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ASPECTUALIZE AND CONQUER IN ARCHITECTURAL DESIGN

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Abstract. This paper describes architectural design processes from a cognitive science/artificial intelligence perspective. It characterizes the design task in terms of classical AI problem solving attributes. As architectural design specifications leave many relevant dimensions unspecified, it is a fascinating question how these dimensions are fixed during the design process. We identify general strategies to cope with the complex space of spatial design by considering cognitive approaches to understanding and problem solving. The AI "divide and conquer" problem solving strategy is adapted to the common design strategy of reducing problem complexity by focusing on different aspects of the design problem at a time. Examples from design principles in architecture are presented.

1. The Designer's Dilemma

The domain of creative design in general and the domain of architectural spatial design in particular pose special challenges for the modeling of the processes involved. We will briefly outline some of the characteristics of the problem space that architects are confronted with. We will use concepts and terminology from computer science/artificial intelligence to describe the architectural domain. In the article, we analyze the design problem from a knowledge representation and reasoning point of view. For this purpose, various abstract spaces are introduced to characterize the design task and the design process. In this framework, cognitive principles are considered and applied to principles from architectural design.

1.1. DESIGN IS FOR HUMAN USE AND FOR PLEASURE

Architectural design has two objectives which 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). In this article, we focus on the design of functional spaces, although the principles we discuss seem not to be limited to spatial design.

There are lots of variables designers can ‘play around’ with: they include spatial dimensions like lengths, widths, or heights; shapes, materials, colors, to name but a few. Abstractly speaking, we can view design as consisting of a large feature space spun up by such variables; each point in this feature space in turn may expand to a large feature space by its own as a decision for a given feature value opens up yet more dimensions to be decided upon. Theoretically, there is no limit to the degree of nesting of those feature spaces; the nesting corresponds to a hierarchical decomposition of features into sub-features. In practice, there will be a limit when designers resort to the use of pre-designed components (rather than designing all the details of their components from scratch).

1.2. DESIGN ACTS IN HIGH-DIMENSIONAL DECISION SPACES

While the feature spaces just described correspond to the composition of physical entities from components, we also can consider the structure of decisions to be taken in the design process as abstract spaces. The corresponding decision space consists of all decisions that could be taken during the design (including those decisions that do not need to be taken because preceding decisions eliminated certain options that might exist when previously different decisions had been taken). This decision space is a high-dimensional space when we attribute separate dimensions to separate types of decisions that we could choose to take at any stage in the design process.

1.3. DYNAMICS OF FILTERED DECISION SPACE

The decision space can be conceptualized as a structure built upon the states of the problem space. Depending on the actual problem and the methods employed to traverse the problem space, the decision space can be as simple as a sequence or a tree; however, generally, it is a directed graph, in which the nodes correspond to individual problem states and the directed edges to transitions between states. Edges in the graph are directed as not all transitions are reversible, and where they are a transition and its reverse still differ conceptually and should, thus, be denoted separately.

It is one of the key properties of designing that not all states of the problem space are considered during a design process; the same holds for the state-to-state transitions from the decision space. Also, at any given instant during the 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 (Katz 1994).

As a result, the part of the decision space that is considered at a given time varies over time as its edges are dynamically activated or deactivated depending on the decisions taken along the way. The mechanism compares to dynamic multi-band filtering, where the parts of the spectrum that pass through the filter are continuously varied: Here, it is not different wavelengths that are filtered but, rather, certain *aspects* of the problem space are dynamically chosen to be considered during the next design step, resulting in simply ignoring others (at least, for the time being). Aspects often correspond to feature dimension in the decision space, Figure 1 shows an example.

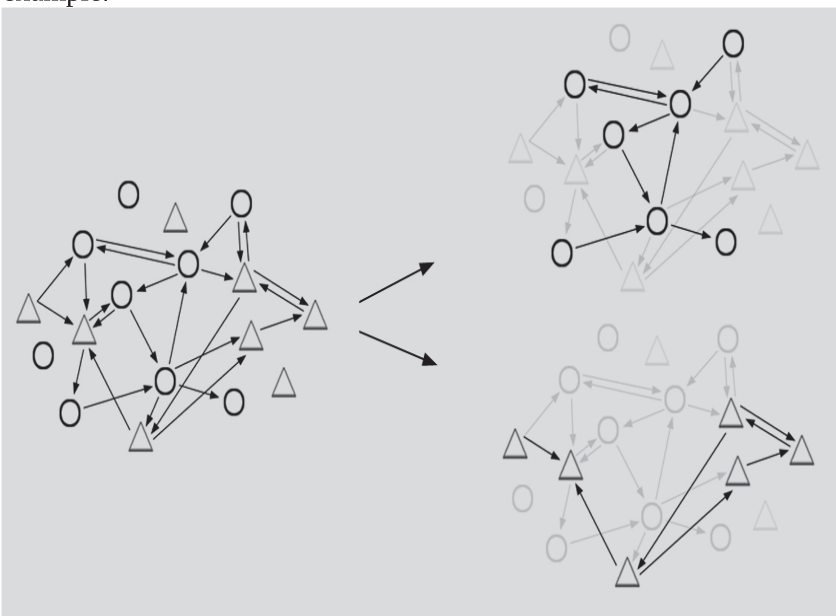

Figure 1. Filtering a problem's decision space for different aspects

Preferred sequences in assigning values to the various feature dimensions of a problem result in sequences of using different *aspect filters*, which in turn produce the dynamic variation in the extent of the filtered decision space described above. 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, the 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 design a complex decision process. We will investigate some of the characteristics of the selection and decision processes in more detail later on, with a particular focus on information processing and complexity issues. The role of aspects in design problem solving will be a recurrent theme throughout the remainder of this paper; in particular, it will be the topic of Section 4.

1.4. DESIGN TASKS ARE UNDER-CONSTRAINED

Design tasks do not have just a single solution which needs to be determined; a potentially large variety of alternative solutions may fulfill the requirements of the design specification. In terms of the feature space, this means that many nodes in the decision graph may correspond to solutions of the design task. Furthermore, there may be several or many different routes in the design decision graph that lead to a given solution, as certain decisions can be sequenced in a variety of ways.

1.5. DESIGN TASKS ARE OVER-CONSTRAINED

To make things worse: many design tasks do not seem to have any solution at all. The requirements may be formulated in such a way that they correspond to unachievable ideal values such that trade-offs must be accepted to enable a solution. This creates new difficulties as trade-offs require the comparison of incommensurable feature dimensions.

1.6. HARD AND SOFT PARAMETERS

Fortunately, the world is not black and white. In our conception of the world, properties are not either 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 our perceptions of the structures and properties of the world help tremendously in modifying and trading-off design decisions. In fact, taking design decisions may turn into establishing tendencies and specifying trade-offs between incommensurable feature dimensions, rather than choosing between discrete alternatives, in certain situations.

1.7. INTERDEPENDENT AND INDEPENDENT PARAMETERS

Certain pairs of design decisions depend strongly on one another, while other decision pairs can be taken rather independently; most pairs, however, are somewhere in between: there exists an (inter-) dependency between decisions, but it is possible to abstract from it, for example, during the earlier phases of the design process, as the dependency may not have global consequences for the design decision process. In a later refinement phase, these more local interdependencies then may be considered.

One of the issues we will address in this paper is how the consideration of only a selected part of the design decision graph serves to reduce of the number of interdependencies considered, thus making the process as a whole more tractable.

1.8. DESIGN INVOLVES EXISTING AND NEW SOLUTIONS

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 (which might not be specified in detail) rather than a collection of details which is configured into a complete design.

1.9. DILEMMAS AND PARADOXES

The list of properties that characterize design problems could be continued further. However, for the purposes of the present analysis we will restrict ourselves to what has been discussed so far. From a modeler's perspective the least that can be said is that design activities hold intriguing challenges and nightmares at the same time: First, a description of design goals can be rather complex in terms of the number of both the features and their properties involved. Conversely, a prescription of adequate operators is as complex. Second, design processes operate in high-dimensional, filtered decision spaces that reconfigure dynamically. Past stages of the current or other design processes can again become important later on which further adds to the complexity. Third, the requirements that determine decision and solution spaces are regularly too few or too many.

Design problems are difficult to model and even more difficult to prescribe. Seen as searching for states in problem spaces, design problem solving becomes prototypically ill-defined as neither start states, goals states, nor transitions can usually be fully specified in advance (Simon 1973). Yet, houses, airplanes, tools, etc. exist, they get designed and constructed by humans, and, in most cases, they fulfill their functions as planned, i.e. we live, work, or fly in them, or use them otherwise.

It is, thus, reasonable to assume that human problem solving in design is different from the search-through-problem-space paradigm of *Human Problem Solving* (Newell and Simon 1972). Many authors before have pointed towards this issue (Goel 1995). As we are interested in the cognitive mechanisms of descriptive and prescriptive levels of modeling, we will continue the present analysis and examine the cognitive efforts involved in solving design problems.

2. Cognitive Effort in Architectural Design

Looking at description and modeling needs is only one way to reach an understanding of design problem solving. This section presents a selection of cognitive faculties involved in designing, and of cognitive efforts associated with design tasks.

2.1. VISUAL PERCEPTION STRUCTURES MENTAL REPRESENTATIONS

Vision seems to be the most important of the human senses for understanding the environment, in particular, in terms of the feature dimensions exploited in parallel. The graduated organization of information processing in the human visual system has great impact on the organization of visual percepts, and this organization influences the segmentation of the environment into objects, classes, and categories (Rosch 1975). Gestalt effects (Wertheimer 1912) provide good evidence of such organization. Perceptual processes mediate external organizational properties to mental representations and create analogical relationships (i.e. in the sense of Sloman 1975) between mental conception and manipulation, and objects and processes in the world.

2.2. VISUAL EXTERNALIZATION IN ARCHITECTURAL DESIGN

Architectural practice makes extensive use of all kinds of representation formats (diagrams, sketches, drawings, layouts) on various kinds of graphical media (regular paper, plan size paper, Post-Its, CAD models, physical models, VR models, etc.). Many of the representations are apprehended visually and spatially, and the importance of computational offloading of content and processes from the mental to the external world has been frequently stressed (Wilson 2002). Graphical representations are used also in the communication between designers (Healey et al. 2002). In this case, stable semantic interpretations of graphical symbols can lead to a reduction of cognitive load (Giordano 2002). Furthermore, a special relationship between the designer and her sketches seems to get established, such that they enter into a private dialogue in which mental constructions are externalized, visually analyzed, internalized, mentally processed, externalized again, and so on (Goldschmidt 1991; 1995). Generally, the basics of this relationship is attributed to a close coupling between visual mental imagery and visual perceptive systems (Finke 1990; Kosslyn 2003).

2.3. MENTAL CONSTRUCTIONS

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 working memory constructions; they serve integrative purposes in that they are instantiations in which some of the information and demands are coherently arranged. Mental model based problem solving is specific, and instead of the systematic construction of all possible models the construction of some is preferred over that of others (Knauff et al. 1995). Mental images are special kinds of mental models in which some of the content is in visuo-analogical formats.

2.4. IMAGERY AND SKETCHING

In the *dialectics* between the designer and her sketches (Goldschmidt 1991) the constant re-representation of contents together with effects of graphical constraints can be seen as a driving force in imagery-based graphical reasoning (Scaife and Rogers 1996), as structural variants favor different mechanisms of inference and lead to the introduction of new operators and operands. In design processes, the iteration between mental and external representation of content can indeed lead to detailed design (Purcell and Gero 1998). Mental imagery models based on processes such as image generation, inspection, and transformation have further been suggested to explain behavioral differences in sketching between expert and novice designers (Kavakli and Gero 2001).

2.5. IMAGERY AND CREATIVITY

Mental imagery processes seem to play an important role for creative discovery in design (Roskos-Ewoldson et al. 1993; Kosslyn 1999), especially through their link to external pictorial representations. Manipulations to representational content differ in the mental and external realm in the ease with which they may be exerted. With respect to physical and mental synthesis tasks many similarities have been found (Finke et al. 1992; Anderson and Helstrup 1993) while structural manipulations seem to require external representations, e.g. a sketch (Verstijnen et al. 1998), in particular, when they entail the semantic reinterpretation of object parts.

2.6. CREATIVE ACTS IN DESIGN

The designer's creative thought is often related to her inspiration, inventiveness and ingenuity. However, there exist many facets in design (and in architectural design, in particular) where creative acts seem less of an art, and more of a craft, i.e. a craft that can be taught and learned. In some of the current endeavors to create meta-theories for architectural design (Friedman 2003), the fundaments are laid for a transition "from the notion of Christopher Alexander's (Alexander 1964) of a partially unself-conscious design to self-conscious and explicit design processes" (Eastman 1999). There seem to be design activities where the "creative leap" can indeed be related to necessary and sufficient conditions that must hold for creative acts to occur (Arkin 1998). Finally, there is good reason to believe that such activities can be adequately conceptualized in terms of mental model construction, inspection, and manipulation. The postulation of moves and arguments in design (Goldschmidt 1991) rests on similar theoretical grounds.

2.7. USE OF EXISTING SOLUTIONS IN DESIGN

It has already been stated that design practice significantly relies on modifying existing designs rather than constructing entirely new ones. Existing solutions play a two-fold role in design: (1) they provide context that helps identify decision criteria and (2) they provide analogies that may be exploited for the design (i.e. in that concepts, partial solutions, or methods are mapped from an existing design to the current problem). The mapping between base and target of the analogy is influenced by the differences in decision criteria between both problems, and, often, it is partial in that only certain aspects of the problems are considered. With respect to mental and external representations, many descriptions exist that point to the fundamental role of analogical mental reasoning (i.e. exploiting structural or visual properties; Goldschmidt 1994).

2.8. RE-REPRESENTATIONAL SYSTEMS

We have seen that specific properties of organization in mental and external representations seem to be important for solving design tasks, This is in particular true where differences in organizational schemes lead to re-representations of knowledge and entail new (structural) insights into the nature of a task as well as of its potential solutions. The duality of specific mental models and specific external representations (e.g. in the coupling of visual mental imagery and visual perception) thus creates a powerful system that sits at the core of cognitive faculties engaged in design tasks.

3. Techniques, Representations and Models

So far, we have seen characteristics of architectural design problems as well as of human cognitive systems that contribute to solving the problems. The following section presents a third part of the analysis: A range of examples will be given of methods and techniques that are characteristic of architectural design problem solving, and representational formats and model types will be discussed on which the methods and techniques operate.

3.1. TOP-LEVEL DESIGN METHODS

Rittel (1999) describes the process of architectural design as the production, the drawing up of the intention of building and the construction of a project. The processes that take place are cognitive and in the world of ideas. In the operations that correspond to the processes, architects invent or manipulate representations of objects, situations, and concepts instead of inventing and manipulating their counterparts in the real world. Interaction with the world of ideas is aimed at the preparation of real interaction.

Architects work with models to achieve a satisfactory coupling between the world of ideas and the real world. Various kinds of sketches, diagrams, cardboards, CAD-, and mathematical models are used as representations to assist the designer's imagination, and different representations are adequate for different tasks. Many forms of mental activity are covert during the design process, and do not show up externally: mental transformations performed by the designer include arranging and supposing; designers suddenly have ideas, they imagine and speculate, they dream something up, they examine, or they calculate (Rittel 1992). Several of these mental operations take place subconsciously (which does not necessarily imply that they cannot be made explicit), while other activities are intentional and go on under considered intellectual control.

A host of design methods exist to guide the architect in her activities (Neufert 1936; Itten 1963; Alexander 1964; 1977; Lawson 1980; 1994; Groat and Wang 2001). In the following, we will discuss some of the more frequent methods, namely top-down and bottom-up compositions, thinking in layers, and the introduction of a big idea.

3.1.1. Top-Down Decomposition

After having started by developing concepts of form and function, the architect has to work out the details of the system, Figure 2. The process is set hierarchically and her task is in refining the design to a point where the forms of components on the lowest-level of abstraction are completely specified, and their functional adequacy can be demonstrated (Mitchell 1990). Especially in Computer Aided Architectural Design (CAAD), *top-down decomposition* is a prevailing method (Schmitt 1993).

Beginning with a concrete aim, top-down methods incrementally lead to the production of a fully specified design conception by dismantling the problem into sub-problems. The procedure requires abstract and well-defined problem specifications, which can be recursively divided into smaller section specifications, until basic operators are applicable to the sections. In established theories of architectural design, top-down methods are compared to hierarchical decomposition. Experienced and professional architects frequently start with a schematic sketch of the entire project and gradually refine the design structure until the required degree of detail is achieved (Lawson 1980; Broadbent 1988).

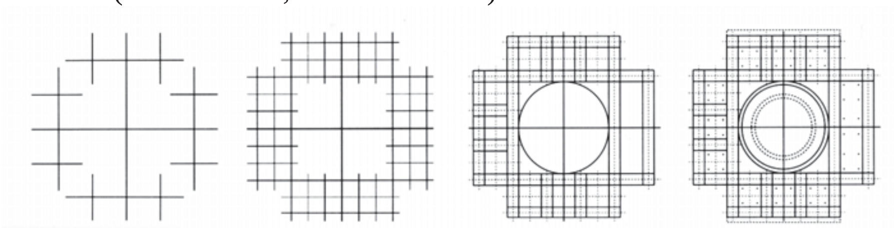

Figure 2. Steps of a top-down design process in which a layout of a ground floor is successively refined into a detail component design plan (from Durand 1802)

3.1.2. Bottom-Up Composition

Bottom-up methods involve the configuration of an overall design solution by successive (e.g. abstraction-forming), or recursive combination of basic design components. As with top-down decomposition, in order to be applicable, design problems need to be solvable by rational decision taking, i.e. the individual design components must be well-known and amenable to combination operators that integrate them into new assemblies, compound objects, or hypotheses.

Mitchell (1998) describes for that purpose: “Composition problems arise when the architect must choose, adapt and arrange elements to satisfy specified formal and functional requirements”. After the architect has started out with elements of familiar forms and functions, design grammars specify various relations between useful sub-systems in order to set up adaptability and utility. The complexity of bottom up compositions in design process results from developing accessible ways for constructing high-level functions from lower ones causes the complexity of bottom-up compositions.

3.1.3. Thinking in (Conceptual) Layers

Extensive research has been carried out into the role of sketching and the use of diagrams in architectural design processes, in particular from a cognitive point of view (Akin 2003; Do 2001; 2002), see also Section 2. Based on the idea that sketching and scribbling is important especially during the early phases of architectural design (Do 2002; Do and Gross 2001), we can identify a course of action that exhibits a specific method of design processes: thinking in layers.

Architects are trained to draw and to use diagrams to communicate their thoughts and to describe ideas and suggestions. Characteristic of a designer's sketching actions is "redrawing" (Do 2003) in which the designer repeatedly outlines a particular area of a drawing, e.g. as to define the final shapes of a building, compare Figure 3. The combination of redrawing techniques with tracing paper as a medium serves as a complex and efficient design method to the experienced architect.

Figure 3. Gradual refinement of ideas in sketches shows thinking in layers

3.1.4. The Big Idea

Architectural design from an artistic and more imaginative point of view claims that structural design is the product of intuitive inspiration and creation. The design of Le Corbusier´s chapel *Notre Dame du Haut* (1950-65) for examples, was inspired by a crap shell that he found somewhere on a beach of Long Island. Years later, when making the first drawings of the roof shape, the crab shell was lying next to his sketchbook and, thus, was used with respect to function and form. The introduction of a "big idea" into a design process can lend further structure to it, for instance, by implicitly or explicitly introducing structural analogies to problems, solutions, and methods in other domains. In addition, big ideas often promote more artistic aspects of architectural design.

3.2. REPRESENTING DOMAINS

Finding appropriate descriptions for architectural design processes that adequately capture the ill-defined interconnections between the different sub-processes remains one of the main challenges of architectural design research. At every time in the history of architecture, the paradoxical process existed of moving back and forth among the rational and the non-rational, the objective and the subjective, and the individual and the universal. However, we know that most features in architectural design thinking range in continua between those two-paired extremes, (Bamford 2002). Akin (2001) describes buildings as a complex system whose intention is to bring the user in line with a number of dimensions: functional, psychological, cognitive, ergonomic, climatic, economical, etc.

3.2.1. Volumetric Design

Architects often resort to using basic three-dimensional volumes. Le Corbusier, for example, suggested this method in a well-known sketch (Le

Corbusier 1923*)* in which he introduced a vocabulary of fundamental architectural elements and illustrated how these might be assembled into more complex compositions. The architectural composition of volumetric basic shapes remains popular in architectural design education, because the underlying theory is easily understood, the conceptual and graphic manipulations of the shapes follow simple rules, while the resulting drawings are nevertheless representative of various relevant design aspects. Particularly with regard to the discussion of cognitive effort in Section 2, it seems plausible to assume that basic volumetric shapes are more accessible to mental imagery faculties than more complex 3D-shapes.

Each architect knows how to operate cubes, prisms, spheres, cones and combinations thereof. However, volumes can be seen as solid elements of construction or as bounded voids. Mitchell (1996) explains that especially in CAD-based design a building appears in two complementary ways: as composition of voids or as composition of solids.

3.2.2. Case-Based Reasoning

For most cases, architectural design involves a blending of existing and new solutions. CAD-based systems usually include a knowledge base of classified past or otherwise accessible designs. A case-based reasoning system can assist the development of a design solution by looking up similar cases, adapt them to the current problem, and provide the architect with background knowledge. Characteristic aspects of the case-based system are the database of cases, methods for matching cases, and methods for adapting them to current requirements (Schmitt 1993), Casually, the most comprehensive case base is the real, built environment that we experience daily; it is a collective starting point for all new designs in architecture.

3.2.3. Symmetrical Means in Architecture

Throughout the history of architectural design, there exists a clear tendency to use symmetry for aesthetical expression. Pythagorean architectural theory, for example, transformed buildings into mathematical models that illustrate and demonstrate the idea of a universal order. Le Corbusier described the cognitive need of order and arrangement for keeping thoughts together (Giedeon 1949). Creativity, thus, is a process of structuring. Ideas of symmetry and the claim of pure architecture can be traced back to Aristotle’s idea of nature: that is, recognizing the nature of something means in particular to emphasize a difference (*species est genus et differentia*).

3.3. REPRESENTING RELEVANT PROCESSES

While considering the design of a garden greenhouse, Lawson (1980) describes a number of design features whose values are subject to variation by the architect. For example, he could choose from a number of different materials for the frame, such as wood, steel, aluminum, orplastic. “In fact there are many more design variables including the glazing material, method of ventilation and type of door. What the architect has to do is to select the combination of all these features, which will give the most satisfactory performance”. Thus, the focus is on selecting features, as well as their values.

3.3.1. Working with Prototypes

In architectural design, prototypes are conceptual patterns that represent generalized design knowledge. They are structured hierarchically, from the most general patterns to the most specific ones (Schmitt 1993). Three classes of design operations with prototypes have been proposed: the refinement of prototypes, their adjustment, and the development of new prototypes. The classes are suggested to correspond to applications in routine, innovative, and creative design (Gero 1990). The use of design prototypes in architecture can lead to extensive investigations into design parts, as the designer has the possibility to develop various levels of details.

3.4. PRIORITIZING CONSTRAINTS

Constraints in design largely result from required or desired relationships between two or more elements (Lawson 1980). We can distinguish internal and external constraints: internal constraints can be easily changed by the architect, their values can be varied by common design methods. External constraints, on the other hand, cannot be changed without problems (or cannot be changed at all); they are commonly outside the problem’s subspace on which design methods have an effect. A building site’s direction relation to the sun is a good example of an external relation. Despite being widely inaccessible, external constraints are often extremely important for the design as a whole, as they set the frame of possible action, and provide seeds for introducing structure.

If we reconsider the greenhouse example for a moment, we see that there exist too many features to be possibly considered all. The challenge lies in selecting the features that are considered (i.e. the aspects) and to choose an order of their respective considerations. There is good empirical indication that experienced architects and novices behaviorally differ in how they prioritize a collection of constraints. There exist differences in the order in which features are considered (Katz 1994). Along this line, Carrara, Kalay and Novembri (1994) recommend that “a prioritization of goals, reflecting a descending order of preferences, may be imposed by the designer or by the client. It will indicate which combination of performances the designer should attempt to accomplish first. Prioritization of preferences […] has a very profound effect on the direction of the design process and on its results. This is due to the fact that design is inherently a linear process, where the decisions leading to the specification of a design solution are made in sequence and are linked to each other.”

3.5. CONTROLLING THE SIZE OF THE PROBLEM SPACE

We use abstraction to describe and manipulate reality. In the case of architectural design, reality means an existing building or a plan. Naturally, each attempt to representation is already an abstraction, such that the only veridical representation of a real object is the object itself (Akin 1986). In architectural design, abstraction is employed to control, to design, or to generate new facts. What abstraction means can vary between abstraction levels, or from situation to situation, and single modes of abstraction do not seem sufficient for architectural design (Schmitt 1996). The number of different abstractions considered for a design is usually depends on the methods that are applied to structure the design process.

The number of alternatives that are considered on the same level of abstraction may further depend more on aspects of solution quality or personal style, rather than on the general design method. Near-optimal approaches to finding appropriate levels of abstraction have been proposed for conceptual design; they involve alternating phases of a divergent and convergent problem space (Liu 2003).

3.6. SCHEMATIZING REPRESENTATIONS AND PROCESSES

An essential and important quality of architectural design processes is the use of diagrammatic representations, particularly in the early phases (e.g. for functional reasoning, formal arrangements, analogy transfer, structure mapping, and knowledge acquisition; Do 2002). In general, architectural diagrams represent and symbolize not only physical entities, but also forces and flows, i.e. forces of sun or wind and flows of people passing by, as well as materials (Do and Gross 2001). It appears that the use of varying degrees of schematization helps to distinguish different aspects in architectural diagrams, as well as different qualities of the architectural design process. Schematizations enable the designer to focus on specific aspects of a design problem, and to explore her design from various viewpoints.

3.7. EXAMPLE TO THE METHODS – A DISCUSSION OF LE CORBUSIER´S VILLA SAVOYE

In the last few subsections we analyzed significant top-level methods of architectural design processes individually. This subsection sees a reprise of those methods as they are exemplarily discussed in relation to Le Corbusier´s *Villa Savoye,* Figure 4.

Order and clarity are significant concepts in Le Corbusier´s architecture. At his time, they reflected an idealistic way of thinking in which the idea of clarity in forms was seen as an architectural analogue to the precision and efficiency of machines (“the house is a dwelling-machine“, Le Corbusier, L´Esprite Nouveau 1921). Le Corbusier regarded geometry as the only conceivable basis of architecture, and the use of basic volumetric shapes (prisms, cubes, cylinders, pyramids, spheres, etc.) can be noticed throughout the villa’s design. In fact, each of his buildings is based on an architectural structure prototype developed until 1915. Comparability to mathematical equations and to rhythm should be made an aesthetical control criterion for well-formed architectural design. In “Five points” which he published in 1923, Figure 5, Le Corbusier proposed a high level of functional articulation and optimal specialization of components (Mitchell 1999). “In order to solve a design problem scientifically you first have to identify the separate elements” (Le Corbusier 1927), he described one of his key ideas, and he illustrated it by schematizing diverse aspects of a building’s construction. This is as much of top-level decomposing as decomposing can be.

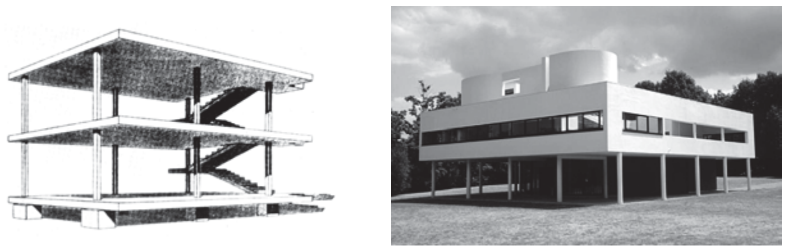

Figure 4. Le Corbusier´s Villa Savoye in Poissy, 1928-30. *left*: A schematic drawing of the building construction. *right*: A photograph of the north-west side of the villa.

Figure 5. Since 1922, Le Corbusier has made use of his five principles of architectural design construction: (a) the pillar, (b) the roof garden, (c) the functional independence of skeleton and wall, (d) the elongated window and (e) the free façade.

The villa is a simple cube lifted up on pillars. There is no uniform façade, no „front side“ or „backside“ and it is impossible for the observer to understand the building from just one viewpoint. The basic geometrical system of the villa is a non-directional orthogonal grid within which a major volumetric unit is established, the rectilinear living zone. This regular cubic form provides the ordering baseline; it states the major theme of the design. Figure 6 shows a gradual development of the building's structure.

Both the roof screen and the access volume explore the fundamental tension between curvature and the orthogonal system. Each of them has directional components that respond to functional and symbolic requirements within the design of the villa. The dynamics induced is controlled within the orthogonal system and particularly by the two major forces implanted into the system by the disposition of forms: the dominant longitudinal axis, reinforced by the ramp, and the living zone volume. In all of Le Corbusier´s buildings, the idea of movement route has a special significance. Big ideas at work, again.

4. Architectural Design by Aspectualization and Prioritization

The analysis presented so far has been threefold: We set off from a list of basic properties that are characteristic of design problems in architecture. We found the seemingly paradoxical situation that the problems to be solved are extremely complex (i.e. in terms of problem space features and their properties) and yet, generally, the human designer discovers solutions with much less effort than would be expected. Intrigued by this, we tried to unveil some of the cognitive factors that are involved in human problem solving in design. The factors were discussed with respect to visual perception and imagery; mental models, images and sketches; and creative thought. In the preceding section, we explored a set of relevant methods (both representation- and process-centered), techniques, and models for architectural design that arose from the amalgamation of the problems' characteristics with cognitive factors.

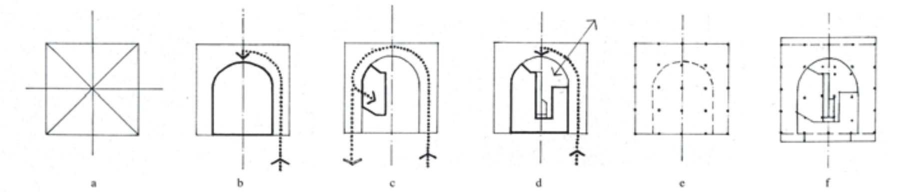

Figure 6. Gradual development of the Villa Savoye's structure. (a) The generic volume is a square with equal axes. The form is centrical and static. (b) The position of the main access to the villa determines the central axis. (c) The garage splits up the volume obliquely. (d) Use of a transparent membrane which allows a visual connection between inside and outside. The vertical access ramp is placed centrally on the axis. (e) An orthogonal grid conforms to the properties of the square. (f) The grid is modified to accommodate requirements.

Now, we will try to interpret the results from the three analyses with respect to general schemes of methods that can span the individual design strategies and techniques which we found, and that further systematize their conceptualization with respect to the cognitive factors involved. The aim is to develop cognitive methodologies for design. We propose and discuss two major schemes: first, *aspectualizations as* specific kinds of abstraction for representations and processes and second, *prioritization of constraints* in the construction of concrete and specific models.

4.1. ASPECTUALIZING REPRESENTATIONS AND PROCESSES

Design problems are often too complex to treat every part in the same way. Top-level design methods, for example, give structure to the set of partial problems that can be identified in a design problem, i.e. in that the methods define distinct levels of abstraction along with a partial ordering of the individual levels' treatment. However, top-level design methods alone are not sufficient for an adequate approach to solving design problems: Feature and problem spaces usually have characteristics that make a direct handling difficult (if not impossible). This is where approximations of problems come into play. The following paragraph presents a more formal description.

4.1.1. Segmentation of Design Problems

Let T be a characteristic design problem and $p_i(T)$ a partial problem of T. Then, the set of all possible partial problems $\Pi(T) = \{p_1(T),..., p_n(T)\}$ cannot be stabilized across methods (i.e. $\Pi(T)$ is always the same no matter which design method is used) such that

$$\forall i, j \in \{1,...,n\}: \left[\left(p_i(T) = p_j(T)\right) \vee \left(p_i(T) \cap p_j(T) = \varnothing\right)\right] \wedge \bigcup_i p_i(T) = T$$

This is mainly for two reasons: first, we need to approximate T in order to solve it. The high-dimensional decision space, the interdependent parameters, and, in particular, the under- or over-constrainedness of T require the introduction of a manageable design problem $m(T)$. For example, $m(T)$ can be a problem for which only a subset of T's parameter interdependencies hold (e.g. one that can be linearized), for which the decision space is reduced in complexity, and third, for which the set of relevant constraints is well-tuned (e.g. either by adding default assumptions to the set of constraints in T if T is under-constrained or by omitting constraints when there are too many). As there exist various possibilities each for selecting such three subsets / subspaces we obtain a set of manageable problems $\mathrm{M}(T) = \{m_{1,1,1}(T), m_{1,1,2}(T),..., m_{1,1,q}(T),..., m_{o,p,q}(T)\}$, rather than a single problem $m(T)$. Clearly, only those elements of $\mathrm{M}(T)$ can be considered for suitable approximation of *T* whose solutions are judged acceptable to be taken for the expected solutions of *T*. As a result, for two suitable problems $m_{a,b,c}(T)$ and $m_{d,e,f}(T)$ from M(*T*) an overlap of their respective subsets / subspaces is likely, as is an overlap of partial problems. Second, the filtered decision space of *T* can be expected to vary during the design process. As a result, even if we could find a $\Pi(T)$ for which equation above holds at a certain time *t*, variations that occur until *t+1* may easily introduce partial problems that overlap with those that already are in $\Pi(T)$.

4.1.2. Getting Better Hold of Feature and Problem Spaces

It follows from these deliberations that chances are that the human designer does not solve design problem *T* in a traditional *divide and conquer* fashion, i.e. *T* is split into disjoint partial problems which are solved independently of each other, and their solutions are reassembled afterwards to form a solution for *T* itself, Figure 7. If we further recall the discussion in Section 2 on the role of mental models in design problem solving, along with mental models being concrete rather than abstract mental constructions, it seems likely that the systematic generation of alternatives to (partial) solutions is no characterizing trait in human design problem solving. Rather, it may be the use of features, and of specific feature values.

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. Figure 3 in Section 3 illustrates a conceptualization in design in terms of layers and the selection of certain features across layers for an intermediate result. Obvious candidates for feature selection methods are design methods on top-levels (e.g. the *big idea* that structures the design process) or methods 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 (i.e. in mental model construction, cf. Subsection 2.3).

4.1.3. Aspects of Representations and Processes

Preferences in feature selection do not just concern features individually but sets of features that typically occur in combination. Figure 6 provides examples of drawings in which different features are combined, respectively, for purposes of demonstration and exploration. Each of the drawings is *schematic* in that not all information that could be displayed is displayed and they bring into focus certain *aspects* of the design problem. We have already briefly discussed such roles of aspects in Section 1. More systematically and from a representational point of view, we need to distinguish those aspects that are introduced pictorially (i.e. within the representational medium, such as distance between two points on paper), symbolically (such as the depiction of a house in Fig. 8), or that are excluded from a representation (Berendt et al. 1998).

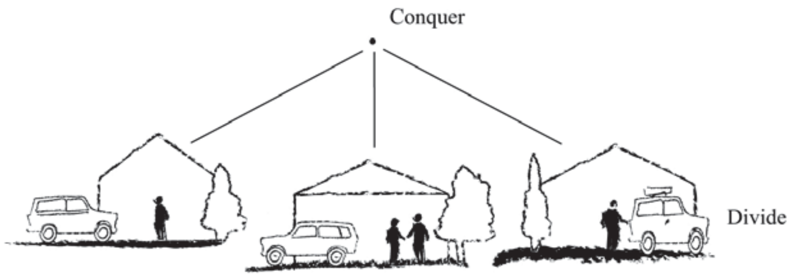

Figure 7. Schematic depictions of *divide and conquer*. The size of a problem is decreased by dividing it into smaller sub-problems that may deal with the same aspects of the overall problem.

Aspectualization of a design problem can result in representations that include features across various feature dimensions, many of which are spatial (lengths, widths, heights, shapes, etc.) and, usually, the representations are tailored for specific purposes. In that an aspectual representation specifically embraces properties and needs of the processes that operate on it high degrees of efficiency can be reached. The cognitive benefits of using aspectual representations lie in a reduced processing load (much information is omitted), a more focused context, and stronger structural analogies between problem, problem solving, and problem representations. All of these are important for solving design problems.

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 too many features to handle, and concrete (mental) models to be built selection of features becomes the crucial task. Aspects provide criteria for the making the selection, and choosing the right aspects must thus be seen as a key factor for successful solving of design processes.

4.1.4. Abstraction and Aspectualization

The realization that abstraction is key to effective design problem solving has been identified by many authors (e.g. Liu et al. 2003). But how are the concepts of ‘abstraction’ and ‘aspectualization’ related? While ‘abstraction’ stands for arbitrary means of omitting types of knowledge in a representation, ‘aspectualization’ denotes the restriction to specific types of knowledge. Formally, aspectualization is a special kind of abstraction, as it reduces knowledge. From a cognitive point of view, however, aspectualization stands for selection rather than for omission.

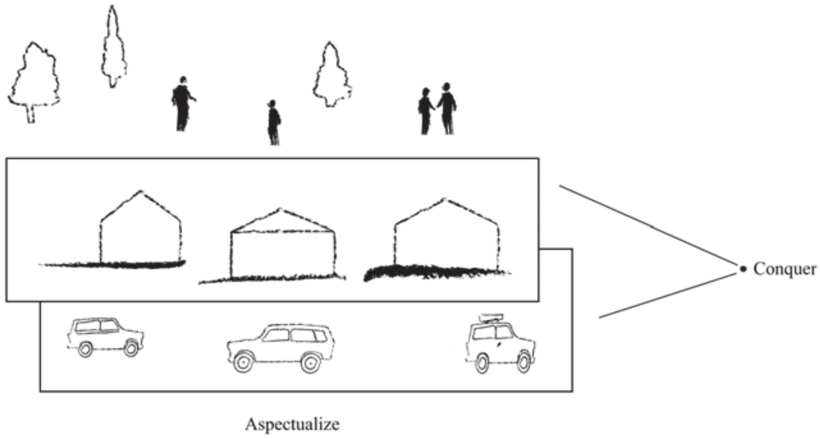

Figure 8. Schematic depiction of *aspectualize and conquer*. Problem solving is facilitated by reducing the number of feature dimensions considered at a time *(aspectualization)* and by establishing an order in which the aspects are considered, rather than by deliberately reducing the problem size on a global/local range (as with traditional divide and conquer).

The distinction is significant when we deal with open problem spaces as we always do in design: omission of certain aspects still leaves us with an open problem space that we cannot completely specify; selection of certain aspects, on the other hand, is solution-oriented and provides us with a closed world that we can deal with much more easily.

For a systematic approach, we can distinguish three types of aspectualizations by way of antonyms: (1) aspectualization vs. concreteness (i.e. the variation is in the degree of instantiation of the feature values), (2) aspectualization vs. specificity (i.e. the number of feature dimensions considered varies), and (3) aspectualization vs. 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 for solving design problems.

4.1.5. Aspectualize and Conquer

Previously, we have seen that the standard *divide and conquer* strategy is not adequate for describing human problem solving activities, at least with respect to the typical design problem. Figure 7 illustrates the two parts of divide and conquer, namely the decomposition of problems and composition of solutions, and the solving of sub-problems. Based on the previous discussion, we propose a variant strategy in which decomposition of problems is not into disjoint parts (i.e. where the goal lies not in reducing the problem size on a global/local range), but that instead is based on the notion of a problem's aspects. Different aspects of the problem are brought to attention at different times during the problem solving. The goal is to reduce the problem in terms of the number of aspects that are considered at a given time; reductions that may occur on the global/local range are incidental. In imitation of the divide and conquer strategy, we call this approach *aspectualize and conquer*. Figure 8 provides an illustration.

As with divide and conquer, the strategy as such does not provide a solution to a specific problem. Rather, it offers a framework to accommodate different classes of processes, such as those that aspectualize a problem, that provide solutions with respect to selected aspects, and those that based on a partial ordering of aspectualizations serve to integrate the partial solutions with one another. According to the aspects chosen, the partial problems are explored with the aim of further concretizing or specifying constraints of the problem. Decisions as to when and how exploration results are to be integrated are subject to various factors.

4.1.6. Aspectualize and Conquer in Architectural Design

A universal method for conquering architectural design problems does not exist. Rather, design practice requires the combination of a host of different methods, techniques, and representational formats. Problem segmentation into non-overlapping parts is not an option for typical design problems. Instead of taking this property as a weak spot (i.e. in comparison to computational properties of well-defined problems) and trying to work around and hide it, *aspectualize and conquer* can serve as a framework to turn the diverse complexity of design problems into an opportunity: We see that humans are able to find solutions to design problems and that working with concrete mental and external models that aspectualizing problems is important to their success. The considerations presented here further support this on a theoretical note.

We argue that setting the focus on design problems as being ill-defined actually results in too much effort being devoted to the marginal parts of them that happen to be well-defined or to special kinds of problems that are not typical of the problem class. Instead, conceptualizations of problem structure should capture the existing properties adequately and without valuation. *Aspectualize and conquer* provides such a framework.

4.2. PRIORITIZING CONSTRAINTS

We have already argued that selecting is key for solving problems which have too many variables (= features) to handle. Since design processes have inherently linear components, in particular when there is only one designer at work, the selected features need be partially sequentialized in that the designer handles them one by one. In a way, we can look at the selection process as one that by selecting leads to the production of a sequential structure.

If we turn our turn our attention to the selection of features, the sequentialization turns into a prioritization process. As model construction for design problems involves aspectualization, and as aspectualization involves selection of features, it is also evident that prioritizing constraints is another facet of aspectualization. In short, prioritization provides the temporal ordering to aspectualization.

Where many roads can be taken, the expert is revealed by her method of finding out which road to take. Likely, where many features can be selected, the design expert has many methods at her disposal (either explicit or implicit ones) that govern the selection. The top-level design methods that were discussed in Section 3 fulfill exactly such purposes. More specifically, empirical studies have revealed behavioral differences in constraint prioritization between experienced and novice architects (Katz 1994). Besides external influence of methods, preferences in mental model construction are likely to contribute to these findings.

5. Conclusion

Our investigation of architectural design processes started with three analyses, namely (1) into properties that we find with architectural design problems; (2) into the cognitive factors that are involved when architects are at designing; and (3) into methods and techniques that architects have developed to structure and facilitate their work. We then proposed two related general strategies to address the properties shown by design problems and to span the cognitive factors and established methods. These strategies are, *aspectualize and conquer* and prioritization of constraints. Aspectualize and conquer is a variant of the well-known *divide and conquer* strategy in artificial intelligence that we propose for open world problems like design. Prioritization of constraints is a result of (mental) model construction and responds to the need for linearization of design decisions.

One of the challenges of analyzing the design process is that there is no well-defined problem space and although most approaches acknowledge this fact, many are still guided by the hope to someday find well-defined work-arounds. A second challenge is that whatever the architect knows about her design will be part of its solution (Rittel 1990). In conclusion, Rittel recommends that design sciences should concentrate on three prime issues: the development of theories of the designer to know more about the thinking during the design process, the development of empirical methodologies to research the interaction between plans in relation to aims. And, finally, the search for useful methods to develop new tools, which can support and assist architects during their work. In that respect, aspects and priorities are just small building blocks for the construction of theories and methodologies. It is, however, important to keep in mind that many relations exist between fields across disciplines whose exploitations can be more than worthwhile for design research.

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