasks to collaboration on design tasks. A good example of current human-computer spatial collaboration is the design critiquing tool created by Oh et al. [20]. In this tool, the human and the computational collaborators alternate in their initiative as freehand sketches drawn by the human are cyclically checked for a list of pre-specified constraints. If the computer finds that any changes to the design are required, it notifies the user of such needs and generates explanations based on the list of violated constraints. This interaction is similar to the collaboration between two humans working with such a sketch, where they each take turns marking up the drawing.

In the following discussion of our design tool, CoSyCAD, we will specifically stress two perspectives on supporting the human designer during collaborative human-computer designing. Outcomes of processes associated with either will be presented in spatial formats. First, we will focus on cognitive aspects of the designer (e.g. on mental loads, or on aspects of reasoning with spatial mental models), and second, on introducing into the design cognitive aspects of the eventual user of the building to be designed (i.e., on wayfinding complexity). We present and discuss CoSyCAD's realizations of these aspects from both perspectives.

3. Wayfinding and Wayfinding Complexity

When designing an environment, several considerations need to be taken into account (e.g. functional, aesthetic, and economic aspects). However, the layout of an environment also has a direct influence on the difficulty of finding one's way around in that environment, i.e. on wayfinding. *Wayfinding* is a purposive, directed, motivated activity to follow a route from origin to destination [10]. According to Montello [19], it reflects the cognitive processes going on during navigation—as opposed to locomotion, which covers the activities of the sensory and motor system.

The layout of an environment, i.e. its structure, influences how easily and integrated a mental representation is formed by people [5, 29]. The structure of an environment, and people's familiarity with it, also influences the strategies they employ to find their way around [4, 14, 15]. Accordingly, wayfinding complexity should be considered in designing environments as well.

There are several approaches that try to capture the layout's influence in measures derived from the environmental structure. One prominent example is the theory of Space Syntax [1, 13] that provides methods to quantitatively analyze perception and accessibility of built indoor and outdoor environments based on graph measures. Other approaches, which are more directly related to wayfinding performance, include Mark's [18] selection criteria for route search that accounts for the assumed complexity of the structure of intersections, and O'Neill's [21] Inter Connection Density (ICD), which captures the average number of possible routes one can take from any given decision point (intersection) of an environment. The latter two approaches only consider structural aspects of an environment, namely the configuration of intersections. Functional aspects also play an important role in wayfinding complexity. Heye and Timpf [12], for example, developed a complexity measure for traveling with public transport that accounts for the structural complexity of stations, but also the actions that need to be performed at these stations given a specific route. Richter [23] developed a computational process, called GUARD, which calculates for a given route those route directions that are the best to conceptualize, using structural and functional aspects of route and communication complexity.

4. CoSyCAD

In the following, we present CoSyCAD, a tool for human-computer interaction through spatial diagrams that accounts for structural and functional aspects of space. We will start with aspects that respect cognitive factors and preferences of the designer and then discuss aspects concerned with a building's users. CoSyCAD enables a designer to layout a floor plan in a two-dimensional space and provides tools for analyzing spatial constraints in the plan. Interactions in CoSyCAD allow the designer to verify the following constraints: topological relations (either based on the RCC family of calculi or the 9-intersection model [6, 22]), distance relations and qualitative orientation relations (e.g., [11]), and route complexity. The goal of CoSyCAD is to alleviate the designer from the need to consider all spatial constraints when designing the floor plan. Also, the status of constraints (fulfilled or unfulfilled) is visually integrated in the layout's spatial representation. On one hand, this allows for an easy—'obvious'—detection of problems in the design. On the other hand, designers can directly see which options for their next design decision are valid; thus offering a "free ride" as explained above.

Building floor plans in CoSyCAD is an iterative process. The first step the designer performs is a specification of relations between different objects within the plan. These constraints are stored in an XML file that specifies topology, orientation, and distance constraints. The designer then places objects in the floor plan. At any time during the layout process, a CoSyCAD interaction can be executed to check spatial constraints and visually display the results to the user (see Figure 2a). CoSyCAD allows the designer to focus on a subset of the floor plan, and then to check if the global constraints are met. This iterative process continues until a satisfactory solution is found.

Specific to CoSyCAD, the system not only allows for checking static spatial constraints in a design, but also provides an interaction for analyzing wayfinding complexity in a floor plan, which is a dynamic aspect of a layout and takes into account cognitive factors of the users of the eventually constructed building. To this end, first, the route interaction builds a route graph using a Voronoi tessellation (see Figure 2b) which connects the rooms in the plan. Each node in the route graph can be considered to be a decision point, i.e., a point where the wayfinder has to decide between alternate routes. Next, the user picks a starting node in the graph and an ending node. The route interaction analyzes the wayfinding complexity of the selected route through the graph, based on distance, complexity of decision points, and the wayfinding actions to be performed. Though route distance is not inherently a measure of complexity in itself, if the distance is particularly long, navigation will involve considerable physical effort.

The main measure of complexity which the route interaction uses is a summation of the complexity of all the decision points along the route. At each decision point, taking into account the direction of travel (i.e., from the starting node to the ending node), the number of branches and the angles between any two branches are taken into account. If the interaction finds an overly complex decision point, a graphical note is placed in the floor plan to warn the designer. For example, the route interaction looks for decision points with greater than three branches (not counting the incident branch). This number reflects that intersections with more than four branches (counting the incident branch) can become overly confusing for a human, especially if more than one branch leads in the intended direction [21, 23]. Therefore, the route interactor will warn the user about possible confusion resulting from this floor plan configuration, suggesting that the designer reduce the number of meeting branches at this point.

In addition to checking the number of branches which meet at a decision point, the route interaction also checks whether or not two consecutive decision points have the wayfinder turning right and then left, or left and then right. If this happens, the route interaction suggests that the environment be reconfigured to let the wayfinder proceed in a straight direction, without making both these turns. Finally, the route interaction checks the angles of the branches at a decision point to determine whether or not multiple branches are competing or require the wayfinder to make a sharp turn. Competing branches are defined to be separated by an angle less than forty degrees, whereas sharp turns require the wayfinder to turn greater than ninety degrees to the right or to the left of the direction they are facing.

Again, the results of the wayfinding complexity analysis are visually integrated in the layout's design, exploiting a spatial representation's power. Taken as a whole, all these checks allow the designer to more readily create designs without having to consider all the spatial constraints at each step in the design process.

5. Example

In this section, we illustrate the design assistance offered by CoSyCAD using the following scenario for demonstration: An annex is to be added to the Cartesium building at Universität Bremen. The annex includes a lobby, lecture room, and coffee corner. The following spatial constraints must be met in order to reflect functional constraints originating from considerations of how people interact with the building: the coffee corner must be close to the original part of the building, so that it is usable for people in both parts. The coffee corner cannot touch the staircase of the Cartesium since this would require costly reconstruction in the Cartesium. The annex's lobby is to be built in the southern part; hence, the coffee corner must be northwest of the lobby. The lecture room should be easily accessible from the lobby which results in its placement north of the lobby. These constraints are represented by the following qualitative relations:

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close ( CoffeeCorner, Cartesium )
north ( Lobby, LectureRoom )
northwest ( Lobby, CoffeeCorner )
dc[1] ( CoffeeCorner, Staircase )
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The design process for the Annex begins by placing the lecture room, lobby, and coffee corner. Next, hallways and additional rooms are added to the design. A partially complete design is presented in Figure 2. The proposed floor plan meets the spatial constraints specified in the relations above. However, analyzing wayfinding complexity results in high complexity as shown in Figure 2b. For example, seven turns are required to travel from the lobby to the southwest lab.

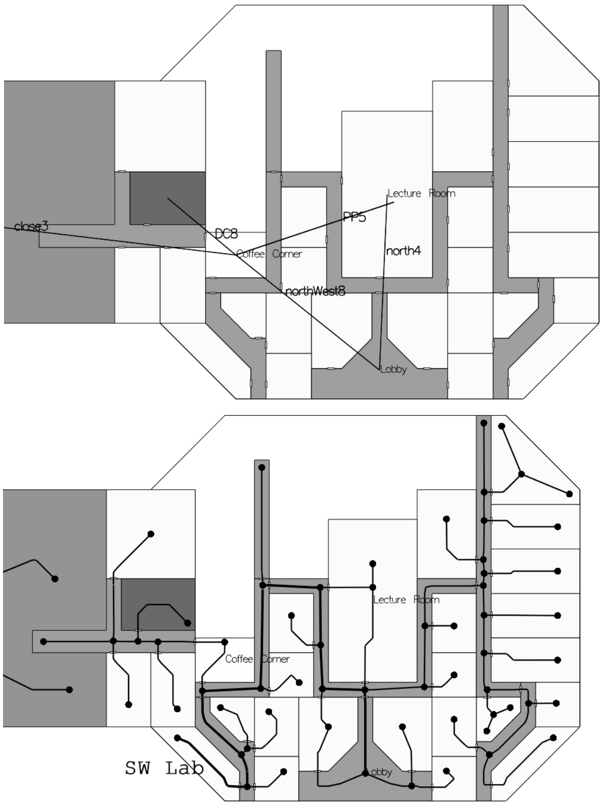

Figure 2. A partially finished design of the proposed annex showing the main rooms and their spatial relations (a) and the calculated route graph (b).

Thus, the initial floor plan needs to be redesigned. Based on hints provided by the system regarding the reasons for the high wayfinding complexity, the designer decides to rotate the hallway connecting the

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[1] dc is a relation of the RCC calculus and stands for "disconnected."

coffee corner to the rest of the Annex by 180 degrees; the coffee corner is shifted east to compensate for this rotation. The resulting floor plan is shown in Figure 3. The new design meets the spatial constraints and has a low wayfinding complexity. The route graph for the new floor plan is shown in Figure 3b. Reaching the southwest lab now requires a simpler sequence of five turns.

These results demonstrate human-computer interaction through spatial representations and automated constraint checking. Using a computer-aided design process enables a designer to tackle problems larger than the capacity of a human's short-term memory without having to recurrently go through each constraint after each local design decision.

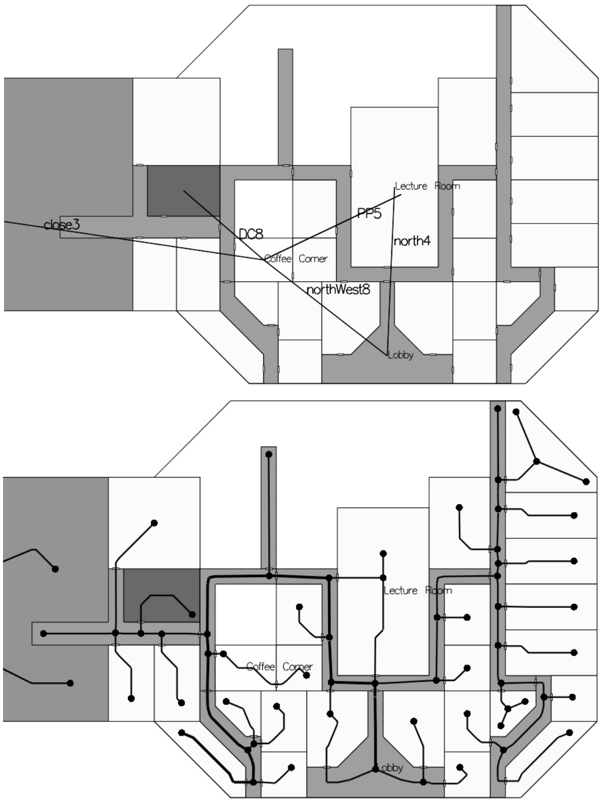

Figure 3.The updated floor plan. The spatial constraints are still met (a), and the route graph illustrates the reduced wayfinding complexity (b).

6. Conclusions and Future Work

Two main forms of knowledge representation are used mentally as well as in external sources: sentential and spatial representations. Sentential knowledge representations are comprised primarily of sentences and are sequential in nature. Spatial knowledge representations, on the other hand, are composed of spatial structures, such as diagrams, and are defined by properties of (planar) space.

Humans regularly use spatial representations for human-human collaboration. This is facilitated by the fact that humans have comparable cognitive capabilities. When humans create a diagram, they can approximate how another human will react to and interact with it. Using spatial representations for human-computer collaboration is a sensible method for collaboration because offloading information to a diagram reduces the burden on human memory, freeing cognitive capacity for other uses. Spatial representations can also be more efficient in collaborative activities, thus freeing up time for humans to perform other tasks.

Diagrammatic collaboration is very beneficial for human-computer interaction in domains such as architecture and graphic design, where this interaction can rapidly speed up development and improve the quality of products and designs. Building a computer system that can predict how changes to a diagram influences a human's perception is a good start in enabling spatial collaboration between computers and humans. As research continues, we can expect these predictive cognitive models to become both more complex and substantially useful. As an example, we introduced CoSyCAD, a system for interactively designing indoor spaces. Currently, it provides interactions for verifying spatial constraints. However, future tools will utilize conceptual neighborhoods [7] to automatically generate alternative solutions for the designer and follow up on the modeling of the designer's cognitive factors and preferences. Also, exploratory empirical studies will provide feedback on a designer's interaction with CosyCAD which will allow for identifying further factors that may help increase wayfinding performance.

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