Possibilities and limitations of CFD simulation for indoor climate analysis

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ABSTRACT

With the democratization of information and communication technologies, simulation techniques that used to be computationally expensive and time-consuming are becoming feasible instruments for the analysis of architectural design. Simulation is an indispensable ingredient of the descriptive design approach, which provides the designer with precise and accurate projections of the performance and behavior of a design. The paper describes the application of a particular class of simulation techniques, *computational fluid dynamics* (CFD), to the analysis and evaluation of indoor climate. Using two different CFD systems as representatives of the class, we describe: relevant computational possibilities and limitations of CFD simulation; the accessibility of CFD simulation for architects, especially concerning the handling of simulation variables; the compatibility of CFD representations of built space with similar representations in standard CAD and modeling systems, including possibilities for feedback; The relations between geometric representation and accuracy / precision in CFD simulation. We propose that CFD simulation can become an operational instrument for the designer, provided that CFD simulation does not become a trial and error game trying to master computational techniques. A promising solution to this problem is the use of case based reasoning. A case base of analyzed, evaluated and verified buildings provides a flexible source of information (guidance and examples) for both the CFD simulation and the designer.

1 INTRODUCTION: DESIGN AND ANALYSIS OF INDOOR CLIMATE

1.1 **Division between design and analysis**

Current design practice divides analysis and synthesis into two separately executed activities. This division refers to the presence of distinct design stages and the participation of various parties involved in the process. Design synthesis is the domain of the architect, while consulting engineers carry out several design analyses and building performance calculations the results of which are fed back to the designers.
Design processes that hold this division of analysis and synthesis exhibit several weak points. The distance between architect and analysis alienates designers from the possibilities and implications of the analysis. It also degrades the cooperation between designers and consultants to the level of confrontation with far-reaching consequences on the quality of the communication. 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 prove incompatible with the precise mathematical models design specialists employ. Thus, specialists are compelled to build analysis input solely from information found in design drawings. This process is reversed when later in the process, architects face analysis data in quantities and units they are unfamiliar with.

The division of analysis and synthesis shifts the moment specialists are consulted around the end of the design process. Until then, architects are limited to their personal knowledge of building subsystems and, as a result, make design decisions based on a limited amount of information. Moreover, decisions regarding building aspects such as glass areas are made without an accurate prediction of the consequences even though these aspects have a large influence on building performance.

In the final stages of the design process specialists are asked to propose plans and layouts for building services. At the same time they attempt to predict the building's indoor climate. During this process, specialists are often confronted with problems that originate from design decisions that were made by architects earlier in the design process. However, during the final design stages the shape and configuration of the design become permanent and the presuppositions regarding building services and indoor climate are locked in the design. This greatly reduces the ability to accomplish even minor design changes without triggering a large amount of labor for all parties involved. As a result, design flaws that are most responsible for e.g. unhealthy indoor climates can hardly be altered at that stage. This also diminishes the possibilities for specialists to optimize designs on areas such as energy use. The fact that designs during final stages hardly have room and budget to adopt new concepts for indoor climate only adds to the problem.

These observations justify the assumption that in the early stages of the design process a limited amount of design information in the form of shapes and materials is established on the basis of creativity and general knowledge. We also assume that together with the initial information, many the indoor climate features are determined without any analysis of their consequences.

When design optimization needs to be achieved, it must be initiated in the early stages of the design process. One way in which this might be accomplished, is to analyze design performance more systematically during the early stages. Using modern media such as digital visualization, designers could gain easy access to the advantages of advanced simulations and formal analyses. This would enable designers to make more balanced and motivated decisions on areas such as indoor climate. The communication between designers and specialists might also be improved when architects become familiar with the design aspects found in the analyses.

1.2 **Indoor climate**

The indoor climate of buildings comprises four areas of comfort: thermal comfort, olfactory comfort, aural comfort and visual comfort. This paper is mainly concerned with thermal behavior and airflow in buildings. Airflow and related subjects such as ventilation influence both thermal and olfactory comfort. Thermal comfort is influenced, among others, by air temperature (A_T), radiant temperature (R_T), air velocity (A_V) and air humidity (RV). Human bound factors such as metabolism and clothing have a strong impact on the way these physical factors are experienced. Maintaining a healthy air quality, thus maintaining olfactory comfort, implies ventilation of the space (N_V) in order to reduce the concentration of pollution (C_P) in a space. In the case of ventilation, airflow has an impact on factors regarding the thermal comfort (draft). The quantities of these units should be carefully governed and kept between boundary values to avoid discomfort or even an unhealthy indoor climate.

In the Netherlands, building designs are required to comply with the building decree (VROM 1992). In the case of office- or factory-design, the labor condition decree is also in effect. The building decree consists of a number of articles describing, for instance, size of fire compartments, occurrence of faucets and minimum ventilation rates. The labor condition decree aims to guarantee a healthy environment for employees and describes, for instance, light levels, air qualities and hygiene facilities. Both decrees refer to norms released by the *Dutch Normalization Institute* (NNI) to further specify sizes, materials and functions. The norms describe in detail how quantities such as velocities, areas and dimensions should be defined and measured according to the classifications in the codes. Examples of such norms include *NEN 1068: Thermal insulation of buildings*, *NEN 1087: Ventilation of buildings and NEN-EN-ISO 7730:1994 Moderate thermal environments* (NNI 1996, 1997).

When building performance parameters such as air velocity and temperature are required in order to assess thermal comfort, norms describe procedures for taking these measurements by use of laboratory experiments. However, with the growing use of computers in design, automated code compliance checking (de Waard 1992) and building simulations have become more popular. Computer simulations can replace expensive laboratory experiments and show designers design directions with insightful and complete descriptions of the building's behavior. One such a simulation is Computational Fluid Dynamics (CFD) that can accurately predict airflow patterns in building. Other promising developments are made within the fields of scientific visualization and cognitively optimized representations. These techniques proved useful in adapting and presenting large amounts of complex data in a sophisticated manner.

2 COMPUTATIONAL FLUID DYNAMICS

2.1 **What is computational fluid dynamics?**

Computational Fluid Dynamics is a technique for calculating patterns of fluid flow. CFD makes use of a fundamental set of partial differential equations that describe the essence of the fluid flow. These equations derive from three basic principles: conservation of mass, conservation of momentum and conservation of energy within that fluid. Since the equations are far to complex to be solved analytically, iteration is used to arrive at a solution that describes the characteristics of the moving fluid with, among others, specific numbers for velocities, temperatures and pressures. Fast computers are used to solve the equations thousands of times while each step makes the solution more accurate.

Present CFD research efforts are aimed at improving the accuracy and speed of simulations using faster computers and more advanced models. Both geometrical and mathematical complexity need to be refined constantly in order to keep up with the technological advancements made in e.g. mechanical engineering and aeronautics. The permanent quest for more accuracy also calls for more advanced and realistic turbulence models to simulate this highly dynamic effect in airflow.

2.2 **Computational background**

In order to have CFD predict the airflow in a certain situation, several aspects of that situation need to be modeled into a CFD problem definition. These aspects include the size of the situation and the properties of the flowing fluid. Additional information might describe variables such as turbulence parameters, mass and heat fluxes and conduction coefficients.

Most definitions of CFD problems start with marking a bounded three-dimensional space. Calculation of air speeds and temperature is done within this *solution domain*. Usually the domain is equal to the overall dimensions of the space under investigation. In cases where a space has one or more symmetry planes, only a specific part of the space is modeled. After that, the sizes and locations of the walls should be entered, as well as wall properties such as roughness, temperature or conduction coefficients. Most CFD applications for building design work with spaces that built with orthogonal geometry. Other, more general cores handle non-orthogonal geometry in the form of unstructured grids. However, these kinds of cores are difficult to use and provide no help in defining building related problem definitions.

A solution domain may contain one or multiple sources. A source is anything that will force air into motion, will in- or decrease temperature or will change its composition. Examples of sources include momentum sources such as air inlet jets and open windows, heat sources such as radiators and computers and mass sources such as people and carpets. To define a source, one may specify its location within the domain and source properties like inlet velocities, mass flows, heat fluxes or temperatures.

Because computer power is still the limiting factor in CFD, the equations cannot be solved at atom or molecule level. Instead, the solution domain is divided into a set of larger elements on the basis of the Finite Element Analysis (FEA) method. The properties of each spatial element are represented centered on a single dimensionless point. The governing differential equations are then integrated over the dimensions of elements. Since the equations are now solved for a number of discrete points in space instead of at each molecule, this greatly reduces the computer power required (Anderson 1995).

Grids are a fundamental scheme for deriving the elements required for the FEA method. A grid is defined separately along the x-, y- and z-axes (**Figure 1**). For building designs the element sizes normally vary from 10mm to 300mm. Elements should be made smaller at places where large changes in airflow are anticipated. Element sizes should increase or decrease gradually and at the same time follow the geometry of the solution space (sources and obstructions). The simulation starts after the grid has been defined and control parameters have been adjusted so to speed up the simulation.

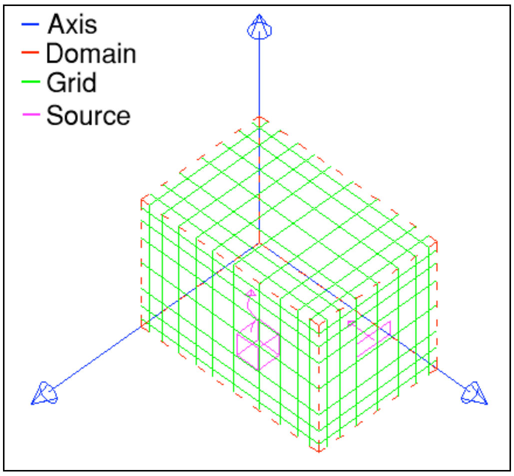

Figure 1: **Schematic representation of a CFD model**

2.3 **CFD and architectural design**

2.3.1 *The necessity for CFD analysis in buildings*

The production of healthy buildings presupposes monitoring and control of several qualities of indoor climate in the design process. Of huge importance for the indoor climate are the temperature and air velocities that occur in spaces where occupants reside. The indoor climate of buildings is a result of active conditions such as sun and occupant activity and passive building features such a window area and shape, natural shading and material properties. In optimal cases, the passive building features are configured in a manner that results in comfortable indoor climate with temperatures, air velocities and air purity within prescribed ranges. More often than not, however, climate parameters exceed ranges that are considered comfortable or even healthy. In those cases additional cooling, heating or ventilation is needed. In these cases, building services are needed to control the indoor climate effectively. Installation components like boilers, radiators, fans and air inlets are installed on strategic positions in the design.

In paragraph 0 we suggested that designers seldom analyze the effects of early design decisions on the indoor climate of their design. For instance, the effects of solar radiation and internal heat sources on the indoor temperatures are often greatly underestimated. The addition of building service components further complicates matters. Employing standard solutions for these installations is no guarantee that temperatures and velocities will remain within acceptable boundaries. A complete evaluation of the design situation including all complicating facets is imperative for stimulating an optimization of both building characteristics and indoor climate.

However, descriptions of the transport of heat and the flow of air in buildings are most difficult to produce. Heat and air transport have the characteristic of being highly variable. In most cases, the situations that are analyzed change over time. Especially when additional elements are brought in to control processes such as air transport, situations change fundamentally and new problems arise. In other words, problem and solution interact. This interaction makes it difficult to predict building features such as indoor climate or heat transport. Even experts find it hard to judge design situations that are different every time and where small variations can have large effects.

2.3.2 *The role of CFD in building design*

Rules and models built from experience and experiments provide engineers a means to reason towards solutions. However, these types of calculation require a considerable amount of time and suffer from limited accuracy. The only way to determine building performance with certainty is to perform real-life experiments. This involves building scale models of the situations and observing behavior under realistic conditions. Certainly in the case of indoor airflow, these experiments require a lot of time, experience and budget. It is practically impossible to perform these experiments in early design stages where shapes may vary freely and where each variant would require a separate test.

With the rise of the computer, many experts recognized the computer's potential to solve these highly complex problems with more speed and accuracy. Tools were developed that could read design definitions and perform the necessary calculations to arrive at a prediction of relevant phenomena. The results produced by the tools would form a reliable basis from which new design actions could be taken. The use of these design tools is very common nowadays and few buildings are designed entirely without the aid of design tools.

In paragraph 0 we mentioned several indoor climate parameters were mentioned. From the above it should be clear that predicting these parameters manually is impossible and that performing experiments is difficult and expensive.

Table 1: **Indoor climate parameters and CFD**

INDOOR CLIMATE PARAMETER	*PROVIDED BY CFD?*
Air Temperature (A_T)	Yes
Radiant Temperature (R_T)	Yes
Air Velocity (A_V)	Yes
Relative Humidity (RV)	No
Ventilation Rate (N_V)	Yes
Pollution concentrations (C_P)	when modeled

A more feasible solution is using CFD simulations to perform these estimations. Given the right amount of correct input, CFD can provide projections of most of the climate parameters at any point in time or at any location in the building (table 1).Moreover, it can simulate dynamic phenomena such as temperature oscillations and turbulence that could be used by climate specialists to ultimately judge design performance.

2.3.3 *Limitations and complications*

The application of CFD in any area of expertise requires a fair amount of knowledge and experience with both CFD and the phenomena under investigation. Until recently, only CFD researchers and design specialists held the amount of knowledge regarding building properties, installations and CFD that was needed to successfully apply these simulation techniques in building design. However, in the past years some software companies developed tools aimed at less expert users. These tools include advanced techniques that automate much of the data specification process for common situations. Some were specifically developed for use in building practice and the built environment. Applications like *FLOVENT* exhibited functionality that automated the definition of building services such as fan-coil and induction units. This greatly reduced the amount of user operations and input information while still guaranteeing a reliable simulation. However, even user-friendly CFD applications still require a fair amount of input. In addition, some basic knowledge concerning airflow mechanisms is needed in order to formulate CFD solvable questions. Users are assumed to have some awareness of quantities such as 'Reynolds number' and phenomena like turbulence and coanda effect. Practice shows however that most architects are not particularly educated in these areas and find it hard to focus on these aspects while designing.

3 A SYSTEM TO DESIGN AND ANALYZE

3.1 **Introduction**

As part of our research we develop a prototype of a system that supports architects in designing and analyzing simultaneously. The prototype employs several existing methods and applications to form a system that allows easy representation and manipulation of conceptual designs and gives access to information regarding the indoor climate of buildings. In the past years, Computer Aided Design (CAD) applications have become quite popular to draw and design. The prototype makes use of the popular CAD tool AutoCAD to provide users with an instrument for design representation and manipulation. Using this tool, designers can enter the overall shapes, spaces and elements in a digital drawing without much effort. The open format and configuration possibilities make AutoCAD an excellent choice for development purposes. However, the techniques and methods used by the prototype could be implemented on most three-dimensional CAD applications.

During our research, a cooperation with both the *Netherlands Organization for Applied Scientific Research* (TNO) and the *Association for Computerization in Building and Installation Technology* (VABI) was established. T. Lemaire of TNO developed the CFD application *WISHPC* and a CFD data protocol for the VABI. We received access to these applications in order to perform indoor climate analyses of the designs. The open protocol enabled us to link the CFD core to the prototype. This greatly reduced the amount of labor needed to perform these analyses and made it possible to use the design representation in AutoCAD as the basis for analysis. This allows designers to benefit from the information provided by CFD simulations without requiring much knowledge of CFD applications and airflow phenomena.

The prototype connected representation and analysis in a transparent and straightforward manner to facilitate design analysis. It uses several techniques to perform the transformations needed to join opposing information requirements and characteristics. Representation prescriptions ensure that designs have sufficient structure to allow channeling of their information for other applications. Automated recognition and the use of precedents supplement design information to the point where it can be used for analysis. Apart from monitoring, the CFD simulation needs little user intervention. Simulation produces large amounts of numerical data that should be aggregated into information levels which designers can connect to. Scientific visualization has proved powerful enough to carry out this task for several other design areas (Post and van Wijk 1994). The prototype uses techniques such as particle tracing and surface visualization to achieve similar results in architectural design. The following paragraphs will elaborate on the techniques used.

3.2 **Representation**

The design representation needs to provide easy input of designs and external control over the contained information. To accomplish this, we developed a drawing method that would ensure correct handling and interpretation of drawing data represented in the CAD tool. This method is called the META Drawing method) describes a few guidelines that are to be followed in order to create representations that are suitable for analysis. This involves representing building elements such as spaces and windows using recognizable objects. Using ordinary CAD functionality, it is easy to designate the intrinsic drawing entities to serve as objects with this functionality.

3.2.1 *Entities*

The META Drawing method requires that building representations are built out of symbols representing, for instance, individual spaces such as rooms and hallways, groups of spaces such as stories, wings or clusters and openings between spaces such as windows and doors. These objects should be drawn using connected lines to indicate their perimeter within the plan. Drawing with these so-called ‘Polylines’ is not a complex procedure, many architectural drawings already use polylines. The requirement that the polylines should be ‘closed’ and ‘planar’ will undoubtedly cause very few problems. All objects can be given a height (*Thickness*) to add a third

dimension. Placement of these objects is not restricted and can vary in any of the three dimensions. This kind of geometric modeling is often called *2.5D modeling*.
Drawing these objects is straightforward and can be done quickly, while still allowing for rather complex geometry to be modeled. If additional objects such as complex façades need to be represented, new guidelines might be developed.

3.2.2 *Modularization*
To further clarify the drawing, the drawing method requests classification of the entities that have been drawn. Layering and a layer name convention are used to modularize the represented objects. Different floors of the building are stored in different layers. Layer names indicating ground floor start with: "00", the first floor start with: "01", the first basement: "-1" and so on. In addition, we used a classification in space ('void') and building components ('solids'). Spaces are categorized further into; common spaces, traffic areas and other spaces. Openings are divided into windows, doors and other openings. Walls & floors, if specified, are divided into internal and external types (**Figure 2**). Extension of the categories is possible and relatively easy to do.

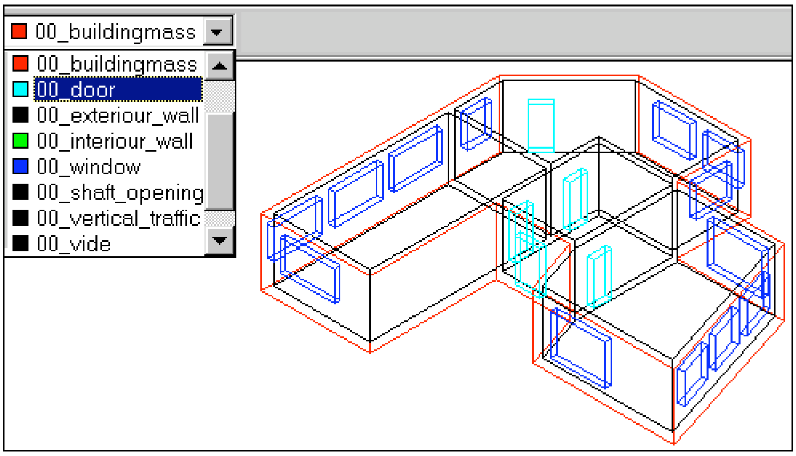

Figure 2: **Modularization of geometry**

3.2.3 *Relations*
In a building representation, relations are not defined explicitly. Neighboring objects are drawn next to each other, but otherwise no linking information is entered. However, the strength of a representation is largely determined by the availability of information regarding the relations between building elements. It is therefore important that these relations are a formal element of any design representation.
Relations may either determine hierarchy or topology. Both are needed when analyzing designs. Topology data provides, for instance, temperatures of adjacent room when calculating heat gains and losses. Hierarchy enables an evaluation to collect regional results into more general predictions.

3.2.4 *Abstraction*
In most cases, the geometry contained within the CAD representation cannot be mapped directly onto simulation geometry. The simulation equations have limitations with regard to curvilinear shapes and small details. In the case of CFD simulation, designers have to avoid drawing small rims and holes. Also, curvilinear shapes need to be transformed into angled lines. In turn, angled walls are represented by filling rectangles with multiple small boxes.

However, in the near future, CFD cores that support more complex geometry will become available to building design. Other promising developments are made in the fields of aeronautics and industrial engineering where advanced geometric abstraction algorithms translate complex shapes automatically into meshes that can be used by simulation tools (Owen 1998).

3.3 **Automated recognition**

Although the information in the digital representation comprises a fair amount of usable data, it is not enough for an indoor climate analysis. In order to perform realistic analyses, the representation needs structure and information regarding the building services. For this task, the prototype uses automated recognition and information from precedents.

Automated recognition is a technique that brings structure to digital design representations. It translates and stores the data found in the drawing into more sophisticated information without user intervention. Recognition uses geometric algorithms that can discover hierarchical relations between elements such as spaces included in a building and openings included in a wall or floor. This provides, for instance, the possibility to group spaces into a single floor or wing and allows users to address multiple objects using a single handle.

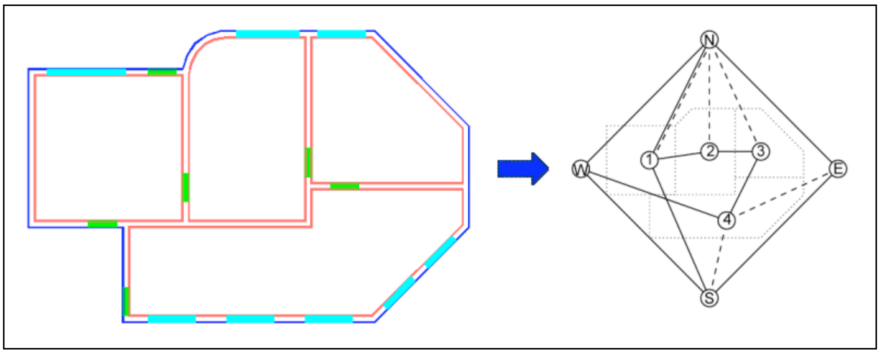

Figure 3: **Automated recognition of topology**

Other algorithms add topology or information about adjacency to the representation (Figure 3). This includes access between spaces that are joined by windows, doors or other types of openings. The relation inside-outside is also topological. In other cases it might be of interest to know which spaces are entirely separated by walls. Automated recognition is also able to find implicitly drawn objects such as the walls and floors between adjacent spaces. These objects do not have to be drawn but can be needed when analysis input is compiled. Automated creation of implicit element might simplify the drawing process and enables easier manipulation of shapes.

3.4 **Use of precedents**

The use of precedents in design has received much attention lately. The availability of precedent information is believed to provide valuable design steering by proposing solutions and alternatives from previous projects. Much of the information from these projects is likely to be re-used when the new design situation resembles that of a precedent. Comparison is done on aspects such as building type, space types, floor-area, occupancy levels etc. In current design practice, architects often make use of reference information and solutions from previous projects. This might help them to get started with new designs and prevent from doing the same work twice.

Designers could look for precedents that resemble the new design and look for clues and directions in the case data. This could be of use when designs are fitted with conceptual building services. Seeing the problem definitions, analysis results and design solutions of other projects might spark ideas that otherwise would have gone unnoticed. Designers could copy building service concepts from precedents to their designs and at the same time have a good idea of how this new equipment will function.

The prototype offers designers the use of precedents when preparing designs for analysis. Designers have the option of browsing through the precedent database and copy general characteristics of building services. The cases and any related information are presented in a user-friendly interface. This interface organizes the relevant cases in a way that make interactive browsing possible. Program, layout and evaluation of the cases is displayed enabling designers to determine similarities and to learn the behavior of specific indoor climate configurations (Figure 4). Using the interface, it is possible to sift through the ventilation, heating or cooling systems of the precedent, mark what is valuable and have the system copy the marked information to the new design. This process is divided into several distinct steps that each handle a specific facet of the indoor climate. Additional information on indoor climate concepts and service components is accessible. Also, spreadsheets are available containing examples and explanations of calculations performed by the prototype.

3.5 **Simulation and visualization**

After the design has been represented and conceptual building services have been chosen, the prototype is able to translate the accumulated information to simulation input. The CFD simulation can be started without further user intervention. For special cases, some additional control over the simulation parameters is provided. For instance, ambient temperatures can be controlled to represent various seasons. In most cases, the analysis runs successfully and results on the indicated indoor climate parameters are calculated.

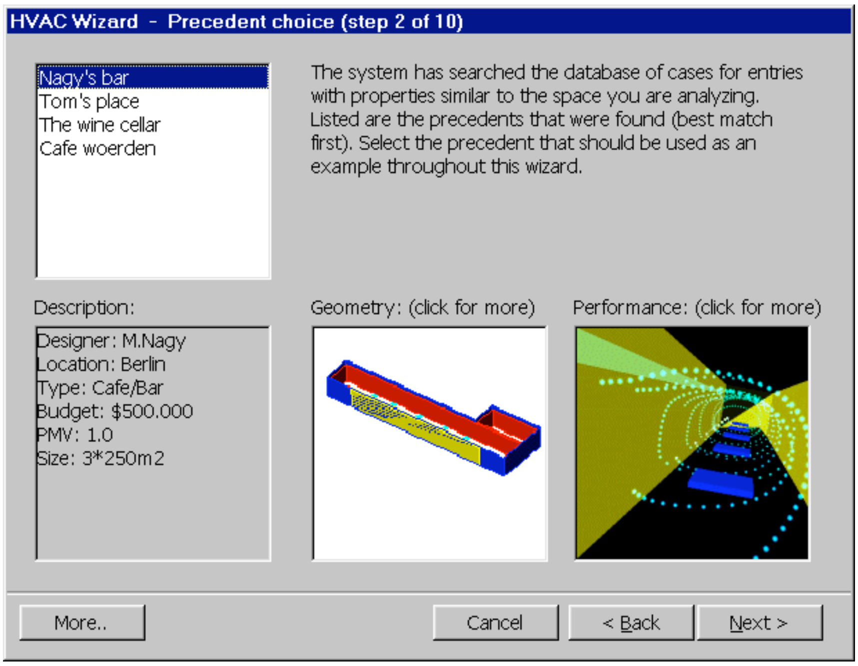

Figure 4: **Precedent choice using the interface**

Analysis results consist typically of large amounts of numbers for velocities and temperatures. Designers find it hard to relate to this data and have difficulties in drawing conclusions from large tables containing numerical data. Visualization of indoor climate aims to let designers interact with the analysis results in stead of merely confronting them with data they do not understand. In order to accomplish this, the analysis results can be represented both globally and locally. These representations can employ scientific visualization techniques such as particle tracing and iso-surface construction. For a global representation of climate parameters and an easy identification of problem areas, a two-dimensional, approximation of results is required (Figure 5).

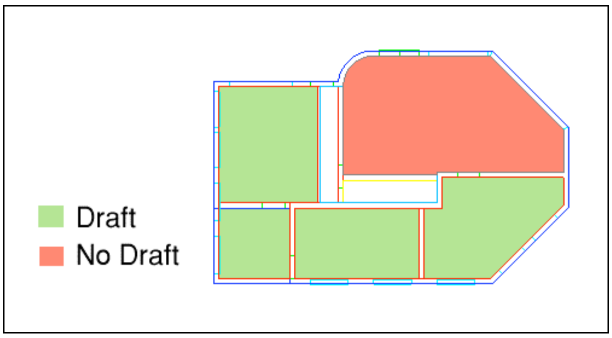

Figure 5: **Global visualization of draft problems**

This allows for designers to concentrate on analysis content rather than confusing them with geometrical ambiguity. Computed indoor temperatures, air velocities and heat loads are accumulated into an easy to read plan view of the design. This view can draw attention to local problem areas in the building. It is also possible that spaces that function well are investigated so to be able to copy the positive properties to spaces that perform less. Local visualizations offer designers the possibility to determine the level of detail and the climate aspects that should be displayed.

Using particle tracing, it is possible to identify both global and local airflow characteristics (Post and van Walsum 1993). Placing particle sources for air-inlets, contamination sources and windows gives much insight in the three-dimensional behavior of air within spaces.

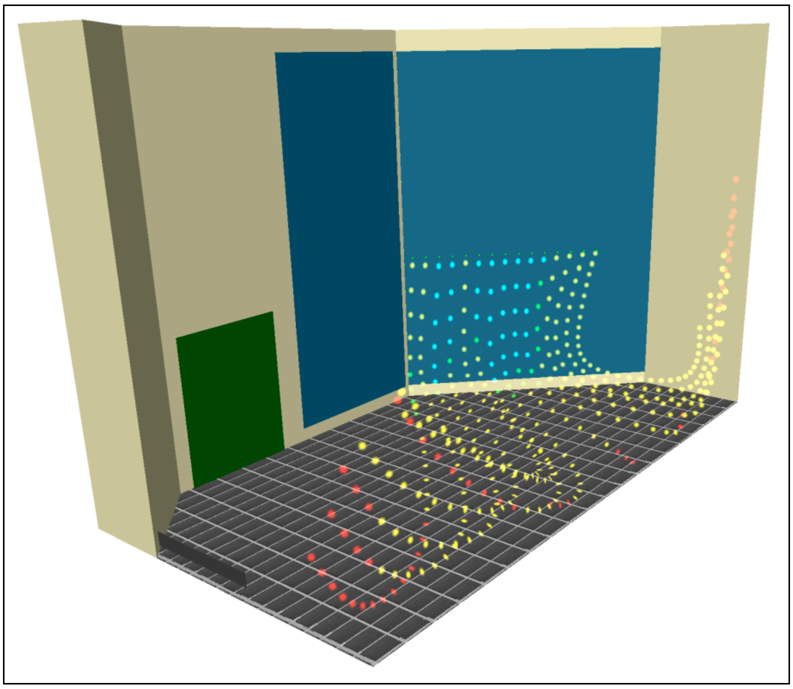

Figure 6: **Visualization using a particle source for a window**

This type of visualization also has the characteristic of pointing to relations between building properties and indoor climate aspects. (
Figure 6)One important aspect of indoor climate analyses is the zoning of spaces into areas related to user activity envelopes. Areas where people normally would not remain for long can in some cases safely expose air velocity rates or temperatures that are considered uncomfortable.

Visualization facilitates investigation of these aspects by dividing spaces into areas of varying importance and by displaying indoor climate parameters only in important zones. This is a spatially complex technique that requires a three-dimensional visualization of results. However, two-dimensional projections of three-dimensional spaces are known to be difficult to interpret and search. Adding interaction and real-time manipulation to these types of visualization will largely improve the legibility of the picture (Felger 1995).

4 DISCUSSION

4.1 **Implications and conditions**

CFD simulation is a rather new technique in building design. Not many indoor climate specialists use such simulations when advising designers. Among architects CFD is almost unknown. However, there is little doubt that airflow simulations can be valuable in architectural design. Especially during the design of complex or demanding spaces, CFD can provide insight in the effects of unusual shapes on the indoor climate and gives clues and answers to building service problems.

Using simulations has implications for the design data that is employed as analysis input. The CFD engines require accurate specification of material properties and spatial conditions. For conceptual design representations, this involves adding information from aspects where designers do not have much experience. However, libraries, automated recognition and precedents can help them in this process. In contrast with the accurate specification of properties is the abstraction of geometry that is needed to comply with the mathematical methods of the simulation. Until advanced transformation algorithms become widely available, it will take some skill and imagination to handle the geometry manually.

A building scale at which consequences of design actions are quite noticeable is the large space. Large spaces frequently accommodate a single activity such as an auditorium or sports center. Spaces such as exhibition spaces or open-plan offices contain separated or semi-separated activities. Both active and passive indoor climate aspects have a significant influence on the way in which these spaces can be used and on the way inhabitants experience their environments. CFD analysis proves powerful enough to predict large air circulation patterns that cause annoying drafts. In exhibition spaces, these effects can be amplified by the climate control mechanisms that are actively controlling the indoor environment. Placing air inlet jets at strategic places is essential when healthy climate control is important. Simulation provides the means for studying and improving the design of such installations.

Reversely, it is also possible to study room shape with parametrical CFD models. While keeping the building service configuration unchanged, the shape of a room is gradually changed to represent various layouts. When the simulation results are put together, recurring airflow patterns emerge. This makes explicit the frequently implicit relation between space and climate and gives designers awareness of how far a specific climate control principle might stretch.

Lack of prior experience could be a severe limitation to the wider applicability of CFD simulation. Together with the novelty of the instrument, it might lead to a general lack of design direction, which would result in extensive trial and error design analyses. Although the systems automates most of the data specification process, users still need to design components such as air-inlets and heat sources together with properties like inlet-velocity and surface temperature. Most designers will be unfamiliar this information and will have difficulty dealing with it. However, the characteristics and accuracy of the input information directly influences the accuracy and reliability of the simulation. In order to obtain accurate results that compare closely to the real situation, the simulation input will need to contain as much information as possible. Using approximations and defaults in input will produce less accurate results. This inaccuracy will not often cause for problems in architectural design since most of the early design process is concerned with order-of-magnitude information. In this context, even approximate results will be of interest for these will indicate the general direction of airflow. However, generalization of simulation parameters cannot be carried to far or inaccurate input will, at some point, produce unrealistic results. These kinds of simulations should not be used for design guidance and might even direct designers in wrong directions.

As awareness of and acquaintance with analysis by simulation increases, we expect that the problems related to the novelty of the tool will be alleviated but only with respect to efficiency and accuracy. Effectiveness remains a matter of design guidance that should not be expected from a design system but from relevant architectural research that focuses on two main subjects:

1. The representation of built space, not only in terms of volumetric spatial or building elements, but also of activity surfaces, fields and flexible, adaptive subdivisions. This should provide the background to the interpretation of simulation results with respect to the activities and actors that are accommodated in a building.
2. The collection and formalization of design experience in case bases that facilitate definition of possible solution types and spaces, as well as provide additional input to the analysis and simulation of building designs.

Both subjects have been identified as priorities in our research into the applicability of CFD simulation to building design and analysis. New technologies such as simulation presuppose a comprehensive and consistent conceptual infrastructure, capable of accommodating new media and methods without loss of direction and effectiveness in the main pursue of the architect, the creation of appropriate built space.

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