Supporting the Designer's and the User's Perspectives in Computer-Aided Architectural Design

Kai-Florian Richter[a,1], Ben Weber[b], Brett Bojduj[c], Sven Bertel[a,d]

[a] *Transregional Collaborative Research Center SFB/TR 8 Spatial Cognition, University of Bremen, PO Box 330 440, 28334 Bremen, Germany*
[b] *Dept. of Computer Science, University of California, Santa Cruz, USA*
[c] *Dept. of Computer Science, California Polytechnic State University, San Luis Obispo, USA*
[d] *Human Factors Division & Beckman Institute for Advanced Science and Technology, University of Illinois at Urbana-Champaign, USA*

Abstract

At any given step in the architectural design process, a designer can usually only consider a small subset of the actions that can be applied to a design along with the consequences of those actions on the overall design process. Computer-based design tools can enable humans to operate more efficiently in this process. In the end, the design product (i.e., a built environment) is meant to be used by people other than the designer. Taking the users' perspective into account while creating a layout is crucial to not only creating an environment that fulfills all design constraints but that is also usable in everyday life. We present CoSyCAD, a program that can be used to assist architects in the layout of a floor plan; it simultaneously analyzes the cognitive complexity of routes through an indoor environment, thereby enabling direct feedback on a layout's usability. We provide a sample scenario that utilizes the program and discuss further possible enhancements.

Key words: Spatial cognition, computer-aided architectural design, floor plan complexity wayfinding, spatial constraints.

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1. Introduction

Design (e.g., of buildings) is usually regarded as a complex process that requires a variety of skills in the designer and demands high cognitive resources. Despite being bounded in their rationality [1], humans find ways to deal with

*Corresponding Author

Email addresses: richter@sfbtr8.uni-bremen.de (Kai-Florian Richter), bweber@soe.ucsc.edu (Ben Weber), bbojduj@calpoly.edu (Brett Bojduj), bertel@illinois.edu (Sven Bertel)

the complexity of design in a satisfactory manner; they are able to accomplish many design tasks.

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

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

Thus, the process of design can be conceptualized as a sequential selection of actions from a set of respectively available possible design actions. Viewing design as a process of selection puts an emphasis on the need to make the correct decision when selecting an action to apply to a design. Since the result of the design process is typically to be used by people other than the designer, a designer should always be aware of the consequences that decisions that are reasonable from a designer's perspective have from the users' perspective.

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 between design elements online while the human designer is making decisions and altering the design. It warns the designer of constraint violations and produces suggestions for improvement. It also supports the designer in checking for the consequences that design decisions have on the design's usability; namely, the tool allows for analyzing a floor plan layout's wayfinding complexity with respect to how a user of the design cognizes the environment, i.e., how a person navigates the building.

To start, we will provide a short excursion into the field of knowledge representation, while looking at the strengths of spatial representations, in particular. In Section 2, we introduce some background related to the two perspectives in architectural design: first, design in general and human-computer collaboration in design (the designer's perspective); second, wayfinding complexity and its analysis (the users' perspective). We then present CoSyCAD in Section 3, illustrating how a building's layout is collaboratively designed and how this layout is analyzed with respect to its consequences for the building's users. This section also contains a detailed example demonstrating both aspects. Section 4 then concludes the paper with an outlook on future work.

1.1. A Short Excursion into Knowledge Representation

Spatial representations are a common format for humans to represent knowledge, as are sentential representations. Larkin and Simon [2] 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 information explicit that is only implicitly stated in sentential representations. As a consequence, spatial representations often require higher degrees of representational specificity and information integration than sentential ones [2]. 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 that is represented mentally. 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 contribution (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 [3, 4]. This is because spatial representations make information more readily understandable, which saves a considerable amount of computational cost, given that methods for decoding knowledge from the spatial representation are available. Webber and Feeney [5] demonstrated this observation when they created both sentential and spatial representations of the same information (see Figure 1 for the spatial representation).

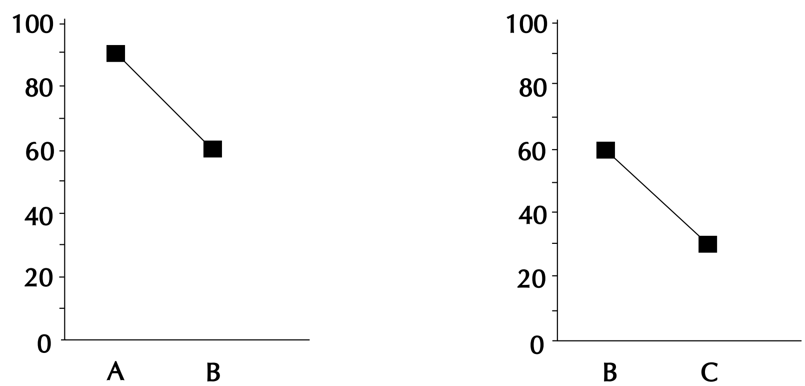

Figure 1: Diagrammatic representation of two spatial relations as used in the experiments of Webber and Feeney ([5], adapted).

Webber and Feeney required subjects to determine the veracity of premises involving line graphs with endpoints represented by letters, such as A, B, and C. Premises involving these endpoints could be "A is greater than B" and "B is greater than C." A conclusion involving these premises can be represented sententially as "A is greater than C." To arrive at this conclusion using only the sentential representations, 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 premises 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, the premises were represented spatially, you can just look at the diagrams and read off the answer easily. This is a process that Shimojima [6] 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 [5] 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 terms of using spatial representations for design tasks, architectural design lends itself especially well to the use of spatial representations, due to the large number of aspects involved in the architectural design process [7]. In particular, spatial representations in diagrammatic formats (e.g., plans or sketches) have been frequently shown to be crucial for organizing and driving the design process, such as via mechanisms that frequently recode design information in mental or external diagrammatic formats [8, 9]. We will elaborate on this further in the next section.

2. Architectural Design and Wayfinding Complexity

In the following, we provide some background information on the two perspectives addressed in this paper, namely the designer's and the users' perspectives (see also [10, 11, 12]). For the designer, facilitating interaction with the design tools and the design itself is important. A designer uses tools to create a representation of the item to be constructed in the real world, such as a new building. This representation is used to communicate to others what needs to be done in the construction process, but it also is a crucial way for the designer to come up with a design in the first place as further discussed below. The support provided by tools in creating the external representation alleviate a (considerable) part of the design work.

For the user, facilitating interaction with the built environment itself is crucial. Users have to deal with the real world, i.e., with the item or environment that, in the end, has been constructed based on the designer's representation. They have to rely on their mental conceptualization and on the information communicated by the constructed environment (including signage). Usually, no additional tools are available to users for interacting with the environment—in a properly designed environment they should not be necessary.

In their interactions, designer and user are faced with two different types of spaces. The designer deals with a space much smaller than that occupied by the designed item in the real world (i.e., a drawing on a screen or a model of the building), often termed *figural* or *desktop* space. The user deals with the environment itself, i.e., interacts in *environmental* space. Both types of spaces differ in their perception and afford different kinds of interaction.

2.1. The Designer's Perspective: Computer-Aided Design

Many of the representations that get created during an architectural design process (and many other design processes as well) are in a diagrammatic format, and hence spatial. The use of diagrams has a number of representational advantages for designing, since design problems are often complex in that they involve much information as well as information of different kinds. 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 the designers' mental reasoning processes and their 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 of the degree of interaction between the mental and the external, as well as a measure of the designer's expertise (for discussions, see e.g. [7, 8, 13]).

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 [14]. 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, for example, by explaining past and predicting future interactions (e.g., [15]). Computer-aided design tools are nothing new [16], although currently available tools still fall short of providing adequate support for all design phases (cf. e.g., [17]). However, the emphasis has shifted from automation of design tasks to automation of collaboration and cooperation on design tasks. Consequently, one has to address issues of human-computer cooperation that go beyond intelligent interface design (cf. [18]). A good example of current human-computer spatial collaboration is the design critiquing tool created by Oh et al. [19]. 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 and critiquing the drawing.

2.2. The Users' Perspective: Wayfinding and Wayfinding Complexity

When designing an environment, several aspects, such as functional, aesthetic, and economic ones, need to be taken into account. However, the layout of an environment also has a direct influence on the difficulty of interacting with it. This holds especially for finding one's way around. We will focus on those aspects related to wayfinding in the following. Wayfinding is a purposive, directed, motivated activity to follow a route from origin to destination [20]. According to Montello [20], 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 an integrated mental representation is formed by people [11, 12]. The structure of an environment, and people's familiarity with it, also influences the strategies they employ to find their way around [21, 22, 23]. Accordingly, wayfinding complexity should be one of the crucial aspects being considered when designing environments.

There are several approaches that try to capture the layout's influence on human behavior in measures based on spatial properties of an environment. One prominent example is the theory of Space Syntax [24, 25] that provides methods to quantitatively analyze perception and accessibility of built indoor and outdoor environments based on graph measures. Other approaches, that are more directly related to wayfinding performance, include Mark's [26] selection criteria for path search that accounts for the assumed complexity of the structure of intersections, and O'Neill's [27] Inter Connection Density (ICD), which captures the average number of paths one can take from any given decision point (intersection) of an environment. These two approaches only consider structural aspects of an environment, namely the configuration of intersections. However, often this does not adequately reflect the actual complexity of navigating an environment. Functional aspects need to be accounted for as well, such as capturing situations where intersections differ in their complexity depending on the direction of approach.

Along that line of reasoning, Heye and Timpf [28] developed a complexity measure for traveling with public transport that considers not only the structural complexity of stations, but also the actions that need to be performed at these stations given a specific route. Klippel [29] explicated a set of prototypes for turning actions at intersections that he termed wayfinding choremes; he discusses turning actions and route directions with respect to structural and functional aspects of an environment. Richter [30, 31] developed a computational process 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.

3. CoSyCAD

In the following, we present CoSyCAD, a tool for human-computer interaction that accounts for both 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 through the context of wayfinding. We will exemplify both aspects by illustrating some steps of a building's design process.

The duality of perspectives is fundamental 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. In this way, the system accounts for the two perspectives addressed above: the designer's (mostly) static perspective on a representation of the environment and the users' dynamic perspective of a real world environment. In that, it differs to other approaches, such as those by [32] and [33], for example. Mora et al. [32] present a system that enables architects and engineers to interact in early building design. In their system, the two addressed groups—the two perspectives of architect and engineer, respectively—are actually both involved in the design process. In [33], a design tool is presented that allows several designers to collaborate in the early stages of design. It uses sketching and gesturing methods to ease interaction with the system and peer-to-peer connections to enable collaboration. Its focus is on facilitation of the designer's workflow (see Section 2); it does not consider the users' perspective in the design process. CoSyCAD, however, allows an architect to consider the users' perspective by simulating users' expected behavior. It does not require direct user participation in the design process.

3.1. The Designer's Perspective

CoSyCAD enables a designer to create 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 [34, 35]), distance relations and qualitative orientation relations (e.g., [36]), 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 (see Figure 2 for an example). On one hand, this allows for an '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.

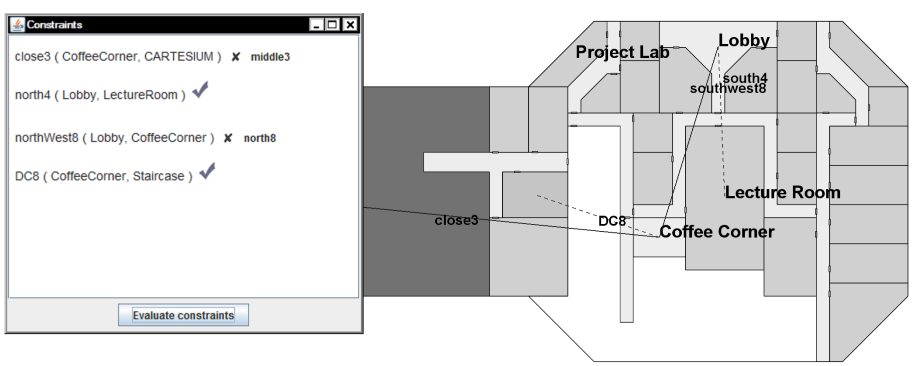

Figure 2: Visual integration of the status of constraints. In this example, two of them are fulfilled (marked by the tick) and two are unfulfilled, which is marked by an x. Further the relation currently holding is displayed to indicate how far the current design is off.

Building a floor plan in CoSyCAD is an iterative process. The first step the designer performs is a specification of relations between different objects within the plan. The designer then places objects in the floor plan. At any time during the layout process, spatial constraints can be checked and the results can be visually displayed to the user (see Figure 3b). 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.

CosyCAD provides an interface for specifying topology, orientation, and distance constraints. Topology constraints specify an RCC relation [36] between two objects in the design and are verified using the Java Topology Suite[1]. Orientation constraints specify a cardinal or intercardinal direction between two objects. The system checks orientation constraints by computing the closest intercardinal direction between the centroids of the objects. Distance constraints specify a qualitative relation between two objects. Thresholds for close, medium, and far distances are currently hard-coded in CosyCAD, but will be made configurable in the future, for example, to cover different scales of designs.

Example

We illustrate the design assistance offered by CoSyCAD using the following scenario for demonstration: An annex is to be added to the "Cartesium" building (named after the Latin name of Descartes, Renatus Cartesius) at the University of 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 of the existing structure.
- The annex' lobby is to be built in the northern part; hence, the coffee corner must be southwest of the lobby.
- The lecture room should be easily accessible from the lobby, which results in its placement south of the lobby.

These constraints are represented by the following qualitative relations:

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close ( CoffeeCorner, Cartesium )
south ( Lobby, LectureRoom )
southwest ( Lobby, CoffeeCorner )
disconnected ( CoffeeCorner, Staircase )
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[1] http://www.vividsolutions.com/jts

The design process for the annex begins by placing the lobby to the north of the annex. Next, the coffee corner is placed near the “Cartesium,” in the western part of the annex. The lecture room is then added in the middle of the annex, such that it is located south of the lobby. A partially complete design capturing these three steps is shown in Figure 3. At this step, all the specified constraints are fulfilled, i.e., the current design is globally consistent and, therefore, a valid solution (see Figure 3b).

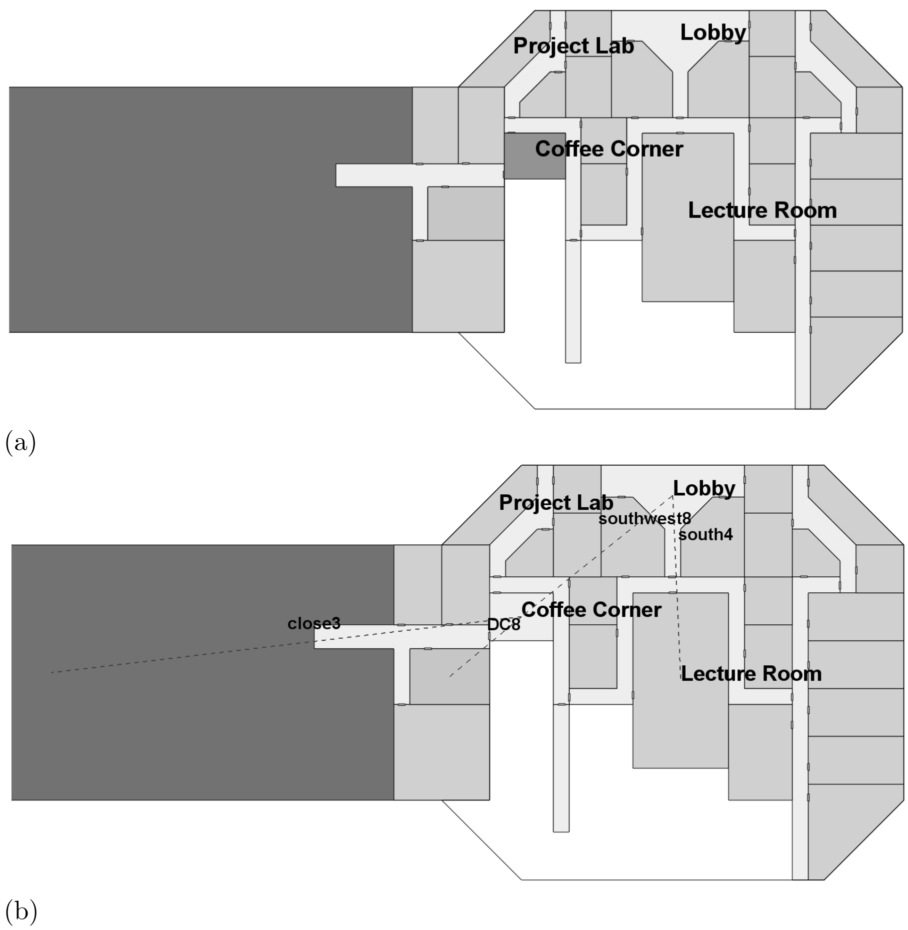

Figure 3: A partially finished design of the proposed annex showing the main rooms (a), and their spatial relations (b).

3.2. The Users’ Perspective

From the users’ perspective, difficulties in finding their way through the building are in focus, i.e., the complexity of the evolving floor plan. For the floor plan analysis, first, the route interaction module builds a route graph using a Voronoi tessellation (see Figure 4a) that 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 [37]. Next, the designer picks a starting node in the graph and an ending node according to the connection between two locations that is to be tested. 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. In the future, this analysis will be further extended to having CoSyCAD automatically analyze the main routes through a building (cf. [38]).

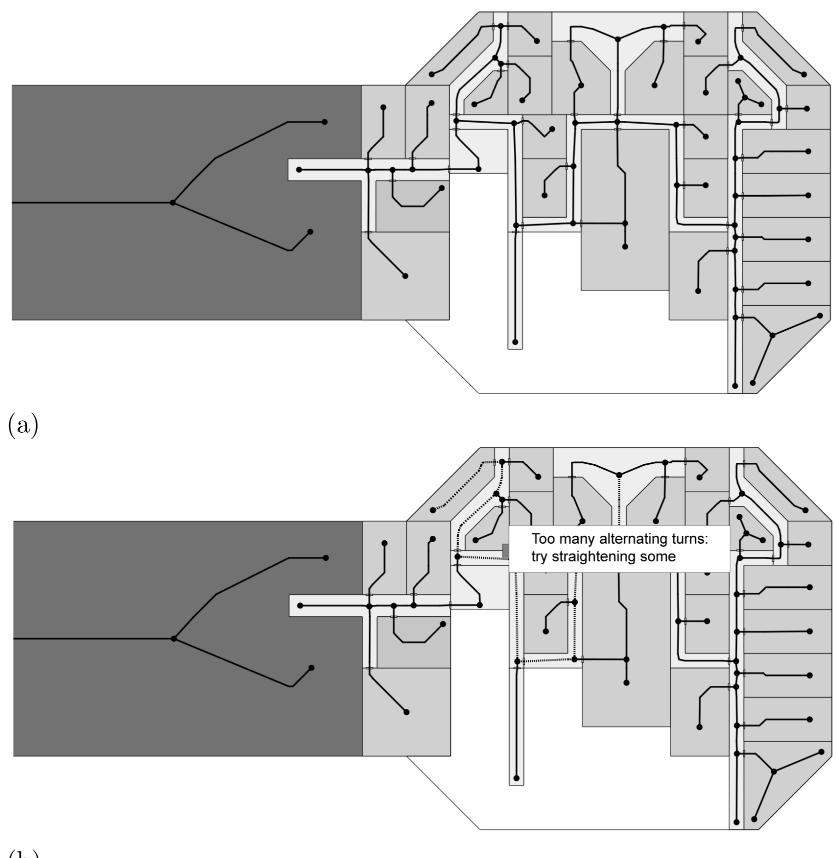

Figure 4: The generated route graph (a), and an overly complex path leading from the lobby to the project lab (b).

The main measure of complexity that 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 them is calculated. Based on the number of branches (a structural measure) and the angles formed between them (a functional measure as it determines the kinds of turns possible at the decision point), the decision points' complexity is determined. According to O'Neill [27] and Mark [26], the more branches there are at a decision point, the higher its complexity. Especially, 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. This holds even more so if more than one branch leads in the intended direction [30]. Directions are checked according to the direction model elicited as part of the wayfinding choreme theory [29]. Competing branches are defined to be separated by an angle less than 45 degrees. Finally, the route interaction checks the angles of the branches at a decision point to determine whether branches require the wayfinder to make a sharp turn. Sharp turns require the wayfinder to turn greater than 90 degrees to the right or to the left of the direction they are facing.

The route interactor warns about possible confusion resulting from the floor plan configuration, suggesting that the designer reduces or alters the number of meeting branches at this point.

In addition to checking the complexity of individual decision points, the route interaction also accounts for the interplay of consecutive decision points. It checks whether or not two consecutive decision points have the wayfinder turning right and then left, or left and then right. Frequent changes of direction, especially in alternating directions, aggravate orientation of users in the building (e.g., [12]) and can make it more difficult to mentally organize the route such that it can be remembered [31]. Therefore, if such alternating directions occur, the route interaction suggests the environment be reconfigured to let the wayfinder proceed in a straight direction, without making both these turns (see Figure 3b).

The results of the wayfinding complexity analysis are visually integrated in the layout's design, exploiting a spatial representation's power. A graphical note is placed in the floor plan to warn the designer of overly complex areas; this note states the reason for the warning and a possible solution for resolving it (Figure 4b).

Example

As illustrated in Section 3.1, the proposed floor plan shown in Figure 3 meets the spatial constraints specified in the relations above. However, the route interaction results in high wayfinding complexity. For example, seven turns are required to travel from the lobby to the project lab. Thus, the initial floor-plan needs to be redesigned.

Based on the warnings provided by the system regarding the reasons for the high wayfinding complexity, the designer reconsiders the design. One such warning states there are too many alternating turns near the coffee corner (see Figure 4b). Based on the accompanying hint to straighten some of the turns, the designer decides to rotate the hallway connecting the 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 5. This design update still meets the spatial constraints and wayfinding complexity is also lower than in the initial design.

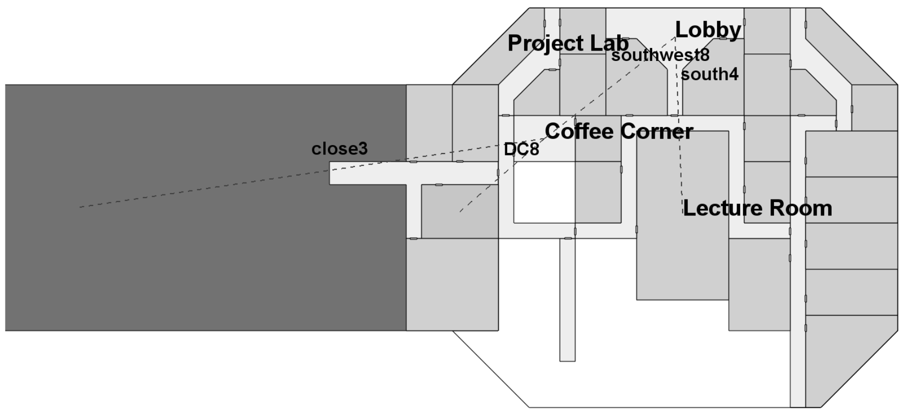

Figure 5: The initial updated floor plan. The spatial constraints are met and wayfinding complexity is reduced to a small extent.

However, looking at this solution, an even better one is immediately obvious, illustrating once again the power of spatial representations and their ability to offer "free rides." Shifting the whole complex around the coffee corner to the south and, thereby, introducing a new corridor connecting the corridor north of the lecture hall with the previously rotated one eases wayfinding complexity drastically. Reaching the project lab, for example, now requires a simple sequence of just three turns (including turning into the lab). In this solution, all static contraints still hold (see Figure 6a). The route graph for the new floor plan is shown in Figure 6b.

3.3. Discussion

As we have illustrated, CoSyCAD allows for a designer considering two different perspectives in designing buildings—the designer's and the users' perspectives. The designer uses (static) representations of an environment in order to offload some of the complexity of the design process. These representations are usually perceived in figural space. The users, on the other hand, have to deal with the real world environment and all its dynamic aspects. The users interact in environmental space.

This consideration can be done in a single design session. The designer can remain in the current design context and can perform the floor plan analysis

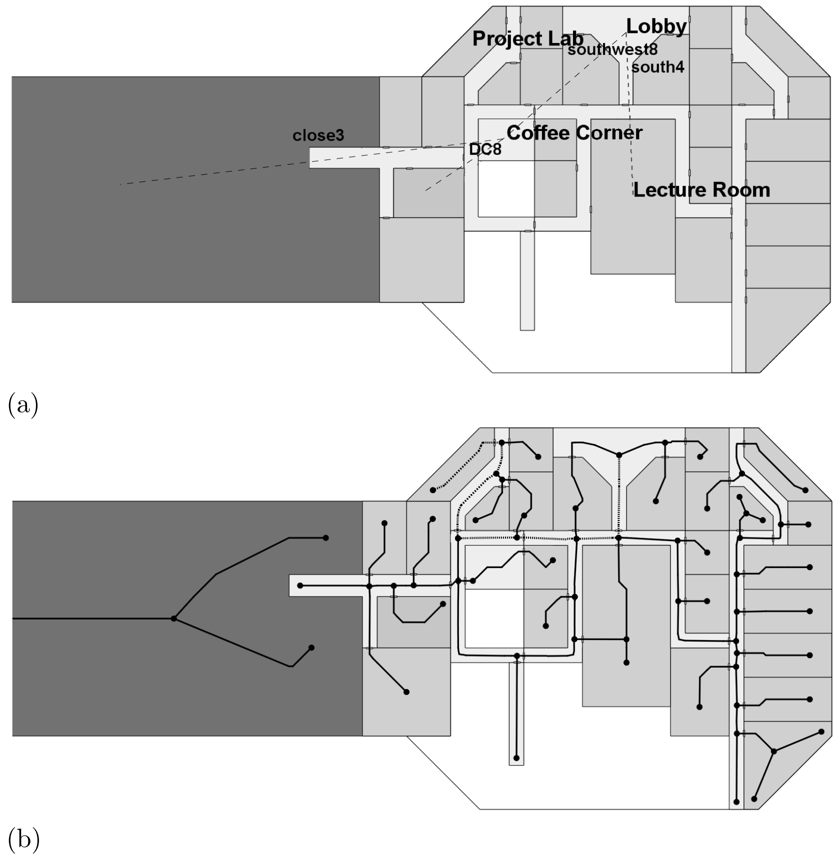

Figure 6: The final step in updating the floor plan. The spatial constraints are still met (a), and the route graph illustrates the reduced wayfinding complexity (b).

just as any other check for constraints. We believe this is of great advantage, as accounting for the users' needs may become a regular, natural step in the design process. Ideally, every major decision for a building's layout should be accompanied by checking for the consequences for the building's users. This will result in an iterative design cycle of creating a layout that fulfills all specified spatial constraints by checking the users' perspective, adapting the design to the results of the floor plan analysis, and re-checking the spatial constraints again. In the end, such a procedure will lower the risk of making decisions in the design that will harm either perspective—something especially likely to happen at the end of the design process.

Taken as a whole, the principles employed in CoSyCAD allow the designer to more readily create designs without having to consider all the spatial constraints at each step in the design process. CoSyCAD demonstrates 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 human short-term memory without having to recurrently go through each constraint after each local design decision. Also, in the presented approach, the designer is still left in charge of the overall design. This is favorable as usually only a subset of all constraints in a design process can be sufficiently explicated and formalized, including layout constraints (see e.g. [7, 39]).

4. Conclusions and Future Work

Humans regularly use spatial representations for human-human collaboration in the domain of spatial design. 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 also very beneficial for human-computer interaction, 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 influence a human's perception is a good start in enabling better spatial collaboration between computers and humans. As research continues, we can expect these predictive cognitive models to become both more complex and substantially more useful. As an example, we introduced CoSyCAD, a system for interactively designing indoor spaces. Currently, it provides interactions for verifying spatial constraints and assists the designer by giving possible reasons for constraint violations. However, future tools will utilize conceptual neighborhoods [40] to automatically generate alternative solutions for the designer and follow up on the modeling of the designer's cognitive factors and preferences. For the users' perspective, we will extend the wayfinding complexity analysis by also accounting for the relation between local orientation obtained at entrances to a building and the overall global orientation of the building, in line with the discussion in [12]. Also, individual differences in wayfinding capabilities need to be accounted for, since recent work has shown there to be a vast disparity between individual abilities in spatial navigation tasks [41].

To more formally capture both a designer's and the users' cognitive factors and preferences, we plan to employ ontologies capturing (parts of) a designer's and the expected users' knowledge. Empirical investigations and consequent modeling of results may be useful to ensure sufficient degrees of adequacy in the ontologies. Such an ontology-based approach will enable a more strict, formal representation and reasoning about expectancies of both designer and user, allowing for a better adaption to the given situation (cf. also [42]). Finally, exploratory empirical studies will provide feedback on a designer's interaction with CosyCAD and will allow for identifying further factors that may help improve users' wayfinding performance.

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