10. On Representation

Alexander Koutamanis and Vicky Mitossi

Department of Architecture
Delft University of Technology

10.1 Introduction

The intensive computerization of architectural practice has been primarily motivated by the promise of increased efficiency in documentation processes, as well as by the sheer modernity of the computer. Consequently, the application of computerized instruments in architectural design is largely restricted to superficial but labour-intensive and time-consuming tasks such as technical drawing and specialized or novel areas such as rendering three-dimensional projections and animations.

Despite the relatively low level of architectural computerization, the production of architectural documentation and information occurs at such as scale that practice is confronted with two basic, interrelated problems:

1. Redundancy: The multiplicity of aspects and actors involved in architectural designing requires diversification of input / output for each separate task or activity. The mainstream approach is to produce different design documents for practically each task. For example, analyses of indoor climate are performed on the basis of different drawings and related documents than cost analysis or control of fire safety. Moreover, the results of these analyses are presented in different forms that are unconnected to each other and to the core design representations, i.e. the drawings that describe the spatial and building structure of a building. It is also noteworthy that most current design representations are mere digital transcriptions of analogue practices. This means that they include unnecessary structure derived from the implementation media of their analogue predecessors.
2. Consistency: The use of multiple documents for the various aspects of the design process and its products adds to their complexity in terms of consistency and coordination. Processing of drawings and other documents by computer does not guarantee that decisions taken on the basis of one document are correlated to other documents which may contain crucial, related information. The results of such a decision are normally registered in the documentation of the relevant aspect(s) but are not always propagated to other documents not directly involved in the particular decision taking process. These are usually updated only when and if it is needed and consequently may remain misinformed or incomplete. The overall picture of a design through the collection of such documents can be highly inconsistent and confusing, even to the members of the design team.

These two problems are becoming so obvious in practice that designers and managers are willing to invest in studies of their own processes and corresponding automation research and development (Leusen and Mitossi 1998). The ambition behind such development is to derive structural rather than ad hoc methods and techniques that improve design quality and performance. For research this frequently means new opportunities for already developed approaches and systems which can now be (re)applied to actual problems.

Academic research in areas such as architectural design methods and computer-aided architectural design has a long tradition of novel approaches that confront and attempt to improve mainstream ideas. Some of these approaches derive in part from pre-existing proscriptive methods. These approaches limit design products to certain a priori areas. A design is acceptable if it falls within the confines of the approach or conversely if it does not contravene with the specifications of the approach. Prime examples of proscriptive systems are architectural styles, where specific attributes become the sine qua non of the system. A classical building, for instance, must contain elements from the canonical orders. Otherwise it may fail to register as a classical building (Summerson 1980).
Other approaches can be classified as prescriptive. Rather than constrain the outcome of a process, prescriptive approaches imply that a (good) design can be achieved only when a specific sequence of actions has been followed. Such approaches are usually found in a theoretical or computational context, i.e. as deterministic formal models of designing or as algorithmic design instruments. Prescriptive approaches underlie many computational design methods, as well as recent data-driven notions of design.
Both proscriptive and prescriptive approaches may offer useful insights into the nature and structure of architectural systems and processes. However, they are too restrictive to cover the complexity of current architectural problems. Moreover, they are too inflexible to be popularly accepted and applied. For such reasons we are experiencing a shift towards descriptive approaches. These emerge from the necessity to tackle an ever-increasing number of design aspects and amounts of design information involved in architecture and building of today. Descriptive approaches rely on explicit information that is processed in a transparent way and provides decision support mainly through feedback. This takes place through techniques such as simulation and scientific visualization, which provide explicit, analytical information at an appropriate abstraction level and in relation to known, intuitively understandable visual representations. Also the notion of performance and performance evaluation are central to descriptive approaches (Kalay and Carrara 1996).
Descriptive approaches rely on well-defined representations that accommodate both the input and output of design processes. Earlier academic research as well as software development has been obsessed by the idea of a holistic representation that covers all design aspects and their facets with precision, accuracy and coherence. Unfortunately such representations are too cumbersome and demanding to be a practical proposition. Partial, coordinated representations are better suited for the representation of specific design aspects at a variety of abstraction levels that agree with the stage of design development.

10.2 Architectural representations

10.2.1 Symbolic representation: a definition

Our definition of a representation derives from David Marr (Marr 1982): A representation is a formal system for producing descriptions of a certain class of entities in a transparent manner, i.e. together with an explanation of how the system returns the particular description. Transparency is achieved by establishing a set of symbols used in the representation and a system of decomposition / correspondence by which the symbols are related to the described entity. Examples of such representations are abundant in daily life. For instance, quantities can be described using a set of Arabic numerals:

$S_A = \{0,1,2,3,4,5,6,7,8,9\}$

And the following decomposition rule:

$$n_n \cdot 10^n + n_{n\text{-}1} \cdot 10^{n\text{-}1} + \ldots\ldots + n_1 \cdot 10^1 + n_0 \cdot 10^0 \Rightarrow \quad n_n \cdot n_{n\text{-}1} \ldots\ldots n_1 \cdot n_0$$

Within which n_n, n_{n-1}, ... n_1, n_0 are members of the symbol set. A quantity such a 123 is produced as follows:

$$1 \cdot 10^2 + 2 \cdot 10^1 + 3 \cdot 10^0 \Rightarrow 123$$

The description changes if we alter the symbol set. Binary numerals, for example, use the following set:

$$S_B = \{0,1\}$$

The reduction of the symbol set is reflected by a corresponding change in the decomposition rule (2 replaces 10 as the base):

$$n_n \cdot 2^n + n_{n\text{-}1} \cdot 2^{n\text{-}1} + \ldots\ldots + n_1 \cdot 2^1 + n_0 \cdot 2^0$$

Accordingly 123 is described as:

$$1 \cdot 2^6 + 1 \cdot 2^5 + 1 \cdot 2^4 + 1 \cdot 2^3 + 0 \cdot 2^2 + 1 \cdot 2^1 + 1 \cdot 2^0 \Rightarrow 1111011$$

As the above example shows, there are many alternative representations for each class of entities. Each representation is better suited to different tasks and uses. Arabic decimal numerals appear to be more appropriate for general use by humans, presumably due to the correspondence between the base 10 with the number of fingers in both hands. Binary numerals are preferred for machines as the symbol set maps the two states of a basic device ("on" and "off"). For specialised tasks representations are altered to suit the processing information. For example, when registering incoming of outgoing quantities, humans frequently revert to ancient symbol sets that are handier for the procedural, additive character of the task. "123" Could be initially described by:

~~IIII~~ ~~IIII~~ ~~IIII~~ ~~IIII~~ ~~IIII~~ ~~IIII~~ ~~IIII~~ ~~IIII~~ ~~IIII~~ ~~IIII~~ ~~IIII~~ ~~IIII~~ ~~IIII~~ ~~IIII~~ ~~IIII~~ ~~IIII~~ ~~IIII~~ ~~IIII~~

~~IIII~~ ~~IIII~~ ~~IIII~~ ~~IIII~~ ~~IIII~~ ~~IIII~~ III

while the task is in progress. After completion it can be easily converted to the much more compact Arabic decimal numeral.

Representation should not be confused with the mechanisms used for its implementation, such as a relay or diode for binary numerals. The reason is that a particular representation can exist in various implementations with no change in content, structure or result. Binary numerals, for example, remain unchanged whether on paper, in a computer or in a calculator, despite the superficial differences in the implementation mechanisms. Nevertheless, as many representations are associated with dominant or canonical implementations, the symbols of a representation are frequently confused or equated with implementation mechanisms. In conventional architectural representations, such as floor plans and sections we read spaces, building elements and components (the actual symbols). However, the lines we draw and the surfaces these lines bound (the implementation mechanisms) are only too often discussed as the primitives of architectural composition. This testifies to the significance of geometry as a foundation of architecture and its representations and parallels the shift from the geometric object in Euclidean geometry to its images in descriptive geometry (Evans 1995).

10.2.2 Spatial and building elements

An underlying assumption in most spatial architectural representations concerns the choice of basic primitives for the description of a design. The currently dominant use of lines and other implementation mechanisms is clearly inappropriate for spatial representations, as spatial entities are only implicit in the perceptual grouping of implementation primitives. With respect to such entities, the 'solids' and 'voids' of a building (i.e. the building elements or components and the spaces bounded by them) are the obvious choices. They are linked together by the fundamental relationships of adjacency, proximity and alignment into single holistic or multiple complementary networks that describe one or more aspects of the design in a coherent and comprehensive manner (Steadman 1976, 1983). These networks are generally sufficient for the description of a building at the macroscopic, normative level that characterizes apparent design thinking, including matching to the requirements in a brief, in legislated measures of performance or in a standard textbooks.

At the practical level, representation of a building in terms of its spaces and building elements is directly feasible as a straightforward improvement of current drawing practices. It amounts to a simple transformation of the geometric implementation primitives into more complex shapes and forms that exhibit a one-to-one correspondence with integral, identifiable spatial and building elements. Properties other than the geometry of an element are described by the clustering of the element (e.g. modularization by means of layers) and attached annotations. In the resulting drawings each space and building element is explicitly described but relationships between elements are only implicit. Most relationships can be recognized automatically on the basis of element properties. For example, access from one space to another if there is at least one door or similar opening adjacent to both spaces.

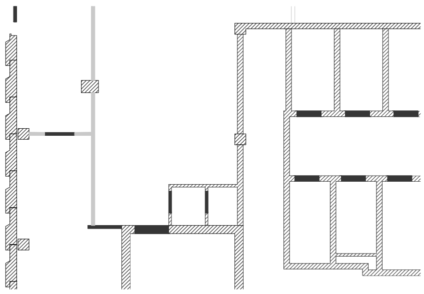

Figure 10.1: Building elements in floor plan.

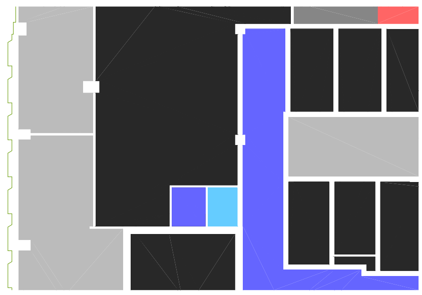

Figure 10.2: Spaces in floor plan.

10.2.3 Beyond solids and voids

The choice of spaces and building elements as the basic spatial primitives of a building is a sensible, relevant one. It allows for a closer correspondence between external design representation and design thinking, as well as for greater explicitness in design documentation, communication and analysis. For several design or analytical tasks building elements have to be subdivided into components, which in turn can be further subdivided down to the level of integral entities such as a brick or a steel bar. Spaces, on the other hand, are more difficult to handle. The transition from the implicit space, as in analogue drawings on paper, and the explicit space in a computerized spatial representation may create the illusion that spaces have to be treated as integral entities, primary parcels of space that cannot be subdivided further.

Standard design tasks, such as the allocation of activities in a space, presuppose a basic analysis of the space into areas or zones, with distinct spatial characteristics. This analysis, however, is normally rather flexible and fuzzy. Consequently, little attention is paid to the explicit representation of the schemata used. Nevertheless, these schemata can be of significance for reducing the complexity of design information, e.g. as attractors in evaluations of environmental aspects. Two techniques that appear to hold promise as elaborations of the basic spatial representation are hierarchical adaptive segmentation (Samet 1990) and the use of activity surfaces in space (Nakayama et al. 1995). Both techniques are sensitive to local conditions within a space and permit identification of areas that relate to specific aspects in the geometry or structure of a building and the interaction between human activities and the built environment.

Another emerging elaboration of the basic spatial representation concerns the geometric precision of spatial and building primitives. In contrast to a freehand sketch, a computer drawing is normally very precise and allows for little flexibility in the spatial relationships between different elements. This, however, does not agree with the abstraction of the earliest design stages, or with recent interest in dynamic, transformable building materials and structures. Fuzziness in the geometry and position of spaces and building elements can be introduced by means of:

- Tolerances around canonical positions.
- Extreme states (e.g. minimum and maximum).
- Variable plasticity and adaptability (i.e. different degrees of hardness and response to adjacent or new elements).

10.2.4 Local co-ordinating devices

While the representation of elements in digital design practices is explicitly supported by symbolic techniques, less importance has been attached to the manner by which elements are integrated in a design. This is normally left to the designer who has to position and connect each new element in a building representation with little help from his instruments. For example, many drafting and modelling systems still fail to address the physical impossibility of two objects occupying the same space, let alone attempt to interpret the designer's intentions in overlapping objects. In analogue design media this is a logical consequence of their implementation structure. An analogue representation is perceived, recognized and interpreted by the human viewer. Computerized representations, on the other hand, should not be limited to human interpretation. On the basis of explicit relationships between objects the computer can provide meaningful feedback on the basis of qualitative and quantitative analyses which complement and support the designer's creativity.

The frequent absence of meaningful explicit relationships between elements in architectural representations does not imply lack of knowledge on the subject. Architectural and building textbooks deal extensively with the relationships between building elements and components. The positioning of one element relative to another derives from formal, functional and constructional decisions and has consequences for the articulation and performance of the building. Textbooks provide guidelines ranging from ergonomically sound distances between chairs and tables to the correct detailing of joints in roof trusses. The frequent and faithful use of textbook examples has resulted in a corpus of architectural stereotypes. Even though stereotypes may lead the designer to repeating known solutions, they help reach levels of reasonable performance in designing and in the built environment. By obeying the underlying

rules and reproducing textbook stereotypes the designer ensures conformity with the norms of building regulations, professional codes and general empirical conclusions.
A prerequisite to the computerization of such stereotypical configurations is thorough analysis of the formal and functional patterns they integrate in a single representation. In the framework of our research we concentrate on the representation of such patterns, based on the hypothesis that, once the overlapping constraint networks are untangled, we will be able to distinguish between properties intrinsic to an architectural element and wider relationships which focus on specific critical elements. These relationships form local coordination devices that apply to interchangeable elements, for example to different window or door types for a particular opening.
In textbooks, aspects of a recommended configuration are usually presented separately in a proscriptive manner, by means of sub-optimal and unacceptable examples. These are annotated with the relevant relationships and usually ordered from general to specific and from simple to complex. It is assumed that the reader of the textbook makes a selective mental aggregate on the basis of the aspects that apply to the problem at hand. Despite the fact that incompatibilities between different aspects and examples are seldom addressed in textbooks, forming an aggregate representation is generally a straightforward hill-climbing process. For example, in designing a door, one starts with basic decisions relating to the door type on the basis of spatial constraints and performance criteria. Depending upon the precise type, the designer proceeds with constraints derived from adjacent elements and activities. In the case of a single inward opening left hinged door of standard width (Figure 10.3), these constraints determine the position and functional properties of the door, i.e. the distance from elements behind the door, and the swing angle, orientation and direction which facilitate the projected entrance and exit requirements. These can be adjusted by other factors unrelated to the initial decision. For example, the existence of a load bearing element in the initial place of the door may necessitate translation of the door and hence a reformulation the initial design problem.
In the same manner as textbooks, drafting templates offer useful insights into the stereotypical interpretation of local coordination constraints. In templates, building elements usually appear as holes or slits. Each hole or slit is accompanied by annotations in the form of dents, notches and painted text. These facilitate the geometrical positioning of a form, as well as the geometric interpretation of spatial constraints. The configuration of forms and annotations typically represents a simplified fusion of parameters reduced to typical cases (Figure 10.4). Even though the superimposition of different patterns makes the template less legible than the more analytical textbooks, the template comes closer to the mental aggregate of the designer.

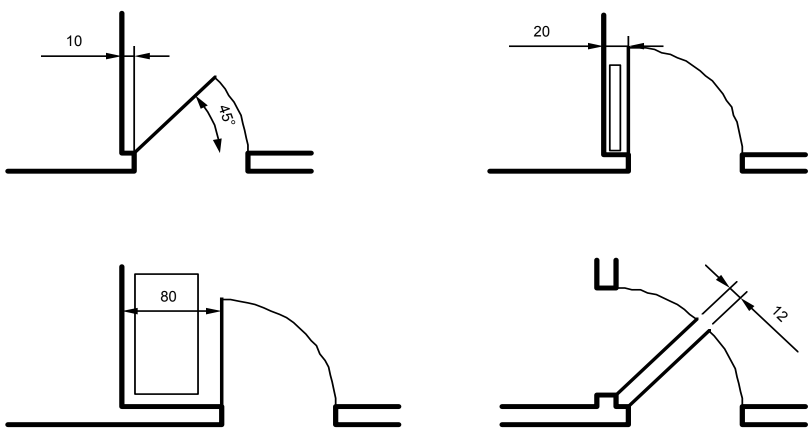

Figure 10.3: Textbook representation of local co-ordination constraints.

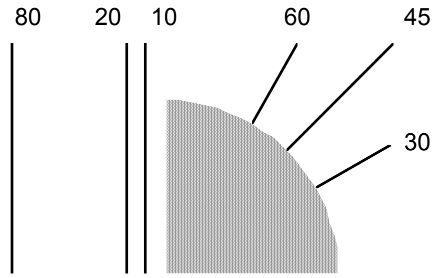

Figure 10.4: Template representation of local co-ordination constraints.

The manner in which local constraints are centred on elements, the connections between elements, and their stereotypical treatment in designing suggest that mechanisms such as frames or objects would be appropriate for the representation of local co-ordination devices. In a frame-based representation the relationships of e.g. a door with walls and other elements of the immediate context can be described as slots and facets which link the door frame with the frames of walls, spaces and other elements. Such an implementation strategy has obvious advantages for the representation of local co-ordination devices, for example with respect to the interchangeability of elements by means of abstraction and inheritance. It is quite plausible that a single prototype would suffice for the representation of all kinds of doors. This could facilitate the manipulation of doors in computer-aided design, including the automated substitution of one door type with another if needed due to spatial conflicts or to a change in the designer's preferences. Another possibility is to distinguish relationships and constraints from elements altogether. By implementing elements and relationships/constraints with separate frames or objects it is possible to resolve a number of limitations in different techniques, e.g. by adding relationships other than IS-A in object systems and generalization/specialization to the links in a semantic net (MacKellar and Peckham 1992; Peckham et al. 1995).

10.2.5 Global co-ordinating devices

Global co-ordinating devices generally appear in two forms. The first is sketches and diagrams that explain the general spatial articulation of a design. Such abstract representations (even if devised post-factum) are commonly seen as the embodiment of the driving forces in the development of the design. For our purposes they form a useful 'précis' which can be placed at the top of a multilevel representation. The other form of global coordinating devices is as product of formal analysis. Being usually applicable to more than one design, it is expressed in more abstract terms, e.g. as grids and zoning schemes. Probably the most celebrated of such devices is the 5x3 grid proposed by Wittkower as the underlying grid of Palladian villas (Wittkower 1952). This grid has been universally accepted as the canonical formal expression of the intuitive perception of the Palladian villa's "triadic composition" of two symmetrical sequences of spaces laterally flanking the central series of spaces along the main axis (Ackerman, 1977). As a result, the 5x3 grid forms the basis of most Palladian studies, including the Palladian shape grammar (Stiny and Mitchell, 1978). In the Palladian grammar the first stage invariably concludes with the definition of the 5x3 grid which serves further as a template for the definition of spaces and the positioning of building elements.

Global coordinating devices can be derived by visual abstraction that eliminates the individual characteristics of elements and returns a skeleton, as in Figure 10.1. This, however, does not imply that these abstractions are accidental products of various, possibly unrelated design decisions. Another option is to treat devices such as the Palladian 5x3 grid as prototypical patterns that are systematically repeated in variations. Such a view underlies most computational studies, even though there is no historical evidence that Palladio set out to exhaust the possibilities presented by a single pattern. The 5x3 grid appears to be an fusion of different preoccupations and influences, from notions of harmony to the traditional centralized arrangement of the local house type (Ackerman 1977).

The representation of global coordinating devices relies on the distinction between contributing aspects. One good example is the analysis of the classical canon as a system of elements, relationships and coordinating devices that constrain design decisions (Tzonis and Lefaivre 1986). This system consists of three major levels: genera, taxis and symmetry. The term genera (preferred over ‘orders’) denotes the “well-determined sets” of architectural elements which are formed on the basis of fixed local relations. Taxis, is responsible for the overall organization of a classical building and contains two sublevels: the grid, which parametrically divides the building into spatial components, and tripartition. A rectangular grid and a simple tripartition schema produce a 3 x 3 pattern. The deletion, addition, repetition and embedding of parts in this generic pattern transform it into the layout of a classical building, including the 5x3 Palladian grid. Symmetry is the collection of relationships that constrains the positioning of a particular genus inside the divisions determined through taxis with respect to each other and to the overall structure of taxis.

The three levels in this formulation of the classical canon have direct correspondences with the division between elements and coordinating devices proposed in the present paper. The genera are the elements of classical architecture (spaces are treated as the final products of the taxis level rather than as separate entities positioned on the basis of taxis). Symmetrical relationships are closely linked to local coordination devices. Taxis the product of the generic general coordinating devices of classicism. Taxis patterns have the advantage of being visually and conceptually compact and coherent and at the same time the products of two distinct sublevels. The resulting flexibility demonstrates the superiority of such analytical global coordinating devices to sketches or diagrams depicting the central idea of a particular design. For example, choice of a different grid results in a direct transformation of a design into something different yet recognizable as related to the original.

Another advantage of analytical global devices such as taxis is their cognitive significance. An anthropocentric view of tripartition in classicism is closely related to spatial reasoning and, in particular, to the division of the world by projective prepositions, i.e. prepositions which convey information about the direction in which an object is located with respect to another. Such prepositions describe orientation and position on the basis of reference frames consisting of a division of the world in general directions (front, back, left, right, up, down), an origin and a viewpoint for the speaker or viewer (André et al. 1987). The affinities between the resulting spatial pattern and the 3x3 generic classical pattern imply that such reference frames can be applied to the analysis of classical buildings at the level of global co-ordinating devices (Koutamanis 1990).

10.3 Representation and analysis

Probably the highest priorities in architectural design at this moment are:

1. The precise and accurate geometric description of built form.
2. The intensive and extensive analysis of design products throughout the design process, with particular emphasis on the early stages.
3. The seamless transition from design to realization, including applications such as rapid prototyping and robotics in building.

Well-defined architectural representations are central to all three issues. In (1) and (3) we could be excused for assuming that geometric representations are sufficient, even though this would amount to diminishing the significance of the final product of the architect, i.e. space for the accommodation of human activities. For analysis, however, it is imperative that the spatial elements of a design are explicitly described. In descriptive approaches the role of analysis is to provide the designer with explicit, transparent information that enriches (rather than overloads) the definition and processing of a particular problem. This information contains the input and the constraints for the output of local processes. A multilevel spatial representation supports these processes and their integration in the total design process by making explicit relevant entities and facilitating a level of local intelligence sufficient for (partial) automation.

10.3.1 Static aspects

A rather large class of analysis concerns aspects that are evident in the representation as properties of specific entities. Examples of this class are comparisons of spatial quantities such as floor area and volume to the brief or legal norms, such as NEN 2580 in the Netherlands. The definitions in NEN 2580 follow generally established principles of position and function, such as the distinction between use and circulation spaces and between exterior and interior walls. Further distinctions are made on the basis of local cultural patterns, e.g. the ways usable or rented areas are calculated, and technologies used for measurement. The norm makes a point of eliminating relatively small perturbations in the form of a space, presumably because it assumes measurement of areas on a drawing on paper rather than in a digital drawing, where complexity of form does not normally make measurement more time-consuming and labour-intensive.

Analysis of a design to a brief or norms such as NEN 2580 on the basis of a well-defined spatial representation amounts to (Mitossi and Koutamanis 1998):

1. Identification of relevant entities e.g. circulation spaces on a specific floor. This normally takes place automatically, on the basis of user-defined properties such as the layer of each entity. User interaction generally implies an arbitrary selection, e.g. a subset of the automatically-made selection.
2. Measurement of relevant properties for each entity. These properties are generally explicit attributes of the implementation mechanism used, e.g. area of a shape.
3. Simple processing and communication of the information, such as making total sums for each category and placing them in the agreed cells of a spreadsheet.

10.3.2 Dynamic aspects

Most static aspects are straightforward, also without the computer, but generally time-consuming and labour-intensive. Other aspects involve more complex human interaction with the built environment. Therefore, they may be less evident in the designer's perception of the representation. Such aspects include pedestrian circulation in buildings and the identification and measurement of routes between specific activities, as allocated in a design. In a well-defined spatial representation these tasks are performed at:

1. The topological level, with identification of the starting and end point of a route through user interaction or known properties of spaces. The route is identified mostly automatically, using adjacency properties to move from space to door to another space on the basis of circulation criteria, such as following the shortest route or using predominantly circulation spaces.
2. The geometric level, where the path of the route is calculated, usually on the basis of normative guidelines.

Identification of the route is followed by measurement and evaluation of not only the route length, as for fire escape routes (Koutamanis 1995), but also of intervening opportunities and time-related issues, especially for overlapping or intersecting parts of different routes (Koutamanis and Mitossi 1993).

10.3.3 Simulation and scientific visualisation

Spatial representations also provide ready input and a comprehensive container for the output of even more complex analysis, such as light and airflow simulation. As such simulations are normally performed at the level of individual spaces, the representation facilitates recognition and transformation of relevant entities, e.g. of a space into its interior wall surfaces and of a window into a light-emitting or air-supplying hole in a wall (Hartog et al. 1998). Following the principles of scientific visualization, the simulation results are presented both as analytical alphanumeric data and as visual patterns of light intensity or air movement in the particular space.

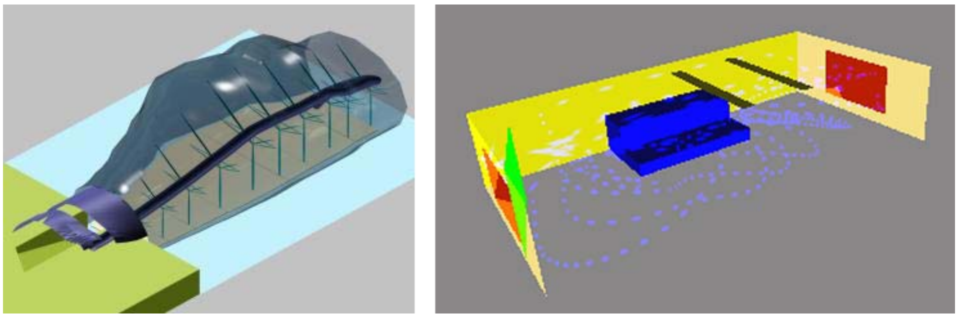

Figure 10.5: Airflow simulation by means of computational fluid dynamics.

10.3.4 Aesthetics

To the trained eye a drawing or photograph of a building provides ready evidence of building style and aesthetic quality. These relate to the acceptability of the design with respect to a particular formal system and the degree of acceptability. From a slightly different viewpoint, aesthetics arguably amounts to preference for one of the possible descriptions of an image. The preferred description meets the specifications of the particular formal system in terms of elements used in the design and relationships between elements that determine grouping into identifiable compound entities such as a colonnade or a wing. Grouping relates the design to global coordinating devices that can be matches to the specifications of the formal system. Drawing from cognitive science and in particular from the recognition-by-components (Biederman 1987, 1995) and the structural information theory (Leeuwenberg 1967, 1971), we can devise systems that relate the spatial and/or building articulation of a building to preferences in human perception and to the specifications of an architectural formal system. Entities in the spatial representation are grouped together on the basis of preference for specific spatial relationships. The resulting configuration of groups makes explicit the canonical parts of the design and their overall arrangement in terms of the devices of the formal system, e.g. classical tripartition. This configuration constitutes an evaluation of 'figural goodness' and by extension of the aesthetic preference for the design (Koutamanis 1997).

10.4 References

Ackerman, J. S. (1977). *Palladio*, Penguin, Harmondsworth, Middlesex.

André, E. and Bosch, G. and Herzog, G. and Rist, T. (1987). Coping With the Intrinsic and Deictic Uses of Spatial Prepositions, in: Jorrand, P. and Sgurev, V. (eds.), *Artificial Intelligence II: Methodology, Systems, Applications*, North-Holland, Amsterdam.

Biederman, I. (1987). Recognition-By-Components: A Theory of Human Image Understanding, *Psychological Review* 94(**2**): pp. 115–147.

Biederman, I. (1995). Visual Object Recognition, in: Kosslyn, S.M. and Osherson, D.N. (eds.), *Visual Cognition - An Invitation to Cognitive Science, 2nd ed.*, Cambridge, Massachusetts.

Evans, R. (1995). *The Projective Cast - Architecture and Its Three Geometries*, MIT Press, Cambridge, Massachusetts.

Hartog, J. P. de and Koutamanis, A. and Luscuere, P. G. (1998). Simulation and Evaluation of Environmental Aspects Throughout the Design Process, in: Timmermans, H. (ed.) *4th Design and Decision Support Systems in Architecture and Urban Planning Conference*, Eindhoven.

Kalay, Y. E., and Carrara, G. (1996). A Performance-Based Paradigm of Design, in: J.S. Gero, (ed.), *Advances in Formal Design Methods for CAD*, Chapman & Hall, London.

Koutamanis, A. (1990). *Development of a Computerized Handbook of Architectural Plans*, Ph.D. thesis, Delft University of Technology.

Koutamanis, A. (1995). Multilevel Analysis of Fire Escape Routes in a Virtual Environment, in: Tan, M. and Teh, R. (eds.) *The Global Design Studio*, Centre for Advanced Studies in Architecture, National University of Singapore, Singapore.

Koutamanis, A. (1997). On the Evaluation of Figural Architectural Goodness: A Foundation for Computational Architectural Aesthetics, in: R. Junge, (ed.), *CAAD Futures 1997*, Kluwer, Dordrecht.

Koutamanis, A. and Mitossi, V. (1993). On the Representation of Dynamic Aspects of Architectural Design in Machine Environment, in: Beheshti, M.R. and Zreik, K. (eds.), *Advanced Technologies. Architecture, Planning, Civil Engineering*. Elsevier, Amsterdam.

Leeuwenberg, E. L. J. (1967). *Structural Information of Visual Patterns - An Efficient Coding System in Perception*, Doctoral dissertation, Catholic University of Nijmegen. Mouton, The Hague.

Leeuwenberg, E. L. J. (1971). A Perceptual Coding Language for Visual and Auditory Patterns. *American Journal of Psychology* **84**: pp. 307-350.

Leusen, M. van and Mitossi, V. (1998). A Practical Experiment in Representation and Analysis of Buildings, in: Timmermans, H. (ed.) *4th Design and Decision Support Systems in Architecture and Urban Planning Conference*, Eindhoven.

MacKellar, B. and Peckham, J. (1992). Representing Objects in SORAC, in: J. S. Gero, (ed.), *Artificial Intelligence in Design '92*. Kluwer, Dordrecht.

Marr, D. (1982). *Computer Vision*, W.H. Freeman, San Francisco.

Mitossi, V. and Koutamanis, A. (1998). Spatial Representations as the Basis of Formal and Functional Analysis, in: Timmermans, H. (ed.) *4th Design and Decision Support Systems in Architecture and Urban Planning Conference*, Eindhoven.

Nakayama, K. and He, Z. J. and Shimojo, S. (1995). Visual Surface Representation: A Critical Link Between Lower-Level and Higher-Level Vision, in: S. M. Kosslyn, and D. N. Osherson, (eds.), *Visual Cognition - An Invitation to Cognitive Science, 2nd ed.*, Cambridge, Massachusetts.

Peckham, J. and MacKellar, B. and Doherty, M. (1995). Data Model for Extensible Support of Explicit Relationships in Design Databases, in: *Journal of Very Large Data Bases* 4(**2**): pp. 157-191.

Samet, H. (1990). *The Design and Analysis of Spatial Data Structures*, Addison-Wesley, Massachusetts.

Steadman, J.P. (1976). Graph-Theoretic Representation of Architectural Arrangement, in: L.J. March, (ed.), *The Architecture of Form*, Cambridge University Press, Cambridge.

Steadman, J.P. (1983). *Architectural Morphology*, Pion, London.

Stiny, G. and Mitchell, W.J. (1978). The Palladian Grammar, in: *Environment and Planning B* **5**, pp. 5–18.

Summerson, J. (1980). *The Classical Language of Architecture*, Thames and Hudson, London.

Tzonis, A. and Lefaivre, L. (1986). *Classical Architecture: The Poetics of Order*, MIT Press, Cambridge, Massachusetts.

Wittkower, R. (1952). *Architectural Principles in the Age of Humanism*, Alec Tiranti, London.