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Chapter 4

# Aspect-Oriented Building Design: Toward Computer-Aided Approaches to Solving Spatial Constraint Problems in Architecture

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Many people from different professions are involved in the design of buildings. Each profession has its well-established canons of design methods and routines. Building design is a rewarding domain for the study of human problem-solving, both on general and specific levels. In this chapter, building design is analyzed from a cognitive science/artificial intelligence perspective. Our focus is on the global role of special-purpose sketches, plans, diagrams, and 3-D models in different phases of building design, with particular consideration of spatial aspects.

Two *leitmotifs* arise from the combination of these constructive and analytical approaches: (a) the use of computational concepts to describe human problem-solving in building design, and (b) the use of computational tools to support human problem-solving in that field. Although computational concepts can be seen as a theoretical contribution to cognitive modeling, computational tools contribute to the development of Computer-Aided Architectural Design (CAAD).

In the first part of this chapter, we describe contrasting notions that are involved in building design. These contrasting notions show that design is such a rich and, at the same time, ill-structured domain that is difficult to describe formally. These contrasts provide the basis for the approach described in this chapter.

The second part of this chapter introduces the concepts of *aspect* and *aspectualization* as applied to building design. We argue that these concepts are adequate vehicles for describing and understanding how the human architect copes with a substantial part of the challenges of design. Two sorts of aspect-based problem-solving are shown to be functional for interrelating mental representations of spatial properties of the building with external representations of physical objects in space and the design process. One sort enables the architect to generate solutions to design problems; the other enables him or her to turn these solutions from theory into existing buildings. Also, we point to conceptions for the description of building design that are related to our approach and make the case that the notion of aspects is critically different from these.

The section beginning on page 89 looks into an exemplary design process and, in this context, makes the notion of *aspects* concrete. By focusing on different layers of spatial properties of the design over time, we will watch a building's story unfold.

The fourth part of this chapter provides a systematic sorting of what the exemplary design process showed. We assume a representation-theoretic perspective and put forth a number of theses about spatial and nonspatial aspects in building design and designing. By reducing the building ad hoc to the instantiation of a spatial constraint problem, we are able to suggest a number of general issues for the design of computer-based agents that will help the human designer to find solutions for the spatial constraint problem.

## THE MANY INSTANCES OF TWO SIDES OF BUILDING DESIGN

As indicated previously, building design is an enterprise characterized by contrasting notions. In this section, we present several pairs of these notions to illustrate the structural complexity of building design.

### Product and Process

Building design is both a product and a process. It is a product in that the notion "design" refers to the building as the physical entity the architect concepts can be seen as a theoretical contribution to cognitive modeling, computational tools contribute to the development of Computer-Aided Architectural Design (CAAD).

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Building design is inherently spatial, as the constructed building takes up physical space. It structures the spatial environment of humans, and it creates spaces in its own right, in which and by which humans navigate. In the same way, designing is an inherently spatial activity, as it requires the conceptualization of objects along with the spatial relations that hold among them. It also involves the manipulation of such concepts, the anticipation of human use of the conceptualized spaces, and, finally, the manipulation of physical entities to create environmental spaces. In the scope of this contribution, we are interested in the spatial structures embedded in the conceptualizations created during the design process of a building, in the role they play for the process as a whole, and in how they relate to the building as the final product of the design process.

### External and Mental Activity

Building designs emerge from an interplay of mental processing with external artifacts, such as sketches, construction plans, models, and design methods that operate on these artifacts. Much research exists on how the combination of specific mental models and specific external representations (e.g. in the coupling of visual mental imagery and visual perception) creates a powerful system that resides at the core of cognitive faculties engaged in design tasks. The working of this system entails new structural insights into the nature of a design task as well as of its potential solutions. Just how it spawns the emergence of spatial concepts in a given architectural design will be among the core issues here.

### Form and Function

Building design has two objectives that do not always harmonize well: A functional objective—the product of the design must permit specific or unspecific applications—and an aesthetic objective—the product of the design should fulfill unspecific or specific extra-practical goals. Hence, design can be defined both in terms of art and craft. In this chapter, we focus on the design of functional spaces, although the principles we discuss are often not limited to that aspect.

### Too Many and Too Few Constraints

Building design involves solving tasks that are under- and overconstrained at the same time. They are underconstrained in that the tasks do not have just a single solution that needs to be determined. Instead, a potentially large variety of alternative solutions may fulfill the requirements of the design specification. To make things worse, many design tasks or subtasks do not seem to have any solution at all. The task's requirements may be formulated in such a way that they correspond to unachievable ideal values such that trade-offs must be accepted to reach a solution. This fact creates new difficulties, as trade-offs require the comparison of incommensurable variables in the design problem. Also, the prospect of trade-offs introduces a dynamic factor in building design whose effect should not be underestimated: It is only during the design process that some features of the design product and the process get specified.

In the scope of this chapter, we assume a modeler's perspective, and try to explain how designers find solutions despite requirements being regularly too few or too many. From there on, we turn from a descriptive to a prescriptive approach where results from the analysis can be employed for improving the design process.

### Rigidity and Flexibility of Design Problems

Building design involves hard and soft constraints. Often properties are not either completely true or false, feature values are not "all or none," and even feature dimensions may be applicable to a higher or lesser degree. "Soft" transitions in the designer's perception of problem structures and properties help him or her with modifying and trading-off design decisions. In fact, making design decisions frequently turns into establishing tendencies and specifying trade-offs between incommensurable feature dimensions rather than choosing between discrete alternatives for the same feature dimension. Here, we especially look at how such interfeature mechanisms structure and manage the building design process.

### Novel and Existing Structure

Building design is about creating and recreating. One of the most efficient ways to reducing cognitive complexity of a design process lies in modifying existing solutions rather than starting from scratch. Such an approach strongly corresponds to how most designers seem to think about their objects of design. They have in mind a complete solution, albeit one that might not be specified in detail, rather than a collection of details to be configured into a complete design. We are interested in how conceptions of space(s) from previous designs influence spatial conceptions in new design processes.

## Human-Made and Machine-Made Products

Building design is, in many respects, open to automation. Computer-based support to the architect or construction engineer exists for virtually every phase and facet of the design process, from the management of early sketches to the semiautomatic generation of plans or CAD models. We look at some of the existing approaches in more detail in the section beginning on page 98. In spite of the success of CAAD tools, however, many parts of the trade currently cannot be addressed by computational approaches, at least not to a sufficient degree. One of the reasons is that design usually involves finding solutions for problems that are hard to describe formally, thus, hard to model and even more difficult to apply to problems in practice. Subproblems, for which constraint solving may not be fully automated, include situations in which constraints preferences, style, or implicit knowledge are involved.

Many authors have pointed towards the issue of *ill-defined problems* in design (e.g. Goel, 1995). In terms of classical problem-solving attributes (cf. Newell & Simon, 1972), all possible products of an architectural design process, including the intermediate products, can be conceptualized as individual states of the process. Transitions exist between states, that is the architect can apply certain design methods to one state and thereby turn it into a different state. Design, then, is the search for a suitable final state in the problem space that is comprised of states and transitions. It is an ill-defined activity as, generally, neither start states, goal states, nor transitions can be fully specified in advance (cf. Simon, 1973). This is the main reason why computational approaches are so difficult to instantiate.

From a cognitive science/artificial intelligence perspective, however, it is exactly this quality of being ill-defined that makes building design so attractive. Entirely human-driven design is no longer a desirable option, and entirely computer-driven design is not yet an option because the process cannot be fully specified. Therefore, humans and computers are required to collaborate. Design calls for an intimate partnership involving both sides, and this partnership, in turn, requires a thorough understanding of the problem structure to be jointly resolved.

### Analysis as a Tool to Improve Products and Processes

The point is that tools at present do not yet support such intimate partnership. This is where this contribution's second *leitmotif*, the use of computational tools to support human problem-solving in building design, ties in with studying design. We argue that for human–computer collaboration in this field to function properly, the computational partner needs to be able to adequately probe and assess the architect's design acts and tailor his actions accordingly. The architect, on the other hand, needs to be able to rely on contributions to the design process by the computational parts that are meaningful and can be consistently interpreted.

Our thesis is that these conditions require a number of different computational cognitive models, among them models of the designer's goals, his or her mental processes and representations, and how these interact with external artifacts (such as a building plan, or a partial construction). Clearly, interaction models of the dealings between the human and computational partner are also desirable. It is the task of the designer of the assistive system to come up with interaction schemes that link up and exploit those faculties of the two partners that are complementary and to establish and communicate to both partners the other subproblems for which activities or faculties overlap.

Thus, each analysis of design and designing has to be instrumental in creating assistance, interaction, and collaboration, all in the service of ultimately enabling better design processes and products. The following section introduces a concept that is especially well suited for closing gaps between the study of building design and the creation of design tools. As the representations and objects we focus on are inherently spatial (plans, CAD models, etc.), it will be spatial relations among objects that play the predominant role.

## SPATIAL AND NONSPATIAL ASPECTS IN THE BUILDING DESIGN PROCESS

If we take home just one message from the discussion of contrasting notions, it is that building design may be addressed in many different ways and from various points of view. In fact, one has to incorporate a multifaceted view if one is to find solutions to the specific kinds of problems that are inherent in the enterprise. In order to get a firmer grip on the domain, we start with a short theoretical investigation into what constitutes building design when seen as a problem-solving activity.

### Nested Feature Space

There are lots of variables that designers of buildings confront. They include fundamental spatial dimensions such as length, width, height, and shape. In addition, there are numerous variables that relate to the building's future use and feel, from normal use to evacuation, from lighting to sound conditions. Abstractly speaking, we can view building design as engaging a large *feature space* generated by such variables. Each point in this feature space in turn may expand into a large feature space of its own, as a decision concerning a given feature opens up yet more dimensions on which to be decided. Theoretically, there is no limit to the degree of nesting of those feature spaces; the nesting corresponds to a hierarchical decomposition of features into subfeatures. In practice, however, there will be a limit when designers resort to the use of predesigned components rather than designing all the details of their components from scratch.

### Properties of Decision Space in Building Design

While the feature spaces correspond to the composition of physical entities from components, or effects thereof, we also can consider another kind of abstract space that is generated by the structure of decisions that are to be taken in building design. We refer to this space as *decision space.* This space is exhaustive in that it consists of all decisions that could be taken during the design process, including those decisions that, in practice, do not need to be made because preceding decisions eliminated their precipitating conditions. The decision space is also high-dimensional when we attribute separate dimensions to separate types of decisions that we could choose to take at any stage in the building design process.

The decision space is closely related to the concept of *design states.* A design state merely pertains to the state that the process of building design is in at a given moment. We can conceptualize the decision space as a structure built on the set of all theoretically possible design states. Depending on the actual problem and the design methods employed to solve it, the decision space can be as simple as a sequence or tree. Generally, it is a directed graph, in which the nodes correspond to individual design states and the directed edges to transitions between states.

Edges in the graph are directed, as not all transitions are reversible. Where such reversal is possible, a transition and its reverse still differ conceptually and should, thus, also be denoted separately.

### Building Design as an Ill-Defined Problem

We have already pointed to the issue of over- and underconstrainedness in the typical building design problem. As a matter of fact, much of the classical problem-solving literature describes design as a prototypically ill-defined problem-solving activity (cf. Simon, 1973). This characterization holds for design in general as it does for building design in particular. On the one hand, the fewer the constraints, the more design is a matter of art rather than of craft. On the other hand, the more well-established and prescriptive a field of design, the more it is amenable to the descriptive mechanisms offered by classical problem solving.

### Dynamic Variations of the Decision Space

One may argue at this point that houses, airplanes, tools, and so forth are all products of design processes and that they are successfully designed and constructed by humans every day; thus, the degree to which the underlying design problem is defined seems to matter but little. It is, in fact, reasonable to assume that human problem solving in design is somewhat different from the search-through-problem-space paradigm of classical *Human Problem Solving* (Newell & Simon, 1972) and that other additional mechanisms are at work.

One also has to keep in mind that the set of all possible design states is an abstract conception. The building designer will never consider all design states, nor will he or she touch all state-to-state transitions that exist in a specific decision space. At any given moment during problem solving, with particular problem states as the current ones, commonly not all possible outgoing transitions are considered for next actions. Rather, there exist preferred sequences in which values are assigned to a problem's individual features, resulting in preferences in exploring, considering, and choosing certain substructures of the decision space over others (cf. Katz, 1994).

To quote Börner (2001), "Design tasks are inherently complex" (p. 3). If this is indeed the case, then how do designers manage to solve them, nevertheless? One strategy involves extensive use of defaults in the case of underconstrained problems. In many cases, decisions regarding which defaults to set and which values to assume seem to be guided as much by professional experience as by setting constraint priorities.

In addition, even for intermediate design steps, concrete solutions are preferred over abstract ones. Let us return for a moment to properties of mental problem solving in the human reasoner. Problem solving in the architectural domain requires the integration of various kinds of information with various demands. Mental models (Johnson-Laird, 1983) are dynamically assembled constructions in working memory constructions. They serve integrative purposes in that they are instantiations in which available information and demands are coherently arranged. Mental model-based problem solving is thus specific, and instead of the systematic construction of all possible models, only some are constructed. Preferences in mental models and mental model construction further come into play (cf. Knauff, Rauh, & Schlieder, 1995; Schlieder & Hagen, 2000) as well as specific ways of representing the relevant domains.

### Aspects and the Process of Aspectualization

The restriction to subsets of design states and transitions is, in fact, one of the main characteristics of human design. In terms of decision space and design states, what happens from the designer's perspective during a building design process? The part of the decision space that the designer considers varies over time, as its edges are dynamically activated or deactivated depending on the decisions taken along the way. The mechanism at work is analogous to dynamic multiband filtering, in which the parts of the spectrum that pass through the filter are continuously varied. Here, of course, it is not different wavelengths that are filtered. Instead, certain features of the problem space are dynamically chosen to be considered during the next design step, which results in others being simply ignored for the time being (see Fig. 4.1). In the following, we use the term *aspect* to denote a feature dimension that has been dynamically chosen in such a way (Bertel, Freksa, & Vrachhotis, 2004). We will use the term *aspectualization* to refer to building design processes that are driven by a selection of aspects.

### Properties of Aspectualization

The point has been often made that abstraction is the key to effective design problem solving (e.g. Liu, Bligh, & Chakrabarti, 2003). But how are the concepts of abstraction and 'aspectualization' related? Are they synonymous? We argue that they are not. The mechanism of aspectualization is one of selection rather than of omission. The distinction becomes

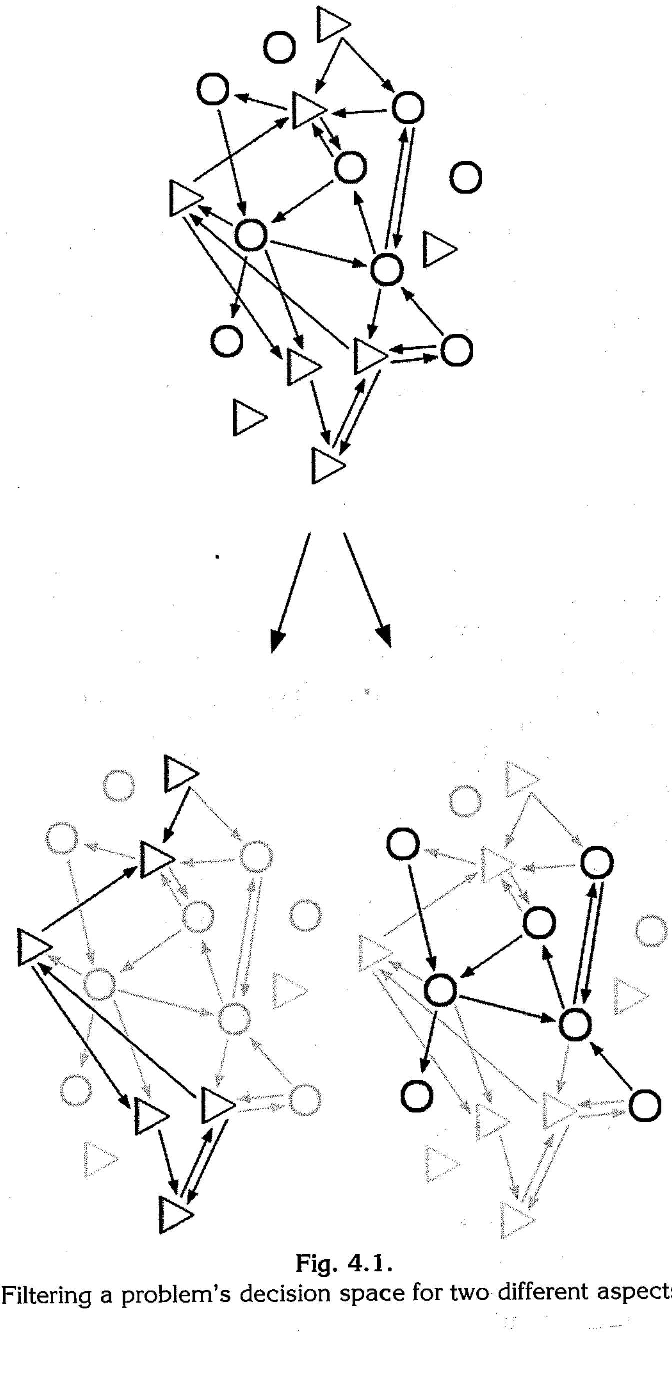

**Fig. 4.1.**
Filtering a problem's decision space for two different aspects.

significant when we deal with open problem spaces as we always do in building design. Omission of certain aspects still leaves us with an open problem space that we cannot completely specify. Selection of certain aspects, in contrast, is solution-oriented and provides us with a closed world that we can deal with much more easily. Formally, aspectualization is a special kind of abstraction, as it condenses knowledge.

For a systematic approach, we propose to distinguish among three types of aspectualizations by way of antonyms: (1) aspectualization versus concreteness (i.e., the variation is in the degree of instantiation of the feature values); (2) aspectualization versus specificity (i.e., the number of feature dimensions considered varies); and (3) aspectualization versus integration (i.e., the degree of interdependency of feature dimensions in the context of the overall design is altered). All three types play essential roles in solving design problems.

### Reduction of Problem Complexity

Aspectualization of a design problem can result in representations that include features across various feature dimensions, many of which are spatial (length, width, height, shape, and so forth). These representations are typically tailored for specific purposes. Because an aspectual representation specifically embraces the properties and needs of the processes that operate on it, high degrees of efficiency can be achieved. The cognitive benefits of using aspectual representations lie in a reduced processing load. Because much information is omitted, a more focused context is provided and stronger structural analogies are possible between problems, problems solving, and problem representations.

In comparison to novices, experienced architects have learned to develop different viewpoints and perspectives of a building by directly using an assortment of aspects. With so many features to handle and mental models to be built, selection of features becomes a crucial task. Aspects provide criteria for making the selection, and choosing the right aspects must thus be seen as a key factor for successfully solving design tasks.

On a more abstract level, we can compare aspect-based design problem solving to problem solving that is based on abstraction in general. Standard problem-solving methods for dividing a complex problem into subproblems (e.g., "*divide and conquer*") often produce subproblems that differ from the complex problem in complexity but not necessarily in the number of feature dimensions involved (see Fig. 4.2 for an example).

The essential identifying characteristic of aspectualization, in contrast, is the reduction of problem complexity through the reduction of the number of

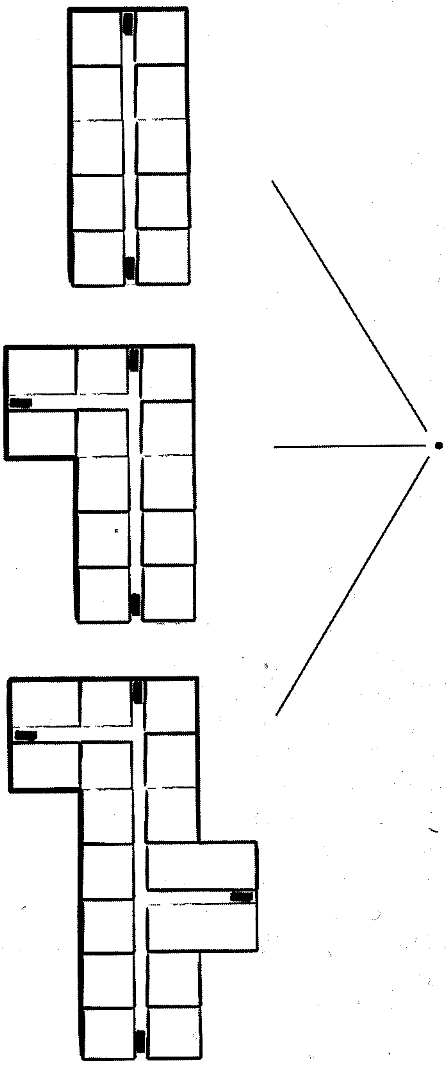

**Fig. 4.2.**
Schematic depictions of dividing a complex problem into subproblems that are reduced in complexity but not in number of feature dimensions.

feature dimensions (see Fig. 4.3). In the end, it is this reduction that is responsible for creating closed subproblems from open problems and for gradually turning an ill-defined problem into a number of well-defined ones.

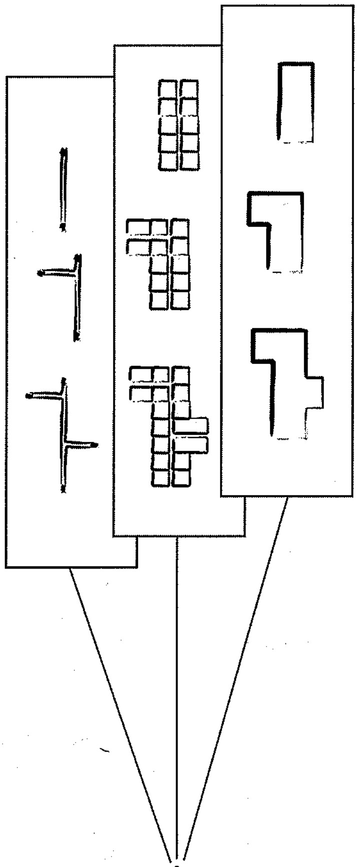

**Fig. 4.3.**
Schematic depictions of dividing a complex problem into subproblems that are reduced in complexity by reducing the number of feature dimensions (aspectualization).

### Aspect-Oriented Building Design

It is intriguing to see how, by considering different aspects in sequence, the building designer can create a series of closed subspaces from the open decision space and, in so doing, is actually able to complete a design.

The use of preferred sequences in assigning values to the various feature dimensions of a problem results in the application of a series of different aspect filters, which in turn produce the dynamic variation in the extent of the filtered decision space described previously. The selection of aspects for a given design step reflects the context-sensitivity of design. Each decision opens up or precludes certain subsequent decisions, respectively. As a result of considering only a subset of all aspects for a certain design decision, a designer's decisions are often not irrevocable. Rather, they may serve as tentative assumptions to set the stage for further considerations, and they may be revised later. The underlying feature dependencies make building design a complex decision process.

The design of buildings generates many intermediate design products *en route* to the building as the final step of the process. From many building design studies, we know that architects produce a host of different sketches and models, especially during the early phases of a project. These products in fact play an important role for successful design (Akin, 1998; Do, 2002; Do & Gross, 2001, 2002). They can differ significantly in scope, degree of completion, and quality. We see examples of this in the following section. Among others, the products serve the purposes of exploring and charting the design problem. On a functional level, the host of products serves to approach an ill-defined problem from many angles and gradually specify start states, goals states, and transitions between states.

Aspects and aspectualization help to explain why intermediate products play such an important role. On a theoretical level, aspectualization often results in closed subspaces of the decision space; on a practical level, it allows for the creation of prototypes at early stages of design. A design product is a model that instantiates the set of constraints that comprise the design problem. If this set is ill-defined, however, how can it be instantiated? Creating intermediate design products (each of which is based on different closed partial problems) is much easier than creating even one product for an open problem. In that respect, it is the focus on different aspects at different times that makes prototype-based design an option. Functionally, it is the mechanism of aspectualization by which parts of the building design problem are explored and solutions generated.

### Selecting the Right Aspects

Aspectualization of a design problem inevitably leads to the creation of various partial problems that are, at least at some point during the design, treated individually. It is no surprise, then, that the structure (i.e., order) of aspects that are focused on is the key for a successful solution to the partial problems, just as it is for the solution to the complete problem. We have already discussed that the feature space is not searched completely. Instead, there exist preferences for the order in which features are considered and in how the selection of the features is accomplished.

This is the conceptual point at which architectural design methods come into play. As an example, Fig. 4.4 illustrates a conceptualization in design in terms of layers and the selection of certain features across layers for an intermediate result. Based on the idea that sketching and scribbling is important especially during the early phases of architectural design (Do, 2002; Do & Gross, 2001), we can identify a course of action that exhibits a specific method of design processes, specifically, *"thinking in layers"*. Architects are trained to draw and use diagrams to communicate their thoughts and to describe ideas and suggestions. Characteristic of a designer's sketching actions is "re-drawing" (Do, 2002), in which the designer repeatedly outlines a particular area of a drawing, for example, as in an effort to define a building's final shape.

Obvious other candidates for feature selection mechanisms are architectural design methods on top levels (e.g., the so-called *"big idea"* that structures the building design process: *"This building should be like a tent"*) and techniques on lower levels of abstraction, such as the use of volumetric primitives for depictions in some design stages (which, in turn, entails detailed prescriptions of which features are to be included). No less important but perhaps less obvious in its influence on feature selection are the designer's personal cognitive preferences.

## OBSERVATIONS FROM AN EXEMPLARY BUILDING DESIGN PROCESS

Before looking at some conceptual strategies with respect to spatial design elements, it seems necessary to lay out some groundwork regarding the common idea of building design and building analysis. There are several ways to classify and specify building design, depending on what we want as an outcome. A spatial-cognitive approach to building design allows for a better analysis of the built environment with respect to perceiving the spatial nature of the building and of the mental representations induced through interaction with the design.

### Characterizing Building Design

Designing a building is more than just choosing a form. Building design deals with the design, construction, and conceptualization of built space. Akin (2002) clarifies that the architect aims at constructing buildings as complex systems of numerous architectural aspects, such as functional, aesthetical, emotional, or psychological aspects.

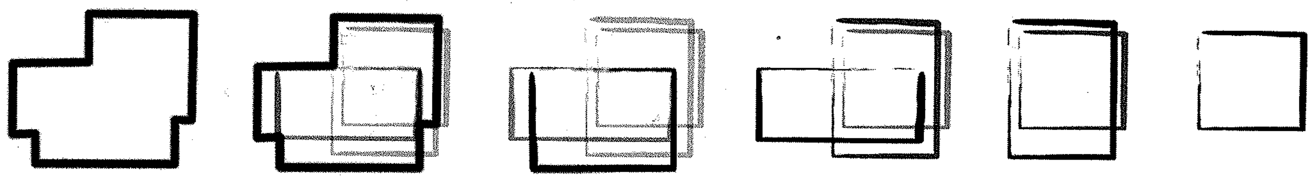

**Fig. 4.4.**
Thinking in layers is one traditional method in architectural design that requires sequences of design steps. It results in a gradual refinement of ideas in sketches.

Building design is a purposeful, goal-oriented decision-making activity that attempts to resolve conflicts arising in the design process. The outcome should be the best possible state or balance over time, therefore creating the best possible architectural quality. Conflicts arise, for example, when the architectural quality of the building for all parties involved is not factored into the equation or when two or more requirements seem to be mutually exclusive.

Discussing the design of an existing building also means analyzing the interrelations involved in its emergence. Whoever develops a design, whether it is an ensemble of buildings, a single building, or a part of a building, basically is concerned with a given functional program, a location or a site, and the client's wishes. The activity of arranging all the relevant design data and facts before starting to design the building is called *programming* and can be seen as a framework for structuring the problem that has to be solved by classifying both the existing and future facts (i.e., constraints). Structuring existing and future facts has a great influence on the later stages of building design as the architect is faced with a number of fixed percepts and hard constraints, for example, those provided by the client. Finally, the design of a building must satisfy conditions of functionality, usability, and construction in accordance to the client's requirements. Knowledge of how to fulfill all these requirements and expectations is one of the keys to successful building design.

### Organizing Building Design Data

The act of programming describes important facts, acknowledges conflicting interests, and works to resolve major conflicts before the building design takes its final shape. According to this description, we should distinguish two directions of programming. One refers to the existing state of the design project; the other to the future state of the design project.

Analyzing relevant data about the existing state is an important step to understanding specific constraints of a given building design problem. Facts relating to the building site, the building users, the culture, or economics, should be uncovered. Facts are not matters of opinion; their existence can be verified. For example, facts of the building site consist of views to and from the site, the existing topography, flora, climate, available utilities, the visual context, existing behavior patterns of the people who use the site, potential future trends, or economics.

Generally, there are four steps in developing a building program to describe the future state of a design project. These steps are to create a mission statement, develop project goals, design measurable performance requirements, and develop a building concept. In order to integrate this kind of predesign into the general building design process, we have to identify common architectural design elements that architects use to communicate about existing states and the client's wishes. We must know the elements of the building design to specify the way architects communicate about buildings.

### Identifying Building Elements

The design of buildings can be seen in a number of ways. Building designers often base their classifications on spatial features, such as geometric, topographic, aesthetic, and functional features of building design. For a building design analysis, there exist three main points of viewing the building (Rowe & Koetter, 1978). First, the building can be described in terms of its existing context and interpreted according to various aesthetic design principles. Second, the building can be examined for its architectural usability and its conformity with theoretical prescriptions of what constitutes a "good form" in architecture (cf. Lynch, 1981). Third, the study of a building design can involve observing what architects and designers do during the design process.

With respect to this last perspective, architectural design has often occupied an ambivalent position, being described variously as a form of fine art or as a form of technical science. Spatial elements of the building include essentials of construction, such as walls, columns, or girders, and functional areas, such as pathways or public entrances. Building elements often can be described in terms of their basic geometric form, for example circular or quadratic space. According to various ways of breaking down the design process into its components (cf. Lawson, 1980; 1994), every building can be classified and grouped by its spatial elements with respect to its design. To better understand the relations between the spatial elements of the building and their characteristics as aspects within the spatial problem-solving process, it is necessary to look into various layers and at particular steps within the building design process.

### Designing a University Building

In the following section, we provide examples of design processes. We analyze design options of a current building design project at the University of Bremen. From an architectural point of view, the building design consists of three functional building sections visualized as a composition of three volumes: A longish main part of the building structure that includes most of the offices and research rooms, a small added cube that includes a public area and the main entrance to the building, and a rotunda placed within the small section functioning as a communication area and the main auditorium of the department.

This example clarifies the architect's play with form and function and provides an adequate design solution by finding a composed balance between the three building parts. It clearly illustrates the process of programming relevant building data and of generating the form of the building with respect to its function. Thus, it provides insight into the emergence of an architectural concept.

## Form and Function in Building Design

While interpreting the client's brief and engaging in the initial consideration of design, the architect is led to the creation of a concept. In this connotation, a "concept" is a very general notion in architecture, an abstract idea or a mental image. It expresses the idea underlying a design and can appear in an early sketch, an object, or text. It provides directions to spatial design decisions, organizing them and developing variants. According to this interpretation, the concept for the university building can be seen as a diagrammatical sequence in which all three building sections (main building, small cube, and rotunda) emerge into the final building design. To achieve this design, first, the main building section was conceived; second, a significant part of the main building was chosen as the location of the added cube; third, the communication area was located schematically within the cube; and finally, the rotunda was defined in relation to the cube and the main building. (see Fig. 4.5).

## Unfolding the Building Design Process

To illustrate the unfolding of this particular design story through exemplary design steps, we focus on the most iconic section of the university building, the rotunda. Consistent with the idea of building design as both process and product, we first highlight various layers early in the design process and then show aspects of the final building design.

## Classifying Interrelations between Design Steps and Design Layers

We have identified various design layers, namely *shape, volume, position,* and *pathways layers,* with respect to both form and function (see Fig. 4.6).

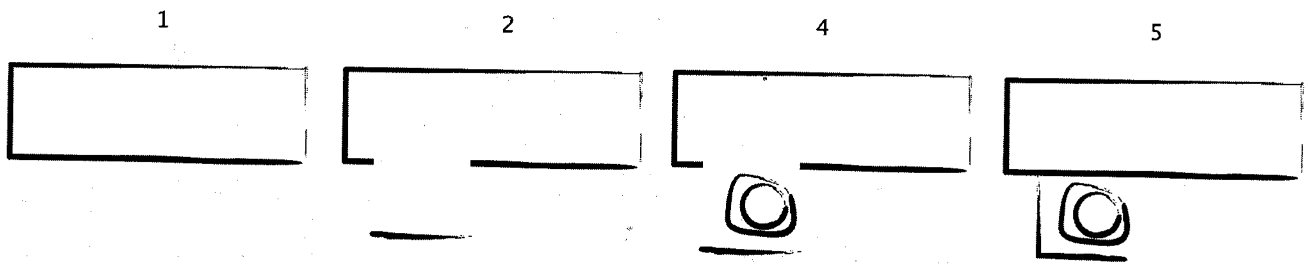


**Fig. 4.5.**
Exploration of form and function of the Bremen rotunda.

These four layers are illustrated as horizontal panels interconnected by specific relations and intersections. To specify and characterize the particular interrelations among the four layers, we analyze briefly sequences within the design process. Analyzing the diagrams and their interrelations can help us better understand characteristics of the design process.

- Looking at the shape-layer of *steps 52* to *87*, the architect starts sketching out particular form variants of important sections of the building very roughly, but always with respect to the building's function, the overall architectural concept, and the client's specifications. In this case, one of the client's requirements to the architect was to be inspired by the shape of an existing rotunda of another building.
- At *steps 112* to *187*, shaping and modeling the layout of the rotunda and its position (see *position-layer)* in the building results in an interim functional design evaluation. Thus, on the *pathway-layer* the generated shapes of the *volume-layer* were verified from a more functional perspective, regarding aspects of, for example, circulation, pathways, entrance situation, and elevator location.
- From the *pathway-layer* at *steps 187* to *303*, the shape of the rotunda is re-designed and redeveloped with respect to its volume and position (see *volume* and *position-layer*).

### Expanded Aspects of the Final Building Design

Because a wide variety of people, ranging from clients to professionals in engineering, acoustics, and building service, are involved in the design of buildings, the architect has to select adequate techniques of visualizing spatial information. As shown in Fig. 4.7, the main blueprint (on the bottom) can include a number of subdocuments, each with its specific spatial information, such as public circulation area (second from the bottom), network of escape routes (third from the bottom), or the main structure of the building (on the top). This example illustrates the fact that the architect must create visualizations of specific aspects of the building for specific professions. This process involves selectivity; it is not necessary to represent particular aspects about acoustics to the engineer who is concerned with the building's superstructure.

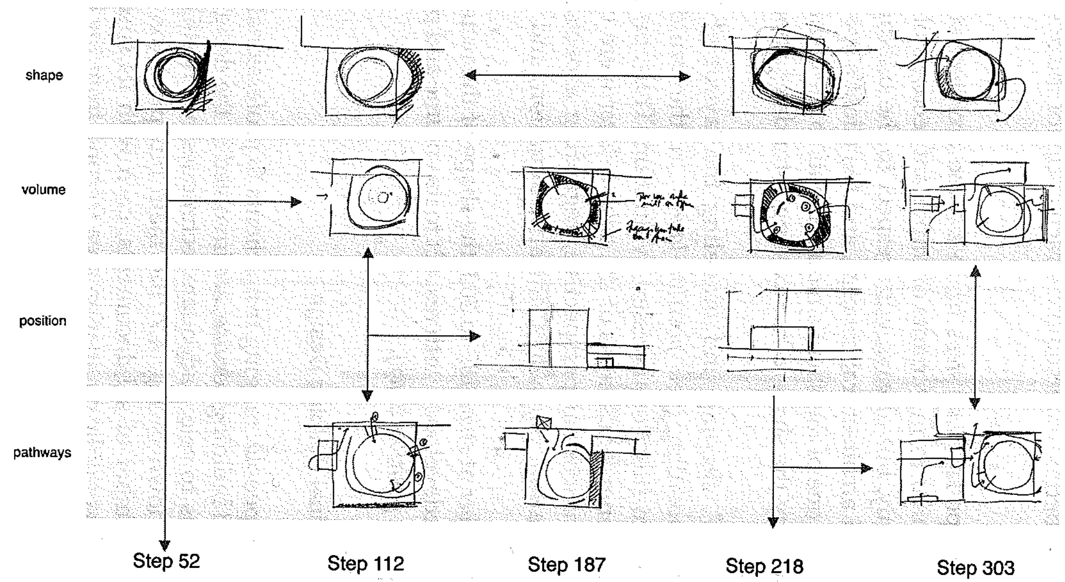


**Fig. 4.6.**

Steps of the design process regarding shape, volume, position, and pathways. *Steps 52 to 112*: Shaping the rotunda by rough sketches in respect to an existing rotunda in another building. Should the rotunda be positioned outside of the main building as a specific building part for communication? *Steps 112 to 187:* Thinking about a nonsymmetrical shape of the rotunda. Should there be two walls to create a small hall way? *Steps* 187 to 218: Evaluating the position of the rotunda by thinking about circulation pathways in respect to the elevator and the hallway. How is the user's everyday access to the rotunda? Steps 218 to 303: Going back to the shape again. Various modifications of the rotunda to a more organic, non-geometrical shape.

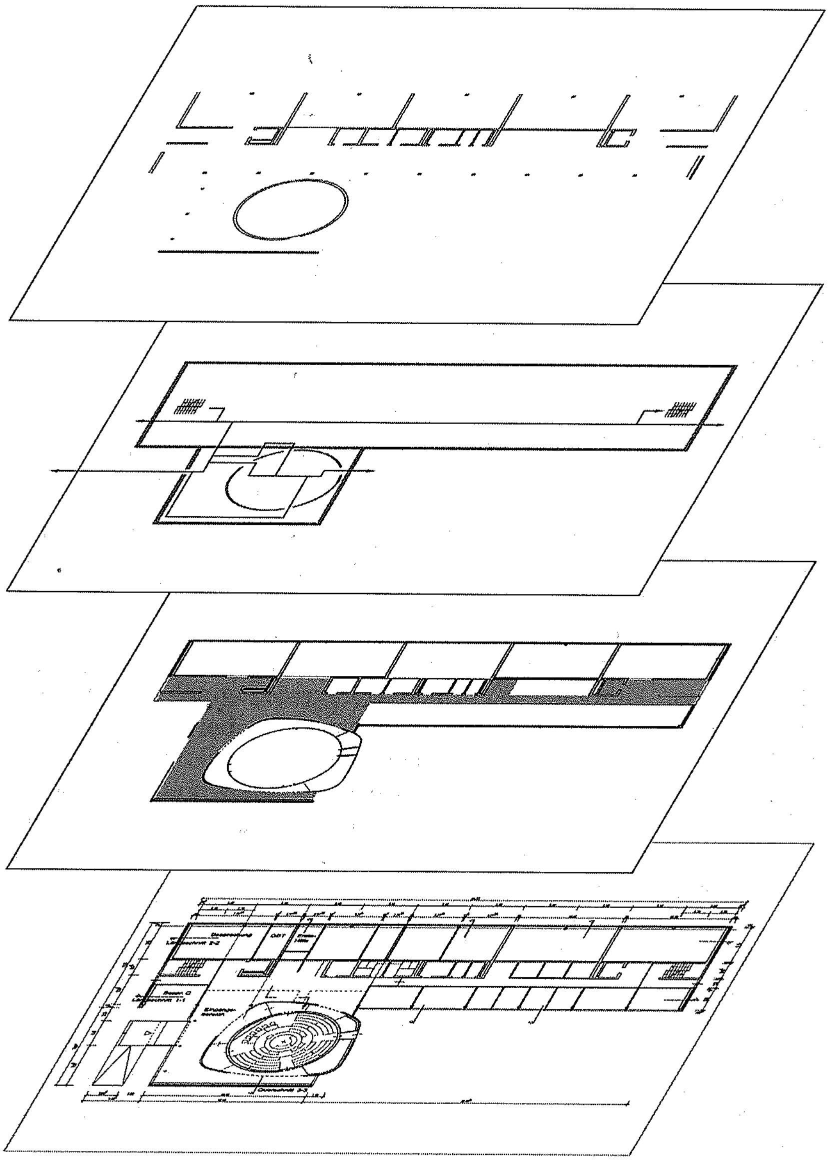

**Fig. 4.7.**
From bottom to top: (a) the complete blueprint of the university building including Do those changes influence the user's behavior? How? all spatial information produced by the architect; (b) an illustration of the circulation area; (c) showing different escape routes on the floor; (d) focusing on the structural framework of the building.

## THESES ON ASPECT-ORIENTED BUILDING DESIGN

Once we look for evidence of aspect-based design in the case of the Bremen rotunda, we find that it, in fact, permeates all levels of the process. Aspectual representations in early design stages included studies of the annex' general geometric form. Intermediate design stages yielded hand-made and CAD drawings that focused on functional aspects of the building, such as positions and pathways. Functional representations were refined in later stages as aspectual plans of the entire building centered on structural and construction issues, among others. Each of these representations had its particular role in the building design as a whole, but none actually represented the whole design.

### Semantics of Products in Building Design

Representations typically make sense only when they are paired with a process that operates on them. In building design, we are confronted with a host of intermediate and final designs that are produced in the design process and that are meaningful at the moment and in the context in which they are created.

The majority of the design representations presented were in diagrammatic formats. Although, in principle, representations of all formats (including propositional formats) can be aspectual, there are good reasons why diagrams are so prominent in aspect-oriented building design. In the design research literature, for instance, we find that diagrams may be part of the dialectic involving a reasoner's inner processes and the external world (Goldschmidt, 1991), part of an "eternal loop" (Gorayska & Mey, 1996) in which mental constructs are externalized, internalized again, externalized, and so on. The reasoner and his or her sketches enter into an intimate dialog; they become "a team of one" (Goldschmidt, 1995). The semantics of a design product is thus not only determined by its structural (i.e., temporal) position in the design process, but also by the mental interpretation associated with it by the designer.

The dialog between designers and their sketches is affected by a variety of factors, including level of experience and expertise. An expert's sketches may be more structured and, therefore, offer more clues for perceptual and cognitive inferences than comparable sketches of a novice. Self-produced sketches may be more ambiguous for novices than for expert designers (Kavakli & Gero, 2001), and the graphical "language" used in the reflexive dialogue between the novice sketcher and his or her own sketch may be less refined and stable. Additionally, the notion of a sketch's interpretative stability may account for differences in reinterpretation of mental and external images (e.g. Verstijnen, Van Leeuwen, Goldschmidt, Hamel, & Hennessey, 1998).

### Collaboration Through Diagrams

The intimate relationship between the designer and his or her design products that usually drives design, however, turns into a communication task where more than one designer are involved. In such situations, graphical representations are used for communication purposes (Healey, Swoboda, Umata, & Katagiri, 2002). Under these circumstances, the stability of sketch interpretation has an influence on the development of interpersonal graphical codes. By establishing "common ground" among team members, stable codes can lead to a reduction in the cognitive load involved in interpretation (Giordano, 2002).

Graph-based communication involving two or more designers is naturally less closely coupled than is the "dialog" between a designer and his or her sketches. Two or more designers require that much of the otherwise implicit interpretations need to be negotiated and made explicit. This may be one reason why, with certain tasks, teams have been found to produce significantly fewer diagrams and less effective ones than is the case with individuals (Heiser & Tversky, 2004).

### Requirements for Computer-Aided Approaches

In theory, a building design team comprised of a human designer and a computer-based electronic partner should be comparable to one in which the team consists of two human designers. In both partnerships, team members communicate (e.g., through common diagrams and language) for effective collaboration to take place. Accordingly, there is little room for an intimate "team of one" made up solely of the human designer and his or her generated design products.

Yet, it is important to note that human and computer-based electronic partners diverge in terms of their respective reasoning abilities and limitations. This divergence creates an asymmetric collaboration that differentiates such design teams from those that only have human members. As collaboration is asymmetric, so also are the communication needs between partners.

Computer-based systems whose goal it is to assist the human architect in building design have to take these asymmetries into account. In fact, their designers should make every effort to ensure that they disturb as little as possible the private dialog between the human designer and the external design representations. The system should intervene in the design process only on the basis of need, as, for example, when the human reasoner specifically calls for assistance, or when he or she pursues reasoning tracks that clearly will lead to no design solution.

But how can such a reserved role on behalf of the computer-based partner be reconciled with both partner's extensive communication needs? We would like to propose that one potential answer lies in using a variety of unobtrusive sensors to record the behavior of the human designer and to feed resulting data into computational cognitive models that map graphical entities on a diagram onto conceptual entities in the design problem.

### Outlook

Building design is a highly complex task and will always remain so. The human architect is good at certain subtasks of building design, and computer-based systems are good at others. The tasks best performed by humans and by computer-based systems overlap only in part. Consequently, there is enormous potential for human-computer collaboration. Humans tackle design problems by aspectualization in order to reduce problem complexity. If they are to collaborate effectively with computational systems, these systems will have to follow the human designers' temporal sequence of aspectual representations. Future work will have to produce specifications for the design of computational systems in aspect-oriented building design. In particular, these specifications will have to address issues of how to find an adequate sequence of aspects in which to successfully address a design problem and then integrate partial results from aspect-based design into a solution for the entire problem.

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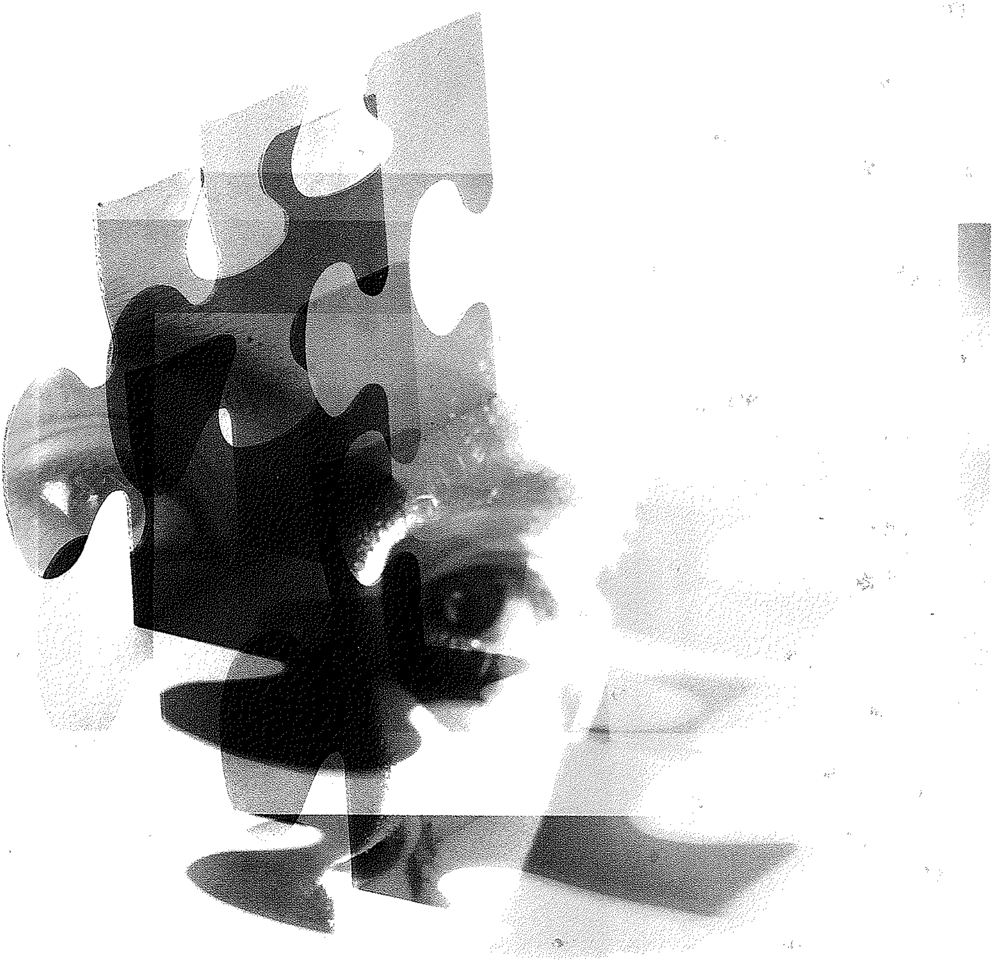

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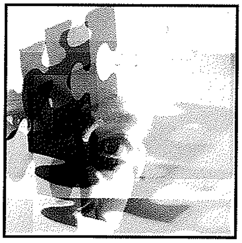

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