Simulation and representation

Learning from airflow analyses in buildings

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Abstract: The simulation of environmental aspects is a current priority in design research and practice. The availability of relatively efficient and reliable simulation systems and the emphasis on environmental aspects throughout a building's lifecycle combine to stimulate exploration of aspects such as lighting and air quality by computational means. Nevertheless, a frequent complaint is that the addition of such simulations makes design information processing time-consuming and cumbersome, thereby increasing uncertainty and indecision. Therefore, it is imperative that simulation is integrated in the strategies and tools normally used by the digitally-minded architect. In this respect a central issue is the relations between the simulation and the design representation used as connecting tissue for the whole design environment. Input of design information in the simulation means identification of relevant objects, aspects, parts and properties of these objects, as well as relationships between objects. The explicit description of objects such as spaces, doors and windows in the design representation allows for ready extraction of relevant information, including automatic recognition of relationships such as adjacency between a window and a space. The addition of information specific to the airflow analysis was resolved by the extension of the representation to cover front-end service components such as inlets and outlets and general properties (annotations) such as activities accommodated in a space and the primary choice of cooling and heating subsystems. The design representation is also the obvious target for the output of the simulation (feedback). Visualization of airflow in terms of the resulting voxels makes effortless and enjoyable viewing but merely allowing the visualization to coexist with the representation of spaces and building elements does not provide design guidance. One way of achieving that is by treating spaces not as integral entities but as containers of relevant surfaces. These surfaces determine the adaptive subdivision of the space and function as attractors for voxel clustering.

1. SIMULATION IN CONTEXT

The simulation of environmental aspects is a current priority in design research and practice. The increasing consciousness of indoor climate problems and possibilities, as well as the multiplicity of human activities and their intensive technological support, is leading to a growing number of programmatic and legal requirements with a rising specificity. The indoor climate of a building is the product of active conditions such as sun and occupant activity and passive building features such a window area and shape, natural shading and material properties. Unfortunately indoor climate is at best reduced to simplistic rules of thumb while the production of healthy buildings presupposes monitoring and control of several qualities of indoor climate throughout the design process. In optimal cases the passive building features are configured in a manner that results in comfortable indoor climate with temperature, air velocity and air purity within prescribed ranges. More often than not however, they exceed ranges that are considered healthy and additional cooling, heating or ventilation is needed.

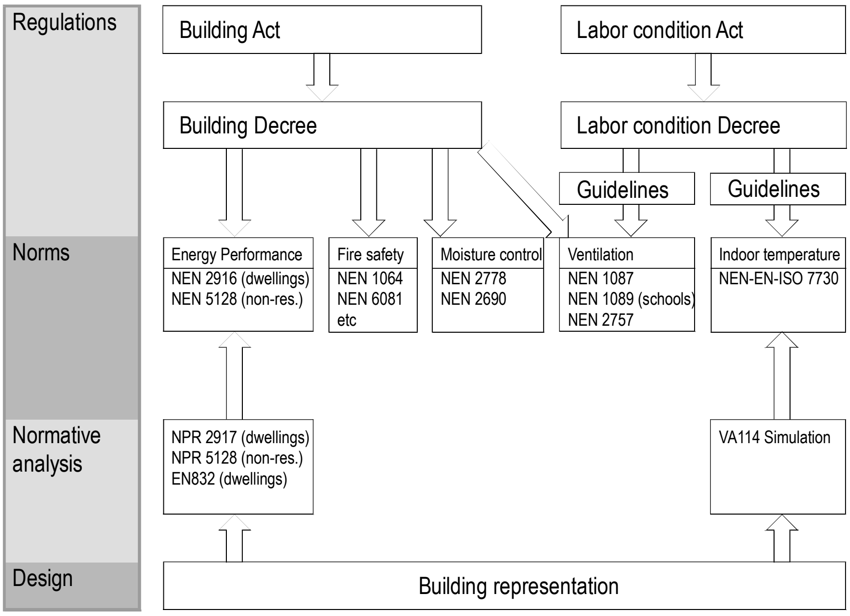

Figure 1. Requirements complexity: Dutch norms and regulations on indoor climate

The addition of building services further complicates the design of indoor climate. Employing standard solutions for these subsystems is no guarantee for acceptable results. A complete analysis and evaluation of the design situation is imperative for the design of both building features and indoor climate. Current design practices separate analysis and synthesis in terms of design stage and participation of various parties. Design synthesis is the domain of the architect, while consulting engineers carry out analyses and performance calculations the results of which are fed back to the designers.

The distance between architect and analysis may alienate designers from the possibilities and implications of the analysis. It may also degrade the cooperation between designers and consultants to unproductive confrontation. As a result, the relevance and accuracy of both the analysis and the feedback of results suffer. For example, architects regularly use general rules of thumb that may be incompatible with the precise mathematical models advising specialists employ. This means that specialists are frequently compelled to extract analysis input from their own interpretation of design documentation. The position is reversed later in the process, when architects face unfamiliar analysis data and formats.

One solution to both the communication problem between designers and specialist advisers and the lack of analysis in the early design stages relies on computer simulation. With the democratization of the computer, experts started recognizing its potential for solving efficiently and accurately the highly complex problems of indoor climate analysis. The methods and techniques that were developed in response to that managed to provide a stable basis for confronting realistic problems, as well as for further development. Paramount among these for indoor climate analysis is computational fluid dynamics (CFD). CFD is a technique to calculate patterns of fluid flow using a fundamental set of partial differential equations. These equations derive from three basic principles: conservation of mass, conservation of momentum and conservation of energy within that fluid. The equations are partial integral, non-linear and too complex to be solved analytically. For this reason, discretization and iteration are used to arrive at a solution that describes the characteristics of the moving fluid with specific numbers for velocity, temperature, pressures and other characteristics (Anderson, 1995; Wendt, Anderson et al., 1996).

The transition of CFD simulations from specialist to design tool is being accelerated by the increasing availability of computational power and by the rising interest in building and design performance. The integration of analysis by simulation into designing early on in the design process empowers the designer with predictions of building behaviour and performance that may be less accurate and precise than the ones a specialist could achieve but nevertheless provide valuable feedback and hence possibilities for design guidance (Mahdavi, Mathew et al., 1997; Mahdavi, and Suter, 1997; Papamichael, Laporta et al., 1997; Hartog, Koutamanis et al., 1998; Hartog, Koutamanis et al., 2000). In particular, the possibility of representing dynamically and visually processes of a dynamic nature such as airflow that are experienced only fragmentary and tentatively is a major factor of increasing awareness of causes and effects in the indoor climate of a design. Even in the hands of novice designers it is instrumental in transforming trial-and-error improvisations to generate-and-test explorations of a design's variables (Hartog and Koutamanis, 2000). Moreover, the combination of qualitative and quantitative aspects in the presentation of analysis results lays the foundation of meaningful and productive communication between designer and specialist towards a mutual comprehension of the full extent of design problems and decisions.

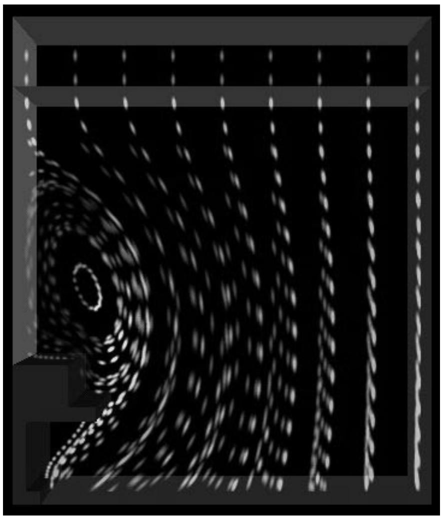

Figure 2. CFD simulation of airflow

2. REPRESENTATION AND INPUT

The integration of CFD simulation in the strategies and tools of the digitally-minded architects depends on a number of pragmatic factors. These include:

1. The availability of affordable simulation systems
2. The efficiency and reliability of simulation systems
3. The educational potential of simulation systems, including interface design and background information
4. The ease of inputting building information in simulation systems

The first two factors are a matter of market dynamics and can be expected to have a positive development with the growing demand for CFD simulation. The third factor relates more to architectural education and will probably remain one of the main shortcomings of commercial software development. The fourth one is a purely methodical issue. Digital design information management is arguably one of the emerging hot items in architectural computerization and one that cannot be resolved by opportunistic solutions such as bilateral data exchange between programs or procrustean or gargantuan standardization schemes. Our working hypothesis is that the connecting tissue between different modalities, activities and aspects is a modular, hierarchical representation of buildings that permits transition from one aspect or abstraction level to another without loss of overview or design focus (Koutamanis, 1993; 1997; 2000).

Input of design information in the CFD simulation means identification of relevant objects, aspects, parts and properties of these objects, as well as relationships between objects. Such information is normally not explicit in a conventional CAD drawing or other digital design document. This is not a limitation of CAD programs but of the mindless reproduction of analogue design and drawing practices in the computer. Admittedly CAD programs offer little support for the flexible and efficient manipulation of meaningful design entities but this is something that can be easily alleviated by customization, i.e. the addition of purpose-built modules that structure and interpret the low-level geometric primitives of CAD (Koutamanis and Mitossi, 1993; 2000a). These facilitate the development of structured representations that cover a wide scope of design aspects and activities with minimal deviation from current professional practices (Mitossi and Koutamanis, 1998; Koutamanis and Mitossi, 2000b).

The explicit description of entities such as spaces, doors and windows in the design representation allows for ready extraction of relevant information. This refers to entity properties that can be derived from its geometry: location, shape, area and volume. Property recognition can be augmented by means of alphanumeric and graphic indications of non-geometric properties, such as color and material, which can be correlated with e.g. sizes derived from the geometry of the entity. Such information is essential input to simulations and analyses of indoor climate (Hartog, Koutamanis et al., 1998).

The advantages of a structured representation for the input to a CFD simulation go beyond what can be identified and measured in individual entities. Also relationships between entities can be recognized automatically. For example, the presence and position of openings in a space can be recognized by relationships of adjacency between a space and windows, doors or other openings. As a result, it is possible to automate input of information on the context of entities and global characteristics of a building, such as orientation, compactness and zoning.

Recognition of properties and relationships is facilitated by a modular organization of the entities in clusters defined by spatial properties such as location in the building and intrinsic entity properties such as construction or functional type. This modularization of information can be achieved by means of layers. In our system these indicate the floor level and the functional type of the entities, such as “windows on the ground floor” or *00_window* in our coding convention.

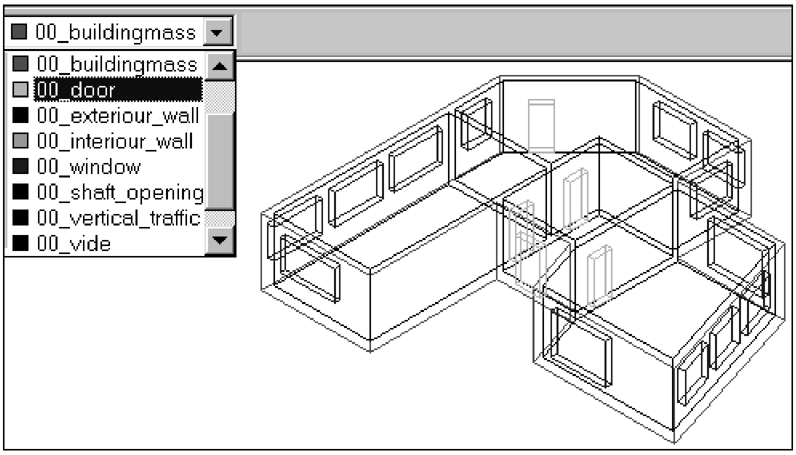

Figure 3. Modularization of design information by means of layers indicating floor level and entity type

The addition of information specific to the airflow analysis follows the same principles. The building representation is extended to cover front-end service components such as inlets and outlets and general properties such as activities accommodated in a space and the primary choice of cooling and heating subsystems. These are generally represented by alphanumeric annotations on spaces and building elements. When these components carry instance-specific information (properties) it is also possible to represent them with separate entities contained mostly in spaces.

In general lines, the use of the representation for inputting design data to the CFD airflow simulation followed the same principles and required similar structuring as other formal and functional analyses (Mitossi and Koutamanis, 1998). In particular, it echoed earlier experiences with light simulation. There too input to the simulation referred to integral, recognizable design entities, their properties and interrelationships. The only difference lies in the input range of each individual act of simulation: airflow simulation requires information on the wider context of a space that is not relevant to light simulation.

3. REPRESENTATION AND OUTPUT

The design representation was also the obvious target for the output of the airflow simulation (feedback). In normative situations feedback can take the form of alphanumeric annotations that describe relevant performance properties of a space. This, however, reduces the detail and specificity of the simulation to global, static measures that do not do justice to the potential of CFD. More specifically, such measures fail to depict the emerging climatic zoning in a space, as well as the dynamic nature of climatic phenomena.

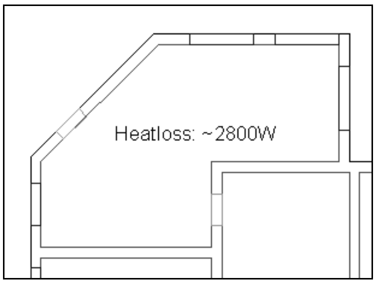

Figure 4. Normative feedback by means of annotations

The superimposition of analysis results, as in light simulation, is the obvious starting point for meaningful feedback to the design representation. In contrast to light simulation, however, the analysis results did not merely form graphic annotations of existing elements in the design representation. The finite elements quantization and calculation in the CFD subdivides a space by a uniform or adaptive grid that does not necessarily express fully its spatial articulation. This is generally viewed as an input and precision problem. Given the rapid progress of computational technologies, we may consider it as a mere temporary limitation that will be lifted by algorithmic improvement and added brute computational force.

In the accommodation of output, differences in the geometry of a space and that of the analysis results can be approached in two ways. The first relies on positive feedback that determines the abstraction of the space geometry by the structure and hence the required fineness of simulation results. This makes the analysis a cyclical process, with added advantages for the overall accuracy and relevance of the simulation. The second way relies on adaptive hierarchical subdivision techniques that are capable of organizing the simulation output using the form of the space as reference framework (Samet, 1990). The added advantage of the second way is the explicitness of airflow grain in different regions and, through that, recognition of climatic zoning in a space.

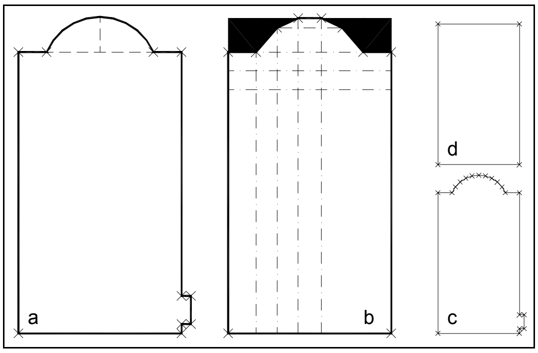

Figure 5. Form, geometry and abstraction: (a) input; (b) for CFD; (c) maximal precision; (d) global description

Feedback of dynamic aspects requires a finer subdivision of the space into voxels that can be used by techniques such as particles so as to give an impression of movement in the depicted qualities and quantities. The addition of such elements in the representation is demanding in computer power but otherwise straightforward and makes visualization of airflow effortless and enjoyable viewing. However, merely allowing the simulation results to coexist with the representation of spaces and building elements does not provide clear design guidance because it relies too heavily on human interpretation. Consequently, one can expect interference from spurious perceptual recognition and logical jumps, especially concerning causal relationships between analysis input and output.

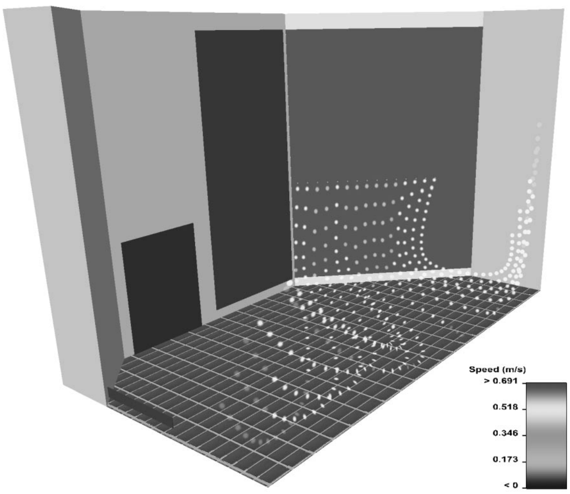

Figure 6. Particle visualization of airflow

4. REPRESENTATION REVISITED

The integration of simulation results into the design representation of a building suggests a need for elaboration of the representation beyond the level of apparent entities such as spaces and building elements, as well as their aggregates into conventional clusters such as wings or abstract coordinating devices (Koutamanis, 1996). One way of achieving that is by treating spaces not as integral entities but as containers of other, intermediate elements. From cognitive science we have evidence that surfaces form such intermediate elements between low and high level vision (Nakayama, He et al., 1995). These surfaces do not merely describe the internal structure of three-dimensional objects in a scene: surface recognition is relatively free from top-down, object-level knowledge and determines perceptual grouping and perceptual recognition. Hence it forms a prerequisite to rather than an effect of object recognition.

In the analysis of built space surfaces also play an important role. Our activities in the built environment relate strongly to dominant surfaces such as the ground, visual boundaries, the horizon and illusory contours. Such surfaces are contained in a space but in many cases they transcend individual spaces and may even unify or otherwise connect spaces with each other. In the specific case of CFD feedback to the design representation we can distinguish between:

– *Formal surfaces:* surfaces relating to the form of the building
– *Activity surfaces:* these accommodate human activities in the built environment and may coincide with formal surfaces, e.g. the ground.
– *Emerging surfaces:* aggregations of analysis results or relations
– *Subdivision boundaries:* products of subdivision schemes such as quadtrees in relation to analysis results

Such surfaces can be approached as reference structures that determine the organization and subdivision of the visual scene comprising the design representation and the visualization of the analysis. Activity surfaces are a pragmatic choice, as they relate climatic conditions to human interaction with objects such as work surfaces and desktops. Formal surfaces have the added property of constraining and modifying the behavior of airflow. Emerging surfaces and subdivision boundaries can be tentatively related to climatic changes in a space. In short, these surfaces arguably define the interaction between the simulation of indoor climate and the representation of its spatial form. Therefore, they are a key element in the formulation and interpretation of the analysis, e.g. as attractors for voxel clustering, and as such deserve explicitness in the representation.

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