DESIGNING INDOOR CLIMATE

A thesis on the integration of indoor climate analysis in architectural design

PROEFSCHRIFT

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1 Introduction

1.1 Background and Problem definition

In contemporary architecture education, indoor climate and building installations suffer from a lack of popularity. Students of architecture, filled with great expectations and awe for the famous designers of the 20th century, find inspiration in examples such as Le Corbusier's *Villa Savoy*, Lloyd Wright's *falling water* or the Rietveld's Schröder *house*. Recognizable as this may be, great aesthetics constitute only a small part of creating architecture. The process of designing and constructing buildings comprises the involvement of a multitude of skills such as creating clear functional layouts, designing solid structures and taking care of healthy indoor climates.

Most textbooks and magazines on contemporary architecture do not cover the less attractive aspects of the indoor climate such as heating, ventilation and cooling unless these services form an important part of the buildings aesthetic identity. Recent examples regarding the integration of second skin facades and natural ventilation in indoor climate, sometimes fail to convince as a result of the lack of thorough evaluations and detailed information.

International awards honor designs with exceptional aesthetics or slender construction. Recently, awards for environmentally conscious buildings have been introduced, however, the first award for designs that display exemplary treatment of inhabitant comfort still has to be initiated. This can be explained in the light of the mechanical and purely functional appearance of building services. The geometrical intrusions they impose on the surfaces and the spaces often conflict with the preference for smooth, straight or curved shapes often found in architectural design.

In many design reviews building services are hardly mentioned because many critics, reviewers and architects do not regard a healthy indoor climate interesting or important enough. Among the reasons for this disregard is the fact that some of the well-known architects were capable of designing in such a way that their buildings naturally provided optimal conditions for the indoor climate. As a result, controlling the indoor climate may not have been a large enough problem to be mentioned in literature and magazines. Another common misconception is that the design of building services is not the responsibility of architects. As a result, indoor climate receives little attention in current design practice. The effects of passive building features are estimated with rules-of-the-thumb if at all. The influence of solar radiation and internal heat sources are easily falsely estimated. The addition of building service components further complicates matters. Employing obvious solutions for these installations does not guarantee an acceptable indoor climate.

Evaluating the design's indoor climate behavior is imperative for stimulating an optimization of passive building characteristics. Too few architects display a particular interest in building services and indoor climate. In addition, building project principals often neglect to define clear and verifiable requirements for the indoor climate and inhabitant comfort at the start of building projects. This might explain the low amount of information regarding service equipment and indoor climate requirements present during the early stages of a building project. Nevertheless, building services represent a slowly but steadily increasing percentage of the total building costs.

In the past few decades, building inhabitants and employees have become more sensitive to their immediate surroundings. With the rise of the curtain walls, all-glass façades and new office space concepts such as the open plan office, sensitivity concerning indoor climate grew, resulting in an ever-increasing number of recurring complaints. These refer not only drafts and high temperatures, but also to health aspects and productivity problems. In a considerable amount of cases, a causal relationship between building services and climate complaints was proved (Preller e.a. 1990). Surprising was the fact that in many buildings with complaints the building services were not malfunctioning with regards to their design specifications. This raised questions not only regarding the realization and occupation of the buildings but also concerning the design process and the integration of other disciplines in particular.

As early as in the sixties and seventies, it was hypothesized that the source of building shortcomings should rather be investigated in the design process rather than in the construction or use of these buildings. Researchers at schools of architecture and design theorists analyzed the design process and saw signs of intrinsic problems in the integration of different design areas. It seemed that during the inevitable trade-offs, certain areas and effects were ignored which, in time, led to the design faults that caused complaints. For example, budget cuts are often transferred to the costs of building services since these are last in line of the design process. Whether these observations concerned incidental errors of individual architects or that it was an indication that the architectural design process had fundamental inadequacies remained an item of many debates (Pollalis e.a. 1994).

As a result of the detailed analyses of the design process, understanding of the process grew. Together with the growing use of computers and theories such as systems theory, *design methods* for architects were developed. These methods were meant to guide designers during complicated tradeoffs and difficult decisions by employing mathematical models and decisions trees. The methods themselves ranged from simple models for spatial layout to advanced computer tools that automated much of the selection and configuration process (Putter 1998). Despite the enormous amount of effort put into their development, architects and designers have been slow to adopt these new techniques. The reason for this hesitation can be found in the complexity of the design process in combination with many exceptions that arise during design and production. The design methods were unable to completely capture design semantics in a manner that allowed flexible and extendible application in design practice and often proved counterproductive in situations that required expertise and rapid deployment.

The experiences with design methods and early computer applications built around structured design theories has taught us that design information is the most influential element of the overall design process. In spite of their failure to manage the entire design process, the design methods had positive side effects. When working with structured methods and process models, architects became more aware of the way in which they designed. In addition, the information that accompanied these design methods gave architects a better overview of the performances of the various sub-systems and of potential conflicts between them. Designers showed a preference for services and tools that provide more information on areas of their choice. In cases where designers had access to various information sources that provide performance assessments, risk evaluations, design variants et cetera, results have been promising. These results lead to the thesis that a better-informed architect is a better designer (Tzonis e.a.1994).

Recent developments concerning low-energy buildings, self-supporting houses and environmentally conscious designs have raised a growing interest in this matter. Architects take pride and pleasure in inventing novel solutions for environmental issues even if it implies that they have to familiarize themselves with the underlying physics. This is most notable in the growing availability of environmental impact data sheets, which provide information on the complete lifecycle of building materials and products. Architects seem to use this information to more consciously choose materials and products that have less impact on natural resources and will cause less pollution during construction, use and demolition (Kristinsson 2002).

At the start of this research, two notions recurred from past observations. Firstly, if your goal is to improve the product of the design process, you need to address the persons doing the design. Informing designers about the problems observed in building is a promising path for further research. Supplying them with possible solutions is an even better option. Secondly, the quality and the availability of the provided information is an important factor for success. As can be seen from the research on using renewable energy in building, chances of successful integration in the design are high when the information is readily accessible and stimulates creativity.

1.1.1 Architectural Design

Similarly to other design professions, architectural design is a discipline where overall design performance is made up of several, at times conflicting, aspects. Architecture distinguishes itself by the high level of emphasis placed on aesthetics. This impedes the definition of objective goals and criteria for the aesthetic part of the building. The performance of other aspects may also be hard to qualify or judge in advance. Moreover, design decisions may interact and negatively affect the performance of earlier moves.

The performance of some of these aspects such as the structural system can be expressed in clear criteria such as load carrying capacity or resistance to earthquake forces. Failure to meet these criteria may result in dramatic evidence of poor design performance, i.e. building collapse. Aspects of indoor climate are more difficult to measure and can only be indirectly tested by e.g. stating overheating and air quality requirements. It is not easy to determine compliance with indoor comfort criteria with a high degree of certainty before the building is constructed. Although this will make the building less attractive for tenants and buyers, it will not render it useless. These types of design flaws might often be corrected afterwards.

Making architecture is dealing with these uncertainties without loosing oversight (Verheijen 2002). In cases where design information is not available or highly unreliable, problems that arise from this lack can be postponed to a later stage. Intuitively choosing which problems to solve and which to postpone is a skill that architects need to develop. This requires a level of boldness regarding decisions and information that alienates some of the more scientifically skilled team members.

However, aesthetics is, and probably will remain, the most important issue in the architectural design process. Most architects choose their profession because they want to make buildings that above all look great (Hamel 1990). They attempt to capture space by defining masses and to encourage movement by connecting spaces with openings that transport light and people. The experience of walking through a building must bring about a sense of lightness, timelessness and awe among visitors. The delicate play of light and shadows is perhaps the most powerful instrument of architects. Le Corbusier put it this way:
“Architecture is the masterly correct and magnificent play of masses brought together in light.”

Architecture can be said to design facilities that shelter human activity in such a way that staying in them is considered pleasant. What is considered pleasant is not a static concept but depends on the definition and interests of the people that will actually use the building. In fact, the objectives that the design must fulfill stem from a large number of building project participants. These different parties have many criteria and goals, some purely functional, some aesthetic. Most of these parties have long- or short-term financial interests and even municipalities concern themselves with legal issues surround the construction of a new building.
Some of these parties involved are:
- Principal / building owner
- Building manager
- Building tenants

- Government
- Contractor
- Subcontractor
- Inhabitants
- Architect
- Building Services consultant
- Structural Design consultant

Architects face the task of integrating the interests of all these parties into a single building. These interests often conflict and contend for priority. Wittgenstein clearly recognized the complexity of architectural design when he wrote:
“You think philosophy is difficult enough, but I tell you it is nothing to the difficulty of being a good architect.”

Integrating the wide range of requirements into a building is not an easy task. This process can be complicated by the individual goals of other building team members or the possibilities and limitations of the applied building materials and products. In recent years the increased stress on building code compliance and lower building budgets has produced a shift in the design goals. Building managers consider a good building to meet the requirements of the paying parties. This does not necessarily include good aesthetics. Architect Renzo Piano expressed this problem when he said:
“Architecture is a great art but it is happily contaminated by life, society, tradition, modernity, technology and science.“

1.1.2 Design and Indoor climate

To a large extend the indoor climate of buildings is the result of design decisions that architects make. The definition of shapes, choice of materials, daylighting choices and other decisions determine the quality of the indoor climate. They concern building elements that by their presence, position and substance become a part of the thermal, acoustic and aerodynamic processes within the building. Although the sum of the passive building elements does not constitute achieving inhabitant comfort, they form the basis for an unrefined indoor climate that can be supported and optimized using building services. In many cases, this initial climate determines much of the realized indoor climate’s quality.

In turn, the indoor climate of buildings has great impact on the occupants’ interaction and well being in the realized buildings. In offices it can have a large influence on employee performance and the occurrence of absence. In hospitals and nursing homes, poor quality of the indoor climate can account for an increase in the number of illnesses and even deaths (Luscuere e.a. 2002).

Architects make design decisions that determine the performance and quality of the building on many aspects including indoor climate. In doing so, they may unintentionally establish a level of inhabitant comfort that does not correspond with the requirements in the design brief.

In order to have the ability to control indoor climate, designers need feedback on the performance of the design. However, the parameters needed for the assessment of indoor comfort can be difficult to read or measure in the design documentation (Morbitzer e.a. 2001).
Indoor climate is the result of several physical processes such as installations and occupant behavior that dynamically interact and form a complex network of causes and effects. Moreover, some of the aspects required for indoor climate prediction may remain uncertain until the construction of the building. For instance, the manner in which the inhabitants will use the building can only be observed in real-life. People are unpredictable when it concerns their preference for sunshading and use of equipment.

Still, much of the feedback that is required to make design decisions can be supplied by specialized design analyses. These analyses calculate performance with respect to a particular aspect of the building from the available design data. Examples range from floor area calculations to advanced computers simulations that mimic and display the process of air or heat moving through the building. Over the past decennia, many tools for such analyses have been developed, commercialized and applied in the design process. However, these tools were developed by and for disciplines other than architectural design.

A source of many problems is the time when the analyses are performed (Augenbroe e.a. 1993). Current design practice separates analysis and synthesis into two activities that are executed at different stages of the design process. Design synthesis is the domain of the architect, while the consulting engineers carry out the specialized climate analyses (Luscuere 1996b). During the design of buildings such as offices and hotels, consultants are called in to design the building services. These specialists are trained in interpreting and analyzing design drawings in terms of indoor climate and detecting climate hazards. During design meetings, specialists advise architects on the presence of these hazards and how to employ equipment to reduce or neutralize these effects.

In traditional design practice, design consultations are requested at a time when the design has almost reached its final form. In order to allow the specialist's advice to contribute to key design decisions, this should occur earlier. Designs loose their capacity to incorporate elements introduced by specialists when it advances in time. However, building budgets are usually tight and leave little or no room for these early design specialist consultations.

The unfamiliarity of architects with building services and indoor climate means that even when analysis results are at their disposal, they find it difficult to relate the analysis outcome to the designs and to draw conclusions based on their observations of the data. This problem is also caused by the nature of the software developed for indoor climate analyses. These often produce large amounts of detailed data such as temperature distributions and material properties. Architects generally prefer more abstract assessments of whether or not the desired performance goals will be achieved. Although there are programs that connect more closely to architectural decision-making, these tools are not well known or not easily available to architects.

Architects are often limited to their personal knowledge and experience of specialized building subsystems and, as a result, seldom have all information on building performance. Luscuere has pointed out that, in the early stages of design, the decisions that affect the indoor climate most are taken on the basis of a limited amount of information on the actual consequences (Luscuere 1992). In addition to being incomplete, this information is also at a high abstraction level that leaves much room for confusion. Closer examination of the design process reveals that architects often use rules-of-thumb or experience to provide the basis for their decisions in the absence of reliable feedback.

An example of an early design move with large consequences is the application of all-glass façades or large space heights in living areas. The increased material and construction costs are usually accounted for. However, few designers realize that the consequences of such moves also purport to other parts of the building. In cases where large glass façades are used additional attention to the ventilation, heating and cooling is inevitable. Often it takes a considerable amount of effort to convince the other design team members that additional budget needs to be reserved for this.

Another effect of the division between synthesis and analysis is a professional separation that 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. Consequently, architects may neglect to consider and decide on areas on which they have little expertise. 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.

Instead of communicating early in the process, consultants and architects start their cooperation at the point where the principals want assurances that the building will perform as required (Wilde e.a. 1999). In these stages of the design process, building service specialists are asked to propose plans and layouts for building services. To do this they have 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 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 unhealthy indoor climates can hardly be altered at that stage. This also diminishes the possibilities for specialists to optimize designs on aspects such as energy use. In addition, most building projects hardly have budgets to adopt building service systems that cost more than assumed. This puts additional stress on advisors to agree the present course and develop climate control within these boundaries. The result of this is that architectural creativity and general knowledge on indoor climate establishes shapes, materials and topology that largely contribute to the level of inhabitant comfort (or discomfort) in the completed building. Often, the building budgets are depleted at this time and the design team cannot choose adequate equipment for the control of the indoor climate.

The result is a growing number of buildings that do not perform as expected from the viewpoint of the building's occupants. Several research projects have investigated inhabitant complaints in modern buildings (Finnegan e.a. 1984, Kroling 1988, Preller e.a. 1990, Zweers e.a. 1992, Bluyssen e.a. 1996, Kurvers e.a. 2000).
In most of these cases, the researchers did not look for the source of the complaints. However, if the complaints stem from the presence of an unhealthy indoor climate, several causes may exist. One of them is the deterioration of the building services. When owners continue to use services after the functional lifespan has terminated, failure may occur. Another reason might be the improper use of the building. When a considerable larger number of people than was intended, use the building, the capacity of the building services may not suffice. Not all inhabitant complaints can be attributed to physical causes; there is a number of examples in which psychological aspects are at the source of inhabitant complaints (Vroon 1990). Vroon found that workers with low social status or payment complained more often and expressed more serious complaints than management-level employees.
Still, in most cases it proved hard to find the exact cause of the complaints. Investigators found relations between health and indoor climate complaints and the type of building service system or between complaints and social status (Hedge 1996). Building service advisors usually have little trouble in explaining the problems that arise in indoor climate control. To them it is clear that the building or the building service or both do not perform in the manner they should. Moreover, the mismatch between service system and indoor climate requirements was often clear at the time of the design of the building. This indicated that the building services were *designed incorrectly*.

The definitive character of a constructed building causes an additional complication. Not only is it expensive to modify buildings afterwards, it is also legally hazardous. A verdict of the Dutch high court showed that architects as owners of the intellectual copyright of their designs, can forbid alterations such as adding sunshading when they deem this in violation with their aesthetic objectives (Kabel 1999). This can cause problems when buildings do not live up to their expected performance. Since altering the façade of a building by adding sunshading devices violates this copyright, the possibilities to improve a faulty design afterwards can be severely limited by the views of the architect.

In recent years a new type of design team cooperation has gained in popularity. Construction projects that employ *design teams* are characterized by an early involvement of design specialists in the design process. This enables architects to call upon design specialists and address complex issues such as indoor climate during conceptual design. Although this type of collaboration has produced innovative and exemplary results, it requires a commitment of all involved parties that is not always present. A complaint too often heard concerns the engagement of these specialists. Having a background in mathematics and physics, most specialists have difficulties relating to the aesthetic and architectural questions that live among designers at those early stages. Moreover, in cases where parts of a design may develop multiple directions, it also is time consuming and unprofitable for specialists to exhaustively generate details for every alternative. More often they will postpone advising until the design has reached a more definitive stage. Although employing design teams may imply the availability of an adequate amount of design information, this is not always the case when feedback fails due to communication difficulties.

Integrated design approaches are meant to overcome these difficulties by providing methods that systematically investigate the consequences of design moves on areas such as construction, costs, life cycle and indoor climate at early design stages. Architects that chose to design on quantitative grounds have developed many of these methods. In order to compare different design alternatives, designers looked for a method of expressing all design consequences in a single number of uniform cost figures. These methods require that architects have access to more detailed and reliable information on building behavior than conceptual designs can provide. As a result, rough area-related figures are often supplemented by rules-of-thumb.

In spite of these developments in the design process, the problems caused by the absence of performance information remain. Design optimization must be initiated in the early stages of the design process. However, enhancing the design data contained in conceptual designs is not an easy task. In order to avoid the generalizing effect of employing statistical data, the available architectural definitions must be used to the full extend. One way this might be accomplished is to connect conceptual designs to mathematic models that design specialists use. These experts have tools that can perform detailed analyses and evaluations. If architects would have the ability to employ these design analyses without much effort, they might evaluate design performance more systematically during the early stages. Moreover, using modern media such as digital visualization and computer-aided drawing, designers could gain access to the advantages of analyses using terms and elements that are within their perception. Familiarity of architects with technical analysis characteristics and output might also prepare them better for the communication with specialists.

1.2 Research Objective

Prof. Luscuere of the Delft University of Technology is one of several scientists that initiated a program aimed at solving the issues surrounding indoor climate in architectural design. Prof. Mahdavi of Carnegie Mellon University and Prof. Papamichael of the University of California are others working on similar issues. Luscuere defined an approach that targets one of the main causes of many design problems: lack of information. In Luscuere's vision, designing buildings should evolve into a process wherein all design participants work together as much and as early on as possible. This design process should approach is supported by a system that provides information on product and performance. He emphasized that this system should be so easy to use that architects are tempted to try its possibilities and receive indoor climate feedback even if they operate without the help of design consultants. Under no circumstance should the users become frustrated by complex procedures and specifications. Luscuere calls his framework *'the Meta Design Environment'* and advocates the use of this method for all types of architectural design support disciplines including structural design, cost control, planning and facility management (Luscuere 1996b). In his research outline, Luscuere uses the following hypothesis:

"Analysis of indoor climate performance of a design during the early stages of the design process will improve the quality of the design in this respect."

In order to research the validity of this hypothesis, we need a quick, easy and inexpensive way of enabling analysis during design. Next, we can investigate the chance of acceptance of such systems and the impact they have of the design process. However, we cannot develop a design support system without considering the possibilities and constraints of the design process and design analysis. At the same time, we need to consider how design analysis can be stimulated in architectural design.

1.2.1 Constraints and considerations

In order to narrow down the research, some constraints and considerations apply. These are the result of limited time-span and resources on the one hand and the fact that we are best known with the issues in Dutch Building practice on the other.

Although Luscuere's definition of the 'Meta Design Environment' includes a numbers of specialist disciplines in design such as costs, mechanical engineering and indoor climate, we will focus this research on indoor climate. The research and its experiments are created for the indoor climate of newly designed office buildings. This means that the assessment of indoor climate quality will be done using common rules and regulation for office workplaces.

In bringing analysis to architectural design, there are generally two approaches. The first approach is to employ the existing, validated and highly optimized analysis tools that are used in design advice practice and capsulate them in a way that makes utilization by less specialized, architectural domains possible. The second approach is to develop new models for analysis tools that are specifically tailored to the requirements and modalities of architects. In both cases a considerable effort has to be made to develop innovative user interaction to ensure acceptance by architects on the one hand and a sufficiently reliable physical analysis model on the other. The past few decades have seen a huge investment in new developments and improvements with regard to indoor climate analysis. Predominantly architecture-oriented advancements in design support have been much more sparse. Therefore, this research aims at supporting architecture and does not concentrate on developing new analysis models. This implies we start our developments from the notion that several well-known, validated and reliable analysis instruments are available for incorporation in our research.

Design support for architect is not uncommon. For the semi-final and final design stages, architects use the advise of design consultants. We focus on early design for reasons described in the previous paragraph. Early design is the stage where the aid of consultants is scarce or non-existent.
There are also other options for early design support that remain out of focus in this research. One of those options is the possibility for close cooperation between architect and consultants in the early design stages. Since this is costly and must be initiated by the principal, in most ‘regular’ design assignments architects have to go through the first stages without the aid of consultants. Our research is focused on automated use of analysis tools by architects during the early, schematic phases of the design.

If we attempt to integrate indoor climate information into the design decision-making process, it implies that designers must accept the introduction of indoor climate themes into their design processes. In order to heighten the chances of the acceptance of these new themes, the developed additions need to involve as little intrusions and disruptions as possible. Usually, designers do not react well to prescribing new design methods even when these deal with designing specific parts of the building.

The Meta Design Environment was defined around the design process occurring in The Netherlands. This means that in our definition of the design process, the architect is often also the project manager and has a large influence on the (aesthetic) quality of the end product. Also typical for the Dutch situation is the fact that architects bear no responsibility for the structural or environmental quality of their design or the building (Kabel 1999). This greatly reduces the chances of creating legal incentives for improving the indoor climate quality of design.

1.3 Research Questions

If we try to promote the use of tools in architectural design, we will need to consider the introduction of these techniques. It will not suffice to simply make available the software to the designated users. Generally speaking, architects are not looking for new tasks in their already busy schedules. At the very least, the introduction of new techniques or instruments will need to be accompanied by descriptions of the requirements, benefits and limitations. It is also likely that existing techniques and data will need to be modified in order to facilitate integration.
If we want to find a quick, easy and inexpensive way to give architects access to indoor climate analysis, the following question needs to be answered:

Q1: What are the currently available climate analysis tools that can be used in our research and what are the opportunities they provide for use in a design support system?

If we assume that the information these tools produce can be applied in design, the next question concerns the integration of these tools into the tasks surrounding architectural design.

Q2: Taking into account another commonly used computer instrument (CAD), can this be used to provide (geometrical) input for the analysis tools?

Q3: If the information in CAD and analysis does not completely match, is there another quick, easy and inexpensive way of providing analysis input?

Design support systems produce output. This information will need to be evaluated in order to determine subsequent design actions. Support systems often provide assistance by filtering and presenting this information.

Q4: How can the output of climate analyses be processed in order to support designers involved in design decision-making?

When connecting architectural design and climate analysis there are several issues that stem from the informational differences that exist between these two areas. Firstly, architectural design concentrates on defining primary processes, shapes and materials. Indoor climate analyses focus on building services, climate-related building properties and service control. Secondly, architectural design data is dynamic and fluid. Architects may quickly define multiple variants and can change properties and occurrences in rapid succession. Analysis takes a considerable amount of effort and time. This makes it difficult to process many variants. Another problem is caused by the results of calculations. These are produced for utilization by specialists and are of a high level of detail. This level contains more data than architects are able to process at times when they are designing.

1.4 Research Method

In order to resolve the research questions we performed several experiments. One goal of these experiments was to focus on a research question and consolidate our ideas into concrete products. This part of the experiments produced parts of the system we described in the previous paragraphs. Another goal of the experiments was to determine the effectiveness of our developments by having several subjects (mostly specialists and students) test and evaluate system. In cases some, development and validation occurred within one experiment.

Experiment 1 (E1) consisted of the first part of the system development. It answered questions regarding the abstraction of analysis input and the usability of design representations. First, we categorized the in- and output of thermal analysis tool and selected the data specifying design geometry. Next, we devised a drawing method to provide the geometrical input for this tool. Finally, we tested if the connection between drawing and analysis input could be made solid.

Experiment 2 (E2) expanded on the in- and output lists made for the thermal analysis. We did the same for CFD analysis. Next, we researched existing information structures that could be used to store the data involved in analysis. We developed a dedicated information structure for our environment and expanded the link with design drawing to process more data.

Experiment 3 (E3) was a case study where several existing designs were inputted using our drawing method and processed into the information structure. Manually, we inputted some of these designs in the CFD and thermal analysis tools to produce reference data that could be used to validate our developments surrounding automated recognition and translation of design drawing into analysis input.

The D7 experiment (D7) consisted of a student exercise. Students that did the D7: design and computer science course, used our system to input and analyze their designs using CFD simulation. The purpose of this exercise was to make students aware of climate hotspots in their design. Another goal was to test the acceptability of the abstraction method we used for analysis. The designs were included in our case-base.

Experiment 4 (E4) concentrated on the questions regarding alternative information sources. It expanded our representation method to include installation data. This meant that we needed to develop a method and symbols for including installation components. It also implied recognizing and storing this data into our information structure. It then looked for ways of providing this information based upon the use of precedents. The installation component database was based upon the ‘combine’ research and adapted to our system. The developments in this experiment were closely related to the cooperation with TNO we were setting up.

The cooperation with the Netherlands Organization for Applied Scientific Research (TNO) focused upon connecting the information structure to a CFD simulation tool. TNO developed a CFD communication language on which we connected using the META-CML interface. We submitted several of our cases to TNO computers using the interface. Both the technical solution and the validity of the calculated results were evaluated.

Experiment 5 (E5) concentrated on the questions regarding the feedback of analysis results. A masters student used these questions and the techniques of scientific visualization to research and develop visualization methods for indoor environment. He used a list of indoor climate phenomena and design criteria to determine the effectiveness of several visualization types.

Experiment 6 (E6) consisted of another masters project. The student used representation and interface techniques to develop a front-end for the thermal analysis tool. He then set up an exercise where students input designs and use the tool to research building and indoor climate interaction. This experiment represented a significant validation of the use of indoor climate analysis in design. Several hundreds of students used the tool in a design assignment and reported back their findings.

Table 1 contains an overview of which research questions are addressed by the experiments

Table 1: Research Questions and Experiments

Experiment: / *Research Question:*	*E1*	*E2*	*E3*	*D7*	*E4*	*Tno*	*E5*	*E6*
Q1: Analysis tools	X			X		X		X
Q2: Design representation (CAD)	X	X		X		X		X
Q3: Completing input		X	X	X	X			
Q4: Visualization of output							X	X

1.5 Thesis outline

Chapter 2 deals with the first research question. It starts with background information on indoor climate for readers not familiar with the theory. It contains a way of assessing indoor climate quality through the rules and regulations for indoor climate in The Netherlands. Two climate analysis tools are selected and described in more detail. An overview of the in- and output of the analysis tools is given. The chapter concludes with an assessment of the application of the tools in the context of this research. Readers already familiar with indoor climate and climate analysis might want to skip this section.

Chapter 3 covers the topic of using CAD data as input for analysis tools. It introduces design support in general and briefly describes the concept of design representations. It relates the analysis in- and output to the information found in design representations. An overview of past and current research in this area is given. The rest of the chapter is dedicated to describing the methods required for translating architectural drawings into structured data. The chapter also deals with the place of building service information and storage of data. It continues to describe techniques used for structuring and processing the geometric design data.

Chapter 4 discusses what must be done when the information from design representations is insufficient. It shows why we choose precedents as the key solution to this problem. It builds on the vast amount of research done on the re-use of information through case-based reasoning. The chapter describes the way these techniques can be employed in the Meta Design Environment.

Chapter 5 applies visualization techniques to indoor climate analysis results. It starts with a review of the analysis results that need to be presented. It introduces the area of scientific visualization and several of the most prominent visualization types. It makes a match between indoor climate feedback requirements and the available techniques. Successful matches are accompanied by examples. The final part of this chapter presents some of our new developments regarding visualization techniques for architectural design.

Chapter 6 describes a method that can be used to connect the architectural design process to indoor climate themes. This method makes use of a collection of these themes and a procedure to execute the required analysis. It will show examples of architectural issues that can be related to indoor climate questions. Using the Meta Design environment, users can generate answers and new insights in climate issues. Finally, several design examples are presented. These will demonstrate the purpose of the Meta Design environment.

Finally, Chapter 7 will recapitulate the findings from the previous chapters and try to provide answers for the research questions.

Outlook

The findings of our research are combined in a framework that is called '*the Meta Design Environment for indoor climate*'. The framework contains four distinct elements that stem from the research questions. At the end of our research, the requirements of each of these elements had been researched individually and prototypical solutions for each of these elements had been developed accordingly.

The developments are combined to create an architecture-oriented environment that automates the application of technical analyses for the purpose of providing designers with information on the indoor climate performance of designs. All developments are done on the assumption that the execution of analyses purports a positive effect on the integration of indoor climate in the process and the performance of the building realized. A computer-based environment would arguably provide the best possibilities for facilitating such integration. This environment should display the following properties:

1. A design representation that closely follows existing architectural drawing techniques.
2. Access to analysis techniques that provide indoor climate performance predictions with sufficient reliability to be applicable in the early design process.
3. Support for the preparation and execution of analyses.
4. Feedback of analysis results in manner that closely relates to architectural thinking and supports the identification of conclusions with regard to the relation between design and climate performance.

2 Indoor Climate Analysis

This chapter contains the results of study to the possibilities and limitations to use indoor climate analysis in design. It has an introduction to some general indoor climate aspects for readers not familiar with this area. A closer look is taken towards two climate analysis tools to determine which properties are useful for design support. This also includes background information that describes method and application for readers foreign to these tools. As a conclusion, the tool's input item are arranged to reflect their influence on accuracy of output results.

2.1 Indoor climate

When people reside within buildings, they expect to find more than a pleasant aesthetic experience alone. Occupants of buildings need to spend prolonged periods of time inside buildings or other enclosed spaces. Control over aspects such as temperature, air quality and light are of major importance to the short-term as well as the long-term well being of humans. The domain of indoor climate designs this well being as a part of the built environment and researches the perception of indoor comfort. Perception of indoor comfort is a judgment of individual satisfaction as far as this can be attributed to the indoor climate. It is also influenced by emotions such as stress, happiness and social status. The perceptive part of climate theory has strong links with human psychology. The well being of people is related to healthiness and the occurrence of physical complaints such as headaches and eye-irritations. This part of indoor climate theory is more clearly defined and is able to take exact measurements such as the number of ill occupants and hour-by-hour temperatures of spaces. Another possibility is to interview occupant as to their perceived state of comfort. Comfort is a state of satisfaction with a certain situation; individuals that are comfortable have no desire to change any aspect in their surroundings. Discomfort is typically expressed in the degree in which occupant feel removed from the neutral situation.

When dealing with the indoor climate of building, four focus areas exist:

Table 2: Indoor Climate Domains

Indoor Climate			
Focus area	*Parameters*	*Theory*	*Objective*
Thermal / hygric	T_a, T_r, v, RH, M, I_{cl}	Fanger PMV/PPD	Thermal Comfort
Indoor air quality (IAQ)	Amount of fresh air dpol / olf	Fanger PMV/PPD	Healthy & pleasant IAQ / Olfactory comfort

Indoor Climate			
Focus area	*Parameters*	*Theory*	*Objective*
Acoustical	dB(A)	Acoustics / Threshold values	Aural Comfort
Light situation	Lux	Threshold values / Avoiding contrasts	Visual Comfort
Key:			
T_a [K]: air temperature			
T_r [K]: mean radiant temperature			
ν [m/s]: air velocity			
RH [%]: relative air humidity			
M [met]: metabolism			
I_{cl} [clo]: clothing insulation			
dB(A): sound level in decibel			
lux: Light level in lux			
PMV: Predicted Mean Vote			
PPD: Predicted Percentage of Dissatisfied			

Indoor Environment has the same focus areas and objectives as Indoor Climate with the addition of the attention for more aggressive contaminants:

Table 3: Indoor Environment Domains

Indoor Environment			
Focus area	*Parameters*	*Theory*	*Objective*
Chemical contaminants	Threshold values for known substances with negative health effects	Epidermal studies	Avoid exposure to substances
Biological contaminants			

This thesis concentrates on the role of thermal and olfactory comfort in architectural design. Research at other institutions has already made progress in the areas of aural and visual comfort in relation to architecture (Neukermans 1992, Papamichael e.a. 1997a, Mahdavi 1997b, Groot 1999, Plokker e.a. 2000, Bluyssen e.a. 2002).

Thermal and olfactory comfort consist of multiple physical attributes. Thermal comfort is determined by the combination of air temperature: T_a [K], mean radiant temperature: T_r [K], air velocity: ν [m/s] and relative air humidity: RH [%]. Two additional factors that are bound to the human body are metabolism: M [met] and clothing insulation I_{cl} [clo]. Maintaining a healthy air quality (olfactory comfort) implies sufficient ventilation of the space: N_v [m^3/h or m^3/s]. The influence of parameters such as health, age, gender, tolerance and emotional state on the perception of thermal comfort is more difficult to quantify. People with asthma or lung diseases will make higher demands with regard to air quality than most healthy people. Older individuals usually prefer higher temperatures, whereas people that spend most of their time outside will have more tolerance for lower temperatures.

Thermal management of the human body
Thermal comfort is as much related to outside conditions as it is to human physiologic processes. The interaction between a human and its environment is at the basis of indoor climate control. According to McIntyre (McIntyre 1980), human body temperature is a result of metabolism, which is the burning of carbohydrates. The amount of heat produced by basic metabolism depends on the age and gender of the subject. It can be increased by performing activities such as walking or cycling or by a change in ambient temperatures. The heat produced is foremost used to keep core body temperature within a narrow range. The muscles use another part of the energy to perform external labor. In order to dissipate excess heat, the body transfers it to the outside. The body can control skin conductivity and the blood flow in order to maintain a healthy core temperature. As a result skin temperature fluctuates to respond to changing internal and external temperature conditions.
Heat transfer can occur through radiation, convection and conduction. Heat transfer by radiation is based on the principle that a body with a temperature above absolute minimum will emit heat by electromagnetic radiation. Multiple bodies will emit and receive radiation and attempt to achieve a common temperature. In order to determine how much heat is received or emitted by radiation, the concept of plane radiant temperature can be used. It denotes the temperature of a black sphere that would project the same amount of irradiance on a small element as would occur in the actual environment. The mean radiant temperature can be used to estimate the amount of heat a body exchanges with the environment through radiation. In addition to radiation, heat transfer by convection makes up for a large part of the total heat transport. Convective heat transfer consists of air moving alongside a body and carrying heat from or to that body. When a fan or natural breeze is present, we speak of *forced convection*. Otherwise, the natural buoyancy of the air will cause the air to move upwards. This process is called *natural convection*. The occurrence of a strong airflow rapidly replaces the air in proximity of the body with new air of the source temperature. The flow will increase the heat transfer coefficient of the air considerably. When placed in a breeze, bodies will cool down or heat up faster. The principle of draft involves the cooling down of a part of or the entire body due to a breeze.

Conduction occurs when two surfaces make direct contact and exchange heat by the interaction of their molecules and atoms. This effect is most notable when standing on a cold concrete floor with bare feet or when touching a hot radiator. Clothing and furniture will increase the insulation around the body and make it less susceptible to heat loss by radiation, convection and conduction. The heat conductive properties of clothing have been researched and are denoted by the unit: *Clo* (W/m^2K). A nude body is assumed to have a clo value of 0, a summer outfit equals 0.5 clo and a winter outfit equals 0.9 clo.

When a body needs to loose a large amount of heat, it will employ sweating. The fluid that leaves the body through the skin will evaporate in contact with the air. This evaporation process requires an amount of latent heat in order to take place. This heat is extracted from the body, which results in a cooling down of that body. As the humidity of the air surrounding a human body rises, the evaporation process slows down. In addition, air humidity has an effect on respiratory functions and also increases air thermal conductivity.

Indoor climate
When humans reside inside an enclosed space they require fresh air through ventilation. Breathing produces CO_2, which in large concentrations can cause negative effects such as headaches. In high concentrations, contaminants such as CO_2 can become a danger to health. Dust, body odors and emissions from building materials must also be removed from the indoor air before they cause discomfort to nose, mouth and lungs. An open window is in most cases enough to remove pollution from the air inside. However, in deep spaces and spaces with much pollution such as from engines, forced ventilation is a better alternative. Fans force the air in motion and cause a circulation of air between the polluted indoor space and the fresh outside environment. In some cases, this principle is also used to replace indoor warm air with cooler air. Usually this requires the airflow to be increased above the level required for ventilation. Employing large airflow entails the risk of draft. The trick in ventilation is to provide a large (enough) airflow without causing high air velocities. Several ventilation principles have been developed that use forced, natural or hybrid forms of ventilation and mixing techniques to introduce air into a space without disturbing thermal comfort.

The properties of an indoor climate should prevent human physiology from taking extreme measures such as sweating and shivering in order to keep the core temperature within limits. It also should prevent skin temperature to drop or rise to values that are considered annoying and not comfortable. However, qualifying indoor climate is complicated by the fact that most indoor climate parameters are interrelated and the processes that are involved are dynamic. On occasion, some of the indoor climate parameters are constant and cannot be controlled without much effort. For instance, the low temperature of windows largely influences the indoor climate of a building in the winter. Supplying air of high temperature can compensate for the low radiant temperatures of the windows and result in a comfortable climate. However, large differences between surface and air temperatures will be considered less pleasant than more balanced values. To add to the complexity, the relation between climate parameters is seldom linear. More often, higher order equations or iterative procedures are needed to describe the interaction. An example of this interrelation involves ventilation and temperature control. When ventilating spaces, the imposed airflow has impact on several elements of thermal comfort. In periods of high temperature, much ventilation (high air velocities) will be regarded as pleasant while in similar cases during cooler seasons this might lead to draft.

In addition to complex relations and uncertainties, indoor climate theory needs to take into account the interaction between various indoor climate actors. Temperature and velocity fluctuations can cause a considerable amount of discomfort. The adaptive capabilities of the human body can deal with long-term variations to a certain degree.

However small, short-terms fluctuation in air velocity (turbulence) are difficult to measure but will heighten the chance of draft sensations by inhabitants (Fanger 1972, McIntyre 1980). The dynamic character of heat and airflows also complicates acting control over them. In many cases, elements that are brought in to control the indoor climate become an active part of the system thereby influencing and obscuring measurements and other control elements.

Human beings have preferences for certain temperatures, air velocities, types of heat source etc. They also have various tolerances to factors such as air pollution and noise. The factors of the climate should be carefully governed and kept between boundary values in order to avoid discomfort or unhealthy indoor climates. Most industrialized countries employ *building regulations* for indoor climate that describe, among others, criteria regarding thermal comfort and ventilation. The climate criteria describe, for instance, upper and lower limits for indoor temperature, minimum amounts of ventilation and safety procedures.

Thermal comfort models

In order to qualify the indoor climate more efficiently, climate models were developed that described an element of the climate with a single value. Two well-known models are those of Fanger and Humphreys. Fanger (Fanger 1972) based his model on a steady state heat balance equation for the human body. Using this equation and a large number of experiments, he described an equation that could predict a *mean vote* regarding thermal comfort in an arbitrary climate. This predicted mean vote (PMV) described thermal sensation on a scale from –3 to 3, with a value of –3 meaning cold and 3 meaning hot. Together with other values –2 (cool), 2 (warm), –1 (slightly cool), 1 (slightly warm) and 0 (neutral) this could describe how individuals felt in a certain indoor climate. The PMV can be used to describe the thermal sensation of a large group of people with a single number. This number is a function air temperature, mean radiant temperature, air velocity, air humidity, clothing insulation and metabolism. From empirical research, the relation between the PMV and the (predicted) percentage of dissatisfied people (PPD) was found. The PPD can be used to predict the number inhabitants that will express complaints due to the indoor climate. Figure 1 displays a graph with the relation between PMV and PPD.

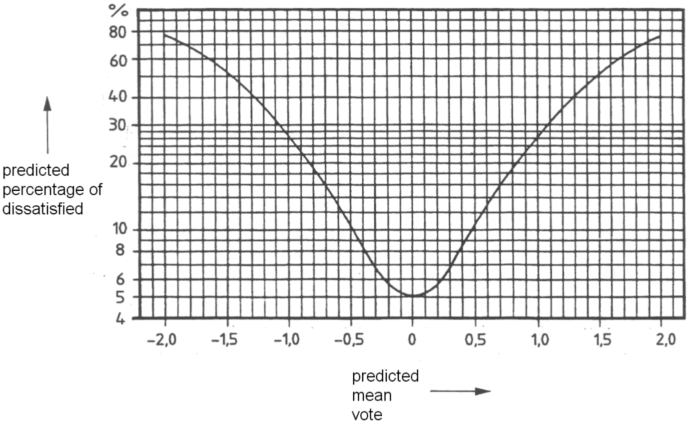

Figure 1: The predicted percentage of dissatisfied as a function of the predicted mean vote

Humphreys (Humphreys 1976) proposed another type of model. He found a relation between what people defined as the 'neutral' (not too warm or too cold) temperature and the conditions they spend most of their time in. It turned out that people who spend much time in hot climates accept higher temperatures as comfortable than people in moderate climates. Using this information he defined the adaptive model that contained a relation for the prediction of thermal comfort as a function of the prevailing room temperature. The adaptation model, although less popular that Fanger's model, is still subject to research (Dear e.a. 1998).

Thermal comfort models provide a means to more accurately design the indoor climate of buildings. Designers can make predictions of the building's conditions and employ climate control in order to achieve a predefined measure of comfort. Exceeding the boundaries of what experts consider a healthy indoor climate can cause severe problems. Complaints about headaches, eye-irritations and respiratory problems can and will occur. This can result in problems regarding the functioning of people such as drops in performance, increased sick leave and stress (Vroon 1990). However, it is not possible to provide a hazard-free indoor climate in every situation. In places where extreme conditions are imminent, such as bakeries or green houses, occupants have to accept certain excess in discomfort levels. Building regulation and labor conditions have limited the periods of over-exposure. Even during the design of ordinary office buildings it is not always obvious that the indoor climate complies with the latest and applicable standards. Budget and time are two factors that reduce attention for occupant well being. When that occurs, incidents like building overheating and the resulting reduction in employee performance are only one step away.
In the 1970's and 80's, new problems concerning indoor climate received much attention. Even in buildings that had relatively high quality climate control, users started to complain about illnesses such as eye-irritations, headaches and concentration problems that up to then had always been related to faulty indoor climates. Due to the unexplained rise in prevalence, research was conducted as to the precise cause of these

complaints. The research showed in some cases that the buildings performed poorly. However, not all complaints could be related to buildings or building services. It also turned out that a significant part of Sick Building Syndrome (SBS) related complaints stem from stress, lack of individual control over indoor climate or other surrounding conditions and others kinds of social factors.

2.2 Climate analysis

2.2.1 Introduction

The production of healthy buildings presupposes definition and control of several qualities of indoor climate in the design process. The temperatures and air velocities that occur in spaces where occupants reside are of huge importance for the indoor climate. Indoor climate is a combination of humans and the built environment. With regards to the design of indoor climate, the basis for climate control 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.
In an ideal situation cases, the passive building features are configured in a manner which results in an indoor climate that provides an excellent starting point for attaining inhabitant comfort. In such a case, little control in the form of building services or user intervention is required to have indoor temperature, light and air within the prescribed boundaries.

In order to balance building and indoor climate, information on building behavior is compulsory. However, the flows of heat, air and water through a building are among the processes that are most difficult to predict and depict. Heat and air transport have the characteristic of being highly variable (Paassen 1997). In most cases, the situations that are analyzed change over time. Especially when additional elements are brought in to control processes such forced 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 each time and where small variations can have large effects.

Until the 1930’s the only means architects had to control the indoor climate were passive building features. With the introduction of mechanical building services such as cooling equipment and air conditioning a need arose for additional design steering. The services provided greater possibilities in the areas of architectural expression and occupant comfort. Building service design became a separate profession. Service consultants calculated building performance from design drawings and advised architects on indoor climate and building services. Nowadays buildings without services are considered utopian. Even in cases where inhabitants are willing to accept more uncomfortable climates, such as in ecological conscious communities, additional building services are required. In most cases, designs need additional cooling, heating or ventilation in order to enable the inhabitants for safely and comfortably control the indoor climate of the buildings.

Dimensioning and configuring building services is a complicated process for a number of reasons. Engineers built models to aid them in controlling these difficult tasks. Early models were built around the fundamental physical principles and expanded with information of common building materials and outdoor climate data. Later models were extended further with knowledge from experience and experiments. They provided engineers a means to reason more quickly towards a solution. Design guidance involves answering many questions about the indoor climate and building services in a limited amount of time. In cases where consultants were required to do many detailed calculations, they started to look for quicker methods. Several simplified models were developed. These rules-of-thumb and selection graphs are examples of paper aids that provide rapid estimates of service capacities and characteristics. Figure 2 presents a selection graph that relates building orientation, glass quality and building mass available for heat storage to a maximum percentage of glazing that can be safely installed when applying natural cooling.

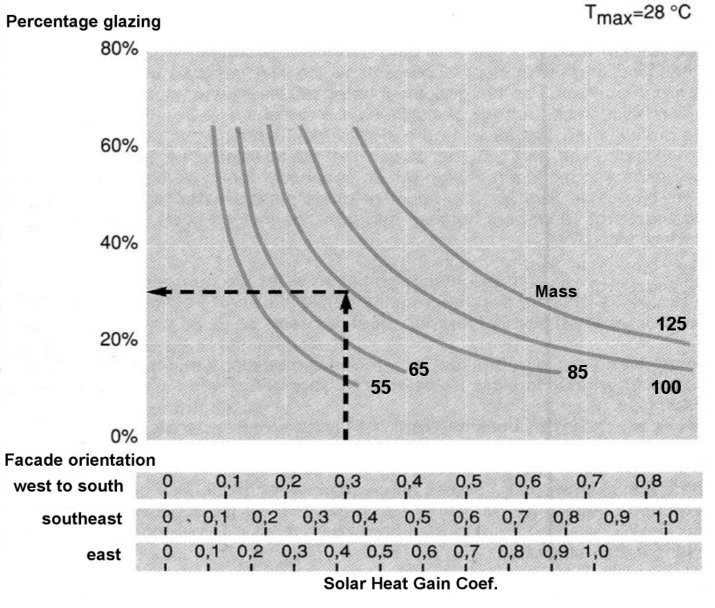

Figure 2: Example of a selection graph for building window sizes (source: Schaik e.a. 1994)

Still, making useful building service calculations involves a considerable amount of labor, even for straightforward buildings. Especially the rules-of-thumb suffer from limited accuracy in cases where dynamic processes are crucial (Boyer e.a. 1996, 1998). An alternative way to determine building performance with a high degree of certainty is to perform real-life experiments. This involves building scale models of the situations and measuring 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 complex models with much speed and accuracy (Liddament 1999). The early models were converted into more sophisticated tools that could read design problem definitions and perform the necessary calculations to arrive at a prediction of relevant phenomena. (Hensen 1993a, Augenbroe 1995) The results produced by the tools would form a sufficiently reliable basis from which new design actions could be taken.

2.2.2 Temperature simulation

In The Netherlands, a combination of tradition and the moderate sea-climate resulted in a reluctant attitude towards the principle of cooling buildings. The application of mechanical ventilation encountered less opposition since it is less expensive and more directly related to health. Efforts to minimize the use and size of cooling machinery concentrated on making more accurate predictions of the building's thermal behavior. Since early thermal models were based on a 'worst case scenario', the plant capacities they generated were considered large in relation to the cooling load that occurred during moderate conditions. Hot days when the outside air temperature reaches values of 30 to 35 °C are sparse in The Netherlands. Furthermore, it turned out that reducing plant capacities by 30 to 50% lead to a rather limited amount of building overheating (Schalkoort 1994). Most principals, architects and service consultants still consider the resultant decrease in thermal comfort defendable in view of the economic benefits. These professionals called for more accurate temperature analysis that would incorporate damping effects to arrive at smaller service capacities. The result was an investment in the development of a computer based temperature simulation tool. This tool was refined and modified over a number of years. This paragraph will describe this leading temperature simulation tool in The Netherlands.

2.2.2.1 History and overview

Temperature simulations typically describe hourly temperature behavior of buildings for a one-year cycle. For each space in a building one determines to what extent indoor temperatures will exceed standard thresholds. Using these assessments, the thermal characteristics of designs can be examined while taking into account internal heat-loads, heat accumulative capacities and climatic aspects. The results of the simulations are used to make Temperature Overheating Risk Assessments (TORA's). In practice, TORA's are usually only performed when designs have reached semi-final or final stages. During these stages, specialist engineers are consulted and asked to determine if designs comply with the Rgd guidelines or the design brief.

In The Netherlands the *Association for Computerization in Building and Installation Technology* (VABI) releases the leading temperature simulation tool. The *Netherlands Organization for Applied Scientific Research* (TNO) developed in assignment of the VABI the basis for this dynamic building simulation application that produced temperatures, temperature excesses, heating- and cooling-loads and energy uses. The model allowed for simulation of several types of building services and their controls. Since its conception in 1977 a great deal of effort was put into improvement, development and validation. This application, called VA114, is the leading temperature simulation tool in The Netherlands (Nieuwkerk e.a. 1991, Wijsman 1996). It is used by approximately 80% of the building services consultant companies. VA114 is validated and compared in accuracy and ease-of-use to programs like DOE and ESP (Soethout 1998) and turned out to be at the worldwide top of building simulations tools.

In order to analyze designs with VA114, they must be represented according to the intrinsic building model. This transformation of project information is not an easy task. It often involves an abstraction of form and almost always a tedious, manual input of building geometry and features. Moreover, it takes experience to operate the programs and specialist knowledge to produce meaningful results. This makes the use of this tool by architects unlikely and reduces its potential for design guidance.

2.2.2.2 VA114 Building simulation: Operation and calculation

Input for VA114 consists of some fourteen data forms which require description of project information, geometry, building services and the operation of both building and services. The more common data is described here since the complete list is rather large. General project information contains data like building orientation, level of detail, references to component databases and several aspects of the indoor climate control installation. Input of space geometry has entries for space ID, space origin and dimensions of walls, doors and windows. Temperature simulation can be done on multiple adjacent rooms. Specifying material characteristics involves linking walls and windows to entries from component databases. Windows can use configurable shading devices. Air conditioning and heating/cooling are treated as separate elements. For air conditioning, capacities, temperatures and humidity parameters can be given; heating and cooling can be provided by either a 2- or 4-pipe induction or fan-coil system. Heating with radiators is a fifth option. The internal heat load should be entered for people, equipment and lighting using a dissipation load schedule. Figure 3 shows an example of an input data form. After the relevant information has been supplied, a dynamic calculation can be performed for an extremely warm and cold year or parts thereof.

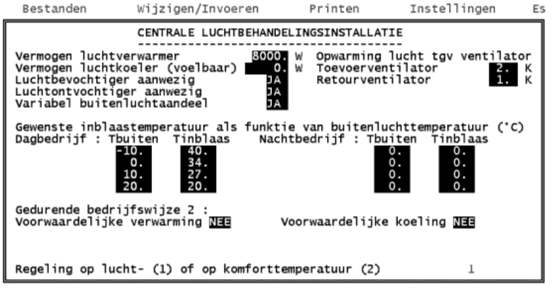

Figure 3: VA114, data form for input of A/C parameters

The computational model makes use of a finite difference method in combination with a Fourier form of the heat transport equations. For each room and wall, a matrix of equations is set up that describe the fundamental heat transport. To account for the characteristics of the situation, specific coefficients for the conductive, convective and radiant heat transport are calculated. Radiant exchange coefficients are determined from the space geometry and airflow rates are assumed or input by users to account for convective transport.
Next, equations are solved using the outside air temperature and an assumed indoor temperature. The final indoor temperature values are only obtained after a number of iterations. Each time, the calculated temperature values are used as input for the next calculations. Eventually the differences between the results of subsequent calculations will become smaller until they fall below the termination threshold. At this stage the calculation is converged and the results are at optimal accuracy.

VA114 writes the data in the interface to 17 ASCII files. Each file contains data on a specific building part.

The output provides hourly, daily, weekly and monthly temperatures for each of the given spaces. Time intervals in which temperature exceeds comfort values can be added up per month and per year. In addition, wall surface temperature values can be calculated as well as thermal characteristics of the service components. These figures are presented in text format only, though it is relatively easy to process and visualize them graphically (Figure 4). Interpretation of the results in relation to the relevant norm is simply a matter of counting the number of overheating hours.

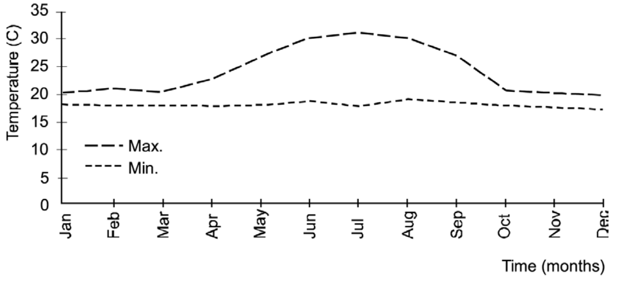

Figure 4: VA114, graph of analysis results

2.2.2.3 Current application

Temperature simulations are mostly used in building service design and by service consultants. The building service designers have put a considerable amount of effort into the development of simulations. They still take most of the initiatives for further development and more accuracy. However, in daily practice temperature overheating simulations are not part of the standard design procedure. Simulations are only performed in special situations where great stress is laid on aspects such as budget, energy use or indoor comfort. Examples include designs in which energy use must be minimized by using extra insulation or by employing smart controls and situations where the aesthetic and budget requirements constrain building services to the point where indoor comfort is at risk. In situations where service designers are not completely confident that the service they propose will function properly, they might call for temperature simulations to provide the required assurance.

Environmentally conscious designers favor building simulations in order to prove the energy saving capabilities of new service concepts and inventions. These simulations provide the means to determine weak point in their designs and at the same time allow assessment of the contributions of energy saving components. Some associated tools are developed to optimize an aspect of energy-use such as building envelope insulation or temperature setpoints in controllers.

Researchers use temperature simulations to perform sensitivity studies to determine the influence of specific building elements or new building services and controllers. At present, new technologies have become popular such as aquifers, low temperature heating and cooling and the incorporation of solar energy sources. More advanced building temperature simulations provide systems to test the efficiency of these types of services. Since it has become clear that the control and supervision of both building and building services is the largest remaining variable in energy use optimization, tools such as ECO-Quantum and GreenCalc have been developed that focus on various possibilities for energy reduction.
The application of temperature simulations provides the means for comfort and energy optimizations in situations where the margins for costly innovations are small. However, the design stage in which most simulations are performed has passed the

point where designs lose the ability to incorporate the modifications needed for these optimizations. Energy-saving innovations also call for an early analysis of building behavior since their successful application strongly depends on the interaction between design, building use, building services and their control.

2.2.3 Airflow simulation

In addition to developing its own tools, the area of indoor climate control has also been successful in adopting knowledge and techniques from related domains. Simulation of airflow was initiated in of space flight aerodynamics but quickly spread to other areas where flow is also problematic. Because the application of these sophisticated tools is costly, at first they were only used in cases that contained mission-critical building services such as integrated circuit factories and medical facilities (Luscuere 1996a). Nowadays, airflow simulations have become more common. This paragraph elaborates on the background, technique and application of airflow simulation in indoor climate.

2.2.3.1 History and overview

Computational Fluid Dynamics (CFD) 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. The equations are partial integral, non-linear and too complex to be solved analytically. Instead discrete methods and iteration are used to arrive at a solution that describes the characteristics of the moving fluid with 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.

In the 19th century two scientists, Claude Navier and George Stokes, separately described an equation that could be used to predict the motion of a viscous, compressible fluid. This equation is currently known as the Navier-Stokes Equation (NSE). Based on the principle of preservation of momentum in a given domain of fluid, a partial differential equation was derived which described the forces and velocities within that fluid. At a later stage the equations based on the preservation of mass and energy were added. In 1947, Kopal first used the NSE and a primitive computer to compile tables of supersonic airflow around sharp cones. This was the first known use of a combination of computers and the NSE to solve (highly dynamic) fluid flow problems. This combination proved characteristic for the technique that later was called Computational Fluid Dynamics.

In the 1950s and 60s, engineers struggled with extremely complicated space flight problems. Bodies re-entering the earth's atmosphere experience extreme temperatures and vibrations. Since the possibilities for experimenting are limited, simulation of these phenomena using CFD was considered an essential part of the process of designing and testing spacecraft (Figure 5). Several institutes invested in developing CFD simulation engines. In the 1960s, CFD evolved further into the techniques we use today.

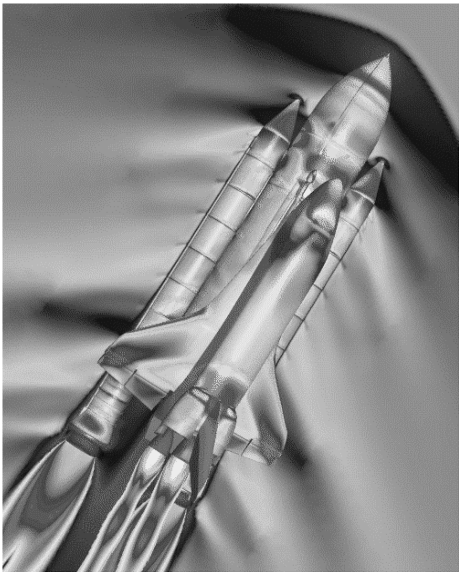

Figure 5: CFD simulation of space shuttle in flight (source: CFD research corporation)

In the 1970s and 1980s, a broader range of areas, including indoor climate research (Nielsen 1974), started using CFD. Each of them developed additional techniques to model complex phenomena found in various kinds of problems specific to each area. Although the basis for CFD is relatively straightforward, there exist numerous phenomena that require particular approaches and additional variables and equations. An example of this was the modeling of the effects of turbulence that were added to a large number of CFD application areas. Predicting and understanding turbulence is a field that has implications that go far beyond the definition of the required turbulence formulae (Nieuwstadt 1989). In addition, the research for turbulence models for flows with low Reynolds numbers has been lagging. A reason for this might be formed by the fact that it is extremely difficult to accurately and dynamically measure low air speeds in spaces.

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, for instance, mechanical engineering and aeronautics. The permanent quest for more accuracy also calls for more advanced and realistic turbulence models to simulate the highly dynamic effects in airflow.

2.2.3.2 Operation and calculation

Domain

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 the unique 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 heat transfer coefficients. Special attention should be paid to the space energy balance in general and the wall Heat Transfer Coefficients (HTC) in particular. To prevent the simulation from heating up or cooling down the domain, it is advisable to use additional calculation in advance to balance the incoming and outgoing energy flows in the CFD problems. HTC's for walls are hard to determine and depend largely on the indoor climate conditions such as air velocity. Using non-conducting walls or HTC's from libraries are two options that simplify the domain definition and simulation process.

Most CFD applications for building design work with spaces that have orthogonal geometry or moving boundaries. Other, more general cores handle non-orthogonal geometry in the form of unstructured grids.

Equations

The governing equations that are derived from the conservation principles are at the core of CFD technology. These equations require fluid and domain properties and the products of linked equations to produce the values of multiple fluid flow characteristics. In most cases, the flow characteristics include fluid velocity, temperature (of both fluid and solids), pressure and contaminant concentrations at different locations in a space. Additional equations produce auxiliary variables such as turbulence parameters, mass and heat fluxes and conduction coefficients.

Source

A solution domain may contain one or multiple sources. A source is anything that will change the speed, pressure, temperature or composition of the fluid. Examples of source 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 dusty carpets. To define a source, one may specify its location within the domain and the source properties like inlet velocities, mass flows, heat fluxes or temperatures.

Turbulence

Instantaneous air velocity at a certain point in time and space can be defined as the sum of a mean velocity air ($\overline{v}$) and a fluctuating air velocity (v'),

$$v = \overline{v} + v' \quad (2.1)$$

The fluctuating velocity component can vary in time and by location. The cause of the fluctuation can be called turbulence. Calculating turbulence accurately requires highly dense and intensive simulations. In most cases, available computer power prohibits that the turbulent velocity component is simulated properly and only the mean velocity is computed. However, in order to increase the accuracy and applicability of CFD simulations, several turbulence models that require less computing time were developed. An example of an advanced model is the 'Large Eddy Simulation' (LES) (Anderson 1995). In LES, only large-scale turbulence is modeled and simulated. Although this reduces calculation time considerably, running LES type-CFD programs on desktop PC's is still unrealistic. As a result, turbulence models that determine a 'mean' or average turbulence flow were developed. The statistical properties of turbulence are easier and faster to calculate than real turbulent velocities. The averaged turbulence characteristics are 'added to' the mean velocity components.
A well-known example of turbulence models is the k-ε model. This model establishes a value for the turbulent viscosity from two equations that calculate turbulent energy (k) and the turbulent energy dissipation rate (ε). More basic models use constant values for viscosity which further reduces calculation time. However, for a considerable number of airflow situations the k-ε model proved to suffer from limited accuracy (Wendt e.a. 1996). Several refinements were proposed such as the revised k-ε model and the Renormalisation group model (RNG) k-ε model.

Turbulence remains a highly complicated phenomenon. Understanding and modeling turbulence consumes a large part of all airflow research efforts. However, the relevance of turbulent airflow for architectural design must be questioned. In spite of the large influence of dynamic and turbulent effects of airflow on the indoor comfort experience of inhabitants, the cause of turbulence is often not apparent at conceptual design stages. Some building characteristics such as large spaces and natural ventilation inevitably produce turbulence, but the realization that they do so may be more important to architects than the amount of the actual fluctuations.
On the other hand, when airflow simulations comprise high velocity mechanical ventilation systems, turbulent components of the airflow can become quite large (up to 100% of the instantaneous velocity). When this effect is ignored and only the mean velocity is calculated, over-optimistic results may lead to the use of inadequate HVAC systems. The turbulent effects that accompany these types of systems should be displayed adequately. For example, designers might conclude that a specific combination of system and space presents unavoidable airflow problems. Consequently, they could exchange high velocity systems for displacement ventilation which operates with lower velocities. This approach/requirement calls for the incorporation of turbulent parameters in conceptual simulation. Design environments that aim to employ CFD simulations need to address at the very least the most basic type of turbulence modeling in the assimilation of the CFD data. For a Meta Design environment, the k-ε model is the best choice. This model provides the best combination of maintaining problem stability with sufficient prediction of turbulent effects. It provides a means to incorporate the influence of high turbulent service components such as swirl diffusers into CFD problems without much effort. The

typical turbulent energy characteristics of these types of air inlets can be included in the HVAC product library relieving designers from inputting this specialized information.

Grid

Because computer power is still the limiting factor in CFD, the equations cannot be solved at atom or molecule level. Instead, the solution space is divided into a set of larger elements on the basis of the Finite Element Method (FEM) or the Finite Volume Method (FVM).

Other methods sometimes use infinitesimally small elements that essentially center the properties of the spatial element in a single point. These methods use different forms of the governing equations, however the underlying physics are fundamentally similar.

Grids are a fundamental scheme for deriving the elements required for the FEM and FVM methods. Grids can be divided into two major categories; structured and unstructured grids. Structured grids are also known as orthogonal or Cartesian grids and are characterized by the fact that all elements have an equal number of adjacent elements (Owen 1998). These grids usually contain hexahedral or quadrilateral shaped elements and are defined along the Cartesian x-, y- and z-axes separately. Structured grids may be defined on top of a space geometry using techniques such as grating of slicing. These are relatively simple methods that allow treatment of one axis at a time and can be executed manually or automatically. In building design, the element sizes typically vary from 10mm to as much as 300mm.

Unstructured grids are better known as unstructured meshes. They can be built from a number of geometrical primitives such as triangles and tetrahedra. These meshes can contain more complex geometry and their cells can follow the boundary of curved shapes quite accurately. Another property is the lack of restriction on the number of cells that meet in one point. Unstructured meshes are difficult to generate manually and provide little help in defining building related problem definitions. Several automated mesh generation techniques have been developed such as the advancing front method, Delauney or Steiner algorithms or Quadtree or Octree based algorithms. While the software automates much of the labor involved in mesh generating, manually post-processing generated meshes is in most cases unavoidable. Users need to perform consistency checks, clean-ups and mesh smoothing before the mesh can be used for calculations (Thompson e.a. 1999, Owen 1998).

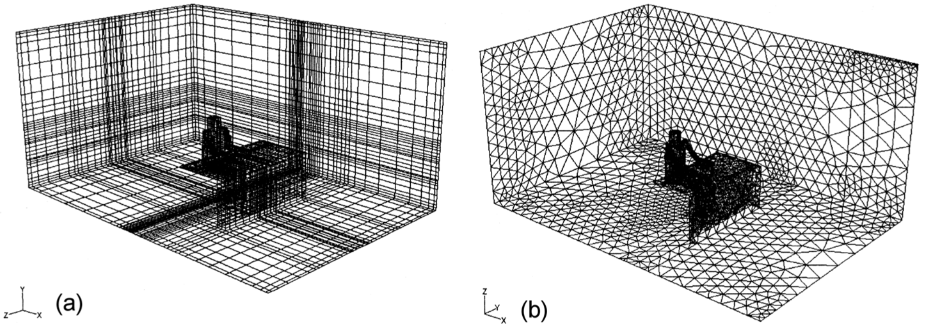

Figure 6: Example of a structured (a) and unstructured grid (b) (source: Loomans 1998).

For both structured and unstructured grids, the elements should be made smaller at places where large changes in airflow are anticipated (Figure 6). Also, the element sizes should increase or decrease gradually, i.e. neighboring grid elements should not differ in size considerably. At the same time, all geometry (solids, sources and obstructions) should coincide with the face of one or multiple grid elements. In cases where they fail to coincide, special interpolation algorithms are used to make adjustments in the boundary conditions. When element sizes are too large, smaller elements can be defined by subdividing the original element. However, this is easier for structured grids. Re-meshing and refining methods developed for unstructured grids can produce errors that need to be eliminated manually.

Calculation

The simulation starts after the grid has been defined and control parameters have been adjusted so to speed up the simulation. Since the equations are now solved for a controlled number of discrete points in space instead of at each molecule, the computer power required is largely reduced (Anderson 1995).

Starting the simulation implies solving the governing equations for each element in the grid. The equations take several variables such as temperatures and pressures. In some cases the values are provided by the results of other equations, in others, they are derived from the starting and boundary conditions of the problem statement. When the equations are in partial differential form, they are integrated over the dimensions of the problem space. When using structured grids, the equations are integrated over the three dimensions of an element. Elements in unstructured grids are expressed in their volume which is the integral length used for the equations. In some cases, the equations are also integrated over an element of time.

After the equations for mass, energy and momentum have been solved for each grid element separately; the influence of one element on its surroundings is accounted for. For temperature and pressure, the values of each variable in a single element are related to those of its neighboring elements. The values of one element influence those of its neighboring other elements (Figure 7). After this inner iteration, another outer iteration is performed and the values of the previous iteration are used as input variables for the new calculation. As this continues, the differences in the results between calculation steps should become smaller. In the event that the differences become larger, the problem might be unstable in which case a solution cannot be obtained. The program keeps comparing the results between two iterations. As soon as the difference between the results is smaller than a preset convergence criterion, calculation stops and the solution are to be viewed.

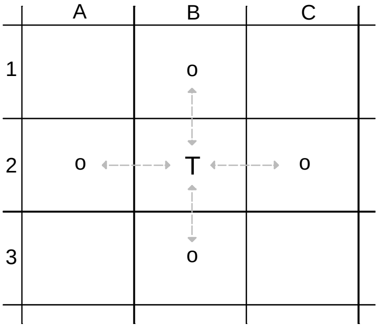

Figure 7: Individual cell (T) interacting with neighboring cells (o)

2.2.3.3 Current applications

CFD is used in many areas that require detailed information on the flow and behavior of liquids and gases. Especially in cases where measurements are hard to make, flow simulations can provide new and valuable information at reasonable cost. In bio-medicine research, flow simulations are used to depict the blood flow through veins. Predicting the performance and behavior of mechanical heart valves is otherwise impossible. Areas like space rocket and airplane design make the most advanced use of CFD. In those fields, CFD simulation is usually one of many techniques to predict every aspect of these complex structures in great detail.

In building design, CFD is used in the design of cleanrooms and operating rooms (Busnaina e.a. 1990, Lemaire e.a. 1996, Luscuere 1996a). These types of spaces must be kept safe from particle contamination such as bacteria or dust. The airflow in these spaces must follow optimal pathways. CFD simulation can be used to determine whether the flows from ventilation and convection interact in the manner that was predicted.
CFD is used in office design to a smaller extent. Only during projects that require special attention to airflow, budget is reserved to have third parties do simulations. Examples include cases where high velocity air inlets are employed and designs that contain large atria or second skin façades. Another common application is the assessment of fire hazards. Tools that combine fire models with CFD can examine smoke dispersal, fire progression and escape routes (Miles e.a. 1994, Koutamanis 1995a).

Various test and sources (Lemaire (ed.) 1992, Chen e.a. 1993, Jouini e.a. 1994, Hu e.a. 1996, Loomans 1998) describe experiments that achieved more than 10 percent accuracy in both airflow and building temperature simulation. These require expert knowledge and experience in compiling and adjusting input. Defining an approach that educates architects to the point where they would be able to perform analysis with high accuracy would be both impossible and unnecessary. The capability of the analysis tools (CFD in particular) to visualize the otherwise invisible content of the indoor climate has intriguing effects. The display of airflow and temperature profiles creates awareness and enthusiasm among designers. It also demonstrates that grasping and controlling these types of building behavior are less difficult than expected.

2.3 Findings

The indoor climate analysis tools described in the previous paragraphs have distinct information requirements that originate from the task of applying the calculation model in realistic situations. In conventional applications, a tool operator that is familiar with the design, inputs as much of the design data as is necessary or possible. For most cases, not all of the possible input is obligatory. Obligatory input can roughly be divided into items that have major influence on the outcome of the analysis and items that have only minor influence. Other types of input items include optional input or provisions for specialized cases.

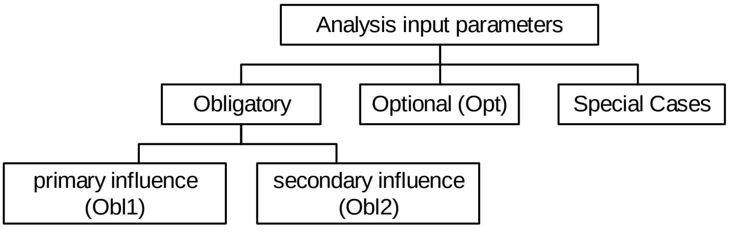

Figure 8: Analysis input categories

The integration of parameters derives from two distinct sets of in- and output lists from all data items found in the climate simulation tools. These contained all input parameters together with descriptions of priority considered in the context of general calculation. Next, we determined for each of the parameters whether their values could be read directly from the design, could be implicitly determined by automated recognition or had to remain at default. Matching these input lists against the informational characteristics of the design process revealed that information concerning building service concepts needs to be introduced. The reason for this is that climate systems and control are necessary to execute even the most indicative of simulations. This holds true for both temperature and airflow analysis.

Closer examination of the in- and output lists brought forward a number of concepts that could be used to perform simulations that concentrated on the interaction of building properties and indoor climate. Table 4 contains a structured shortlist of data items. This list will form the basis for information structuring further on in this research.

Table 4: Summary of Analysis in- and output items

Type:	*Information item:*	*Category:*
Activity:		
	Building function	Opt
	Heat dissipation from occupant activities	Obl1
	Heat dissipation from equipment	Obl1
	Metabolism of occupant activity in comfort equation	Obl2
Shape:		
	Shading by adjacent building	Opt
	Shape, size and topology of space(s)	Obl1
	Size and location of windows	Obl1
Material:		
	Accumulation capacity walls, (density, specific heat, conduction and transmission coefficients)	Obl2
	U-values of façades, windows	Obl2
	Shading coefficients façades, windows	Opt
	Texture of wall surfaces	Opt
Service:		
	Heating, Cooling and Ventilation capacities	Obl1
	Type of HVAC system in space	Obl1/2
	If needed: Air conditioning configuration	Opt
	Setpoint temperatures	Obl2
Performance:		
	Heating & Cooling capacities	
	Temperature over- / underheating hours	
	Energy use, both required and used	
	Air temperatures and Velocities	

The indoor climate analysis tools that will be used in the Meta Design Environment are temperature overheating risk assessment and Computational Fluid Dynamics. Temperature analysis provides a complete overview of indoor temperatures. This data can be processed in graphs that display daily, monthly and yearly summations. These results can be useful to architects tying to assess the indoor climate performance of their designs. The input for this type of analysis contains several elements such as geometry and materials that can be found in designs. Other numbers such as the heat dissipation from people and equipment and building service configuration is less likely to be present in conceptual designs. Using CFD can produce several indoor climate properties. Most useful for designing is the depiction of airflow combined with air temperatures. The background information showed examples of insightful visualizations of airflows. Architects can use these to determine the effect of airflows on occupants. The input of CFD hinges on space geometry and the description of sources. The appearance of space geometry in CFD input is not unlike that found in CAD drawings of architectural plans. However, it is unlikely that the configuration of air inlet grilles and heat sources will be present in conceptual designs. Before the research is focused on this issue, we will first try to gain a better understanding of what information can be extracted from architectural designs.

The input of VA114 temperature simulation focuses on the thermal interaction of solar radiation, internal heat dissipation, building materials, openings, capacities of the building services etc. However, the specific nature of this information does can be abstracted into concepts. For instance, it is possible to use general information on aspects such as building material characteristics and service capacities. It is possible to simulate building-climate interaction through the use of a single (default) building service system that can accommodate many situations.
Still, specification of service capacities and configuration is crucial to the outcome of the analysis. This information cannot be left out of analysis or be replaced by a single, static item. Sun shading devices and night ventilation can have considerable benefits when coordinated properly. Simulating the behavior of services implies, among others, the definition of a heating curve which is a precise process and makes the simulation sensitive to small changes in the input. These types of parameters constitute an important part of the tool's functionality and need to obtain a place in the system's information flow. It is important that input on building equipment is considered prior to making general analyses.

When employing an airflow simulation to investigate draft risk and ventilation efficiency, the input requires data on aspects such as user workplaces, location, size and properties of air inlets, outlets and window properties (Flomerics 1995). The operation of services and windows might also change with the varying outside conditions (summer and winter). More accurate airflow analysis concentrates on acquiring the subtle aerodynamic properties of building materials and service elements. Replacing all the input data on building services with default statements has consequences that are too extensive for the purpose of supporting architecture. Doing so will limit designers to the use of several fixed service configurations. This approach lacks support for unusual or innovative design solutions. In order to facilitate the simulation of various and unique air flow situations, the building service units that influence airflow need to be present in the analysis input. Their occurrence does not need to be built from scratch but can consist of references to items in a product library as is often the case in modern CFD software (Stribling e.a. 2000). This can reduce the workload involved in simulation.

3 Correlation of representation and indoor climate analysis

This chapter deals with the possibilities and issues that arise when design documentation and analysis input are connected. The first step in connecting the two locations is to re-use the (geometric) information contained in design representation (CAD documents) in analysis. To determine similarities between representation and analysis, this chapter introduces design representations and provides an overview of design information characteristics. Existing research on this topic is reviewed in the context of our system. To answer the question whether the information in design representations can be compiled to match the input for analysis tools, we assume that most of the information translation can be done automatically. It is interesting to see what automated system can do in this regard. Using computer algorithms to deduct facts from the design representation may be a way of doing this. Our developments surrounding this issue are presented and discussed.

3.1 Introduction

In the past decade the computer has been transformed from an instrument of the scientific community to a general-purpose and widely available tool. The applications range from effectiveness and efficiency improvement in professional processes to electronic leisure and recreational activities. This *democratization* of Information and Communication Technologies (ICT) has been having a profound effect on the acceptance of computing in new areas, as well as on the integration of existing applications in their context. In architecture, integration has been twofold. Firstly, older basic ICT such as CAD have finally found their place in mainstream architectural practice. There, they have improved efficiency in some aspects of design practice such as drawing exchange and modification.

Probably the most promising issue in these developments is *design analysis*. More than communication and presentation possibilities, the availability of ICT facilitates fast and accurate evaluations of building behavior. This prompted researchers to investigate if and how the early stages of the design process could benefit from the convenience of computerized evaluation models. These stages, when many fundamental decisions are taken, form an obvious target for design improvement in terms of information processing.

Performance objectives are necessary in order to interpret analysis feedback effectively. For the early design stages, performance assessments are made with information from the available design representations and external corpora, from programmatic requirements to ergonomic norms. Simulation of design behavior can help architects to assess bandwidths and thresholds for building performance parameters and set new objectives for the remainder of the process. Using advanced ICT tools for design analysis provides the computational means for projecting building behavior and performance with sufficient reliability and accuracy.

The main obstacle in employing simulations is related to their original application area. Highly specialized domains that focus on modeling reality and measuring physical quantities developed most of the simulation tools. The transformation from early design shapes and concepts to specific quantities that fit analysis is a substantial task.

3.2 Design representations

Our definition of a representation derives from the framework for computer vision defined by David Marr (Marr 1982). According to this, 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.

Representation should not be confused with the mechanisms used for its implementation, such as the lines of a piece of paper. The reason for that is 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 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 often discussed as the primitives of architectural composition. This testifies the significance of geometry as a foundation of architecture and its representations.
We also find parallels between this notion and the shift from the geometric object in Euclidean geometry to its images in descriptive geometry (Evans 1995).

The transition from descriptive and projective geometry on paper to their computational equivalents has reinforced attention to implementation mechanisms such as lines and surfaces (Gasson 1983). Especially the definition and description of geometric shapes in architectural plans has received much attention. In an attempt to integrate the facilities of new computer media in architectural design, CAAD research has focused on modeling and visualization with computer media at the level of practical skills (Mitchell e.a. 1991). These skills are guided by developments in the study of spatial descriptive formalisms such as rectangular arrangements and shape grammars, which interpret the geometric or other models of a design in terms of surfaces which bound a space or component of a building subsystem.

Rather than merely manipulating loosely and arbitrarily grouped geometric primitives in a CAD system, we can organize spatial information in multiple, closely correlated structures, as in the dual graph representation (Steadman 1983). The advantage of these structures is that they link design thinking with the appropriate implementation mechanisms. An underlying assumption in most spatial architectural representations concerns the choice of basic primitives for the description of a design. The 'solids' and 'voids' of a building, i.e., the building elements or components and the spaces bounded by them, are the obvious choice. They are linked together by adjacency into networks which describe one or more aspects of the design in a coherent and comprehensive manner. These networks connect more closely to both design thinking and analysis methods including matching to requirements in design briefs or legislated measures of performance.

3.2.1 Design Information categories

An environment that links design with the outcomes from descriptive analysis will constitute an information flow that is not limited to building geometry. The flow also includes data with various levels of design materialization, performance and services. Analysis tools require additional control information that provides for distinct requirements of the various design analysis applications.

In order to obtain clearer insight in the characteristics of the information flow, we examine functional elements in design information. These information types are exposed when we closely examine the data involved in the design process. The introduction to this chapter addressed the presence of functional and programmatic objects such as occupant activity as part of designer's vocabulary. At the same time, it stressed the importance of correct treatment of the mechanisms for symbolizing these objects, i.e. shapes and geometric descriptions. Design briefs usually lay down lists of occupant activities. In practice, these lists form the basis for routing and layout in most designs. Architects need to transform adjacency requirements into spatial layouts and might create new conditions that relate to aesthetics or originate from building regulations. The process of determining conceptual space layout receives much attention early in the design. A familiar design aid for this task comes in the form of the adjacency matrices and bubble diagrams seen in early sketches (Steadman 1983, Akin 1986). User activities also form the basis for performance assessments such as the quality of the indoor climate and the occupational efficiency. Human activities such as sleeping, reading or walking make specific demands on areas such as thermal comfort and safety. They also become an active part of the building itself and should be taken into account when calculating structural and heat loads.

Architectural design is, for a part, occupied with creating containers for human activities (Carrara e.a. 1994). During the design process, the containers are materialized by the definition of spaces. These continue to be present during the remainder of the design process and are still recognizable in the constructed building. However, it is important to realize that a space is not equal to the building elements that bound it. The transition of space represented by geometric symbols to building elements is one that receives little support in current CAD education (Koutamanis 1994). The representation of shapes during early design requires symbols that are easy to invoke and that can accommodate to change. The transition from manually drawing geometry on paper to CAD applications does not immediately change these criteria. In this research, the definition of spaces in CAD is done using intrinsic entities that are straightforward to create and manipulate.

The part of building that act as the load-bearing infrastructure is made up of the walls, floors, columns and other solid, bearing elements. In most cases, structural elements are placed on the zones where space need to be separated either from each other or from the outside (façade). The function and appearance of each wall and floor is coordinated with the design of a coherent structural system. Other material building components include elements such as interior walls, staircases and ceilings.
One leading architectural theory advocates the functional and topological separation of the structural (load bearing) system and the system used to fill in this structure (the interior) (Habraken 1985). When this paradigm is followed in both design and construction, buildings display the flexibility to adapt to and keep adapting to the wishes of users. Despite the obvious benefits of this approach, the distinction between structure and interior is not always clear when spaces are defined early in the design process. The definition of different categories for structural walls and interior walls has not much influence on the operation of climate analyses. Therefore, there is no need to provide for an extensive categorization of structural elements in the indoor climate part of the Meta Design Environment. This enables us to leave out an additional complicating module in the implementation of the experimental applications. However, the structure of the data model should include the possibility to integrate at a later stage with design environments that focus on aspects such as Life Cycle analysis or structural analysis.

Nevertheless, the materialization of a building can be taken into account when analyzing building performance. Doing so will improve accuracy and enables designers to add the effect of materialization on performance aspects such as thermal comfort and energy use to their designs. When making Lifecycle Analyses, materials may expose inhabitants to hazardous agents or prove to be difficult to dispose of (Bluyssen e.a. 1995). Costs are for a large part determined by the quality of materialization of the building. In order to incorporate material elements into climate analysis, general data on material shape, density and conductivity suffice. Decomposition and detailing of building elements has little added value in this respect. This is reflected in the representation of building elements such as walls and floors. In the Meta Design Environment only the outlined shapes of the objects need to be drawn and categorized in order to incorporate them in analysis.

Building services provide active control over the indoor climate in buildings. They can compensate for undesired temperatures and provide active indoor air quality control. Most climate analysis applications are designed to incorporate operation of services. Climate analysis on designs without services is not always possible or meaningful. In addition, one of the objectives of the research for a Meta design environment is to create more insight into the influence and interaction of building services on aspects such as thermal comfort. In order to incorporate and encapsulate the data involved in the design and assessment of building services, symbols for the representation of building service objects are added to the drawing model.

The execution of design analysis produces output in the form of estimated building performance on various areas. In order to correctly feedback the analysis results for all analysis types and for all parts of the building, the performance data needs to be stored in a clear and retrievable manner. The analysis results should be incorporated into the data-structure and formatted in a way that allows uniform interpretation. Several standardized formats for analysis data have been defined such as the *CFD General Notation System* (CGNS) (Poirier e.a. 1998) and the *Performance Assessment Method* (PAM) (Wijsman 1998). Although these standards provide the ability to prevent many communication problems and data translations, neither has been accepted broadly.

The Meta Design environment employs design feedback that is concentrated around providing indoor climate aspects such as estimations of thermal comfort and ventilation strategy evaluations. The single most important factor in thermal comfort assessment is the indoor air temperature for spaces over the period of a whole year. These temperatures can be determined by performing a temperature simulation of the design. The result can be displayed as the actual temperature profiles, as weighted temperature exceeding or, in aggregated form, as the Predicted Mean Vote (PMV). When performing temperature simulations, the annual heating and cooling loads and, in case of building service simulations, the annual energy use is also available. Especially in environmentally conscious designs, this can greatly aid design optimization both on passive (building) as on active (building services) features.

Ventilation principles can adversely influence thermal comfort and cause for draft or contamination problems. However, ventilation (airflow) must at the same time adhere to guidelines that prescribe minimum capacities. Airflow simulations can provide many of the quantities required for more detailed assessment. Examples of these quantities are; maximum air velocity in comfort zones, mean life of air / ventilation efficiency, contaminant concentrations at various locations and mean turbulence intensity. Airflow simulations deliver a large amount of detailed climate information that can quickly lead to information overload. Especially for airflow and ventilation, visualization of the large amount of calculated data into a single, comprehensible picture is recommendable.

The relation between climate characteristics and distinguishing building elements is also an interesting aspect on which feedback can be inspiring. Building elements such as windows and shading devices can have distinct effects on thermal comfort. Seeing and experiencing the thermal behavior of their designs helps architects to pre-optimize building features such as window size and shading devices in order to establish better thermal comfort (Mahdavi e.a. 1997b, Boyer e.a. 1996, Shaviv e.a. 1992). Demonstrating the connection between design form and material and thermal behavior is not an easy task. Because of the dynamic nature of heat transport and the number of actors involved, rules-of-thumb are useless. Providing simulations on the basis of *sensitivity analysis* (or *parametric variations*) has a greater chance of success (based on Genetic Algorithms, see: Holland 1975). Building features such as window size or cooling capacities are changed gradually and one-at-a-time. Each new situation is immediately calculated and compared to the results of the previous run. By determining if and to what degree the change affects the thermal behavior of the design, architects obtain an awareness of the sensitivity of their design for, for instance, temperature overheating.

Summarizing the required categories for which the structure should provide storage items, we find the following design information types and definitions (see also Figure 9):

- Activity: Types of human acting, requiring conditions from and influencing conditions in buildings
- Shape: All morphologic properties of a building or a part thereof relevant for analysis
- Structure: Material needed to sustain a building
- Installation: Equipment and services of a building, meant to control indoor climate and use
- Performance: Required performance of the installations in interaction with the structure related to sustaining the activities within a building

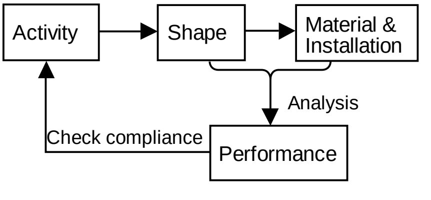

Figure 9: Information types

3.3 Related research

3.3.1 Introduction

A response to the growing number of building regulations has been the development of computer applications which reduce manual labor by evaluating designs with respect to building regulations. As these systems are directly derived from legislation and guidelines, they are useful but limited normative analyses of regulation compliance. One such example is the VABI suite of programs. They require information on building geometry and several design characteristics as input and use mathematical formulas to estimate, for instance, total heat load or noise level. Such tools do not draw any conclusions that can be made from facts implicit in the design information. While architects may expect some explanation of why a building element fails, normative systems respond with figures and provide no reasons.

At the moment, architects may have a growing number of computer driven tools which assist in predicting performance at their disposal. There is a growing need for this kind of prediction of performance since building regulations and contractors demand guarantees that the result will habitable and healthy. When evaluating designs, one investigates the projected performance in relation to the planned activities. There are many tools and methods available that aid designers in assessing design performance on aspects such as light, noise and climate. However, these calculations are often aimed at predicting specific values with great accuracy. Moreover, calculations typically belong to the consultant's tasks. These specialists start their calculations from the design drawings and transform them in an analytical form that supports the required performance assessments. This procedure is rather laborious and efficient only when the design doesn't change much after analysis. Especially during early design phases this is seldom the case. Shapes change constantly, spaces are added or removed and activities are often relocated. Performing analyses during all design stages quickly becomes very costly and as a result, analysis during early design is not very feasible.

However, it is in the early phases of the process that analysis can prove effective. In such cases, variation of shape, activity and topology should be analyzed instantly as to the effects on design performance. The information basis for these analyses should be formed by the architect's design representation to prevent costly and laborious translations. Since the 1960's, researchers have developed frameworks for computer-aided design that aimed to bridge the gap between the process of decision making and the process of information gathering.
This approach became known as *integrated design and analysis*. During the 1990's, the area of indoor climate analysis and building service evaluation became a topic for integration into architecture and several researchers proposed frameworks that combined design and, among others, climate analysis (Shaviv e.a. 1992, Hensen 1993b, Mahdavi e.a. 1997a, 1997b, Papamichael 1997a, Suter e.a. 1998, Zeiler e.a.

2001). All these researches exhibit the expectation that the integration of design and analysis will result in an improved availability of performance and behavior assessment information for the designers. At the same time, it is hypothesized that the information offered by following this approach will be of greater use to designers than the outcomes of the highly detailed specialist analyses in traditional design processes.

Most integrated systems utilize building models that describe the content and semantics of designs through the use of formal objects. These building models appear in the form of digital databases and are managed by a range of computer tools such as drawings, editors and object libraries. The models describe in detail what objects and information are contained in the design representations. This data is accompanied by a set of rules that ensure completeness, consistency and manage relations and modifications. Digital building models are a (essential) part of integrated design systems since they provide an excellent means to manage the information emanating from the integrated domain sources. Some of the building models developed in the 1980's exhibited characteristics that catered for the purpose of integrating information from different sources. Paragraph 3.3.4 contains a survey of several digital building product models of academic and commercial origin.

3.3.2 Integrated design support systems

Most of the integrated environments for design and analysis have been developed to overcome the drawbacks of employing analysis tools separately from design drawings. These integrated systems employ a single, central design representation (the model) and connect to geometric interfaces and analysis modules. Most systems use existing analysis and simulation tools since these had long traditions of improvements and proven degrees of accuracy. However, some developed dedicated analysis models based on existing techniques to more closely respond to the demands of integrated design.
The changing position of designers that would work with integrated systems has an effect on the design process. Firstly, designers are faced with the task of providing more information earlier in the process. Secondly, the involvement of specialized analyses requires more domain knowledge. Integrated approaches that aim at designers working alone attempt to employ only the domain knowledge architects have at their disposal. Other systems focus mainly on supporting communication with design specialists and provide tools to facilitate design collaboration. Lastly, the execution of analysis and the presence of more specialized domain knowledge introduce designers to an increased amount of feedback. This feedback not only informs designers on a risen number of aspects but also shows correlations between building elements or contradictions in optimizing objectives. The research has delivered a considerable amount of knowledge regarding the use of computer-based support in the design process. A survey of the published researches clearly shows the issues and possibilities of an integrated system for design and analysis.

The *Combine* project was set up as an international cooperation between organizations of, among others, The Netherlands, Finland, Germany and France (Augenbroe e.a. 1995). The various partners developed parts that could be combined into a larger system. The central database was connected to a graphical interface for the input of space geometry which employed a remarkable technique to ensure consistency and topological clarity. The connection to the various analysis tools is made by separate modules that exclusively wrote to each of the tools. The Combine project is a good example of an integrated design environment that contains an extensive collection of the information items that can be found in a broad range of design analyses such as temperature, structure and costs. In addition, all information items are arranged in an integrated data model (the IDM) that contains hierarchy, topology and other kinds of relations.

VA114 is one in a suite of computer programs released by the VABI. These tools analyze designs on aspects relating to building physics and building service design. Using multiple tools from the same suite required production of the same amount of design representations each organized according to the information characteristics of the individual tool. Among the tools for building service configuration, for instance, exist common characteristics that rendered making several, separate, representations redundant. The *Uniform Environment (UO)* provides a single interface for input of a design representation which can be used to perform several analyses. This offers the possibility to define geometry, occupancy, building services and structural components once, and use this information in different tools and configurations. Furthermore, results of one analysis can be stored in the UO and then used as input for other analyses. A recent extension of the UO is the possibility to automatically have the system vary certain design parameters and perform analysis of each of the combinations. This type of functionality is called *sensitivity analyses*. It has the ability to point out design parameters with a large potential influence on building performance.
Although the introduction of the UO meant to simplify the use of the VABI tools, it has not encouraged use of the suite in architectural practice. One reason for this reluctance might be formed by the fact that the UO still requires a large amount of expert knowledge and application experience to produce realistic results. Furthermore, possibilities for sketch-wise input and manipulation of design geometry are limited. Another reason might be that feedback of analysis results is related to norms and not directly to the failing design aspects.

The *META-4* project and the *SEMPER* environment (Mahdavi e.a 1995, 1997a) are aimed at the field of building service and indoor comfort. The environment provides graphical input through a CAD application, users can input designs using several drawing aids. Next the representation is automatically translated to the nodal model needed for thermal simulation. A dedicated thermal simulation tool calculated indoor temperatures and predicts energy use. Feedback is given through the display of dynamic charts. The systems are characterized by the bi-directional communication which provides active feedback. This is also supported by an inference engine which can optimize design parameters given a certain objective such as maximum light levels.

The *Building Design Advisor* (BDA) (Papamichael e.a. 1997a) is an interface designed to stimulate simulation in the design process by allowing sophisticated simulation tools to be accessed through a single program. The central interface combines a graphical module for the input 3-dimensional model with several forms and browsers that allow users to provide detailed information regarding materialization, use etc. The central interface then connects to several analysis and visualization tools such as Energy and Daylight evaluations. The modular design of the system enables it to incorporate future simulation models.

Environmental Design Solutions Limited (EDSL) develop *Tas*; a computer tool for the thermal analysis of buildings. It includes a 3D modeler, a thermal/energy analysis module, a systems/controls simulator and a 2D CFD package. Tas can perform indicative thermal simulations of design to optimize energy use in combination with typical HVAC systems and layout.

The university of Eindhoven and the university of Strathclyde are continually developing *ESP-r* (Hensen 1993a, 1993b). This tool was originally designed to perform thermal simulations of buildings, but was enhanced to include other types of simulations such as lighting, airflow and HVAC performance. ESP's geometric modeler provides the graphical interface. Additional modules for feedback of simulation tools and tighter integration with external tools are under development.

At the University of Leuven the *IDEA+* project is executed (Hendrix e.a. 2000, Neuckermans 1992). It attempts to develop a general-purpose building product model accompanied by a functionality model through the use of an advanced object oriented analysis method. The functionality model acts as a bridge between the design process and the product model by automating tasks performed on objects or sets of objects. Design analysis is supported through the connection with advanced simulation tools. These may consist of traditional or new applications for the prediction of light levels, temperature behavior etc, in designs.

Recently the University of Eindhoven started a new project called SMART which is based on a theoretical integration of building and HVAC design (Zeiler 2001). This research attempts to define a common language for design team participants by describing the HVAC design process in terms of general objectives, concept solutions and systems. Through the use of computer simulation and support tools, the remainder of the information gap is closed.

3.3.3 Integrated systems review

A common item in most integrated systems is the ability to graphically input design specifications through some sort of Computer aided drawing interface. The systems that use commercially available and broadly spread CAD systems for this task are the most successful. It comes as no surprise that users will more quickly accept new systems when these are based on well-known, validated techniques. Products such as AutoCAD and MicroStation have been developed over a considerable length of time and are optimized to provide clarity and ease-of-use in handling 3-dimensional data.

Most of the reviewed systems use advanced simulation tools such as radiance and finite element method based calculations. These tools, two of which were described in chapter 2, usually require detailed information on various building aspects. Although some integrated systems provide extensive interfaces that deal with the specifics of the analysis models, most limit the input to most basic aspects such as systems categories. This limitation could cause for less relevant analysis results. However, this is not treated as a source of incompleteness or inaccuracy. This can be seen as neglect to confront the problem but also as indication of the early stage of development for such systems. It could be argued that further development will reveal the scope of conceptual design information as well as the necessity of new levels of detail in design-analysis systems.

Some proposals for integrated systems contain provisions for including automated, formalized knowledge or rules to enhance the application potential. For instance, when users apply two products that are known to conflict, systems with inference engines can warn users about this risk and possible suggest alternatives. Up to now, knowledge-based systems failed to establish a breakthrough in architectural design (Drach e.a. 1993). One of the reasons for the hesitation in acceptance is a limitation that surrounds the use of these systems. Most examples use specific, shallow knowledge since it is widely available and easier to implement. However, systems that employ encoded knowledge with high specificity run the risk of having a very limited applicability. The examples of inference engines demonstrated in papers and presentation often account for a small part of design problem areas. The argument that this solely is a problem of quantity does not hold ground for long. Design methods vary among architects and can require far more and deeper knowledge. In addition, with the number of rules or facts, the possibility of conflicts and exceptions rises dramatically. Moreover, formalized knowledge in integrated systems often displays a strong bias towards the domain knowledge of the developer or the design method of the researcher. Systems that employ high level, general knowledge have the ability to be configured according the wishes and methods of a broad range of designers and can be more broadly applied (Pollalis 1994, Tzonis e.a. 1994, Kalay e.a. 1992, 1995)

Feedback of results often remains at the level of charts and block diagrams. Although these proved a step up from manually interrogating numerical data files, the connection with architectural language could require more qualitative visualization.

Lighting simulation is exemplary in this respect. The 3-dimensional, colored contour plots used to indicate Lux levels are easy to read and point directly to problem or target areas.

Table 5 presents an overview of some general characteristics of the reviewed integrated systems.

Table 5: Review of Design Systems (situation June 2001)

System:	*Geometry Input:*	*Analysis type:*	*Analysis Source:*	*Feedback:*
Combine	CAD import	Thermal, Light, Structure	Existing tools	Graphs
Uniform Environment	Dedicated CAD interface	Thermal, Light, HVAC design	Existing tools	Graphs
META4/ Semper	CAD import	Thermal, Light	Dedicated nodal model	Graphs
BDA	CAD import	Light, Thermal	Existing tools	Graphs and renderings
TAS	Dedicated CAD interface	Thermal, Airflow	Dedicated models	Graphs and arrow charts
ESP-r	CAD import	Thermal	Existing tools	Graphs and renderings
IDEA+	None	Light	Dedicated and existing	Graphs and renderings
SMART			Dedicated and existing	

A common difficulty in developing information systems is the manipulation and transformation of large amounts of data between distributed parts of the system. Data operations are needed whenever users add objects, change properties or exchange data between systems. In contrast to a situation where one central database contains the information for all modules, most of the systems mentioned in the survey, use multiple, separate applications or tools to perform the various tasks involved in design analysis. When a design environment consists of a network of multiple tools and applications, various parts of the system may access and change the same data objects at the same time. If this occurs the transfer of information becomes more difficult and the synchronous changes can cause data loss.

A disadvantage of systems with largely numerical interfaces is that the information once input becomes difficult to change. This fixed character becomes especially clear when large amounts of design data are involved. Numerical interfaces of integral environments do not support dynamic changes and interactive manipulation adequately. This results in limited opportunities for design improvement following the analyses and their findings.

Integrated environments that connect CAD representation and analysis tools are most likely to facilitate examination of building performance. Most of the approaches we have seen up until now are aimed at predicting norm and regulation compliance. However, predictions of building behavior such as routing-, light- or structural simulations are more useful in the early design phases. Although behavioral simulation has distinct information requirements which are different from those of normative analysis, it has several advantages over steady state calculations. One is the level of abstraction required by the simulation mechanisms. These are not incompatible with abstractions made by designers.

3.3.4 Digital Building models

Although the use of building product models for architecture has not caught on, some of the developed product models are worth reviewing. Semantic elements such as the formalized relations between building elements and the data structures used to represent this are valuable tools for future developments. The building product models reviewed here can be found in scientific publications on the subject and designed to accommodate for the design process. In some cases, models cater for the entire building process which places additional requirements on the level of detail and the number of domain views included.

A popular trend is to accompany models by computer tools that simplify use and provide a user interface to input new designs and buildings. These tools can act as shells around the database kernels and hide much of the structure of the model. However, most models address fundamental problems in the storing and structuring of architectural data and concentrate less on ease-of-use and comprehensibility of user interfaces. With a few exceptions, all of the models contained in this paragraph are research models that aim to enhance knowledge about the use of product modeling in construction and building. The VABI model is the only model that is broadly used in practice in The Netherlands.

The *RATAS model* (Björk 1989) was developed to enable information sharing by different participants in the building process. Its aims are comprehensiveness, multi-construction stage coverage, efficiency, portability and soft- and hardware independency. The conceptual model contains objects such as; Building, (sub)System, Part and Detail ordered in a hierarchical manner. In addition, the model tries to support inheritance, multiple abstractions of objects, relations between objects (part_of and connected_to) and particular views of parts of the model.

The *General AEC (Architecture, Engineering & Construction) Reference model* (GARM) is an abstract product data model, meant to serve the information requirements of all building related activities (Gielingh 1988). GARM is build around a common object called the 'Product Definition Unit' and provides data specialization, decomposition, multiple life-cycle stages and data classification. It also provides mechanisms to define classes of products parametrically and work with instances of those classes. The *functional unit* and *technical solution* mechanism system is extended to account for complex relations among Functional units. Although it is not officially part of STEP, much of the structure and shape of GARM has been developed according to STEP methodology. In addition to STEP standardization, it also uses ISO 6241, British Building Industry Code (BIC), Cl-Sfb and BSAB classification systems.

The *Integrated Data Model* (IDM) (Dubois e.a. 1992, Augenbroe 1995, Nederveen (ed)1998) was developed as part of the COMBINE project. This project tried to develop systems which would facilitate design description, analysis and evaluation. The data structure for such a system, i.e. the IDM, comprises a detailed and thorough description for storage of information on geometry, structural engineering, HVAC and project management as well as input for several sophisticated building analysis tools. In addition to a new approach to geometry description, the IDM contains provisions to include aspect-models facilitating information requirements by different building participants. The model is implemented in the COMBINE prototype software which is available on the COMBINE homepage.

The *House model* (Waard 1992) forms a basis for computer-aided compliance checking in building design. The model offers a place for functional and code requirements in the forms of constraints and procedures on the one hand and descriptions of the design on the other hand. This principle, partly adapted from the GARM model, enables matching requirements and design and facilitates regulation checking during the design process. It introduces objects such as: space, space boundary, separation structure, structure element and several relations. These objects are further specialized by choosing a specific type of space or element, like bathroom or internal wall. The House model offers a complete set of objects to model residential buildings as well as a structure to implement automated compliance checking.

The *Space & Boundary model* (Björk 1992) is developed through analysis and combination of four existing models: the RATAS model by VTT, the House model by de Waard, the Synthesis model by GSD and the IDM from the COMBINE project. Its aim is to capture building design semantics for database sharing among different participants of the building process. Objects such as, spaces, space boundaries and structural elements form the basis of this model. It is possible to group objects in ways fit for, for instance, architectural design, structural engineering etc, to support different views of the building. This proposal for a model is not aimed at implementation and also lacks support for HVAC design.

The *VABI data model* was made by TNO to provide a structure for the building analysis tools distributed by the *Association for Computerization in Building and Installation Technology* (VABI). These tools can perform analyses on, for instance, installation components, physical characteristics and energy usage. Currently these tools are being integrated in the 'uniform environment' (UO) to provide them with input from a single information structure. The model includes objects like, space, wall and opening as well as entities for defining occupancy, installations and environment, some of which have multiple abstraction levels. A rather unique feature is the provision for storing analysis results in the model and using it in subsequent analysis runs.

The *NOBI/BM model* (Leeuwen e.a. 1994) is a combination is four existing models; GARM, the BBB cost model, the VABI model and the Space and Boundary model. It is aimed at supporting communication between architect, cost engineer and HVAC consultant during the final stages of the design process. Both spaces and enclosing elements can be defined, as well as the topological relation between these objects. To link spaces and elements, this model also incorporated the space boundary class. Space boundaries can take the form of a physical and a non-physical boundary depending on the relation to the enclosing elements. These elements can be both space-bounding or non-space-bounding. After GARM, this model also includes different states information can take. For the purpose of this project, these states comprise; as required, as designed and as built.

The building model based on *Aspect models* (Nederveen e.a. 1992) attempts to represent different views on building project data as seen by different participants in the building process. It introduces aspect views as an addition to the 'House model' by de Waard. View independent information is stored in a general kernel while information needed by, for instance, structural engineering, energy management and HVAC design is represented by specialized objects. While generally following the House model hierarchy, an aspect model may also introduce new subclasses to provide a structure that follows the semantics of a particular design area.

The *Engineering Data Model* (EDM) (Eastman e.a. 1994a) concentrates on developing structures for design support which facilitate flexibility and extensibility in capturing design knowledge. It is based on combining a number of small structures to capture the semantics of design and engineering information. The model focuses less on objects and their properties but instead concentrates on the relations and constraints which govern the use of elements in building. These constraints are coded into labeled procedures and are combined with labeled collections of values to form higher-level entities with specific purposes. This allows object characteristics to be added when needed and ensures consistency in the design information. The EDM can be considered more of an information structure than a complete building model.

The *General Building Model* (GBM) (Eastman e.a 1994b, 1995) is an attempt to provide a model which supports multiple types of buildings and the information and design knowledge associated with them. Based on the principles of the EDM, It defines entities like Activity, Space_Boundary and Constructed_Form in multi aggregation and abstractions. To prove that the EDM and GBM can capture design semantics of different types of buildings, the model is used to describe designing a hospital.

3.3.5 Building models review

The criteria with which we determine the applicability of the building models in a Meta design environment derive from the requirements for supporting architectural that were defined in chapter 0. These criteria do not necessarily correspond with the guidelines for developing digital data structures that are employed in the software industry. Supporting architectural design adequately has the priority in the development of the Meta Design environment and determines the applicability of the existing building models. Therefore, robustness and guarantied faultless application make way for flexibility and interaction. The implications of architectural design support for information management are discussed in more detail in paragraph 3.4.3. The criteria we defined for the review of the discussed existing building models are:

- Connection to graphical information: Does the model or the management tool that came with it contain provisions for graphically inputting information?
- Blanks allowed: Does the model allow for part of the structure to remain empty for a considerable period of time? This is important if the model is to be employed in early design where not all items are present.
- Inconsistencies (temporarily) allowed: Conceptual designs may contain inconsistencies such as (geometric) overlaps. Does the model allow this for the purpose of design?
- Building service information: Does the model contain objects that model the presence and functioning of building service equipment in the design?
- Degree of building semantics: To what degree are building semantics present in the model? (none = no relationships, med. = topology and hierarchy, high = med. + constraints)

These criteria do not imply a complete review of the models. Their main use is to determine which elements are worth taking a second look at while developing a Meta data structure. Table 6 presents an overview of some general characteristics of the reviewed building models.

Table 6: Characteristics of Building Models

Model:	*Graphic:*	*Blanks:*	*Overlap:*	*Service:*	*Semantic:*
RATAS	No	NC	No	No	Med.
GARM	No	NC	No	No	High
IDM	Yes	No	No	Yes	High
House model	Possible	No	No	Yes	Med.
Space & boundary	No	NC	No	No	Med.

Model:	*Graphic:*	*Blanks:*	*Overlap:*	*Service:*	*Semantic:*
VABI	Yes	Yes	No	Yes	Med.
NOBI/BM	Yes	No	No	No	Med.
Aspect model	No	NC	Yes	No	None
EDM	No	Possible	Possible	Possible	High
GBM	No	No	No	Possible	High

Most of the listed models were developed around the late eighties and early nineties. Roughly half of the models are mostly conceptual in nature and do not include details such as material and administrative properties. The rest of the models is developed for specific application and contain more detail. Out of the eleven models that were analyzed, only the IDM and the VABI model are detailed and comprehensive enough to be used in day-to-day practice. Both contain most of the properties and relations found in building. Most of the researches recognize the necessity to integrate information requirements originating from multiple areas of discipline, but little if any distinction was made between architectural use of product models on the one hand and specialist areas on the other. None of the models meets all the requirements.

At present, the research into architectural product models has come more or less to a halt. The VABI model is used on a large scale by HVAC and energy consultants in practice. In addition, a number of companies are successfully using specialist tools built around product models. A definitive model for use in the architectural design process has not yet emerged. Although some design systems based on product models have been developed, architectural practice has been reluctant to adopt these product models.

One of the reasons many architects reject product models is the fact that these models involve a huge amount of detailed properties and a similar amount of relations. Users are required to specify large amounts of data such as exact dimensions and material properties. In addition, product models require relations between objects to be defined explicitly. Often the information in the models is constrained to impose stability and consistency. However, constraints cause for a more rigid handling of design input and interfere with design freedom.

Using plain CAD drawings or pen and paper offers designers some possibilities that are lost when adapting a rigid product model. For instance, design consultants can recognize and augment information in drawings without help from designers. Relations between elements like spaces and walls are immediately clear and are easily defined by drawing both elements next to each other. Building elements can also temporarily share the same space or ‘float’ freely.

This changes with the use of product models; relations need to be defined explicitly and are subject to hidden constraints. Design actions leading to inconsistencies are rejected while messages urge the user to follow the prescribed method. The EDM project noticed the necessity for a temporary state of inconsistency but does not indicate how this should be realized. Another hazard is formed by the fact that most models are derived from observations of physical buildings or analyses of detailed construction drawings. This method completely ignores the properties and characteristics of the (conceptual) design process. As a result, most building models tend to focus on the building process and have little provisions for design processes. The design process requires representations that have the ability to grow and change with a rate and extend similar to those reflected in the conceptual design drawings. An increasing of number of publications recognizes this problem, however, it proves hard to adapt existing approaches to this new criterion (Krishnamurti e.a. 1997, Mahdavi 1998, Stouffs e.a. 2001)

Another objection is related to the complexity of architectural information management. When synthesizing new design solutions from partial solutions, architect will drop features, invent new ones or change a partial solution radically without much effort or the need to redefine the problem. Product models usually do not support this kind of flexible information management, and architects find that they need workarounds for these restrictions that result in annoying distractions from the mayor design problems.

3.4 Automated recognition of design representations

3.4.1 Introduction

Efficient climate analysis throughout the design process presupposes an advanced information transfer facility that accommodates and processes design information. Processing takes place in several steps. Design information must be stored and retrieved with little effort, time loss and data manipulation. This could be achieved through transformable design representations that meet the requirements of both architectural design process and specialist disciplines. These representations should be amenable to design modifications following the feedback of performance analysis. Feedback and transformability is further facilitated by comparison of results from different analyses necessitating smooth design transitions and rapid execution of analyses.

Chapter 2 introduced existing advanced computational methods and techniques that provide sufficient reliability and effectiveness for executing the design analyses required by the Meta Design environment. Transforming the design representations that will provide the system with input needed for the analyses required the presence of a project database. This database will have access to various information storages and sources. Many of the requirements for this database can be copied from the dedicated data structures of commercial simulation systems. In order to keep the representation compact and non-redundant *automated recognition* of design information can be employed to provide an information source that produces data on relations and adjacency implicitly.

Despite advances in three-dimensional visualization and modeling (paragraph 3.2), two-dimensional geometric representations (in particular floor plans) remain the basic design representation, even in the computerized design office. For our research we accept the practicality and cognitive significance of the floor plan (Koutamanis 1994). Practice has shown that in cases where holistic three-dimensional design drawings were employed, the amount of automated routines reduced to little more than the generation of component listings. Consequently, all transformation and interpretation of the drawings remains the result of manual operations. Especially for large building, changing for example structural dimensions can result in a large amount of manual corrections. The floor plan allows for a less complicated manner input and offers greater possibilities in automated manipulation. A schematic floor plan can contain the structure and clarity that is required to employ various automated information processing techniques.

Unfortunately, architectural CAD Drawings are often an unstructured collection of loose lines. This diminishes the usability of the drawings as both input and geometric interface of analytical processes. When users adapt the principle of drawing with coherent entities instead of only loose lines, other powerful possibilities shift within reach. One of those possibilities is the use of automated recognition (Koutamanis e.a. 1993), so as to restructure the drawing as a network of meaningful primitives (spaces and building elements) that derives from the dual graph representation (Steadman 1983, Koutamanis e.a. 1995b). In addition to adjacency information, this network also enables us to link building elements, service elements and other facilities to their corresponding spaces. The results of automated recognition provide us with the required information in an appropriate representation. In our case, however, we believe that the user should be responsible for the structure of spatial information. Automated recognition can simplify transition from one state to another, but the user should remain actively in control of primitives and relations. This is critical to the feedback stage, in particular for the interactive manipulation of analysis results, so as to produce alternative versions and variations of a design.
For these reasons we have adopted the view that the designer should input spatial information using familiar tools. The same tools are also used for integrating the analysis output with the spatial representation. Conventional CAD programs like AutoCAD can act as our primary design environment. The user should input a design in AutoCAD as a collection of spatial primitives (spaces and building elements) in a manner similar to mainstream drafting (Figure 10).

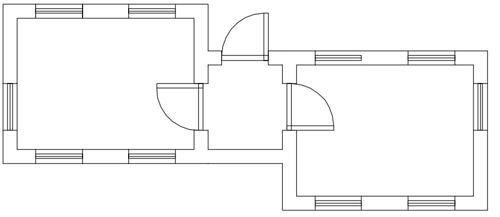

Figure 10: Spatial primitives

In these types of representation, the essential difference lies in the primitives used to construct the image. Instead of using loose lines as in drawings primarily meant for printing (reproduction), each relevant entity is drawn as a single, integral entity. Initially we are using polylines which indicate the perimeter of each entity. As the third dimension is of importance to most environmental analyses, each polyline is given its appropriate height (‘thickness’). The use of layers allows us to distinguish between different information sorts, primarily between the spatial network and the construction network (Figure 11). However, layers can also be used to separate service elements and other facilities into familiar categories which identifies them to both the user and the recognition process.

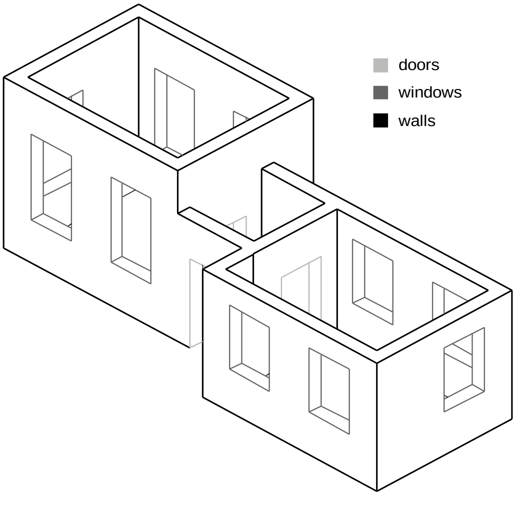

Figure 11: primitives, layout and distinction

The resulting representation exhibits the following properties:

1. It conveys the essential information for the analysis of the aspects we are concerned with. This agrees with other types of formal and functional analysis (Mitossi e.a 1998, Leusen e.a. 1998).
2. Consequently to (1) it permits coupling with the output of analyses (feedback). Feedback can assume a spatial form, either as properties of a space or element or even as subdivisions of a space or element. As such they match elaborations

and augmentations of the basic spatial information in the representation, which are also added as attributes or by subdividing the basic elements in a modular, hierarchical fashion (Koutamanis 1997).

3. The representation includes abstraction levels that correspond with the design information that is available during the early design stages.
4. The user is required to input only the minimal information normally available in abstract architectural representations, that is, the form, the size and position of spaces and building elements. Spatial relations between these and aspects relating to these can be recognized (inferred) automatically with little if any intervention by the user. This reduces the intellectual burden of information processing and facilitates concentration on the relations between analysis and design.

3.4.2 The Meta Drawing Model

In one of the first stages of the research, we set up an experiment that validated the hypothesis regarding the linkage of design representation and technical analysis through the use of automated recognition. During the experiment a prototype application was developed that linked design geometry to the first of the chosen climate analyses tools. This should demonstrate that the exchange of information between a conceptual design representation and analysis tools was possible. During this exchange, the recognition process connected two information centers that have contradicting information characteristics. On the one hand, designers will provide only a limited amount of design information in their drawings such as space shapes, occupant activities and materials. Higher order information on building semantics and relations are not likely to be input at this stage because it would take much effort in relation to the design schematics. Conceptual designs will not contain detailed information such as service capacities and material properties. The climate analysis tools, on the other hand, require a considerable amount of specialized input in order to be executed correctly. In addition, if climate analysis is to have a meaningful relation to the design under investigation, a certain amount of situation specific (direct) design information is needed to prevent the overuse of default values in the analysis input. Often, the two information sources (design and analysis) differ not only in occurrence but also in form. This necessitated additional operators to perform the necessary data transformations.

The application that linked design and analysis contained three implementation elements: 1) a new type of design representation in CAD, 2) integrated automated recognition routines for data management and 3) standards regarding the information export to analysis. The experiment attempted to find a balance between abstract form in the building representation and the information standards of the performance prediction tools. Two constraints were leading in qualifying the implementation efforts of the experiment. Firstly, users should be able to *easily* input designs and, at all times, be allowed to make modifications. Secondly, the Meta data system should have control over the represented information for the purpose of performing the required transformations.

For the graphic input of the design representations, we employed a method that offers an efficient and structured use of CAD applications. Koutamanis, Vitossi and van Leusen (Mitossi e.a. 1998, Leusen e.a. 1998) developed the *RF drawing model* to ensure that designs would be inputted in a manner that would allow correct interpretation and analysis. One useful RF model characteristic is the possibility to easily add element categories for new domain areas. We used this feature to expand the RF model to incorporate building services. The new system was called the *Meta drawing model* (MDM). It describes some guidelines that need to be followed in order to create representations that are suitable for analysis. The two most important are the use of specific entity types and the naming convention for the categorization of the entities.

A commercially available, general purpose CAD application (AutoCAD) is used to provide for the graphic interface and straightforward input of drawings. Using a commercial CAD application has certain advantages over using a dedicated implementation. Firstly much effort has been put into developing an intuitive manipulation of shapes and addition and removal of design entities. Secondly, this approach ensures an easy transfer from Computer Aided Drafting to a more sophisticated way of designing by use of computers because designers usually are familiar with standard CAD tools. This reduces the risk of loosing time by getting acquainted with the new drawing environment. Finally, using a commercial CAD tool with integrated development capabilities requires a relatively small amount of effort to build an example implementation for demonstration purposes. The intrinsic CAD entities can serve as objects with the required functionality to represent the spaces and building elements that are found in designs. Two disadvantages of this approach are the lack of control over the structural and technical validity of building elements and the abstract way in which building elements are drawn. The latter could be an issue when performing complex simulations that must reach a high level of accuracy.

3.4.2.1 Drawing 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 (Figure 12). 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.

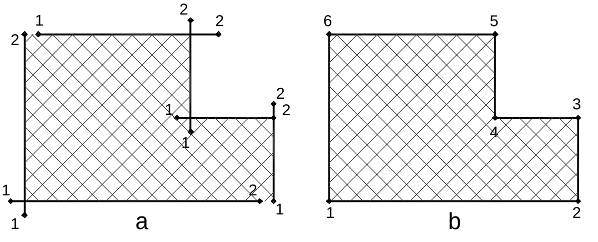

Figure 12: Multiple individual lines versus single Polyline

3.4.2.2 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. Each building element is placed upon a layer that bears a standardized name. De name refers to the function of the element and the floor it is placed on. The first two characters of the layer name are reserved for denoting the floor level. The ground floor is indicated with: “00”, the first floor with: “01”, the first basement with: “-1” and so on. Drawing entities can also be separated spatially by placing them on the according height in the three-dimensional drawing space. The second part of the layer-name classifies the function of the represented element. This part consists of an underscore ("_") and a string attached to one of the categories displayed in Table 7.

Table 7: Some Categories of the Meta Drawing Model

Function category:	*Layer name:*
Façade perimeter	xx_BUILDINGMASS
Elementary space	xx_BUILDINGAREA
Stair case / elevator shaft	xx_VERTICAL_TRAFFIC
Hall-way / corridor	xx_HORIZONTAL_TRAFFIC
Attention area within a space	xx_BUILDINGZONE
Floor field	xx_FLOOR
Interior wall	xx_INTERIOR_WALL
Exterior wall / façade element	xx_EXTERIOR_WALL
Opening in floor field	xx_VIDE
Door (exterior & interior)	xx_DOOR
Window	xx_WINDOW
Building service component (from library)	xx_HVAC
Furniture / non-active object	xx_OBSTRUCTION

In addition, we used a classification in space (‘void’) and building components (‘solids’). Spaces are categorized further into common spaces, circulation areas and miscellaneous spaces. Openings are divided into windows, doors and other openings.

Walls & floors, if specified, are divided into internal and external types (Figure 13). Extension of the categories is possible and relatively easy to do. New categories of spaces or components receive unique layer names that can be used in addition to the existing ones.

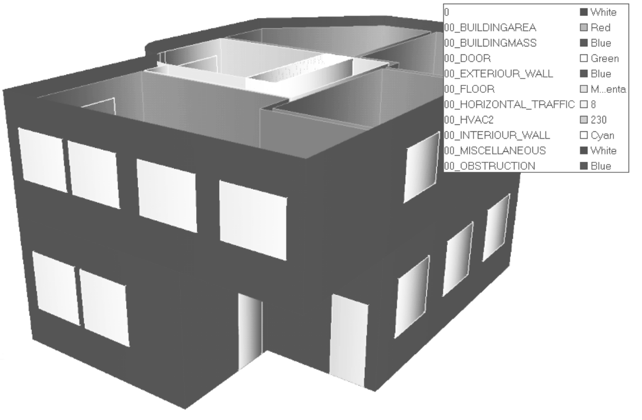

Figure 13: Modularization of geometry

3.4.2.3 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 a 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.

The Meta Design Environment recognizes hierarchical relations such as groups included in a building, spaces included in a group and openings included in a wall or floor. This allows, for instance, to group spaces into a single floor or wing, and allows users to address multiple objects using a single handle. The system uses algorithms that parse the representation and searches for relations. This information is then stored for later use.

Windows, doors and other kinds of openings typically join two spaces together. The system employs a representation that allows the boundaries of spaces and openings to be drawn as objects that coincide with other space objects. This enables the system to recognize which spaces are joined by which elements. A similar procedure applies to walls and floors.

Other types of relations involve the placement of building elements in sequences, encounters between materials and spaces and among building elements. Although not directly needed in climate analysis, the information on these relations can also be recognized from the geometry in the representation.

3.4.2.4 Annotations

In addition to modularization, colors provide a means to link additional information to the representation objects. In the experiment we have provided a list of occupant activities such as sitting down, bathing and sporting that require specific indoor climate characteristics in terms of temperature, humidity and ventilation (Table 8). By assigning a certain color to an entity representing a space, an activity can be mapped onto that space. For building components like walls and floor a similar procedure can be used to select materials. By choosing them from a list, users select and assign material types to drawing entities. These annotations remain visible in the drawing in order to provide full control over the annotated information. Users might also add descriptors or identification markers to enhance clarity and the communicative capabilities of the drawings. Color, hatching, line type and text annotations are standard CAD facilities that may be used for this task.

Table 8: Color annotations

Occupant activity:	*AutoCAD color number:*
Living area	1
Kitchen	2
Bedroom	3
Bathroom	4
Corridor	5
Living area common	6
Living room	7
Office	8
Refrigerating plant	9
Toilet room	30
Wardrobe	40
Library/study	60
Heating plant	120
Entrance	140
Basement	200
Exhibition room	220

3.4.2.5 HVAC library

Spaces and building elements can be easily represented by drawing their perimeters of boundary boxes using a simple outline. For building service components, this procedure is not sufficient. Even in their most abstract form, they require an alternative method to be specified for analysis. To meet this need, we developed the HVAC library to offer users the possibility to manually specify building services. To determine which elements to include in the library, the structure of the Integrated Data Model (see paragraph 3.3.4) was more closely examined. The objects that are needed to perform airflow and temperature simulations were selected and simplified to a flat object structure. The resulting objects were implemented in a HVAC object library.

In the Meta Drawing Model, items from an object library can represent building service components. The MDE HVAC library offers a range of components that can be placed inside buildings and spaces (Table 9). When the user is an architect in the early design stages, there will be little demand for the use of libraries in general and for HVAC design in particular. It is at occasions where examples and specialized designs are created that the object library will prove useful. The structure of the Meta design environment relies on the presence of *example projects* or *precedents*. These precedents are made in a design stage where there is more space for accurately representing the designs. In most cases, the involvement of design specialists will support the definition of building services, lighting systems, furniture, equipment, etc. In these situations, users can select service items from a list; the system will request to indicate the corner vertices of the new component. Next, the attributes are attached to the components. Each component type has several performance related attribute values such as power, operation temperatures and airflow rates. The default values can be changed before finalizing the definition of the component.

Table 9: Building service components in the HVAC library

Component Name:	*Description:*
Air_handling_unit	Air treatment units, heats, cools, humidifies and/or dehumidifies air for (a part of) the building
Air_inlet	Opening for the inlet of (conditioned) air to a space
Air_outlet	Opening for the outlet of air from a space
Boiler	Boiler for warm water supply
Ceiling_cooling_element	Ceiling elements that provide cooling through radiation
Chiller	Refrigerating machine
Electric_radiator	Electrically powered radiator
Fan_coil	Fan-coil unit, air/water based system
Floor_heating_element	Floor elements that provide heating
Induction_unit	Induction unit, air/water based system
Opening	Opening to the outside or other spaces, for the natural inlet or outlet of air
Plenum_box	Lowered ceiling, can contain air outlet and/or other services
Source	Heat and/or pollution source
Water_radiator	Water powered radiator

3.4.2.6 Abstraction algorithms

In order to translate the flat CAD drawing into a more structured and cognitive building model, both implicit and explicit represented data is registered into an information model. This registration ensures that entities are stored as encapsulated objects and that any additional information is linked in a consistent and retrievable

manner. This information model forms the basis from which analyses are steered. It is therefore imperative that the model contains the data needed for analysis and supports retrieval of any missing or indistinct information.
The representations that form the basis for analysis will typically involve ‘sketches’ in this context. Thus geometry may vary from abstract to fairly detailed, even within a single drawing. Since most analysis tools work best with one, usually prescribed, level of abstraction, it is necessary for the system to retain control over the representation and make abstractions or specifications where needed. This abstraction and interpretation of geometry must on the one hand refrain from interfering with the design process and on the other hand address the needs and characteristics of the analysis.

In most cases, the geometry contained within the CAD representation cannot be exported directly to the geometry of climate analysis tools. The equations that form the basis of most simulations have limitations with regard to curvilinear shapes and small details. In the case of airflow simulation, designs should be free of small rims and holes. Also, curvilinear shapes need to be transformed into angled lines. In some cases, angled walls are further abstracted by representing with multiple smaller elements. Shapes such as triangles and trapezoids are filled with many small rectangular boxes to produce geometries that can be described in orthogonal space (Figure 14).

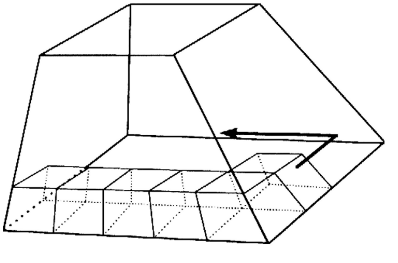

Figure 14: Grid plastering (source: Owen 1999)

When airflow simulations that support more complex geometry become more popular in building design, the abstraction mechanisms can follow the building geometry more closely. Other promising developments are made in the fields of aeronautics and industrial engineering where advanced geometric abstraction algorithms translate complex shapes automatically into orthogonal grids or unstructured meshes that can be used by simulation tools (Owen 1999). These algorithms can also balance between accuracy (much mesh detail) and computation speed (little mesh detail).

For example, when a design representation is labeled for analysis with a CFD application, the geometry must be abstracted in a way that allows rapid and proper analysis. One of the more primitive algorithms for translating this kind of geometry would directly translate Figure 15a into a multifaceted representation. This representation still contains every original detail (Figure 15b). This will result in an information overload for the CFD calculation core. A crude abstraction method may produce results as depicted in Figure 15c. This type of geometry can be quickly solved using CFD but might leave out import aspects. In order to define relevant, solvable CFD problems, small details in geometry have to be left out while other parts must receive data reduction. The abstraction algorithm employed in this experiment must be able to determine the type and amount of abstraction needed for analysis. In addition, it should guarantee closed boundaries and right-handed orientation and prevent self-intersection. The Meta Design environment's algorithms attempt to determine a level of abstraction that matches the tools calculation grid (Figure 15d).

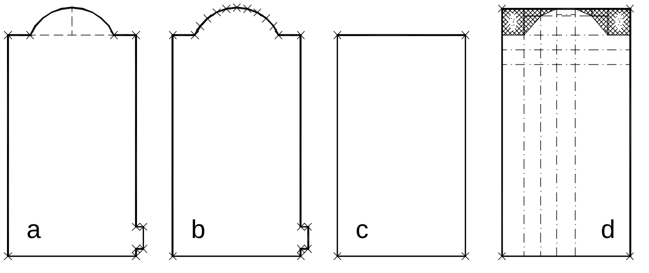

Figure 15: Abstraction of geometry. a) original design, b) max. accuracy, c) max. speed, d) Meta algorithm

3.4.2.7 Hierarchy and topology algorithms

In order to perform realistic analyses, the representation needs structure. This structure can be provided into hierarchical and topological information. Hierarchy determines whole-part relations and establishes dominance. Topology deals with adjacency relations such as proximity, distance, sequence and systems. Hierarchical and topological information in analysis determines the precise functioning of the building as a system and allows the modeling of the interaction of building parts. For instance, the system needs to know which windows are contained within each wall, which walls belong to each space, etc. It might also be necessary to know which spaces are entirely enclosed by internal walls and which spaces lay close to one or two façades. For building service components, it is important to relate inlets and outlets to the systems and to relate the systems to the spaces they service.

Most of the building product models from paragraph 3.3 contain provisions for specifying and storing topology data. Many researchers (Bjork 1992, Eastman 1994a, Leeuwen e.a. 1994, Waard 1992) stress the necessity of this information. Most also mention the additional burden this places on users. By using *automated recognition*, we can add this structure to design representations that contain only shapes. It translates the unassociated data in the drawing into ordered object structures. This relieves users from the tasks of manually specifying all relations between drawn entities and the obligation to keep these definitions up to date when modifying the representation.

The Meta Drawing Model (MDM) requires windows and doors to be drawn across or adjacent to the spaces they connect. This enables the system to find adjacency information in the representation. For hierarchy the principle is partial or complete inclusion. Objects drawn within the perimeter of other objects are assumed to have a part-whole relation. Naturally, an additional filtering is needed to prevent accidental detection.

The process uses proximity and inclusion algorithms combined with the object filters to parse through the design drawing and match each drawn object to all possibly related objects (Kalay 1989).
For instance, the proximity algorithm selects all openings and parses the drawing to find the spaces they connect. Other examples include finding spaces that are included in a building and openings that are included in a wall or floor. Recognition would provide the possibility to group spaces into a single floor. This includes access between spaces that are joined by windows, doors or other types of openings. The relation inside-outside is included in topological data. Once the hierarchy and adjacency information is registered in the information model, the system is able to produce, for instance, space adjacency graphs (Figure 16).

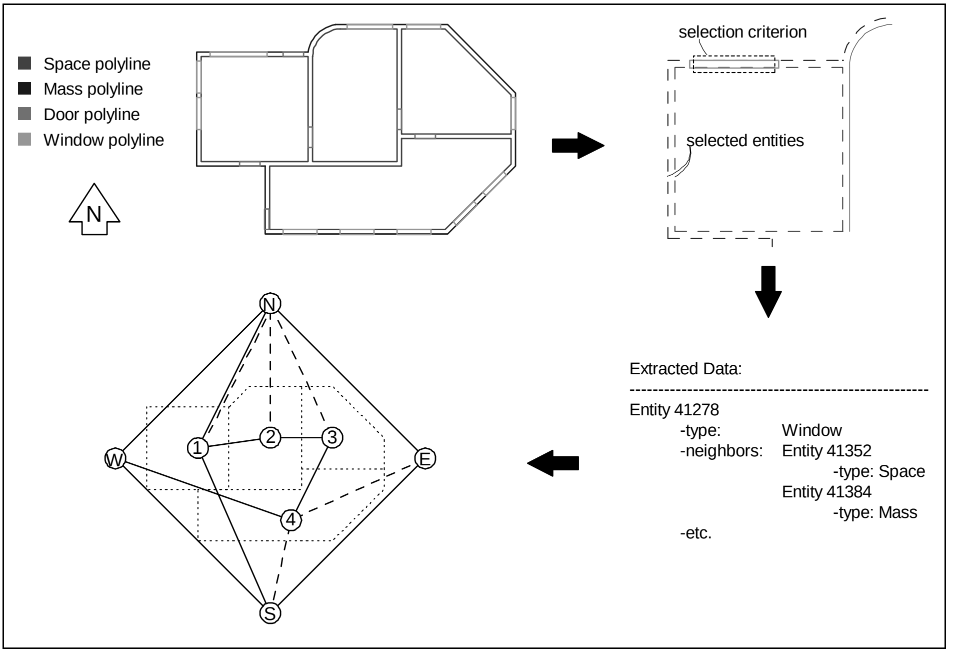

Figure 16: Recognition of topology

A Meta design representation need not contain walls and floors drawn as separate objects. Instead, reserving a zone or distance between space boundaries will specify walls implicitly. This enables the system to deduce wall and floor information from the representation. Defining such a zone between two spaces will result in the generation

of an interior wall, distances between the building's perimeter and the space perimeters are converted into exterior walls. The dimensions of the wall are estimated from the size of the wall zones (Figure 17). A similar mechanism related to the placement in height of building objects will define floors and ceilings.
Since symbols representing walls and floors are often required when performing a building analysis, an algorithm creates them from the information present in the design representation.
These elements are initially hidden from designers and are only used for analysis input and other recognition algorithms, but can be viewed and modified when needed.

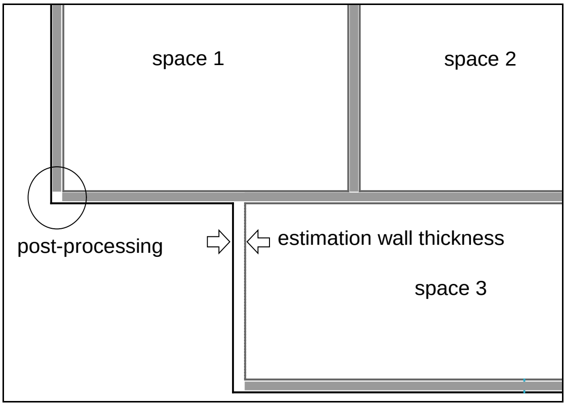

Figure 17: Automated generation of walls

3.4.2.8 Drawing method examples

To test the capabilities of the drawing method further, we copied several existing buildings and building spaces from design documentation using the Meta drawing model. The objective was to represent the spaces and other elements in an approximate manner that would be sufficient for analysis. Special attention was paid to the representation of strange shapes and the inclusion of objects that would be relevant to analysis. During this process, several gaps in the methods were detected, one of which resulted in the production of the HVAC library. Other expansions related to the abstraction algorithms and the diversity of shapes contained within the design representations. The inputted cases were also used to test subsequent developments with regard to automated analysis, this to ensure correct transformation into analysis input.
The first building we drew with the Meta drawing model was an office building that houses a building service consultant. One of the complicating factors here was the round façade. We chose to represent curvilinear shapes with multiple straight segments since this relates closely to the actual construction and does not conflict with the schematic character of early design (Figure 18). Next, we input spaces that contained more detailed elements. These included a typical office space in the building of the faculty of architecture and several spaces of other (Figure 19). One problem we encountered concerned the representation of very small spaces (< 0.3m). The

algorithms for the retrieval of mean wall widths seemed to overlook these types of spaces. With modifications the algorithm worked well with all types of spaces.

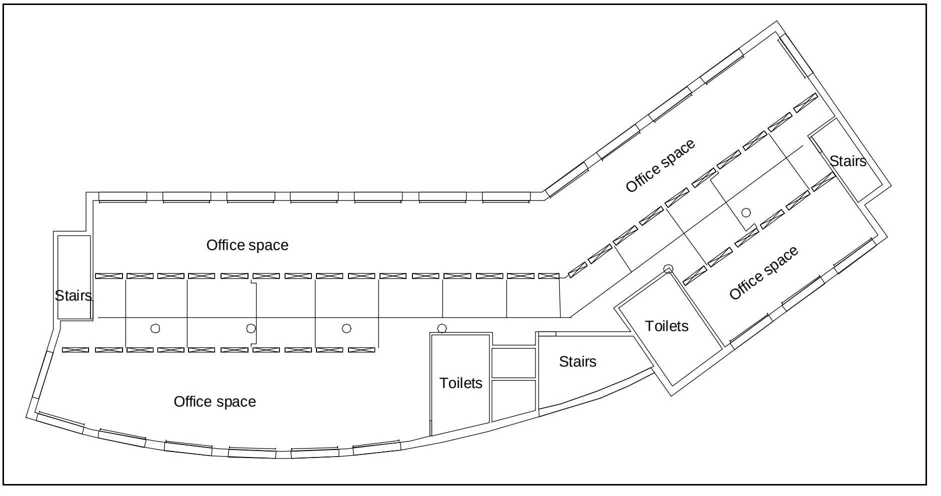

Figure 18: Meta Drawing of a typical office

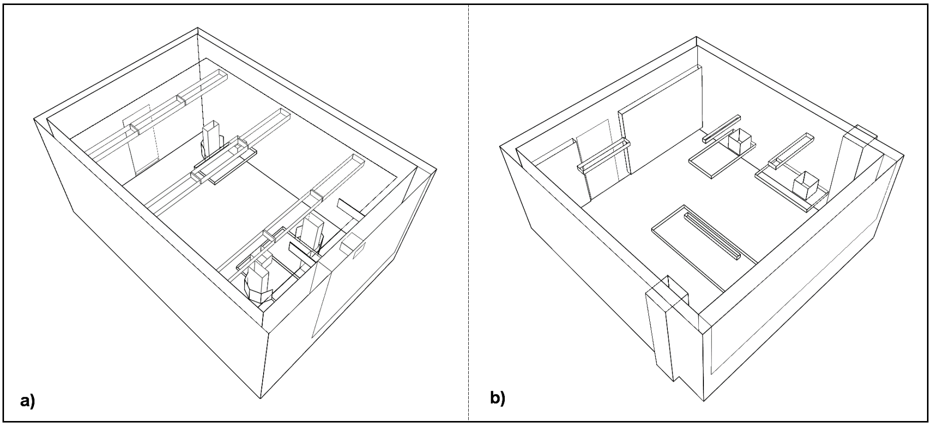

Figure 19: Meta Drawing of two office cells

3.4.2.9 Review

The experiment showed it to be possible to deduct space adjacency information using door and window symbols from the design representation in all these situations. This meant that the system has information on identity of spaces that have access through windows or doors to other spaces. Complete separation by walls can also be marked as a relation. Information on the size and placement of building elements can be read from the drawing as well as the element hierarchy. This means that each opening is related to a wall or floor it is located in. The relation between walls and floors and the spaces they bound is also known to the system. In effect, the entire hierarchy of spaces and building elements can be read from a representation made with the Meta Drawing Method.

The examples buildings represented during the experiment show that the Meta drawing model is able to depict the shapes, elements and services present in buildings and spaces. When modeling buildings in more detail, information regarding the height of spaces and elements might be required. The Meta drawing model employs a principle in which all objects representing a plan view can be given a height. In other words, the shapes represent the floor plan of spaces are extruded in vertical direction. This implies that the shape of the floor plan is fixed over the height of the space or element. Although this complicates the definition of curved walls and prohibits the definition of doubly curved shapes, the procedure suffices for a large portion of office building designs. In addition, the Meta drawing model contains a provision for obstructions and freestanding objects. This makes it possible to block out a part of an orthogonal space thus creating more complex shapes. However, these additional entities could clutter architectural drawings and make it more difficult to modify them.

The main purpose of the Meta Drawing Model, the representation of conceptual designs for the retrieval of topological and relational data, makes demands on aspects such as the level of detail and the consistency of the drawing. It is unlikely that the function of construction or tendering drawings will be replaced by the RF drawing model or the Meta drawing model. They also have limitations as to the complexity of the shapes in all three dimensions. In order to test the applicability of the model, the implementation of the automated recognition algorithms was tested against a number of design situations and representations. In the tested cases, it proved possible to represent the shapes and relations in a degree that correspond with conceptual designs.

3.4.3 Meta information structure

3.4.3.1 Introduction

The development of automated recognition tools necessitates a storage facility in the Meta system. The recognition of architectural drawings can easily result in large amounts of data. This data may require temporarily or permanent storage in order to quickly and robustly perform operations such as consistency checks, unit conversion and analysis steering. This paragraph describes the information structure that provided the storage for data within the Meta design environment. The conditions for developing such a structure stem from the recognition techniques described in the previous paragraphs, geometric content and analysis input. The information extracted from design representations will serve the input of technical analyses. Since the new data structure will provide the input for the analysis tools, the information requirements of the airflow and temperature simulation tools are closely examined.

This identified further conditions for the development of the new data structure (paragraph 2.3).

When placed into the design process, the data structure can be expected to connect to other information sources such as product libraries and CAD systems of other design team members. This will shift the purpose of the data structure into the area of information exchange servers, acting as a pass-through of information between architect and specialist analysis tools. This type of functionality is beyond the scope of our objectives since it often results in holistic solutions that tend to freeze up systems before, at long last, acquiring the required functionality. In paragraph 3.3.4 we saw several attempts for this type of structure. Until now these have served their individual systems well but have failed to break through as international standards.

The building model review revealed that architectural design makes high demands on support mechanisms such as data structures (paragraph 3.3.5). The scope and flexibility of the information and facilitating communication of between designers and other participants is crucial to success of the structure. The main obstacle in this development is the lack of formalized knowledge about the communication process. It will take an additional effort to collect and structure formal communication protocols to the point where they can support automation of the underlying processes.

The objective of the development of the Meta Design environment model is not to provide an information structure for architectural design, building representation or design communication in general. Neither will it attempt to support a single differentiated design process through a specific, dedicated structure. The content of the data model for the Meta Design environment starting from the external techniques used (representation, automated recognition and analysis). The data from architectural representations and the results of automated recognition algorithms typically involves entities, ID's, coordinates, functions, etc. The data input list from temperature and airflow simulation tools are searched for common elements and structured according to a preliminary model. The characteristics of the conceptual architectural design process, such as the fact that it does not contain highly detailed elements, are also of importance for the development of the data structure. In addition, the building elements that contribute to the execution of climate analysis should obtain a place in the Meta Information Structure. The following paragraphs explain some of the common requirements on database engines.

3.4.3.2 Storage requirements

Product modeling theory prescribes that information structures are robust, complete, non-redundant, consistent and unambiguous (Owen 1993, Ullman e.a. 1997). Although a number of additional conditions may be identified, these five are the most important. Robustness addresses the characteristic of well performance under the most demanding circumstances. At no time, a robust model is to break down or to violate any of the other conditions. Since our model is a demonstration and development product, technical robustness is not an important issue.

Complete models contain all information that all connected systems require. Completeness is strongly related to the use and context of the product model and the tools and applications it supports. The context of the Meta data model comprises the selected analysis tools and the architectural representation model. The information contained in the tools is predetermined and fixed. The input of two available commercial tools will be used to create a basis from which developments will start. A similar procedure is followed for the representation format. Paragraphs 3.4.2 and 2.3 discuss the characteristics of these starting points in more detail.

Non-redundant models hold all information in one place only. When a piece of information is stored in two or more locations, at least one copy is considered redundant. Redundancy quickly leads to waste of space and bandwidth and may cause inconsistency when two copies are not synchronous. In some cases however, redundancy is used to serve a practical goal. Using a single location for all operators in combination with large amounts of data can slow information processing down considerably. When processing speed is an essential performance issue, database systems may perform laborious transformations in periods of little activity to enhance overall information retrieval rate. These pre-processing results are stored separately and strictly speaking, this procedure violates the non-redundancy requirement. As is often the case in practice, the tradeoff between speed and redundancy causes programmers to replace the non-redundancy requirements for procedures that guard the relations between the multiple (redundant) information instances.
In the case of the Meta data model, creating a single, holistic model is impractical. It would involve integrating all capabilities of a CAD tool, the information model itself and the database requirements of analysis tools into a single application. Doing this amount of work is not feasible within the time span of our research. Therefore, commercially available CAD and analysis tools are used while the information model is developed as a separate element. The software that transfers information from model to tools and vise versa receives special attention. It must follow strict rules that allow a degree of freedom in the CAD input and at the same time produce realistic and reproducible results that adhere to other conditions described here. However, making a correct tradeoff between non-redundancy and speed will receive some attention within the scope of the project. Whenever possible, we will look for ways to store information in as few places as possible.

Consistency suggests that the total set of information in a particular situation is in state of coherence and prohibits contradictions between any two parts of the information. Architectural design is arguably less structured than other design disciplines in the early, conceptual stages. An architect designing alone will often feel a need to postpone trade-offs or decisions that deal with inconsistencies until more information is available. The Meta data model is developed to function in an environment that relates well to conceptual designing. Conceptual designs often contain inconsistencies such as

overlapping spatial elements and inconsistencies with respect to cost. One important aspect of design in general is the ability to unite opposing requirements into a realizable scheme. In the case of architectural design, the life span of inconsistencies or contradictions is long compared to other disciplines.
Information models developed to support conceptual design have two possible ways of dealing with this. Developers can choose to have the model contain the inconsistencies without the system intervening. This method leaves the responsibility for the consistency of the information with the designer or architect. The main advantage is a large degree of freedom in designing. A disadvantage is that the information in the model is useless to anyone other than the design team without additional scanning and corrections. The second approach contains automated verification of all entered information by the system. It detects any inconsistencies and the system might provide users with warnings. Automating this verification requires coding expert knowledge into the rule systems that provide users with actions and responses. Models that employ this method are called constrained models. One mayor advantage of these types of models is the ability to connect directly to other computational models and third-party design tools. The main disadvantage is the restriction on design freedom these models impose.

Another problem arises when multiple disciplines or specialists share a common information resource. People from different backgrounds have dissimilarities in focus and interpretation which, when made overt, might cause for discrepancies in information types and definitions. When developing information models that facilitate multiple views, chances are that information must be stored differently for different uses. This might cause contradictions in the information model. In these cases, a procedure similar to the non-redundancy requirement is employed. Translating information between views becomes part of the model and requirements for consistency and robustness apply to the translation process.

Unambiguousness relates specifically to the labeling of information. Transparent definitions of the stored items should be used throughout the developments. Each information slot should have an obvious meaning, so users can understand where it refers to and how the information should be processed. The slot definitions should be documented to facilitate communication about the information and prevent erroneous interpretations. In this context, initiatives to arrive at a standard for building terminology such as STEP, the Dutch equivalent BAS and several ISO standards need to be closely investigated in order to overcome the confusion in labeling and naming. Although choosing a standard might seem relatively straightforward, the number of standardization attempts that failed to break through, indicates that there is much work to be done on the definition and organization of the building process.

3.4.3.3 Constraints and considerations

To support architectural design adequately, CAD systems should allow flexible and rapid input of shapes and building elements. Although flexibility and speed can be expressed in more concrete terms such as the numbers of user operations needed to define a given shape, it is difficult to determine in advance whether or not a CAD approach will work. The large amount of available CAD systems for architecture in combination with their slow acceptance proves this. Many systems rely on object libraries and design by use of placing building elements in representations. This might appear to provide rapid and straightforward definition of architectural plans. However, the majority of designers feel hampered by the obligation to build plans with objects when this concerns early schematics. In many cases, the CAD environments require more actions than architects are able or willing to take. Furthermore, redundant information complicates design modifications. Designing with libraries of objects and building components is attractive from the point of view of building elements manufacturers and software developers but architects are comfortable with this idea.

The reason many of the building product models employ these disputed object models derives from computer science. Software programmers rely heavily on the *Object Oriented Programming* (OOP) (Kay 1996) approach to many information technology problems. This approach has many strong points including a strong relation to cognitive problem solving and paradigms such as systems theory. OO programming makes computer applications better suited for maintenance and upgrading. They also offer good overview of large amounts of objects and data because of their intrinsic possibility to be displayed as object trees or lattices. Furthermore, in other areas such as business information management and car and airplane design, the OOP approach has make vast achievements. In the opinion of many software developers, object oriented programming was the biggest step forward since the introduction of the microprocessor.

It comes as no surprise that the OOP approach was at the base of many architectural computer systems. However, accepting designing with objects as the *a priori* approach to Computer Aided Architectural Design is a misguided conception. Architects engaged in the early phases will keep using pencils and paper but are also turning towards computers for sketching and shape experiments. In light of the possible benefits such as computer aided evaluations, this is understandable. However, in the early phases, architects do not design with objects that are available from computer library alone. They also use more abstract guides such as directions, mass-void contrasts and psychological rules. The definition of the objects themselves change as the design process advances. The following example after Stiny (Stiny 1975, Krishnamurti e.a. 1997, Gero 1996, Stouffs 2001) shows quite clearly that the placement of two objects can results in the representation of three spaces (Figure 20). Architects deal with this issue almost unknowingly. OO systems on the other hand, require redefinition of the two existing objects and the creation of an object for the new space. Even in the case that it would be possible to teach a system how to do this, it would require a clear definition of the meaning of these types of situations. In most cases, the designers themselves are not sure whether to interpret this figure as 3, 2 or even a single object. This is also an example of the uncertainties in architecture that was mentioned in the introduction.

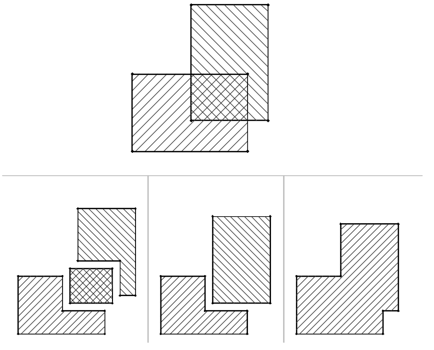

Figure 20: Spaces, implicitly defined

Despite the pitfalls in the OOP approach, the benefits of the use of product models remain appealing enough to attempt development of a compromise. The large amount of structured information contained within product models permits to extend the applications of CAD systems and to link design representations to analysis, calculation and description. In other areas, the use of product models has decreased development and testing costs and reduced the ‘time to market’. At the same time, use of product models has given, for instance, industrial designers more control over the shape, structure and fabrication of their products. Given the proper combination of product model and CAAD system, any of these benefits could also apply in architectural design.

The Meta design environment requires a product model that allows straightforward and flexible input and manipulation of conceptual design information. Secondly, the information contained must be complete enough to steer, for instance, technical climate analysis. The building models mentioned in the survey in of paragraph 3.3.4 do not provide us with the deliverables needed for the Meta Design environment to connect directly to CAD input. The Engineering Data Model (EDM) could be used to device a system that owns the required characteristics, however this would take a considerable effort while the main feature of the EDM, the definition and control of constraints, would remain unused.
Given the short time-span we had and the fact that obtaining and learning one of the existing models would take too much time, we decided to develop a new model that would meet the requirements mentioned earlier. In this development, objects and components that have proven their usefulness were copied from existing models. At the same time, weak elements such as overall structure and especially the restrictive constraints of the existing models were abandoned. Examples of the established objects include the notion of spaces, separate classes for building elements such as walls and floors and openings such as door and windows. Most building models aggregated spaces into larger parts such as wings or stories. The data model of the Combine environment, the IDM, contained an elaborate chain of objects designed to represent building services. Despite the age of the model, this part of the structure was complete

and comprehensive and was adapted into the HVAC library of the Meta Design environment.

3.4.3.4 Information types

Communication with other team members will result in an information flow. This flow may consist of creating, deleting, changing, copying or translating of a certain amount of, among others, graphical, textual or numerical information. The data contained in this flow is stored in a system of paper documents or computer files. Any change in the state of a system could be viewed as part of the information flow. In our research we will define flow as information exchange between two or more systems. When connecting design representations to analysis, analyzing and documenting the information flow is an essential step.

Activity is the key element in any design process. In the field of architectural design, activities are characterized by social and spatial requirements of humans residing in a build environment (Koutamanis 1994). Processes like sleeping, eating and working make demands on the amount of space and the level of comfort offered by the building. Examples of activity characteristics might include adjacency requirements, information regarding equipment and time schedules. This information is often translated to more specific requirements such as area, travel distances, maximum temperatures, minimum light levels, etc. Design briefs usually contain lists of activities that should be accommodated and state activity characteristics. To add to the information in the design brief, architects interpret and supplement the brief through their knowledge and experience. Building codes put additional constraints on designs by stating design performance in quantities such as ventilation rates, escape routes and fire safety. Designers working with the Meta design environment are likely to be occupied with explaining and placing occupant activities, defining spaces and relations between spaces and evaluating what they have produced. They may also define building performance specifications, insert references to library components and copy information from other sources.

In order to accommodate activities, designers may shape spaces around these activities, providing sufficient space, comfort and protection. These spaces can be thought of as being containers of activities. Collections of spaces are usually grouped into buildings, making buildings perceptible as containers of spaces. On a more abstract level, entire buildings may be treated as spatial structures and one may describe building activities (office, hospital, library etc) that should be placed within these structures (Koutamanis 1996). Therefore, spatial structures should accommodate both shapes as well as one or more functions. Representation of spatial structures is one of the main objectives of computer aided design representation. Developers agree that facilitating graphical interfaces and easy manipulation of shapes and form is a prerequisite for modern CAD systems.

The boundaries of spaces are often designated as regions where the materialization of the design will take place. These can correspond with building elements such as walls, floors or series of columns. Such elements might separate spaces, carry other building elements or provide stability.

The previous paragraph mentioned the circumstances under which there is a need to define and represent space boundaries as individual design entities (walls, windows, façades etc). However, manipulating walls and floors together with the spaces they bound is cumbersome and has to be avoided, especially during early design stages. A possible solution to this dilemma is the use of a building representation that employs representations of space-boundaries as well as objects for structural elements. In later design stages, the representation might also comprise links to databases containing detailed building products (Figure 21). This will allow for maximum flexibility in the design representation and at the same time open the representation for more detailed information.

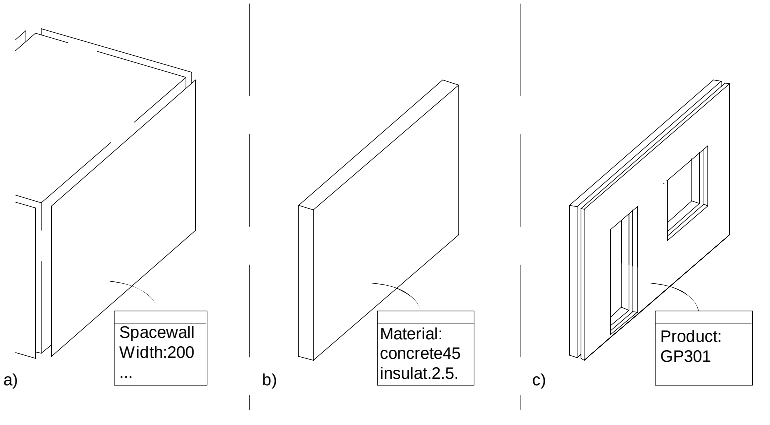

Figure 21: Three types of symbols for wall representation

Detailed building elements such as furniture, support systems and building services can be stored in libraries and represented by placing symbols in the drawing. This enables users to make more detailed designs with relatively little effort. Copying items from previous building projects can be considered as an alternative type of library. A distinct benefit of using information from precedents is the ability to view building elements in the context they were used before, allowing better judgment whether they suit the new design.
Using libraries in early design documents might seem unusual since the extra information can prove of little interest to architects. Moreover, the entities can clutter drawings when these are converted into more detailed tendering drawings. Therefore, in a Meta design environment libraries should remain optional at all times. It also stresses the importance of a transparent early representation. Both the early and the detailed building representation can be placed on top of each other. In this way, both

representations can act as the source of modification for the other without complicating the documentation.

Designers might collect a numbers of spaces or wall segments into stories or structural slabs that cover larger parts of the building. The definition of these collections might stem from to building code requirements such as fire compartments. Using color-annotations on drawing entities will link additional information such as mapping user-activities onto spaces, assigning materials to walls and floors and linking building products to windows and other elements. Designing also involves manipulation and removal of information. Users might remove entities and input new ones or change relations and references. In addition to facilitating information storage, a representation system should also allow for data manipulation and proper handling of those changes.

When using automated recognition algorithms that create, for instance, walls and floors also add information to the representation. The results of which can come to rather large quantities and might be generated solely to provide for the execution of other algorithms. In order not to burden designers with an overload of information, these objects should either be hidden in the design representation or at a convenient location in the information structure. If, at some point, a designer wishes to access algorithm results, this data should be retrieved and represented.
During the initial phase of the conceptual design, the system may employ rules to caution a designer for possible hazardous configurations. It might also compute indicative values for, for instance, shading coefficients, heat loads and duct sizes. Although this information might not be stored in the representation, it will cause for an information flow from system to the user that will have consequences on the interface.

When some aspects of analysis input cannot be found in a design representation, default values might be used. Defaults are a simple means to enhance information to the level of analysis. However, caution must also be taken when using defaults to fill in for, for example, heat conduction coefficients. Using standard values might shift the design to be analyzed out of the solution domains that designers envision. Default values should therefore be treated in a similar manner as precedent information. Wizards should propose default information rather than to instantly copy it.

Table 10 summarizes some of the information items that can be found in early designs. It is this type of information that will be used to steer the process and is likely to change, on occasion as a reaction on feedback from analysis.

Table 10: Summary of Design Information input

Type:	*Information item:*
Activity:	
	Organization size / type
	Activity types within organization
	Traffic requirements (horizontal & vertical)

Type:	*Information item:*
	Extreme / Future use of the building
Shape:	
	Building mass, general building shape
	Space depth, size
	Window sizes
Material:	
	Façade type
	Construction type
	Interior walls type
	Window type
Service:	
	Climate requirements from Program or Norms
	Space service concepts
Performance:	
	Indoor temperatures
	Other indoor air properties

3.4.3.5 Implementation

The previous paragraph concluded with categories for which the structure should provide information storage items:

- Activity: Types of human acting, requiring conditions from and influencing conditions in buildings
- Shape: All morphologic properties of a building or a part thereof relevant for analysis
- Structure: Material needed to sustain a building
- Installation: Equipment and services of a building, meant to control indoor climate and use
- Performance: Required performance of the installations in interaction with the structure related to sustaining the activities within a building

The building product models we reviewed use objects that cover various scale levels within the built environment. When dealing with the entire design process, the scale levels in design drawings can vary from urban areas (building blocks, neighborhoods) to the building details level (joints, fasteners). For indoor climate analyses in the early phases, the scale levels can be narrowed down to the entire building on the on hand and the sub-space level on the other as is done in the VABI model. Some models use objects that describe specific parts of the building and other objects that are aggregations or generalizations of multiple objects on a smaller scale. An aggregation is a collection containing the common properties of the parts. Another common notion is the specialization or decomposition of objects; a single object is extended by defining (multiple) more detailed instances of objects on a lower scale level. Usually, more information is added when traversing down the scale levels. The EDM and GBM use the concept of *functional unit* (FU) and *technical solution* (TS). This refers to the paradigm of specifying requirements and finding a material, product or technical principle that fulfills these requirements.

The representation symbols and the building scale levels they represent, should correspond with the manner in which designers reason about buildings. For instance, architects may consider the gross area of a floor with regard to the design brief and divide this space into smaller (office) spaces. In most traditional representation techniques, buildings are made up out of multiple floors. Large buildings may consist of several wings which are again recognizable in the floor-plans. Office spaces form the smallest coherent cells; larger spaces can be divided into multiple fully or partially separated spaces. This scheme is reflected in the entities of building data models. These contain objects that are defined or can be defined to represent building elements on various scale levels.

The IDM is a data model that provides entities that group spaces into *storeys* or *zones*. Most other models start at the space level and define the entire building as a collection of spaces. In some cases the relation between spaces is also taken into consideration as is done in the IDM method. Although there is no functional objection against defining the building as made up out of multiple spaces, designing around organizational models might be facilitated by the possibility to group spaces freely and define zones whose only purpose is to support identification.

There is a need for two base levels: the *building* level and the *space* level. To support grouping and hierarchical floor layout the additional *group* level is required. This level provides grouping and specification of, among others, wings, floors or fire compartments. Individual spaces may be subject to close examination and may be divided into smaller compartments for the purpose of airflow simulation, visualization or programmatic analysis. In order to provide for this, another secondary level is useful. This scale level is the *sub-space* or *section* level that covers any part within a space.

One important characteristic of the Meta drawing model is the fact that groups can contain spaces that already are included in other groups. I.e., spaces can belong to any number of groups. A similar principle applies to spaces and sections. Multiple sections within spaces may overlap without causing problems in the linked applications. We feel this principle is required to prevent developing a prescriptive and restrictive method that frustrates rapid manipulation of shapes and definitions.

The Meta design environment employs objects on four different scale levels. Each level has individual characteristics. In addition, objects on each level can form aggregations of one or more objects on the scale level below. The four basic scale levels are:

- Building: The complete building
- Group: Every part of a building that could be subject to attention

- Space: A, by material surrounded, part of the building, containing no other spaces
- Section: A part of a space, not completely surrounded by material

The novelty in the Meta information structure is that it facilitates building representations with objects differentiated for the five building aspects and that it does this for all four scale levels. When we combine the five building aspects with the four aggregation levels we obtain 20 objects for the building model (Table 11).

Table 11: Overview of the Meta Information Structure

Object category:	*Object-Name:*	*Description:*
Activity		
	Building-Activity	Function of the building: Office building, hospital, library, etc.
	Group-Activity	Any part of a building activity or group of space activities
	Space-Activity	Function of the space: office cell, living room, bathroom, etc.
	Section-Activity	Subdivision of a space activity into one or multiple user activities
Boundary		
	Building-Boundary	All shapes constituting a building
	Group-Boundary	Any part of the building boundary or group of space boundaries: floor, wing
	Space-Boundary	Shape of a space
	Section-Boundary	Subdivision of a space into smaller zones
Element		
	Building-Element	Structural information on a building
	Group-Element	Any group of structural elements
	Space-Element	Elementary wall or floor, bounding a space
	Section-Element	Any part of a space element: opening, component, etc/
Service		
	Building-Service	Climate and installation constraints
	Group-Service	Central installations: heater, chiller, air units, dividers, etc.
	Space-Service	Local installations: radiators, fan-coil units, etc.
	Section-Service	Workplace installations
Performance		
	Building-Performance	Long term, building wide performance
	Group-Performance	Performance related to norms, or structural and service groups
	Space-Performance	Indoor climate of a space: temperature, air velocities
	Section-Performance	Micro climate parameters

If designers would be required to input manually instances of the object needed for a building representation, the structure would have little chance of success. Fortunately, the Meta drawing model with the automated recognition algorithms relieve users of this laborious task. Entities in the drawing are transformed into instances of the corresponding data objects. Structural elements such as walls and floors are generated automatically as well, while users can create groups of spaces by simply drawing an extra line around them. The complete content of the drawing file is considered to represent the whole building (Figure 22). Links to files with performance results are automatically stored in the objects of the performance class. The entire information structure can remain hidden from the users. The implementation and object instances of the data structure need only be brought up when additional control is required.

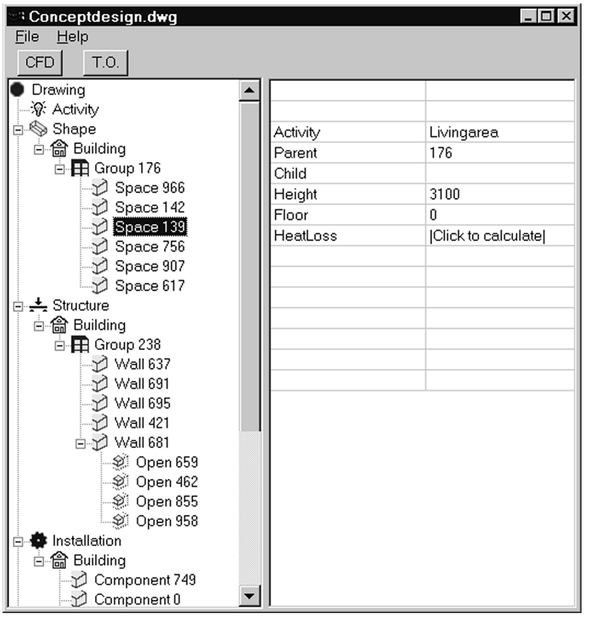

Figure 22: The Meta Information Structure in operation

3.4.3.6 Review

The Meta Information Structure (MIS) has several strong points that are worth mentioning. The tool that was built around the information structure benefited from the organization and the re-usability. The

- The MIS allows all types of grouping on all scale levels and between any number of objects without the restriction that one object can belong to only a single group.
- The loading of the MIS with user data is the result of automated recognition of drawing representation. This allows designers to concentrate on drawing instead of manually and alpha-numerically specifying the digital building model.
- In cases when new scale levels or new design entities are required, the MIS model can be adapted without necessitating redrawing of all design representations.

- The MIS is an unconstrained data structure. In addition, all classes and properties are optional if no value is entered for a specific slot, it will remain at default.
- The MIS does not contain a bias concerning the design process. Information need not be entered in specific order or in prescribed combinations.

Among the weakness of the MIS are some that are related to the dedicated nature of the model. Others are the result of classic Rapid Application Development (RAD) characteristics.

- Integration of the MIS with analyses of other areas of expertise can only be done by building new recognition algorithms. Integration of the MIS with other dedicated data structures is not realistic. Two exceptions to this are functional and structural analysis that could be catered for by the MIS model's *Activity* and *Structure* aspect models.
- In situations where many modifications are made in representation and structure, the integrity of the data, especially the relations between objects can be compromised.
- The automated recognition algorithms require several seconds to execute. This makes it impossible to implement a real-time link between representation and model.

3.5 Compiling Input for Analysis

3.5.1 Thermal analysis

As a first investigation of the possibilities and implications of linking CAD data to analysis input, we set up an experiment that tested some functional elements required to implement this type of link. Since the actual implementation of sending data to the available analysis tools would focus too much attention on technical details in this stage of our research, we adopted an alternate approach. Instead, we build a CAD – Spreadsheet link that was more feasible and could stand model for a more advanced CAD – Temperature Analysis combination. Using a spreadsheet application, we made mock-up data forms (Figure 23) that resembled the input data forms for space geometry present in the temperature analysis tools (Figure 24). Ignoring typographical details, both instances of the forms have identical numerical properties. Especially the topological and functional information included in the data of the forms is of major importance in researching this type of application link.

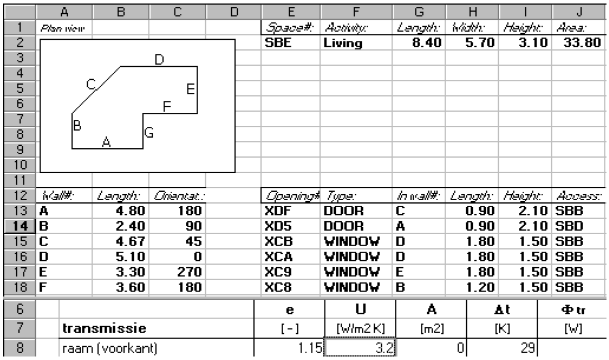

Figure 23: Spreadsheet equivalent geometry input form

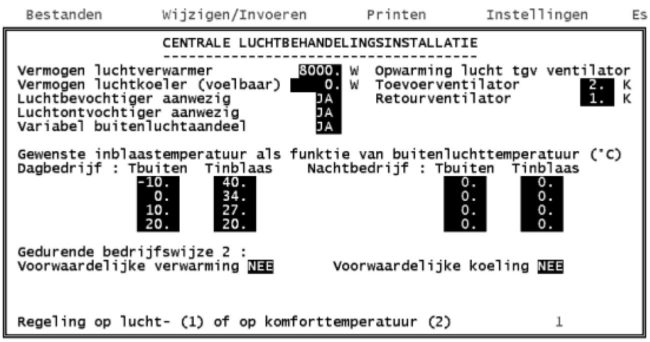

Figure 24: VA114, input form for space geometry

An attempt was made to correspond the data in the Meta database (paragraph 3.4.3) with the information present on the input forms. Were possible, the data in the Meta database was directly transferred to the spreadsheet forms. Occurrence, locations and dimensions of spaces, windows and doors could be displayed without additional transformation by the Meta design environment. However, the forms also require adjacency information, i.e. which opening provides access to which adjacent spaces. Although this information is not instantly accessible in the Meta database, it can be inferred from first order results using straightforward database querying techniques. Since this caused some complications with respect to the agility and consistency of the information flow, an alteration to the Meta database proved desirable. In the original Meta data structure, the procedure to find openings that are present in the enclosure of spaces proved too complicated for stable execution of the application link. In the initial situation, spaces are linked to walls and walls are linked to openings. Emanating from the uncertainty whether all walls are present in the database at the moment of analysis, the possibility existed that openings would be left out of the analysis. To solve this, an additional field was included in the database that linked spaces directly to the openings that surrounded them. This violation of the non-redundancy requirement of database development is amply countered by the benefits with regard to the speed and accuracy of the application.

Thumbnail views of the space plans are presented to assist identification of spaces. Additional handles for spaces and openings are used to aid examination of application consistency. Similar to the procedure when working with the temperature analysis tools, each of the spaces is represented on a separate instance of the data form. In addition to the adjacency information contained within the forms, hyperlinks were added to the fields in order to display space topology with more clarity.

We succeeded in filling the mock-up forms with the required input. Users only have to flag spaces as marked for temperature simulation; the Meta design environment automatically executes the remainder of the process. The success of the experiment proves the feasibility of the theory that the extraction of geometrical and topologic information from a CAD representation to supply temperature analysis with input is possible. In this case, it concerns the thermal simulation tool *VA114*. The information present in representations made with the 'meta' drawing method suffices for this purpose. It can be concluded that the automated recognition algorithms produce data that closely relates to the information needs of the analysis tools. The demonstrations that used the Meta data structure showed that it was able to handle the information flows required by the application link.

Although geometry constitutes only a part of the total amount of information needed for analysis, it is the geometry that causes the most concern in conventional analysis procedures. In conceptual design, geometry changes constantly and manually inputting this information requires experience and is laborious. Special care must be taken when analyzing spaces with complex or curved shapes. The recognition algorithms make assumptions with respect to the convexity of shapes and the amount of bulge on curves. However, most of these problems can be solved with additional effort. Furthermore, the Meta drawing method can be expanded to include links to component databases. This would enable supplemental process support such as extraction of input for windows, doors and wall materials.

After generating the data forms, we decided to link the information in the spreadsheet forms to a steady state heat loss calculation which was implemented in a similar spreadsheet application. The heat loss calculation estimates the amount of heat a space looses through its walls, windows and by ventilation. The essential input for this type of calculation is space, wall and window types and dimensions, space orientation, ventilation and infiltration capacities and outside and inside temperatures. The main difference with a temperature simulation is the fact that the calculation does not take into account the dynamics of temperature transport. Therefore, the calculation indicates the amount of heat transported, not the temperatures that results. In addition to geometry and orientation, the heat loss calculation needs input on material and space occupation. For the sake of the experiment, these properties are kept at common default values. This enabled us to execute the calculation immediately after the data had been transferred.

The calculated heat losses are visualized in the design representation by adding textual annotations in the drawing objects (Figure 25). Similarly, other space characteristic like temperature, humidity and pollution can be fed back to users using color, text or other symbols.

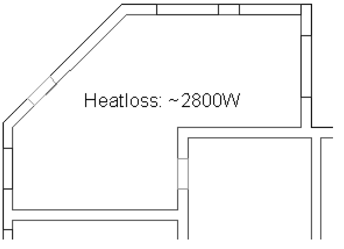

Figure 25: Feedback of data using textual annotation

The implementation of this experiment hinges on two elements, organized design representations and automated recognition algorithms. The ‘meta’ drawing method for producing these organized representations should support a wide variety of building types and design states. The use of the extruded polylines as geometric primitives and a commercial CAD application permits an easy and intuitive input of geometry. Moreover, the recognition algorithm focuses only on spaces and openings. This eliminates the need for procedures for inputting other building elements such as walls and finishing and facilitates the input of a broad scale of space configurations (see paragraph 3.4.2.8).

A drawback is the fact the footprint of a space cannot vary in height. This is related to the use of extruded polylines and prevents definition of angled planes such as in sloped roofs. This hardly proved to be a problem for most designs used in this experiment, since roofs have little influence on subjects like insulation and ventilation. Another inconvenience is the lacking of options to include external libraries such as building components or climate information. This would further reduce the amount of input needed for analysis.

Input of design data is currently restricted to design geometry, space activity and topology. Providing information on installations and occupant circulation is an issue that will be researched during future experiments. There, information obtained from a precedent database will be used to provide designers with suggestions about, for instance, local installation components.

Performance of analysis

The accuracy of analyses returned by VA114 is generally acceptable. The input of information uses a robust implementation. The dialogs provide a constant overview of

the data and coherence checking successfully prevents the input of impossible situations.
Among the tool's drawbacks is the fact that the input of geometry and that of data in general is cumbersome and requires experience. Also, this release had no possibilities to import design data from external sources. Future versions may have an option of this kind.
Another point of attention is the abstraction of geometry often used for this kind of analysis. VA114 offers the possibility to input non-orthogonal spaces, but when takes a closer look at the iteration algorithms, it becomes clear that this increase in complexity might not lead to more accurate results. The view factors calculated for walls and floors to compensate for their thermal interaction are not designed for non-orthogonal, concave spaces. In addition, calculation time increases largely with the use of complex forms.

The heat loss calculation that was used instead of VA114 was build by the Chair of Installations, Delft University of Technology (Schalkoort e.a 1996). The mathematics used in this calculation is straightforward and well known. These types of calculation complete leave out any dynamics in heat transfer and therefore produce only indicative values. Most of the input process is automated by the system of recognition and information transfer. Designers instantly receive feedback on the configuration of spaces with regard to the global heat loss. Although the results are global and should be used for design optimization, the immediate feedback might encourage investigation of different space configurations.

Conclusions
The experiment proves that, starting from the definition of spaces and openings, the geometric input needed to perform a thermal analysis calculation can be generated using a modulated design representation and automated recognition. This is not entirely a new notion. System such as the *Semper* environment and the *Building Design Advisor* (paragraph 3.3.2) demonstrated similar and other effects.

The drawing method to structure representations is flexible enough to support easy input of designs and at the same time it is powerful enough to enable the system to interpret the drawing. The automated recognition algorithms are able to transform the drawing into an organized information structure. This structure meets the geometric data requirements of the analysis tools used in this experiment. Feeding back the analysis results into the representation will complete the 'representation – analysis – feedback' cycle and allows designers to immediately react to the analysis.

3.5.2 Airflow simulation

In order to incorporate the use of airflow simulation within the Meta design environment, we made contact with the building technology division of *Netherlands Organization for Applied Scientific Research* (TNO). A.D. Lemaire implemented a

CFD application for his work as a TNO indoor climate scientist. The WISH3D application is used to simulate a wide range of flow situations (Lemaire 1992, 1996). These vary from straightforward airflow problems within office spaces to highly accurate flow predictions within complex industrial equipment. To enable a wider use of the WISH3D application, Lemaire developed a CFD problem specification language. The CFD modeling language (CML) was based on the format and structure of the Virtual Reality Modeling Language (VRML), a well-known standard for modeling and communicating three-dimensional virtual worlds (Carey e.a. 1997). The familiarity of VRML and the highly structured object hierarchy make it an excellent choice for developing new standards. The clear structure of CML made it possible for third parties to gain insight into the task of specifying CFD problems. In CML, a CFD scene is made up out of many graphical and logical objects. These objects describe the geometrical, thermal and aero dynamical properties of the walls, furniture and building services inside a space. Each of the objects has a distinct format and function that facilitates clear communication between specifying devices and simulation kernel. In many cases, CML allows various degrees of detail in input. Some of these objects can connect to special routines that are present in the kernel's translator. For instance, stating a single temperature for a space will result in the temperature being assigned to all connected objects. This reduces the amount of input. Another highly productive feature is the automated generation of grid. The complex and laborious task of manually specifying the finite element grid can be delegated to the WISH3D autogrid routines.

The structure and object definitions of CML are laid down in documentation. For the purpose of connecting Meta design environment to WISH3D, these documents were made available to us. We then could dedicate our efforts in finding a way to transform the information in the meta project database in to CFD solvable problems.

The first step in the cooperation was to develop a method that could convert a representation following the Meta drawing method into CML data. The goal was to determine the degree of compatibility between the information in both sources. Firstly, the available information from the Meta design representation and the results of automated recognition methods were inventoried and compared to the data needed for CML. As we have seen in paragraph 3.4.2, all space geometry together with the objects inside that space are present in the Meta data structure. It proved possible to transform the coordinate based information found in AutoCAD to CML objects describing geometry. Several automated recognition techniques described in previous paragraphs can be used to translate convex and angled shapes to the orthogonal requirements of structured grid CFD simulation.

The second category consisted of information concerning the elements inside spaces that actively change airspeed or temperatures. In buildings, this constitutes to building services, people and equipment. The Meta HVAC library was matched against the corresponding objects in the CML definition. It turned out that the HVAC library lacked objects for representing temperature and mass sources. Consequently, An object that could be used for this end was added to the library. An additional property was added to the air inlet object. It proved difficult to precisely input air velocity from an airflow rate when the size of the inlet is still unknown. The air velocity property can be used to prescribe velocity in combination with flow direction and have the CFD calculation determine the corresponding airflow rate.

In the next experiment we developed an application extension that would provide automatic translation of spaces into CML standard file sets. This would allow us to make an airflow simulation of every space in a Meta drawing model format building representation.
The extension can be used from within the Meta design environment and provided a set of objects that had two interfaces. One interface connects to the structures and properties of the Meta data model. The other interface conformed to the CML standard and outputs the data to text files. The CML object hierarchy differs from that found in design drawings. The techniques of automated recognition relate openings such as windows and door to their *containers* such as walls and floors. However, the relations between building service elements is also required to correctly define CFD problems. For instance, fan-coil units can contain multiple air inlet and outlets. The relation between those elements needs to be expressed in CML in order to permit accurate calculation of mass balances. In addition, CML defines each object with a logical section and a section that contains geometry. The Meta CML application extension fully automates this transformation.

The implementation of the CML extension to the Meta design environment started with the development of a collection of *container objects* that act as interface for the definition of CML objects. These container objects have similar names, properties and relations as the original CML objects but provide greater accessibility. Next, a *translation module* was developed. This module employs the container objects to make the transition from Meta representation to CML description. The translation module contains a collection of routines that are linked to each of the Meta data structure objects. Each of the routines produces a corresponding set of CML objects. The translation routines specify the properties of the CML objects according to the data found in the Meta representations. The translation module handles occurrence, hierarchy and properties of all new CML objects.

In addition to geometric objects with material properties, several control objects are required to run a CFD simulation. These control objects specify the characteristics of the calculation model employed by the kernel. The CML extension uses a compact user interface to offer designers the possibility to control the most essential simulations settings (Figure 26). One of the available options controls the outdoor temperature. This enables users to simulate different seasons. Both the choice of turbulence model type and grid density can balance accuracy against calculation speed. The interface hides a large amount of META CML system objects that need to be specified in order to run CML solutions. These CFD objects (Figure 27) form a front-end for the more elaborate CML specification language. CML was developed for a broad range of CFD applications such as those used in chemistry, mechanical engineering and building.

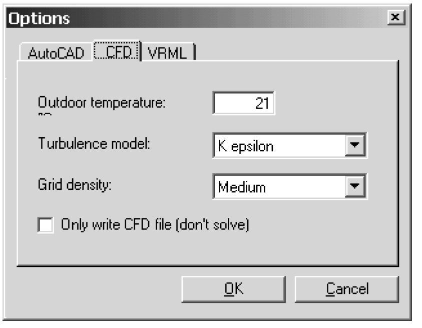

Figure 26: Graphical interface for the META CML extension

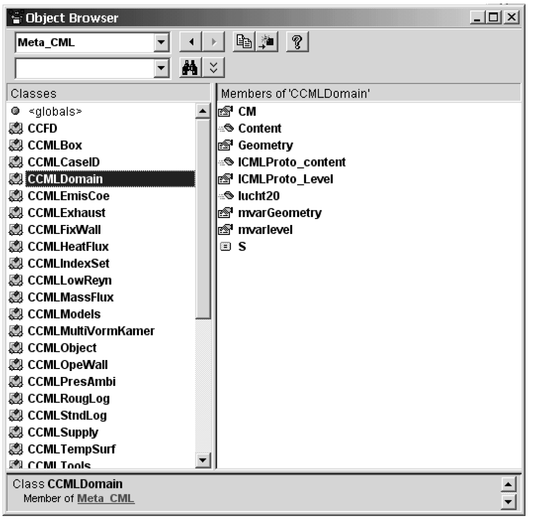

Figure 27: META CML system objects, structure and functions

The division between interface and calculation kernel has several advantages. These already became clear during development of the Meta CML extension. Firstly, it offers greater freedom to implement and distribute CFD simulations across computer networks. Since communication occurs through a set of well-defined files, CFD problem specification can be done on any computer that contains a facility for graphical or textual generation of CML files. The valuable CFD calculation kernel can be kept on secure computers. A single, central supercomputer could solve a large amount of problems with great speed and at the same time allow for easy administration and maintenance.

The division also made the separate development of Meta design environment and WISH3D possible. Both parties could make considerable extensions to the applications as long as they did not break compatibility with the CML definitions. Moreover, the strong hierarchical character of CML made implementing additions to the CML definition straightforward even though these altered the conventions both parties conformed to. However, it required clear communication between the researchers on the precise meaning of some CML entities and the errors in the test cases. This could cause for a trial and error approach to the development of a common standard. However, since the definitions were not changed as a result of the located errors, communication produced only clarity, not confusion.

The conclusion that was drawn from the experience of developing an interface between the Meta design environment and the WISH3D system was twofold. Firstly, it proved that is was possible to build the input for a CFD simulation entirely from the data in a CAD environment. Inevitably, one uses defaults and libraries in this type of conversion, however, this did not degrade the performance of the simulation below the point were it is usable in architecture. The speed with which the CFD input could be assembled provided another advantage in this respect. The second conclusion concerned the data objects in both environments. Although it proved possible to translate the data from the architectural design oriented data structure into the rigid notation of CFD problem specification, this was not without a cost. The building designs needed to be fitted with specifics regarding installation and climate control. This was needed in order to bias the CFD simulation with sufficient sources to converge to a solution. Automatically deducting this information from indoor climate goals such as ventilation rates and temperature limits turned out to be instable. This reaffirmed our notion that a conceptual design for both building and installation is required in order to provide feedback on the relation of these two aspects of architectural design. In many cases the previously defined objects for HVAC units such as air inlets and convectors were reused in the process of assembling new problems. It sufficed to simply place these objects into the design description.

3.5.3 The ORCA project

The building simulation tool VA114 is an excellent tool for indoor climate specialists and building service designers to perform temperature simulations of a theoretical space in a building (paragraph 2.2.2). In order to enable application of the tool in less specialized domains, the organization that releases VA114, the VABI, looked for a way of modifying the program’s interface. As part of an ongoing cooperation between Delft University and the VABI, a thesis project by E. van Dijk within the Meta Design Environment Research Laboratory (Dijk e.a. 2002, Hartog e.a. 2002). The ORCA project concentrated on the notion that it should be possible to leave out much of the original VA114 specific input and replace other input items with more user-friendly controls. The objective of van Dijk’s project was to catalogue and categorize VA114 input, determine an approach to connect to architectural design and examine the possibilities to use Meta design tools in the development of a new interface.

All VA114 input item are screened whether or not they are comprehensible for architects. A second criterion is the degree of influence the input item has on the indoor comfort of the space. Flow charts of VA114 input are made to determine dependability and sequence of input (Figure 28). An example of the findings is the ability to describe up to 4 spaces of a building simultaneously in VA114. This option is to research the interaction between two spaces and is not likely to be used in early design. When disabled this greatly improved legibly of the input screens.

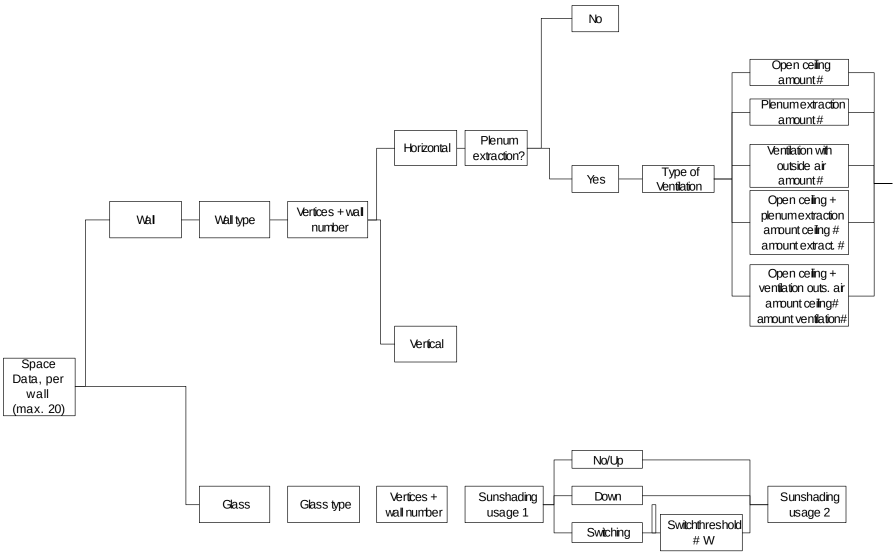

Figure 28: Small section of the VA114 input flowchart

A large portion of the input can be replaced with default values. In addition to determining which fields are kept at default, it is imperative that the values of the default fields are determined with care in order not to bias the calculation model. It is also possible that the value of a default field cannot be directly influenced by the user but at the same time are dependent on the values of other input fields. Sets of interrelated default values are called clusters. Summarizing we find three different types of input:

- Direct input: values are explicitly determined by users
- Default input: values are fixed, and cannot be changed by users
- Implicit input: input values can be changed but (multiple) original input fields are replaced by a single control element. These can consist of library entries, default cluster or references to earlier simulations.

In some cases input fields are renamed to more clearly explain the meaning of input items to architects. To start with, a categorization of input was made. Following the five columns of the Meta Information Structure (paragraph 3.4.3) The new VA114 interface should provide recognition of the following categories:

- General Building data
- Space geometry
- Applied materials
- Building service configuration
- Building use / internal cooling- and heat-load

The *Orca* program was developed as the final part of the research project. A proposal for the interface layout of the new tools was developed first. Several modifications lead to the implementation of the interface for the purpose of making the connection with the temperature overheating simulation. The proposal for the new interface constitutes making a single main window with several subwindows. The subwindows can be controlled through two button bars on the left-hand side and the top of the windows. The bars contain button that call input screen for the input categories mentioned earlier. The top bar contains four buttons for bringing up the calculated output. Output can be given on

- Daily temperatures
- Yearly temperatures
- Weighted temperatures
- Energy use

The input for space geometry has three options to select space types. VA114 does not support an arbitrary number of walls. Therefore, the three configurations are Rectangular, L-shaped and Angled wall. Additional configurations are possible as long as they conform to VA114 requirements. The dimensions are input with length, width and height. In case of non-rectangular shapes two corner points are given. A preview of the space as constructed by the input is available. A separate element determines the north side of the space to enable control over solar orientation (Figure 29).

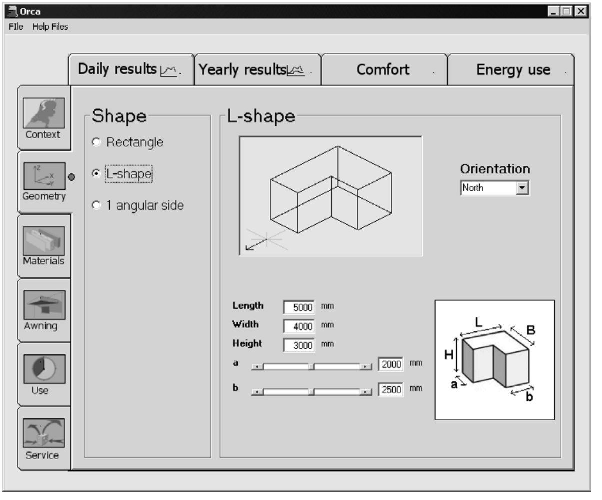

Figure 29: Input of space geometry

Linking to geometry input from other sources such as CAD applications could be a future extension. Other parts of the Meta Design Environment contain examples of such connections. It proved too much labor to both implement a CAD link and develop a new interface. Paragraph 3.4.2.6 showed how CAD applications could be linked to analysis input.

The materialization of the space walls occurs in another sub-window. This sub-window has eight options to correspond with the different walls of the space. The currently selected wall is highlighted in the preview window. For each wall and floor can be specified whether it represents an interior or exterior separation. The wall's material can be selected from a list. An additional window controls the input of holes in the spaces. Openings such as windows and doors can be editing by stating their dimensions. In the case of windows, sun shading can be switched rolled up, down or at intervals (Figure 30).

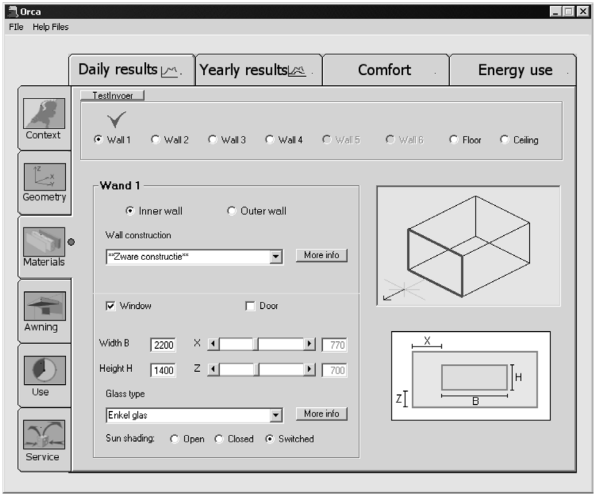

Figure 30: Input of wall specifications

The sub-window that configures building services contains only the most fundamental options that determine the active control over the indoor climate. Two types of ventilation are possible; Natural or Mechanical. The option for mechanically ventilated spaces brings up an additional element for specifying the airflow rate. Heating and cooling can be switched ‘on’ or ‘off’. The capacities are controlled by a single quantity that determines the numbers of Watts installed per square meter space. Users can choose to deliver and extract heat by supplying air or by controlling the temperature of a surface. By default the heating and cooling capacities are set to infinite. This enables a first simulation run without much user intervention. After the calculation, the annual energy use for heating and chilling provides a reasonable ‘first guess’ for the capacities to install. A descriptor displays to the specific building service systems that are applicable within the chosen combination of controls (Figure 31).

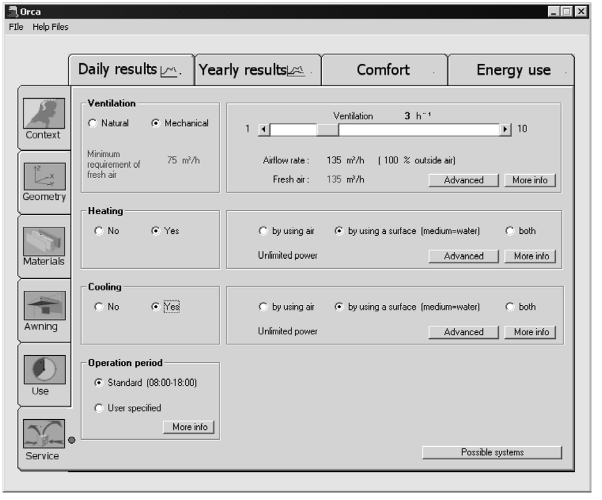

Figure 31: Building Service configuration

After the users have finished specifying their design in ORCA, the simulation can start. The interface writes the data from the input elements to a set of computer files. The content of these files is described in more detail in paragraph 2.2.2.2. This procedure is similar to the way the original VA114 interface interacts with the simulation kernel. The interface and kernel communicate through the use of several ASCII compatible files. This division between input and calculation allows development of a more robust application and enables separate modifications of the application parts. It also helps to shift the application area of the tools towards new domains. The order and manner of input as well as the definitions and terms used can be altered and suited to fit the knowledge and interests of designers. Feedback of the calculation results occurs in a similar manner. The kernel writes the temperatures and powers in several output files. The interfaces read these results and offer the tools to display temperatures and energy use to the users. ORCA contains separate sub-windows for temperature indoor comfort and energy use.

The sub-window for feedback of temperatures holds two diagrams. The top diagram is used to display temperature profiles of the simulated space for a period of a day or a year. The lower diagram displays temperature profiles calculated with previous simulation runs or the temperature characteristics of other projects. This option enables users to graphically review the thermal behavior of the design. The graph supports rapid identification of the number of overheating hours during the hottest day or the entire year. The dual graph display enables users to compare pairs of results and discovers trends or turning points related to or stemming from design actions. An extra button offers the possibility to save the diagram as a bitmap file in order to include the simulation results in reports. The Energy feedback sub-window presents the amount of energy needed to heat and cool the space, summed up for the period of an entire year. Again the results of previous runs can be viewed to determine the effects of design changes (Figure 32).

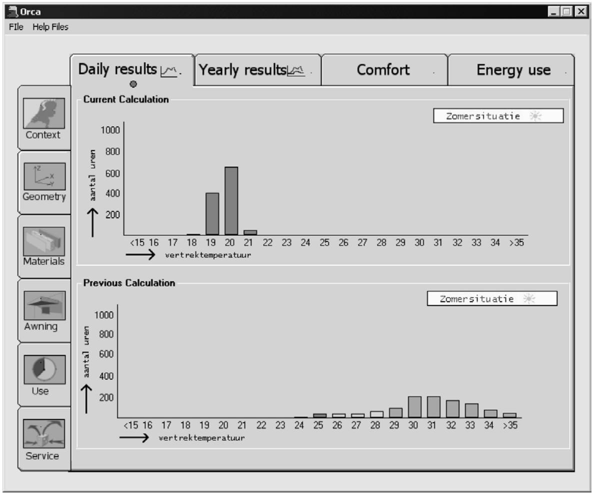

Figure 32: Feedback of simulation results

An important issue for the accuracy of temperature simulations is the correct configuration sunshading devices. The calculation engine of ORCA, VA114, contains options to choose different types of shading. The user interface element that controls shading type, is difficult to recognize when users are not familiar with the tool. The ORCA application has reserved a more prominent place for the interface elements that control sunshading. Since much of the input of geometry and material properties is automated, this leaves space to deal with some special issues. Users can also access the explanation of sunshading devices in the online ORCA help functions. It provides a short overview of the sunshading options as well as the manner in which the simulation engine interpret these options. It also describes the benefits and drawbacks of each option in terms of architecture and indoor climate. This example shows how ORCA deals with the subject of sunshading that has caused for many doubts in the development of architectural design tools. ORCA offers a few interface items that are easy to interpret. Users can quickly investigate the consequences on cooling loads or indoor temperatures by alternately selecting and simulating with no shading, permanent shading or automated shading at different switch values.

The ORCA tool is currently being used in the educational program of the Delft University. Students that graduate at the chair of building service can use the tool to receive feedback on the indoor climatic properties of their design. As the tool is always available and can be used without the aid of lecturers, students can perform temperature analysis when indoor climate questions arise.

The calculation only takes a few seconds on an ordinary computer. As a result, users can execute many simulation runs in a short length of time. This is useful when examining the behavior of a building in relation to, for instance, temperatures or energy use. Each simulation feedback can give rise to another analysis where a specific design property can be changed and immediately evaluated with regard to the climate behavior of their design. This enables users to quickly determine the relation between for instance, material use and extreme temperatures. The ability to use the feedback of simulation results as a stimulation to alter the design's passive or active feature is greatly appreciated as it stimulates design optimization.

The ORCA project showed that it is possible to use a specialist application in the development of a tool for the education of designers. The abstraction process depended on the definition of conceptual systems. These abstracted instances of detailed building service issues bridged the gap between architectural design and building service design and operation. The conceptual systems in ORCA cover a range of detailed service information with a single user interface item. For instance, users can analyze heating and cooling situations by selecting a conceptual mechanism for the delivery or extraction of heat. This speeds up the simulation process. The results of these experiments have been promising enough to motivate us into continuing the development of the ORCA tool

3.6 Findings

Encountered issues

The design process and climate analysis have contradicting information characteristics. Architectural design has a focus on defining occupant activities and the shapes enclosing these activities. The morphologic definition can shift from the entire building to individual spaces and vice versa, depending on the design method and stage. Specialized analysis tools foremost require material and installation properties. In some cases, they use special types of indicators or descriptors which are only familiar to design specialists. Most simulation tools need information on the installation components contained within a space or building such as specific values on capacity, output-velocity and energy consumption. Architects, especially during conceptual design, are not concerned with issues like installations. These differences cause for information exchange problems when attempting to connect both types of information in an integrated design-analysis system. Although much of the information conflict can be prevented by analyzing in a later design stage, at the point where designs contain sufficient information for analysis, there is hardly any time or space left to incorporate the analysis results into the design (Figure 34).

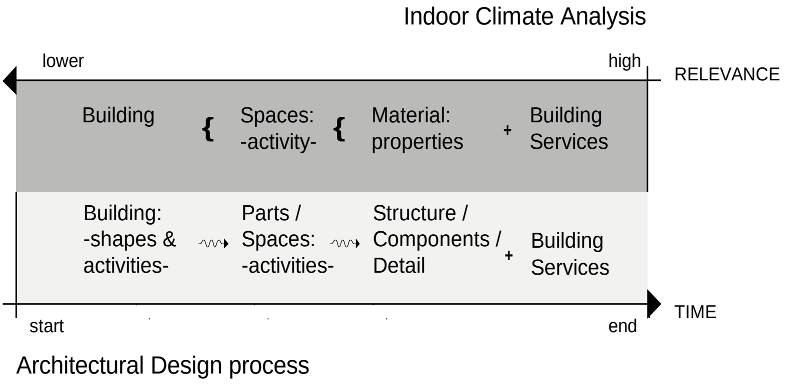

Figure 33: Analysis input relevance vs. Design information chronology

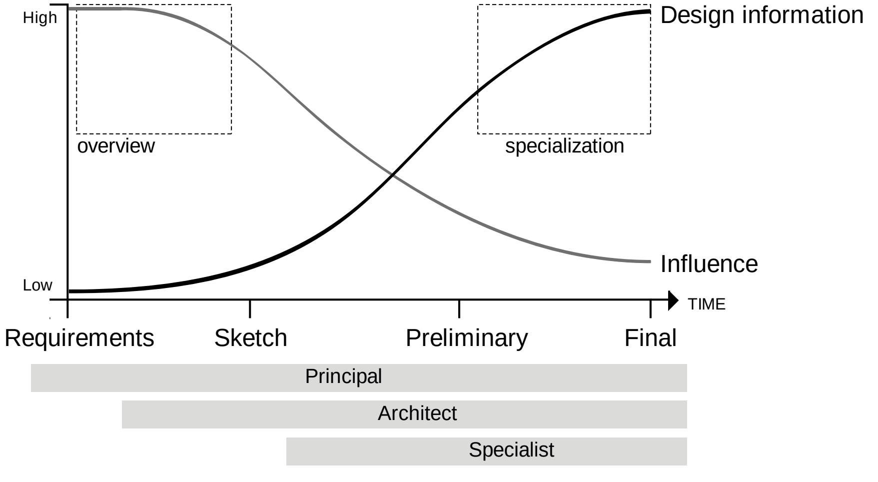

Figure 34: The Influence / Information contradiction

Another type of conflict arises from the multiple ways of viewing a single building object. Architects are interested in the shape and flexibility of structural elements such as walls and floors, while analysis tools use generalized geometry but require specific material properties such as density, conductivity and finishing. When used in analysis, the architectural representation lacks these material properties or uses defaults, while at the same time the shapes may be to complex to be used without abstraction in analysis.

Integrated systems

In recent years, many computer tools were developed that aimed at aiding designers with complex tasks in early design. Unlike CAD applications that only record graphical data, these tools are built around information models that process design information into more interpreted statements. By integrating domain knowledge of the field of architecture into these tools, some evolved into expert systems that promised to aid solving design problems to a higher degree. However, these tools failed to force a breakthrough in traditional designing. One of the problem areas might be the limited scope of these systems. This restriction obliges designers to operate different systems for e.g. offices and schools. Another reason for the lack in acceptance is the large amount of information that needs to be input as well as the knowledge and experience that is required in using expert systems.

Still, design tools can provide valuable information in early stages. Especially when designers lack thorough knowledge on indoor climate and are not assisted by design specialists, computerized tools in the design process can prove valuable. For instance, using environments wherein design information provided by architects and calculation models are integrated, designers can be enabled to make use of analyses results without too much effort. This integration cannot remain merely at the level of mathematical coupling. True integration starts when domain knowledge is included in the development of these programs. That knowledge can then be used to perform *translations* and *inferences* between information states. Although the knowledge contained in automated translation algorithms will remain at a basic or rather simplistic level, the improvements that can be achieved with these results are far from basic. Taking into account that decisions are made without any analysis of the consequences because the use of tools is too time-consuming, the benefits of performing even one analysis can be extensive.

Representations

From the viewpoint of the design representation, we can distinguish three types of input. First, there is data present in the design representation or in any of the related documents (design briefs, regulations, etc.). Examples of direct design data are coordinates and functions. Secondly, there is information that can be acquired indirectly. Two examples of indirect data are the use of defaults and automatic recognition. Default values are sets of general data can apply in a number of analysis situations. Data obtained from automatic recognition can have a stronger link with the analysis situation. It refers to data that is deducted from the design representation for the intended purpose of analysis. An example is the retrieval of relations between building elements (paragraph 3.4). Lastly, there is information that is not present in the design and cannot be recognized automatically. If the designers are unable or unwilling to provide this information, it can be suggested from an alternative source such as precedents.

Ideally, the larger part of the analysis input can be found in the design representation. Some obligatory information can also be obtained from default values that are common for the type of building or situation under analysis. Although this is useful in cases where analysis input is incomplete, it can also degrade the quality of the analysis results. Automatic recognition is often used to simplify user input. Software developers can employ it to prevent user from inputting information twice and to make data conversions more robust. Precedents are useful when a design is a special case. The input data contained within the precedent database can be closely adjusted to analysis of these special cases (Figure 35).

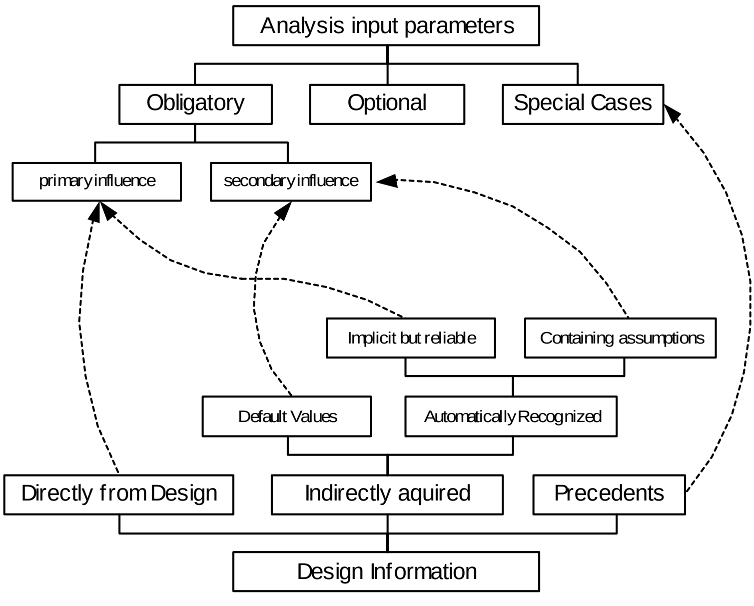

Figure 35: Priority of parameters combined with information availability

Automated recognition has proved valuable in extracting and converting information from an architectural based design representation into a more specialized and structured information model. They allow architects to design by drawing in a familiar manner while algorithms recognize key objects from the drawing, interpret them according to both architectural and specialist knowledge and translate the information into any format. At present we are able to recognize topology of a design, implicit elements such as walls and hierarchy of building elements out of shapes in 2D or 2.5D drawings. We demonstrated a working model for both Computational Fluid Dynamics and temperature simulations. This model processed geometry present in a CAD document structured according to the Meta Drawing Model into an instance of the Meta Information Structure (MIS). The MIS database was then translated through interface modules to represent the geometry parts of the input files of the analysis tools.

In essence, automated recognition is powerful enough to go beyond that and could find space boundaries out of its enclosing elements and group partial walls into larger floor spanning and load bearing structures. These possibilities free architects from manually inputting these kinds of objects and relations into the product data model. However, for a correct execution of design analysis in the early stages, a certain amount of conceptual building service information is necessary. Temperature and airflow analysis require information that enables the tools to make simulations where the influence of building services in taken into account on a conceptual level. This type of conceptual service information is not present in every architectural design process. The user-friendly manner in which the ORCA program deals with this type of service information is promising. Students of architecture at Delft University of Technology appreciated the manner ORCA introduces the service concepts of heating, cooling and ventilating. The support in providing this type of information can be improved further when we introduce information derived from design precedents into the Meta Design environment.

4 Precedents in indoor climate analysis

This chapter continues the research for a system that brings indoor climate analysis closer to architecture. In the research outline, the question was raised how to handle a mismatch in information between design representations and analysis input. We researched ways of overcoming this information gap. The introduction of additional information is considered in the context of architectural design. This places constraints on the presentation and the amount of information.

4.1 Introduction

Chapter 2 brought up two facts regarding indoor climate analysis. Two important conclusions from the simulation tool review are:

1) Temperature Overheating Risk Assessment (TORA): In order to perform indoor climate performance predictions with TORA for the purpose of facilitating the architectural design process, TORA needs to be supplied with conceptual information on the various parts of the building services.
2) CFD simulation: When using CFD simulation in architectural design, the intrinsic, detailed CFD data objects need to be represented by (conceptualized) equivalents that can be integrated with the design representation.

In practice, most conceptual designs will contain little if any information on building services or service concepts. In some cases, the design brief might contain requirements as to the desired condition regarding temperature and air in the building. The reason for the absence of building service ideas must be sought in the limited knowledge that architects have on this subject as well as the low popularity of building services and indoor climate in the building community. If we want to perform simulations that provide global assessments of actual designs, we should introduce this information in the architectural design process.

One approach for this is the default or ad hoc method that defines standard solutions that are preset into the simulation input. The defaults involve typical solutions for specialized parts of the input data (Kalay e.a. 1992). In some cases, it is difficult to use one single value as the typical solution for all situations. Where several defaults may apply, a choice can be made on the basis of a design property such as building use or climate typology. The system determines which value best corresponds with the design status at hand. In some cases, multiple default values are collected into sets that address multiple input fields with a single choice. This approach has the benefit of enabling simulation without user intervention on the building service specification. Some systems allow users to modify one or more values of default sets. This enables

users to customize the focus of the general purpose systems to fit specific requirements of user's environment.
The default values approach suffers from one important drawback. In cases where each piece of missing information is replaced by defaults, it can easily lead to separation of analysis outcome and the design process requirements. Following only the default approach suffices in a very limited amount of design system methods. Using a combination of default information and data emanating from user interface elements has a higher chance of resulting in relevant design analysis.

Another approach concentrates on employing conceptual systems. Conceptual systems are sets of information that are identifiable by labels and descriptions to aid users in choosing a relevant set for their design. In a way, they are the building service equivalents of the architectural sketch. The sets refer to specific input values much in the same way as default sets do. An example of conceptual systems is the choice between several general types of building service systems. User can choose which system to use when performing simulations and have greater control over the content of the simulation input than is the case in the default approach.

Providing information from a reliable and often-used source might aid designers during the treatment of building service concepts. One such an unobtrusive source of information is precedents and cases (Schmitt 1992, 1994a, e.a. 1994b, e.a. 1997, Oxman e.a. 1996, Domeshek e.a. 1997). Drawings and documents from precedents or previous building projects might provide information on building services and indoor climate performance. In conceptual design, precedents provide examples of complete solutions with known behavior and performance.
In order to build an approach around precedent information, a definition of precedent designs is helpful. We define precedents as representations of building projects that have been designed, built and reviewed perform well according to the design objectives. These representations can be explored to uncover design solutions to common or specific problems.

One issue that arises when information is introduced to the design process is that, regardless the familiarity with the source of information, designers can react in different ways. If they are confronted with the fact that their design will involve new features, two things can happen. Designers might choose to investigate these aspects using the possibilities of the application. However, they can also refuse to continue the use of the tool on account of being irrelevant to their design process. In the case of designing building services for indoor comfort this risk is not imaginary since most architects have little knowledge or affinity of this subject. It makes sense to identify this risk in process of developing a Meta Design environment and to look for improved ways of providing support during these critical phases.
Simplifying and supporting the new information might counter the problem. Structured and comprehensive graphical user interfaces make an appeal to the user's knowledge of the subject and can have an educating effect in case of unfamiliarity. Conceptual systems can be used in combination with a user-friendly interface such as

the one used in ORCA. Here descriptions and pictures that explain the content and context accompany the interface elements that address the conceptual systems.

4.2 Precedents in design

4.2.1 Introduction to Case Based Reasoning

4.2.1.1 History

In the late 1970s several researchers started working on methods based on the idea that humans use experience and examples to solve problems (Kolodner 1993). Psychological research indicated that in many professions experts re-used old projects when being confronted with new problems. Also in everyday life, people seemed to recall previous situations and the solutions they constructed in order to quickly cope with new situations. This led to the hypothesis that supporting difficult tasks through computer tools that were designed around the notion of *Case Based Reasoning* (CBR) (Heylighen 2000). CBR tools use a library of precedents to tackle new problems. CBR tools suffer less from problems encountered in knowledge-based approaches such as knowledge deficiencies since they start to reason from an already available solution for a similar problem. This opens possibilities to develop mechanisms that find dissimilarities between the new problem and the old situation and to adapt the precedent accordingly. When the adaptations remain small enough, the knowledge that needs to be employed can concern isolated segments of the design process. This is much easier than constructing a holistic knowledge model for the entire design process.

4.2.1.2 Case matching

Researchers at Yale University (Schank 1982) were among the first to start experimenting with computer tools that made use of precedents and examples to support users with the experience of the past. Much of this experience was contained in the documentation of the *cases*. The first experiments focused mainly on efficiently and effectively searching in databases of cases (Zimring e.a. 1995). In order to search for cases accurately, users needed to specify their problems carefully and in some detail. The programs translated those specifications into database search criteria which would guarantee only relevant and closely related cases were retrieved (Moore e.a. 1999). The retrieved cases were presented to users in a manner that made identification of distinctive and useful design elements easy. Designers could re-use those elements in new design situations. Interestingly, the use of cases had additional benefits. One of these is related to situations where much is still unknown about the details of design assignments, possible pitfalls and requirements that need to be met. These *ill-defined problems* must be explored in more depth before designers can start to develop solutions. This process is known as *problem elaboration* (Kühn e.a 1993). It turned out that tools that provided cases together with the initial and augmented problem definitions were great help during the process of problem elaboration. Cases can also provide sources of alternative design solutions. Although the process of solution generation remains a human task, browsing through a series of designs that dealt with similar problems can stimulate creativity and provides inspiration to try new solutions.

4.2.1.3 Case Adaptation

Subsequent developments introduced the idea of *case adaptation*. In case adaptation, the cases were slightly modified on parameters to make them fit for the new problems (Hua e.a. 1996, Faltings 1997). At first, adaptation was done manually. However, when more models of the case knowledge domains became available, case based reasoning tools started to involve procedures that automatically attempted to adapt a retrieved case to the input specifications (Flemming 1994, Smith e.a. 1995). In the case of architecture, domain models were not readily available for incorporation into computer programs. Still, several institutes developed systems around this approach, some of which will be discussed in paragraph 4.2.2. Closely related to the topic of adaptation is *case evaluation*. In most design areas, an adaptation does not necessarily mean an improvement of design performance. In many cases, the result of one or more case adaptations must be evaluated using simulation or analysis tools (Schmidt-Beltz e.a. 1996). For the area of indoor climate, simulation tools are readily available as discussed in chapter 2. Although most building models used by case based design tools will not be entirely compatible with the data structures of the simulation tools, transferring design representations of case reasoning tools to these tools can be done with similar techniques as were presented in chapter 3.

4.2.1.4 Research questions

Around the same time, the developments around cases started to raise questions as to what degree the adaptation process could change designs. At some point, adapting designs can destroy crucial structures and arrangements. Not surprisingly, most case based design tools with adaptation employed domain models that were accompanied by constraints and general rules that guarded consistency of the design. However, it turned out to be extremely difficult to maintain coherence in design cases where several aspects are manipulated. For instance, increasing window sizes with as little as 3 percent could improve daylighting considerably but it also might render the installed cooling system obsolete (Wijsman 1996). Changing to another building service system is a modification that will entail a (large) number of design moves, each of which with potential consequences. As the chance of using case based tools in practice became higher, other fundamental questions regarding the use of cases became apparent. One question was whether or not copyright violations laws were in place when an architect or designer would re-use an adapted instance of an existing design. If so, how much of a design could one re-use or copy without infringing copyrights. Another issue connected to CBR is that, with regard to knowledge, the system keeps operating within the same, closed, solution space. Despite further research, much of these issues remain.

Confusingly, the term Case Based Reasoning is used in several situations. It is used to indicate the phenomenon that humans use examples and previous solutions when reasoning about newly faced problems. It is also used to describe computer tools that use databases of cases in supporting users to solve problems or to complete difficult tasks. In addition, the computers tools that use CBR can take different approaches. Some tools aim at supporting and enhancing CBR by humans through the presentation of history only. Other tools provide whole or partial solutions in the form of automatically adapted cases. The degree of adaptation depends on many factors such as the strength of the domain knowledge model, the application area or the users preferences.

4.2.2 Case based reasoning in architecture

The use of cases in human reasoning during daily and professional tasks has been researched. Ross (Ross 1989) reported that people learning tasks often use cases. Professionals involved in problem assessments relied heavily on concrete instances of past projects (Lancaster e.a. 1988, Kopeikina e.a. 1988). In most cases, researchers also reported an increase of performance on case supported tasks opposed to reasoning and designing from scratch. However, for some reason the use of case based tools in architectural design practice remained limited. Most examples concern cases were curiosity or demonstrations were involved. An explanation for this reluctance could be sought in the amount of labor that must be put into the maintenance of the case-base. This database must be expanded in order to improve the relevance of the design support in relation to the architect’s style. This means that users have to collect and manage design drawing, reports from specialists and analysis results in consistent manner during the entire design process. Even when a design office decides to invest a considerable amount of time and money in this task, it ends up with a case-base that contains only private projects and isolates them from external influences.
This can be solved through a series of additional techniques such as connecting case-bases through the Internet and determining a common standard for case representation, both of which are not available at present. Although precedent based design support is still in its infancy, the type of information it can provide for the design process remains promising.

To determine more closely if and how CBR is applied in architecture, we reviewed some of the leading CBR related researches and initiatives. The instances described are all at the stage of academic research and background information was readily available. Interesting to see is whether the systems connect to (indoor climate) analysis in a way similar to the approach we have chosen. Also, the CBR tools were reviewed with regard to the possibilities of the geometric input.

Archie is a system developed in a research project of Yale University (Domeshek e.a. 1997). This research was aimed at exploring the possibilities of cased based design aid (CBDA) in architecture. It consists of a system that collects a number of design cases represented by design stories about prominent design elements. Pictures and plans accompany the stories of the design under investigation. A distinctive feature is the insightful and practical query structure that allows users to search for specific cases. The cases are linked through an index of problems, stories and responses that refer from cases to typical design problems and probable design responses. Although the system does not contain modules for design input or plan manipulation, the potential impact on design methods is great. The ability to include any type of story about any type of design and their aspects reduces the chance of users becoming disappointed with the approach when their design interests cannot be incorporated into the system.

The *CADRE* system was developed by the Swiss Federal Institute of Technology in collaboration with several partners. CADRE attempts to bring the concept of Case based design into building design (Hua e.a. 1996). Cases are represented in CAD tools along with models of the design behavior and function through constraints. The constraints guard the design variables that might be changed during the process of case adaptation. The system supports two types of adaptation: dimensional adaptation and topological adaptation. After a relevant design case is selected, much of the adaptation process can be automated through the use of constraint satisfaction techniques that employ advanced computational techniques. The satisfaction techniques can adapt designs to a large degree since most of the design representation can be described using constraints. The model largely depends on a determinate structure and therefore the incorporation of new design aspects and methods will take a considerable amount of effort.

SEED is a software environment for the early design phases that was developed at Carnegie Mellon University (Flemming 1994, e.a. 1995, Snyder e.a. 1995). The objective of the project is to support the design process by allowing rapid generation of design representation and alternatives. This might imply a number of computational techniques, however, support through the application of cases is one of the major focal points of this environment. The system contains several modules that focus on aspects such as programmatic requirements, layout and configuration in relation to constraint satisfaction. SEED uses a common object model to support communication between the application modules and to represent designs in a structured and hierarchical manner. The object model makes use of the partition into design units, functional units and specification units. Users can input design problems by stating functional requirements in a basic form: areas, loads, temperatures etc. the functional units that correspond provide typical solutions for sets of design requirements. Individual or sets of functional units are replaced by specification units which represent materials and building products. These are configured and interrelated during the configuration process.

A simple interface provides the input of design programs and plan layouts. The retrieval of cases is done on the basis of attribute-value matching. Case adaptation can refine initial design problems with more specified functional constructs or allow users to alter selected cases in the same manner as is done with new designs in the layout of configuration modules. Although the complexity of designs remains an issue, the modeling language and communication devices have the potential of treating more difficult cases (Schmitt e.a. 1997).

The *FABEL* system was built during a large project by several German research institutes (Voss 1997). It aimed to produce a system that supported architectural design. Individual researchers developed tools in the shape of individual modules. These modules are able to cooperate in order to form a larger, structured whole. The emphasis in this project was on promising techniques such as case-based reasoning and knowledge modeling.

The FABEL system comprises a large number of tools, object models, process models and interfaces. It deals with the techniques of case indexing, case matching or retrieval, case adaptation, automated assessments, and even solution generation. At the start of the project, much was still unknown with regards to the precise requirements and structure of design aspects such as building service layout and structural analysis. Therefore, earlier stages of the project focused on exploratory knowledge acquisition and encoding.

The researchers have chosen to avoid developing a holistic system that supported multiple design approaches through an integrated model of different case base reasoning techniques and approaches. The reason they gave was that some design approaches may have conflicting requirement with regard to implementation. Instead of anxiously integrating these, they developed separate tools around fundamentally different techniques. Each of the tools has a specific purpose in the diverse context of architectural design. The combination of the entire range of tools should form a network that is able to comply with the broad variety of design approaches and questions.

FABEL contains a central case base which supplies the individual tools with case representations. Case representations consist of collections of design components that will be interpreted in different ways by the various tools. Case matching is done on the basis of attribute-values comparisons. Another type of matching algorithm uses pattern-matching techniques that were adapted from pattern recognition theory. A third type of match is done on the basis of *gestalts* or skeletonized gestalts called *sketches*. These gestalts or sketches allow for a more robust and reliable comparison of the query against the available cases. The tools that implement the case adaptation part of case based reasoning make strong use of topology and geometrical parameters and constraints. The tools check the new variants for validity and make, if needed, further adaptations.

The techniques and tools developed during and used in the project include, among many others, ARMILLA: a model for HVAC layout, A4: an object model for architectural representation, the use of gestalts, keywords and pixel representations for case matching of HVAC layout plans and DOM: a tool for HVAC-layout verification.

4.2.3 Review and Discussion

The Archie system showed that linking precedents with general problem structures or common design aspects is a powerful combination. On the one hand this closely relates to the typical design problems that architects are faced with. On the other, it can quickly display common solutions for a wide range of cases. The link between problem structure and case is done automatically, but the classification of cases must be done manually.
SEED has an advanced case matching procedure. Stemming from the ability to specify early designs for the various types of support offered by SEED, users have the possibility to specify all kinds of design properties and constraints. This representation is linked to an elaborate case matching algorithm that can locate matching case with great precision. This feature enables the tool to deal with large case-bases
An interesting feature of the FABEL system is the Knowledge exploration module that has the potential to reveal new design facts. They can concern the way in which designers interact with these types of systems and the manner in which design specialists operate in a particular design assignment.

Most CBR tools use matching algorithms that are built around attribute searching systems. Some of these contain provisions for automatic definition of value ranges (bandwidths) or enable users to elaborate the search through the use of thesauruses. The experiences from the reviewed systems made clear that case matching techniques that employ parameters or attribute-value pairs searching can achieve results beyond the reach of any human looking through collections of case plans (Domeshek e.a. 1997). Even the handling of textual parameters in the form of keywords or design descriptions has, with the use of thesauruses and full text searches produced promising results. However, case matching on the basis of *problem descriptions* or *design objectives* is still problematic. The reason for this is that many case cased reasoning aimed at architectural design can not successfully decompose problem statements or programmatic requirements into specific design objects and properties that allow for mathematical or textual matching. This is not surprising since many other computational areas concerned with architectural design have failed to formalize the knowledge that is needed to structure and elaborate on architectural design problems.

A similar problem arises in case adaptation. Although designing by adapting cases fundamentally oversteps the process of problem decomposition, it usually requires another form of architectural knowledge to guide the adaptation process (Flemming e.a. 1997). This process typically consists of a generation stage and an evaluation stage (Faltings 1997). As we have seen in chapter 2, the design evaluation process is rather well researched and formalized and can easily be employed in case based reasoning.
Design generation concentrates on finding dissimilarities between case and design specification (Schmitt e.a. 1997). When these differences have been collected, it infers the operators needed to adapt the case to the design specifications. An example of this functionality is the detection of a higher active load-bearing requirement in the design specification and the consequent adaptation of the structural and formal properties of

the appropriate building elements. The knowledge needed for this type of mechanisms entails two problems. The first is the difficulty in modeling the design knowledge needed for the design alternative generation. It is extremely difficult to formally connect the possible causes of design conflicts with clear actions that have the effect of solving them. In the area of indoor climate it is almost impossible to precisely predict indoor comfort problems from small dissimilarities between design specifications and a case. It is even harder to model the knowledge needed to design or adapt the building service systems to the point of compliance. For instance, changing capacities might involve employing a complete different system. This brings about the second problem in knowledge modeling. When two simultaneous design modifications conflict with each other, the system requires higher knowledge to resolve the problem. In case of several dozens of design adaptations, this quickly leads to redoing the entire design process.

Another approach to adaptation is to have the system exhaustively generate every design configuration by varying all known parameters. In most design situations, this will cause for a combinatorial explosion even with relatively small projects. On the other hand, this approach requires little domain knowledge in order to produce alternatives. The problem of domain knowledge re-arises in another form when the design alternatives are validated using constraint satisfaction techniques. In order to truly validate the automatically generated design, an almost infinite number of constraints needs to be checked. Moreover, these constraints necessitate formalization of deep domain knowledge in order to prevent collisions between building subsystems as in for example employing both façade and mechanical ventilation concepts.
Experiments with case adaptation solely on the basis of exhaustive parameters variation are not likely to produce meaningful results. Even when sufficient computer power is available, realistic design problems often require restructuring of structural or functional layout with respect to the starting cases. This restructuring of design representations again implies many of the issues associated with formalizing and automating the process of architectural design.

Our research focuses on the benefits and implications of the availability of precedent information during early design. Presently, technical issues such as case indexing, storage and retrieval receive much attention at institutions such as Eindhoven University, Technion Israel Institute of Technology, Massachusetts Institute of Technology, Yale University, GeorgiaTech etc. We assume the techniques for *case storage*, *-indexing* and *-retrieval* are available to form the basis for further developments. Therefore, we will not address these technical issues in much detail. Instead, we concentrate on an issue that has not been addressed up to now; the use of precedents in compiling analysis input with regards to building services.

We will not employ automated adaptation of cases in this respect. Designers themselves should answer the question which elements should be employed and in which way and to what extent they should be adapted. Architectural design has proven to be extremely hard to formalize (paragraph 3.3.3). Where this concerns Case-Based

Design in architecture, very few systems have successfully implemented the basic elements needed to support knowledge-based case adaptation. (Heylighen 2000).

4.3 Precedents in the Meta Design Environment

4.3.1 Introduction

Precedents are sources of information. In the Meta Design environment, precedent projects can help designers get familiar with the intricacies of maintaining comfortable indoor climate in buildings and applying the necessary building services to support this. In many cases, the representations of completed projects will contain enough information to give architects an idea of what to expect in terms of building services such as the installations, technical spaces and ducts and pipes.

This part of our research concentrates on deploying precedent information in analysis. The first requirement in this system is a method of storing precedents. We will demonstrate the use of the Meta Drawing Model in this regard. Next, retrieval and structuring of the precedent data is in order. The automated recognition techniques presented in the previous chapter might prove useful for this task. Finally, the development of a tool that combines precedent data, user interfaces and the compilation of analysis input is presented.

4.3.2 Precedent representation

According to Oxman (Oxman e.a. 1994), representation of precedents consists of three elements; graphic representation, design stories and domain concept vocabularies. The graphic representation consists of descriptions of geometric form. This includes construction elements, windows and doors, furniture etc. Design stories are defined as verbal descriptions that explain a design move or a 'conceptual point'. Lastly, domain concept vocabularies are collections of all relevant conceptual design elements used in the precedents. Although these three elements were mentioned in the process of describing architectural properties of cases, a similar structure can be used to describe cases for climate design.

The Meta Drawing model describes the procedure that is required to represent spaces and building elements (paragraph 3.4.2). However, storing the graphical contents of the indoor climate requires a slightly different approach from buildings. Indoor climate involves aspects such as air temperature, velocity and radiant temperatures that cannot be read directly from designs. Simulation can reveal indoor climate properties, however, because of the large amount of data, the numerical format the simulation tools produce is not suited for architects. Chapter 5 will describe techniques that more intuitively display properties of the indoor climate to designers.

Design stories are descriptions of prominent passive building elements and active building services together with their typical behavior and influences. Since indoor climate is the result of the complex interaction between many elements, it is difficult to report the indoor climatic consequences of building interventions isolated from their design context. It makes more sense to provide a collection of complete design instances that concern typical indoor climate aspects together with performance characteristics and descriptions of the effects of the climate interventions. This would require a more elaborate case representation than the design representation mentioned in chapter 3, but the informative benefits are apparent.

The domain concept vocabularies are collections of all design moves found in the design stories of the precedents. Paragraph 4.3.4 will give some examples of vocabulary items. The main purpose of such a collection would be to provide an index to manually look for specific items in the case-base. Linking the items in the vocabulary to individual precedents that contain them is straightforward. Users could then browse through the index and look for cases that deal with, for instance, natural ventilation in offices. The design representations and analysis results can then be accessed from the index entries. Automatic generation of indices generally necessitate a formal structure for categorizing case content. Since formal structures can prove to restrict the description cases, it might be more feasible to use the textual case descriptions as input for keyword filtering routines. In this way, the definition of categories remains unrestricted while the retrieval of relevant cases by designers is still good.

The way in which precedents are represented has a strong impact on the success of the case-based support. When the production of precedent material takes much effort in addition to drawing regular design representations, maintenance of case-bases will quickly become costly. Consequently, the databases will remain to contain only a limited amount of projects and rapidly cease to form an inspiration for designers. A better alternative is to use common design drawings as the input for the case-base. These are produced and monitored continuously throughout the design process. The documents are also available and sufficiently accurate for referencing. Searching for and employing precedent information requires the design documents to be organized in a retrievable and manageable fashion. As many design agencies employ document management systems, this will induce little if any adaptation of the information flows. However, using precedent information also required that the content of the drawings is structured and adheres to formalistic rules. It makes sense to use the rules of the Meta Drawing Model to implement the required structure in these design documents.

4.3.3 Automated recognition for precedents

Employing the Meta Drawing Model for the representation of precedents has a number of implications that will affect embedding precedents in the Meta Design Environment. First of all, it allows an important definition regarding the form of precedent representation in the Meta Design environment. “Precedents consist of ordinary design representations that follow the rules of the Meta Drawing Model (paragraph 3.4.2) and that have reached a level of detail that is customary for the preliminary design phase”. This means that the production of precedents involves the use of the same drawing procedures, symbols and entities as are used for new designs.

When we use automated recognition techniques on the precedent representations, it might enable an increase in user-friendliness. As an example, using automated recognition and the Meta Drawing Model will simplify the definition of precedent projects. Users will not be asked to explicitly define relations between design and services. This can be defined implicitly by placing the service elements on a geometric location in the design.
Another effect is that each new design input in the Meta Design environment automatically qualifies as a new case-base entry once it has reached a certain level of completeness and has been evaluated. The underlying hypothesis is that if cases are presented in a manner similar to the new design, the designer will have few problems in producing and interpreting the precedent designs.

To incorporate the building service elements that are needed in the execution of the CFD wizard, design team members can employ the additional HVAC symbols present in the Meta Drawing Model. These allow the definition of building service components on space and building level to model the production and delivery of heat and air. However, the use of information on building services in the CFD wizard necessitated an extension to the automated recognition algorithms. In addition to retrieving the relation between spaces and building elements, the wizard required information on the relations between spaces and service components and between components themselves. We developed new recognition routines that relate the building service components with the spaces they are placed in. It will also uncover the topology of components, i.e., the relation between a fan-coil unit and the air-inlet(s) and outlet(s) (Figure 36). This information can then be used to determine specific figures for the spaces such as installed heat power and air flow rates of the case. These figures are required to provide the design support tools with precedent-based prepositions at various interface input items.

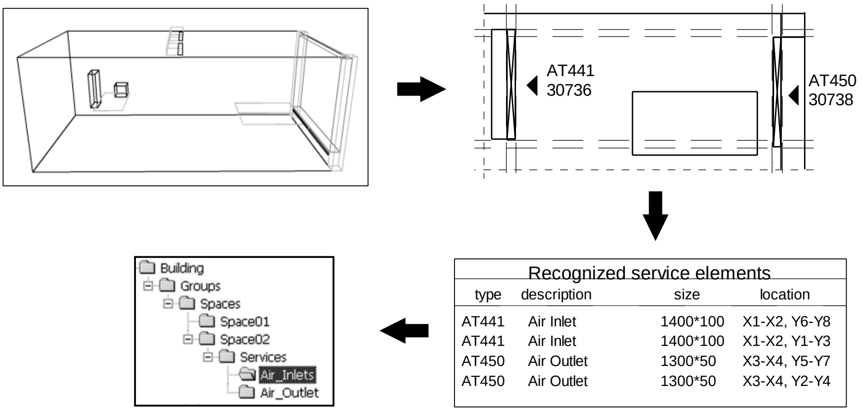

Figure 36: Schematic representation of Automated Recognition for precedents

Technically, the procedure described above has an important advantage: the format of the content of the design documents is kept relatively free from bias with regard to the structure of buildings in a particular field of building design (e.g. hospitals, offices etc.). In other words, when new knowledge emerges and other relations must be retrieved from the design, the drawings in the case-base and the drawing method can remain as they were. There is no need to (automatically or manually) modify the entire collection of design drawings. Instead, the automated recognition algorithms are updated with the most recent understandings regarding the structure of designs.

4.3.4 Indoor climate control concepts

In order to comprehensively organize the information regarding indoor climate and climate control, the Meta Design environment makes use of a model for the handling of indoor climate concepts. This model was developed to provide a method that enables designers to systematically choose the climate control principle for spaces. The indoor climate requirements common in design and building were short-listed. These requirements were expressed in terms of constraints on the indoor temperature and the airflow inside spaces. An overview of the commercially available HVAC systems revealed the mechanisms these types of services use for control of the indoor climate. Again these could be divided into interventions in the flow of heat inside spaces and intervention regarding the airflow. This produced common terms with which designers could systematically relate the climate requirements and climate control for their designs. The model only addresses the intake and extraction of air and thermal energy since our research only focuses on thermal and olfactory comfort.

Another helpful notion is the decomposition of heat and airflow into an *inflow* and an *outflow*. Buildings are subject to external and internal influences such as the changing effects of the sun, wind, rain, outdoor temperature and internal heat dissipation. These types of influences are the forces behind the flow of heat and air through buildings. For instance, an increase in outdoor temperature will cause heat to flow into the building, increasing the indoor temperature as well. As the outdoor temperature drops for instance at night, the process is reversed and the building will cool down as well.

Including all the physical mechanisms in calculating and monitoring the indoor climate is extremely complicated. At present, there is little need to master the thermo- and aerodynamic principle to a high degree. Specialized analysis tools contain accurate models that produce detailed data on long- and short-term heat storage, heat transfer coefficients and solar irradiation. Users need only have a notion of these effects to be able to use these tools and still obtain detailed predictions. Architects often have some idea of the influential forces in climate control but lack the experience to employ the analysis tools without help. The definition of climate control concepts attempts to further simplify the treatment of indoor climate aspects. For example, designers may identify what influences are present in their designs and to what extent these need to be controlled. This would summarize the input to a level that designers can relate to.

Designers use a number of building interventions to control the indoor climate in their building. Some of these interventions are passive in nature and can be employed by altering intrinsic building features such as material, self-shading and windows. Usually, the passive interventions do not provide enough control to achieve the indoor climate objectives. Most buildings need active building services to control ventilation and temperature within the ranges that are considered comfortable and healthy. The passive and active building interventions can be expressed in terms of their effect on either the inflow or the outflow of the physical processes. For example, placing radiators inside spaces controls the inflow of heat in that space. Adding cooling will provide control over the outflow of heat. Similar examples can be given for ventilation systems, combinations of heating and ventilating system and all air systems.

One of the most important indexes for the type and amount of control that is needed are the *indoor climate requirements*. These requirements describe to what degree the building inhabitants can expect to be covered from the natural influences. Although Dutch regulations lay down minimal ventilation quantities, they provide little basis for starting installation design. Designers or indoor climate specialists need to formulate additional requirements that need to be achieved by the design. Although these requirements are not definite and might change in the course of the design process, they support the application of passive control and can provide a demarcation of climate control systems. In the building service education at the faculty of architecture the following table of the most basic indoor climate requirements is used to link space functions to a set of common requirements (Table 12).

Table 12: indoor climate requirement types (source: Schalkoort e.a. 1996)

Type	*Climate requirements*	*Example*	*Temperature (°C)*		*Airspeed*	
			Min.	Max.	Min. (m3/s)	Max. (m/s)
A	Protection against wind and rain	Bus shelter	-	-	-	-
B	Protection against wind, rain and free of frost	Train station shelter	5	-	-	-
C	Acceptable for walking individuals with outdoor adjusted clothing	Shopping mall	10	$T_{outside}$ + 5		0.5
D	Acceptable for individuals sitting down with outdoor adjusted clothing	Covered terrace	12	$T_{outside}$ + 5		0.5
E	Acceptable for walking individuals with season adjusted indoor clothing	Hallways	15	$T_{outside}$ + 5		0.5
F	Acceptable for individuals sitting down with season adjusted indoor clothing (max 15 min)	Coffee corners	15	$T_{outside}$ + 5		0.25
G	Acceptable for individuals sitting down with season adjusted indoor clothing (max 45 min)	Cantina	18	25		0.25
H	Acceptable for non location restricted individuals sitting down with season adjusted indoor clothing (max. several hours	Library	20	25		0.25
I	Acceptable for individuals performing light physical labor in adjusted clothing (max 8 hours)	Laboratory	18	24	Mech. Vent.	0.25
J	Acceptable for individuals performing heavy physical labor in adjusted clothing (max. several hours)	Construction workplace	15	23	Mech. Vent.	0.25
K	Comfortable for non location restricted individuals sitting down with season adjusted clothing (long periods)	Living room	20	$T_{outside}$ + 3		0.25
L	Comfortable for location restricted individuals sitting down with season adjusted clothing (long periods)	Office room	20	25	Mech. Vent.	0.15

Notes:

- In cases where no mechanical cooling is applied, maximum indoor temperatures may be related the temperature of the outside air. On average the temperature of the indoor air may be similar to the outside temperature + 3 to 5 degrees Celsius. When this cannot be achieved, additional (passive or active) measures must be taken.
- Natural ventilation might seem easier to employ than installing mechanical cooling, it does not imply that it is always possible to prevent indoor temperatures rising considerably (+ 10 to 15 degrees) above the outdoor temperatures. In most offices, natural ventilation is only feasible when the climate requirements are relatively low, the external influences are favorable and the design contains several passive measures to control temperature and ventilation.
- In most situations, the temperature of the indoor air may reach values above the indicated criterion, provided that this does not happen more than 5 to 10% of the actual length of time during which the spaces are occupied.
- Airflow is often measured by two quantities, air speed and ventilation amount. Although they seem rather similar, their implications for the indoor climate are not. When looking at boundary values, one can never have too small an air speed, although no air speed usually means that no ventilation is achieved. However, some ventilation systems can ventilate rooms effectively without causing any noticeable airflow. On the other hand, the amount of ventilation in a space tends to be maximized and is usually only limited by the air speeds it causes.

These requirements are not absolute in the manner that they must be strictly abided by in order to provide acceptable or comfortable situations. The criteria are indicative and do not absolutely guarantee user comfort as other factors than clothing and metabolism influence this too. Aspects such as age, gender, humidity and season further complicate the configuration of indoor climate. However, the specific temperatures and velocities will be relatively close to the values given in the table. Therefore, the criteria provide a reasonable aim to test the performance of building and services. In ideal cases, the building's principal or user will provide performance criteria such as required light levels, temperatures and ventilation quantities.

Architects should first determine which passive measures they might apply in their design. Optimizing building behavior by changing features such as geometry or material of buildings can be referred to as *passive control*, adding HVAC or other service elements as *active control*. Passive control is in most cases cheaper and less intrusive than actively controlling the indoor climate. Active control has strong requirements regarding space and budget and it places an additional demand on energy use. Often, designers have objections against the intrusive nature of HVAC elements such as fan-coil units. Moreover, designs that have very little passive control and poor initial conditions for controlling the indoor climate, often have large HVAC systems as a result. It makes sense to optimize a building’s passive features when designers feel a need to build using minimal building services.

To aid designers address various aspects of their design that have potential to improve the initial indoor climate conditions, Table 13 was constructed. This table is a small selection of a multitude of measures that can be taken. Research institutes such as NOVEM and TNO (Novem 1992, Woon\Energie 1988) have extensively described building interventions that increase climate potential and at the same time lower environmental impact. Although most of the recommendations in the table are straightforward and rather well known among architects, their actual implementation in design is usually more complicated. Individual moves have a tendency to conflict with esthetics or construction systems. In some cases, interventions conflict among each other or with other intentions, for instance, lowering ventilation rates, an intervention that saves energy, is considered unhealthy for the indoor climate. In the past years, many attempts have been made to construct rules-of-thumb that balance positive effects of several interventions. Most of these attempts have failed, mainly due to the narrow applicability of these rules. Architects remain responsible for mastering the mechanisms behind these passive interventions and for finding the proper opportunities for implementing them in designs.

Table 13: Examples of building interventions for passive climate control

Flow	*Heat flow*		*Air flow*	
	Inflow	*Outflow*	*Inflow*	*Outflow*
Building intervention	Use awnings	Increase insulation	Keep space depths limited	Use ‘chimneys’
	Increase building mass	Use more ‘dome-shaped’ building forms	Use windows that allow various openings	Use wind induced pressures
	Reduce internal heat load	Use solar heat	Use ‘draft-planes’ to avoid cold sensations	Place outflow opening in high positions
	Reduce solar irradiation by reducing window sizes		Use airtight façades / construction techniques	
	Reduce solar irradiation by using shielding glass types			

Flow quantities

When architects master the application of these buildings interventions, this will denote a positive effect on the building's climate behavior. However, only in rare cases the building will achieve the criteria chosen from Table 12. When humans are to reside in the buildings for a considerable length of time, additional heating, cooling and ventilation are needed to make the building habitable. In order to determine the amount of control that should be provided by building services, the indoor climate analysis tools mentioned in chapter 2 can be used. These tools offer characteristic figures on the amount of additional control needed in their design. These numbers are helpful in choosing the appropriate climate system and to dimension building service elements. The amount of heat flow is typically expressed in Watts [W] or Watt per square meter [$W \cdot m^{-2}$]. Airflow rates, also known as ventilation flows, are expressed in cubic meters per hour or liters per second [$m^3 \cdot h^{-1}$]. Ventilation rates are expressed relative to the building volume. For instance, when a room has a volume of 75 m^3, a ventilation rate of 3 times per hour [$3 \cdot h^{-1}$] implies supplying 3 * 75 = 225 cubic meters of air each hour [$m^3 \cdot h^{-1}$].

In contrast to passive indoor climate design, effects of active control in the form of building services have generally not received much attention in architectural design. The design of the building service systems is still largely the task of building service specialists. However, passive and active control over the indoor climate cannot be regarded as two separated, sequential tasks. The quality of the design's indoor climate objectives determines to what extent passive and active interventions must be combined in order to achieve them. When the objective is a high quality indoor climate, a thorough combination of passive and active measures is the only way to meet them.

Using similar principles as with passive interventions, active building service application can be indexed by their effects on the indoor climate. Again, heat and air as well as in- or outflow is considered. Actively increasing or decreasing the temperature of room *surfaces* (walls, floor, ceiling or additional panels) can control the transport of heat to or from that space. When more heat is dissipated than is desirable inside a space, lowering the temperature of a surface will increase the outflow of heat and contribute to comfortable temperatures. An alternative method is to combine or replace control through surface temperatures by controlling the temperature of the *supply air*. Numerous possibilities of supplying air at various locations and under different conditions exist. Air might be supplied to a room with the use of central or local *fans*. Alternatively or at the same time, air can also be extracted. Mass flow balances make sure that extracting an amount of air will be counterbalanced by an equal amount of air entering through windows or other openings. Table 14 lists the fundamental instruments to conceptually design indoor climate control.

Table 14: Examples of Service applications for active control

Flow	*Heat flow*		*Air flow*	
	Inflow	*Outflow*	*Inflow*	*Outflow*
Service intervention	Increase surface temperature [surf temp +]	Decrease surface temperature [surf temp -]	Supply air [air +]	Extract air [air -]
	Increase air temperature [air temp +]	Decrease air temperature [air temp -]		

Notes:

- Increasing surface temperatures is generally considered a comfortable source of warmth. Note that in the case of wall and floor heating, the temperature of the surface cannot be higher than several degrees above room temperature. Ceiling heating is cannot use high temperatures since humans have a rather high tolerance for cold sensations to the face, but react strongly to heat in that zone.
- Decreasing surface temperatures is also a gentle way of lowering temperature. Ceiling cooling elements are rather expensive but allow much comfort and are able to remove considerable amounts of heat from spaces. Lowering temperatures of panels such as radiators is less common. It is possible to cool spaces by running cold water through radiators or to cool outside air by first transporting it over a cold panel. When surface cooling is combined with air of unknown humidity (natural ventilation), condensation risk is present.
- Heating the ventilation air to a certain degree will increase room temperatures. Whether the warm air is produced centrally or locally does not influence the interaction of the air with thermal comfort much. The heated air will (eventually) mix with the air inside the space. Generally, humans do not favor to be in contact with air of high temperature for a long length of time.
- Decreasing the temperature of supply air will have a similar effect on the temperature of the air inside spaces. Although internal dissipation may heat up the air rather quickly, thermal comfort can be positively influenced by the introduction of chilled air. Again, humans favor chilled surfaces over chilled air since the latter will more quickly lead to cold sensations.
- Supplying air is the result of increase in air pressure at a chosen location. Nature will attempt to even out the pressure difference, resulting in a flow of air. This principle can be used to carry the required amount of fresh (conditioned) air into spaces. However, some provisions must be taken in order to allow an equal amount of air to leave the space.
- Extracting air is the result of a local decrease in air pressure. Again, the pressure will attempt to distribute uniformly resulting in an outflow. This also causes a similar amount of air to flow into the space. Usually this is provided by outside air since extracting air from other locations within the building is not very hygienic.

Consequently to the required level of quality for the indoor climate, architects can choose which principles to apply in their conceptual design. However, the transfer from the mechanisms in Table 14 to building systems is not straightforward. Most commercially available building service systems are specialized combinations of effects and techniques. Choosing and designing an appropriate service system is and will remain a task for indoor climate specialists. Often designers do not oversee all the implications in terms of cost, space and conditions in layout on their designs. It is imperative however, that the imbedding of the climate services in the building starts at a point in the design stage when there is still opportunity to incorporate changes. In the absence of design specialists, determining the correct specifications of building service systems remains a matter of experience and the responsibility of the architect.

The model described here does not constitute a tool by itself. It is an easy to comprehend introduction to the basic principles of indoor climate control. It can be used to support designing the indoor climate by taking passive measures and applying active climate control. Moreover, this model's structured layout lends itself for use in a computer environment. The next paragraph will present a computer tool that uses indoor climate requirements to aid architects in preparing spaces for airflow analysis. It specifies climate control in term of heat and air interventions in a way that is compatible with the process of choosing a building service system.

4.3.5 The CFD wizard

As reported in chapter 2, indoor climate analysis and CFD simulations in particular can comprise large amounts of fairly complex input. Even when the input is reduced to the essential elements needed for an indicative analysis, it might still confuse designers that are not familiar with indoor climate theory or climate simulations. Designers might benefit from an instrument that aids them in compiling the input for indoor climate analyses. This instrument could take the form of an information center that deals with the essential indoor climate issues. At the same time, designer might read explanation and background information on various indoor climate topics. They could also access calculations that explain in more detail how characteristic figures common in indoor climate analysis can be obtained from design representations. Additional help files can describe aspects such as thermal accessibility or sun shading control in more detail. The prospect of such a tool also raises expectations regarding the educational role this type of tool might play. The concept of structured and graphical information combined with explanations of complex issues and on-demand accessibility has many benefits. Individuals that have access to interactive help are more successful in handling unfamiliar task. The use of precedents can provide users with completed examples of the tasks they need to perform with this tool.

The implementation of this tool was done using a technique called *wizards*. Wizards were developed by the computer software industry to encapsulate and communicate complex data in a structured and manageable manner. Wizards are applications that pay much attention to readability and usability of user interfaces. They comprise a number of steps, each of which addresses a momentarily isolated part of the information structure. Another characteristic is the presence of explanations and extensive help functions. Wizards also offer the possibility to step back and review previously input information.

During our research, we dedicated an experiment to developing a wizard for the compilation of input for a Computational Fluid Dynamics simulation. This wizard is called the *CFD wizard*.

The most important property of the CFD wizard is the ability to gather information for CFD simulation that up till then still lacked in the design support system. The use of this tool can aid designers in receiving indoor climate evaluations in a Meta Design environment. It should also provide a means to browse through relevant precedents and review the content and performance on indoor climate aspects. After selection of a suitable case, the wizard deals with the information aspects needed to perform a conceptual airflow analysis of the design. During this process of questioning and answering, the tool should provide suggestions for the input items on the basis of the precedent data. After completion, the Meta Design environment compiles the data into a set that will be sent to the simulation application.

The structure of the wizard interface derives from two notions: a) the use of precedents and b) handling the essential aspects of airflow analysis. The model presented in the previous paragraph showed a method to deal with these aspects straightforwardly. The information needed to perform an indicative CFD climate analysis is treated in a number of steps. Each step should contain a specific, momentarily isolated part of the conceptual airflow design. It will require user input on aspects such as capacities or dimensions. At the users request the interface will offer prepositions at each input element that are based on the precedents. Users should also be able to request information on the precedents themselves or look at typical solutions for general indoor climate design problems. In addition, help files explain jargon and special topics. Summarizing, the following distinct elements were found:

- Precedents: Precedent selection and review of plans, details, conditions and access of previous air flow simulation results.
- Capacity: The amount of control executed inside the space, i.e., airflow rates and heat flow rate.
- Season: Specifies whether to analyse a cooling or heating situation
- Heating: Type of heat supply or extraction mechanism, either by surface or by air.
- Configuration: Specify the locations inside the space where the control is applied.
- Finish: Preparation of simulation data

Step 1: Introduction

The wizard welcomes users and offers them the possibility to go through the rest of the application using an example case. Users can also choose to handle the indoor climate input without an example. When users choose to have case support, the wizard displays the collection of precedents during step 2. The second option allows experienced users to quickly go through the wizard and define all input individually.

Cased based design support depends upon the accuracy and interpretive capabilities of the underlying matching algorithm (Maher 1997, Kolodner 1993). However, available techniques focus on attribute-value matching. These generally lack the geometric comparison needed to support architectural design. New techniques for case indexing and matching on the basis of geometric properties provide a more logical choice for incorporation into precedent support in the Meta Design environment when they become available.

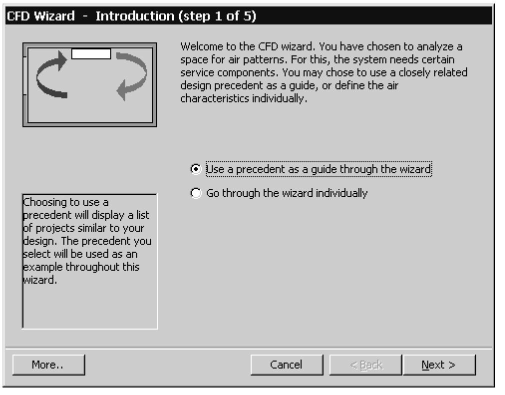

Figure 37: CFD Wizard, step 1

Step 2: Precedents

The list of precedents is presented in step 2. The precedents are accompanied by short descriptions of the context of the design. Users can review precedent geometry, indoor climate performance and design brief properties. The wizard enables users to open drawings, climate visualizations and other textual or graphical design documents. After selecting an interesting precedent, users can proceed to step three of the wizard.

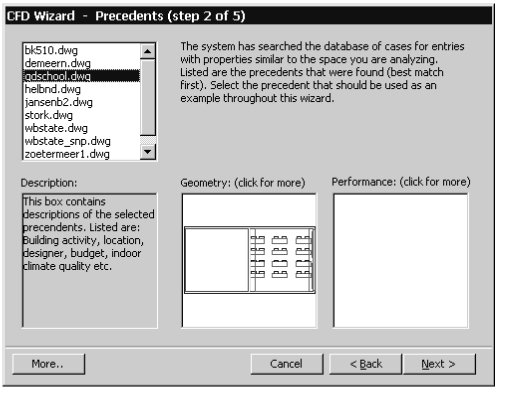

Figure 38: CFD Wizard, step 2

Step 3: Capacity

In this step users are introduced to the concept of building service capacity. For airflow analysis, both heat and airflow capacities are significant. Since some users might not be familiar with typical figures for these capacities, the system makes propositions using a steady-state heat transmission calculation. In addition, the precedent representation is used to display service capacities that are common in corresponding cases. Users can switch between simulating a heating or cooling situation by activating the corresponding item. Also, additional sessions of the steady-state calculations can be accessed to illustrate how the system obtained the proposed figures for heating and cooling. The system can link the air inlet rate with the air outlet rate. When the throughputs from inlet and outlet are not equal, the remainder is modeled as entering or exiting through the room windows. The airflow rates determine the size of the air inlets in such a way that the air speed at the inlets is kept at around 0.5 till 1.0 m/s.

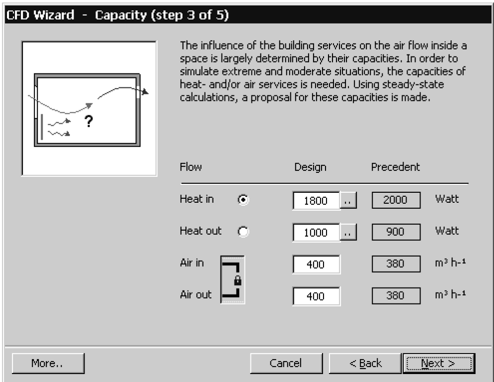

Figure 39: CFD Wizard, step 3

Step 4: Configuration

In order to finalize the conceptual building service design, the general placement of service elements must be indicated. For spaces this means identifying the planes where the service elements are located. In order to simplify this process, placement is restricted to the top, bottom or center of planes. Again, the precedent is used to display typical service layouts as a proposition. The service configuration is required for service elements used for heating, cooling, air-inlet and air-outlet. This step is also especially useful for investigating the influence of different service layouts on the indoor climate.

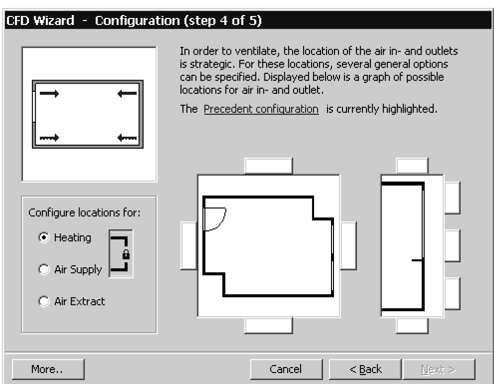

Figure 40: CFD Wizard, step 4

Step 5: Finish

The final step of the wizard allows users to copy (conceptual) information regarding HVAC components to their designs. Users can preview the input information, choose to go back and alter their choices or decide to proceed with simulation. Chapter 5 will show what results are produced by airflow simulations and present ways to visualize them.

Figure 41 shows a space that has been equipped with multiple airflow configurations. The figure contains five variants where the location of the air extracts has been changed. These variants have been simulated using airflow analysis and the results have been visualized using particle tracing (paragraph 5.4.4.3). The air inlets are indicated by the yellow components, the air extracts are red. Although the changes in the simulation results are small, it clearly shows that when air inlet and extract are located close to each other, there is one optimal (Figure 41b) and one less optimal configuration (Figure 41a). It also shows that the location of the air extract at the bottom of the room does not change the shape of the upper vortex much.

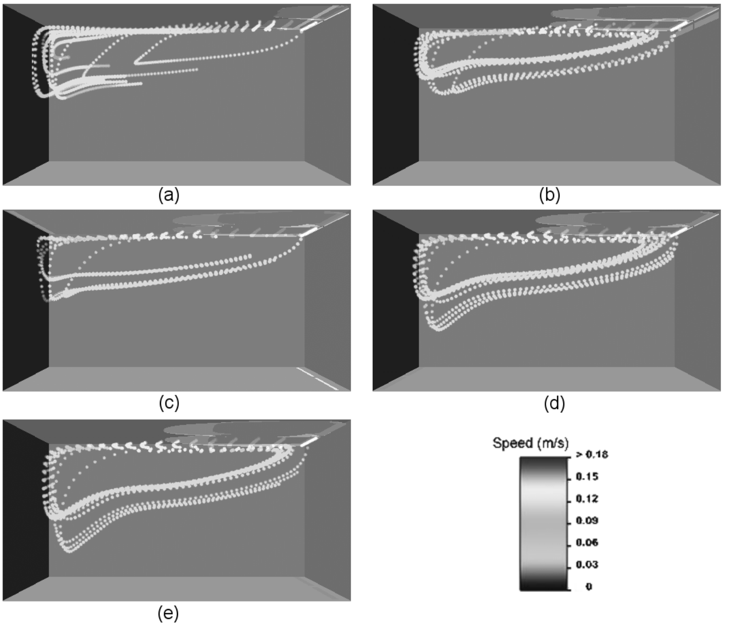

Figure 41: Multiple service configurations simulated (source: Middelkoop 2001)

4.4 Findings

Developments

Climate control concepts define in building services in most abstract terms. It does not design the definitive and specific climate control quantities, such as installed powers and airflow rates. Neither do climate control concepts specify the way in which these quantities are produced and distributed. The design of complete and detailed building service systems is, in almost all cases, not within the capabilities of architects. The design process often delegates this task to indoor climate specialists. The building service design often takes place after the production of the conceptual design. It supplements and specifies the chosen principles into the more detailed systems we find in buildings.

The support of climate control concepts in the Meta Design environment is focused on stimulating the exploration of design potential and the relation between indoor climate and the control principles. The CFD wizard is not intended to fit a space with building services. Its aim is to enable designers to investigate the typical behavior of their design in aspects such as thermal comfort and ventilation. In this context, the place of precedents in the Meta Design environment and more specifically the choice of climate control concepts becomes clearer. Instead of looking for and copying complete climate solutions from precedents, the precedent configurations form a good starting point for simulating the indoor climate. After the initial results have been reviewed, architect may wish to alter some aspects of the climate control concepts to start receiving feedback on the sensitivity of their design to various configurations.

We have seen that precedents contain knowledge in the form of complete design solutions, i.e., identifiable design items with validated solutions. However, since the solutions presented are rather static and do not provide much feedback on the behavior of the relations, it is not likely that the presence of precedents will completely replace expert knowledge regarding indoor climate at any design stage. The CFD wizard makes use of a formal network that deals with specifying the most basic principles of climate control. This structure contains rules regarding capacities and the combination of systems. However, the precise determination of systems, locations and capacities involves too complex a process to be represented by formal knowledge networks. Design specialists often use intuition, indistinct knowledge and experience in performing their tasks. It would not make sense to attempt to formalize this task to the point where it can be capsulated by a computer design support tool. As a result, the information network used by the CFD wizard cannot replace the role of the specialist during the design process. The incorporation of information derived from precedents in the CFD wizard does not change this by any means. The final choice of indoor climate control principles and the precise configuration of HVAC systems is a task for humans, not computers. The CFD wizard will help designers in getting acquainted with the indoor climate and the way in which their design respond to the various ways of controlling indoor climate and user comfort.

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 (Schaelin e.a. 1992, Schild e.a. 1995, Kato e.a. 1995). 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 (paragraph 4.3.5). 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.

Precedents

With regard to the information gap between synthesis and analysis, precedents provide an important part of the missing information, such as common capacities and typical element locations. In cases where architects make use of the interface-based part of the design analysis system, information from precedents can be used to make suggestions and to make pre-selections of default sets.

In the Meta Design Environment, the representation used for new designs is also used to store cases. The strength of the representation also facilitates the actual reuse or replication of precedent information. The term *case adaptation* is avoided for this mechanism, since in a design context it might be regarded as providing a full and definitive solution to the building service design problem. We feel that, at present, this level of precedent design support is not possible for this purpose. The rules that need to be automated and incorporated into the systems in order to adapt the precedent building service systems to new designs are of such complexity that automating them would in fact produce *knowledge systems* that equal that of design specialists. Many attempts have been made in those or similar fields. Most of these have failed to provide tools that are of practical use (Heylighen 2000). In our research, the use of precedent information involves the support of defining *conceptual building service systems* in spaces. These designs may then be analyzed using the integrated design simulation. It is important to realize that both the designs and the analysis results will be indicative and may not have much resemblance with the design as it might be build. However, the aim of precedent support in the Meta Design environment is not to provide complete building service systems but rather to support the design analysis strategies. These developments are based on the assumption that the type of feedback provided by using precedent information and conceptual systems will match the level of detail of designers concerned with early design shapes, directions and possibilities.

Extensions

The design representations and evaluations made with the Meta Design environment relate to the characteristics of conceptual design. This allows inclusion of this information in a precedent-based system without additional abstractions or transformations but it can also lead to diminished reliability of the precedent information. However, the case-base is not limited to documents and analysis results of the conceptual design phase alone. The Meta Drawing Model has the ability to facilitate design specialists with both representation and simulation techniques. The representations and evaluations of specialists could contain more accuracy and reliability if they are taken into the case-base. The techniques of automated recognition can translate the detailed specialist documents into the more abstract models that the user interfaces employs. Advanced case-bases even include information such as tendering briefs and post-occupancy evaluations in the documentation.

When trying to analyze buildings, situations might occur where predicting the indoor climate is difficult or will produce highly unreliable results. In order to find an alternative to the design guidance derived from exploring analysis results, displaying indoor climate behavior of similar and related design solutions might provide an interesting substitute to analysis. It should give insight in the principles of indoor climate issues such as ventilation and temperature control. At the same time, it might also provide observing architects with clues to the performance of their new design.

5 Indoor climate Visualization

This chapter draws from work done by H. Middelkoop in the framework of his graduation thesis at Delft University of Technology. Middelkoop formulated his *VIA3D* project around the question how indoor climate analysis results can be processed to optimally support architects. The first stage was determining the indoor climate factors that needed representation and the assessment criteria that apply. The Via3D project then investigated the application of Scientific Visualization in indoor climate feedback. This made it possible to match and apply the existing visualization techniques to indoor climate. In addition, he developed several new products that were dedicated to designing indoor climate. Included are the starting points and requirements of the graduation research and a selection of the results produced during this project.

5.1 Introduction

Indoor climate analysis results consist of large amounts of numbers for velocities, temperatures, etc. Designers find it hard to relate to this data and have difficulties in drawing conclusions from large tables of figures. In order to provide architects with information on the indoor climate and a comprehensible and abstract display, a translation of the raw data into a single image is necessary. Architects often request ‘go/no-go’ statements regarding design alternatives or building qualities. They are less interested in the exact physical values that make up e.g. thermal comfort. However, most analysis tools produce detailed predictions of temperatures, velocities and pressures at various locations and points in time.

Visualization of indoor climate should have designers interact with the analysis results instead of merely confronting them with data they do not understand. In order to accomplish this, the analysis results may be abstracted. Scientific visualization techniques such as particle tracing and isometric surface construction have been known to provide abstraction for the purpose of understanding (Nielson e.a. (ed.) 1990). A general overview of climate parameters might facilitate identification of problem areas (Figure 42). This enables designers to concentrate on analysis content rather than confusing them with geometrical and physical details.

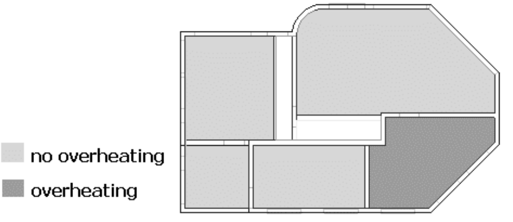

Figure 42: Global visualization of overheating problems

5.2 Rules and regulations

Environmental building regulations in The Netherlands consist of two different levels. The basis of policy forming is the *Housing Act* (Woningwet) which states that building permits shall only be given to designs of buildings that comply with the *Building Decree* (Bouwbesluit, VROM 1992). The building decree consists of a set of requirements concerning the design of new buildings and the evaluation of existing ones. In the case of designs for offices and factories the *Labor Condition (*or *Health and Safety at work*) (ARBO) *Act* is also in effect (SZW 1999). This act also refers to a corresponding decree: the ARBO decree. The ARBO decree aims to guarantee a healthy environment for employees and prescribes, for instance, light levels, ventilations quantities and hygiene facilities.

Building Decree

The rules in the building decree take the form of quantitative performance specifications and design instructions. Minimum and maximum values are given for, e.g., fire safety and facilities. When applying for a building permit, the design is examined for inconstancies with the building decree. When a criterion is not met, designers may prove that their design achieves an equivalent performance. When this cannot be done, the design must be altered or acceptance is withhold.

The building decree includes regulations regarding ventilation. When ventilating, air velocity constitutes a part of the indoor thermal comfort and is bound by maximum values. Chapter 6 of the building decree deals with common technical regulations regarding the construction of non-residential buildings. Article 6.31 handles the ventilation of occupation areas, occupation spaces, toilets and bathrooms. It states that for common and sanitary spaces, a facility must be present which provides for the intake of fresh air and the exhaust of polluted air. This facility must lie within 2 meters from the parcel's perimeter so as not to pollute adjacent parcels. In addition to the previous facility, building elements that separate the exterior from interior must contain a movable building element (in most cases a window) that can allow rapid replacement of heavily polluted air. Table 15 contains some minimum required ventilation rates found in the building decree.

Table 15: Ventilation capacity requirements per space type

Space:	*Capacity:*	*Minimum:*	*Remark:*
Occupation area	See: (VROM 1992)	7.0E-3 m^3/s	50% outside air
Common occupation area	0.9E-3 m^3/s /m^2	7.0E-3 m^3/s	100% outside air
Occupation space	See: (VROM 1992)		
Toilet room	7.0E-3 m^3/s		
Bathroom	14.0 E-3 m^3/s		
Other spaces	0.1E-3 – 7.0E-3 m^3/s		elevator, hallways, etc.

ARBO regulations

The second level of building regulations is contained within the ARBO act and decree, which have been proposed by the trade unions. In the past years, a centralized European organization for Health and Safety at Work coordinates the regulations of the European Union countries. With respect to indoor climate, they safeguard the level of minimum comfort and maximum discomfort an employee may experience in his/her working environment. The ARBO decree states that the indoor climate may not cause any damage to the health of the employees. Also, the indoor climate should be as comfortable and constant as reasonably possible, taking into account the activities conducted by the employee (Table 16). Annoying drafts should be prevented unless not reasonably avoidable.

Table 16: Human activities with corresponding metabolisms (Source: SZW 1999)

Activity:	*Metabolism: (W/m^2)*
Office work	60
Teaching/learning	60
Medium labor	150
Heavy labor	220
Work in cold environment	200

In addition to the ARBO act and decree, there are policies and guidelines to safeguard labor conditions. Recently, the ARBO guidelines have become the basis for negotiations between employer and employees. The negotiation process results in an agreement that describes the employer's obligation to provide for adequate workspace. Although these guidelines lack legal status, they are more explicit about the indoor climate than the ARBO decree. For instance, ARBO guideline 6.1 states that a comfortable and constant indoor climate has a Predicted Mean Vote (PMV) between -0.5 and 0.5 or causes complaints among less than 10% of the employees. Exceeding these limits for no more than 10% of the occupation period is acceptable.

The criterion that at most 10% of the employees may complain is a noteworthy addendum. The norm it refers to mentions a maximum of 10% PPD (Predicted Percentage of Dissatisfied) instead. The percentage of dissatisfied is not equal to the

percentage of people that complain about the indoor climate, since research has shown only 25 to 40% of the dissatisfied actually expresses complaints (Vroon 1990). The danger in this amendment lies in the fact that employers can avoid legal action against unhealthy climates as long as they manage to keep the number of complaining employees down. The situation might be reversed when an organization manages to rally a number of employees to complain. According to ARBO definitions, this would imply an unhealthy indoor climate.
The guidelines are also clearer on the ventilation requirements for indoor climate. Office spaces should have minimal ventilation of $30m^3$ per hour per person ($h^{-1}\cdot p^{-1}$). Spaces for teaching have a minimum value of $20m^3\cdot h^{-1}\cdot p^{-1}$ designed in accordance with NEN 1089. Other spaces should be ventilated with $25m^3\cdot h^{-1}\cdot p^{-1}$. These figures, combined with the volume and function of the spaces, are used to calculate ventilation rates. The facilities for providing for these rates must be designed in accordance with NEN 1087.

A major disadvantage of the ARBO decree is the relativity and level of abstraction of the regulation criteria. The term 'reasonable' is used in many cases to qualify a required performance. The explanation of what is reasonable may depend on the viewpoint chosen by the decision-maker. An architect serving the interests of both his client and the building's occupants may experience difficulties in determining an appropriate level of comfort.

Norms in The Netherlands
Many building regulations and guidelines refer to measurement methods by which performance can be estimated. Norms are documents that record the precise procedure that is involved in measurements or calculations. The use of computer simulations is still scarce in the description of norms. Organization such as the Dutch Institute for Normalization (NNI) and the International Standards Organization (ISO) release many of the norms used in building. When measurements are involved, norms describe in detail the constraints, conditions and settings for determining compliance to the building decree; they also provide rules for interpreting the recorded data. More abstract building performance parameters such as thermal comfort and heat loads are determined using norms that contain lookup tables and calculation models.
Examples of norms for indoor climate include *NEN 1068: Thermal insulation of buildings*, *NEN 1087: Ventilation of buildings* and *NEN-EN-ISO 7730:1994 Moderate thermal environments* (NNI 1996, 1997). Recently, the building decree introduced two norms which are aimed at reducing energy consumption of new buildings. These norms are *NEN 2916: Energy performance of dwellings and residential buildings* and *NEN 5128: Energy performance of non-residential buildings*. Most of the ARBO and Rgd guidelines refer to NEN norms or similar procedures (Figure 43).

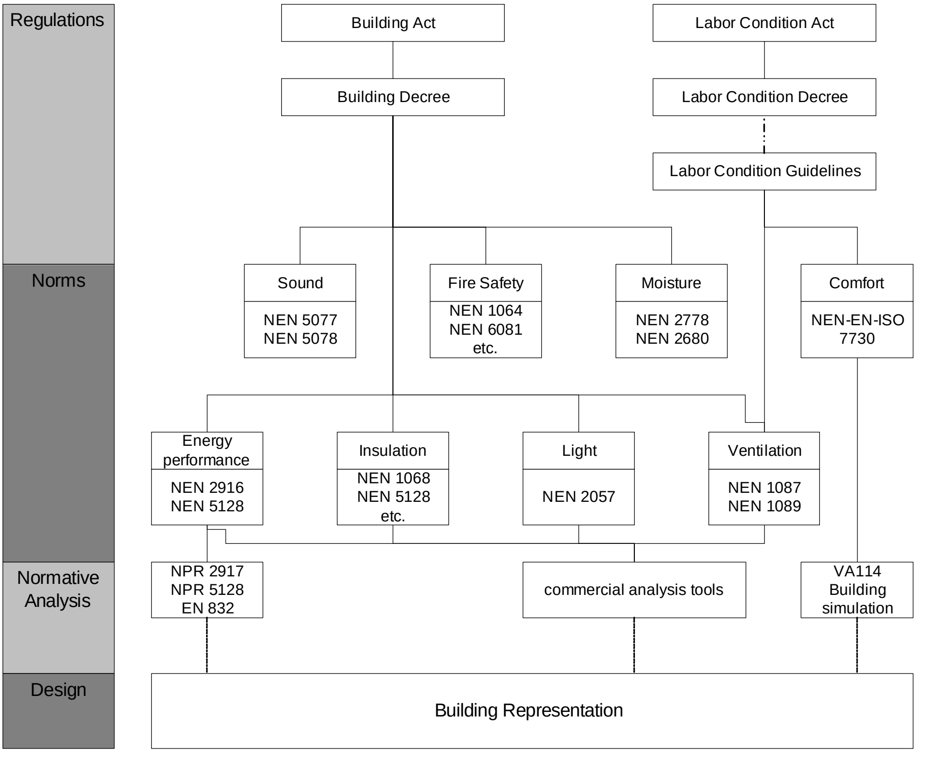

Figure 43: Regulations and norms related to indoor environment in The Netherlands

RDG guidelines

The Governmental Building Agency (Rgd) is a department of the Dutch ministry of Housing, Urban planning and Environment. The Rgd designs, builds and manages most of the buildings used by the Dutch government. Their aim is to have an exemplary influence on the areas of architecture, urban planning and environment. The Rgd releases their views and experiences as recommendations in public documents such as 'The Physical quality of governmental buildings' (VROM 1999). The ARBO legislation stood model for most guidelines regarding thermal comfort. The Rgd defined some additional rules that are worth mentioning.

The Rgd utilizes a rather unique method to define thermal comfort. The basis for this method is NEN-EN-ISO 7730, a thermal comfort evaluation method that rates thermal climates with a Predicted Mean Vote (PMV). The Rgd employs an additional parameter called *Gewogen Temperatuur Over/Onderschrijdingen* (GTO hours). This method takes into account the length of time that indoor temperatures rise or drop beyond given thermal comfort boundaries. The larger the deviation, the heavier the length in time of exceeding weighs. The measure of exceeding comfort boundaries is calculated from the product of the PPD and the length of time this PPD percentage occurs. For instance, one (1) hour with a PMV of 0.7 equals the same amount of GTO hours as 1.5 hours with a PMV of 0.5. On top of the thermal comfort limits of -0.5 till

+0.5 PMV, the Rgd allows one to exceed these limits by a certain number of GTO hours:

- For occupation spaces in offices during with the summer season, a PMV greater than 0.5 is allowed up to a maximum of 150 GTO hours.
- For occupation spaces in offices during the winter and summer season, a PMV less than –0.5 is allowed up to a maximum of 150 GTO hours.

Other regulations include the following:

- Temperature variations between occupation spaces separated by a hallway cannot exceed 6 degrees Celsius. Temperature gradients between occupation spaces not separated by a hallway may not exceed 3 degrees Celsius.
- Vertical temperature gradients inside occupation zones should not be greater than 3°C m^{-1}.
- Regular conditions imply temperatures of floor surfaces that lie between 19 and 26°C.
- Temperatures of floor surfaces in spaces heated by floor heating systems and spaces with low occupancy should not exceed 29°C.
- During a winter season the temperatures of floor surfaces should not be below 19°C for more than 50 hours. The floor should reach a temperature of 19°C within 3 hours after start of occupation.
- Horizontal radiant asymmetry resulting from windows or other cold surfaces should not exceed 10°C (observed from a small vertical plane, 0.6m above floor level)
- Vertical radiant asymmetry resulting from a heated ceiling should not exceed 5°C (observed from a small horizontal plane, 0.6m above floor level)
- During the winter season, the average air velocity should not exceed 0.15 m/s in combination with a maximal operation temperature of 24°C.
- During the summer season, the average air velocity should not exceed 0.25 m/s in combination with a maximal operation temperature of 26°C.
- The air humidity of spaces should be at least 30% or correspond to the relative humidity of the outside air.

Conclusions

The Rgd is more explicit as to the definition of an acceptable indoor climate than the building decree. The Rgd publications state requirements on indoor climate aspects such as radiant asymmetry and temperature gradients that are not mentioned in the building decree. They are also clearer as to maximum air velocity in relation to thermal comfort. However, some definitions of climate requirements leave room for interpretation. For example, average air velocities can be measured on intervals ranging from fractions of seconds to hours. Another important factor is the impedance of the measurement instruments. Older, slower equipment does not detect instantaneous speed variations that would cause discomfort to humans.

As a result of their opposite backgrounds, the Building decree and the ARBO decree concentrate on different aspects of the indoor climate. Some significant differences in quantities exist as well as varying units and definitions. Table 17 lists the quantities found in the three leading building regulations in The Netherlands. The values for offices spaces have been used.

Table 17: Comparison of rules and regulations

Quantity:	*Building Decree:*	*ARBO Decree and Guidelines:*	*Rgd Guidelines:*
Indoor air temperature	No statement	20-24 °C (Summer) 22-27 °C (Winter)	Minimum: –0.5 PMV (150 GTO) Maximum: +0.5 PMV (150 GTO)
Max. air velocity	0.2 m/s	0.1 - 0.3 m/s	0.15 m/s with 24°C 0.25 m/s with 26°C
Air humidity	No statement	30 - 70 % RH	At least 30% RH or similar to the outdoor
Indoor surface temperature	2 °C +/- T_L	No statement	Minimum: 19°C Maximum: 26°C
Ventilation rate Minimal	$0.9 \cdot 10^{-3}$ m^3/s per m^2 floor area	2 - 3 m^3/s per m^3 space volume	same as Building Decree
Ventilation rate Nominal	No statement	40 - 50 m^3/person	
Air temperature gradients	No statement	No statement	Maximum: $3°C \cdot m^{-1}$
Surface temperature asymmetry	No statement	No statement	Horizontal: 10°C Vertical: 5°C

Both the building act and the labor condition decree do not provide much clarity as to the definition of a good indoor climate. The building act states minimum ventilation capacities for all types of spaces and refers to NEN1087 for a procedure to measure those capacities. However, providing sufficient ventilation alone does not entail a good indoor climate. Temperature and preventing drafts also make up for an important part. The labor condition act contains several paragraphs that describe indoor climate, but it remains at the level of negotiations. Where one would expect legally prescribed quantities, the term *reasonable* is often used instead. The labor condition decree often refers to labor condition guidelines that are more explicit on the matter of indoor climate. Designers can use the guidelines to find norms that apply to the indoor climate. The Rgd criterion is stricter when applying norm NEN EN ISO 7730 and more likely to bring thermal comfort.

The building process in The Netherlands has few legal incentives for achieving an acceptable level of indoor comfort. Well-intentioned designers will find proper guidelines that contain clearer thermal comfort objectives. However, most intentions are rapidly abandoned when budget shortages occur. The question remains whether building regulations in their present form can and will be an encouragement to consider thermal comfort during the design process. Most existing regulations leave too much room for interpretation. On the other hand, it is also clear that more strict legislation on thermal comfort would stimulate the application of simulations. The techniques of temperature and airflow simulation have the capability to aid consultants in providing design guidance on these aspects. Simulation can predict building behavior and pinpoint building elements that later in the design process will determine whether or not compliance with building codes or design briefs can be achieved without great additional effort.

5.3 Indoor climate factors

In order to determine visualization requirements for each of the indoor climate factors, they are divided into first order factors and second order factors. First order factors are physical properties of the air and building materials that make up the indoor climate. These properties are often referred to indoor climate *parameters*. Examples are the air temperature, wall temperature and air velocities. Second order indoor climate factors are effects that are the result of a specific combination of first order factors, sometimes accompanied by an exceeding of boundary values or variations. Examples of these indoor climate *effects* are draft and radiant temperature asymmetry. An important difference between first and second order factors is that the first order parameters are always presents inside every building (also outside). Second order effects only occur when the values of indoor climate parameters exceed certain boundaries. For the prediction of indoor climate parameters we employ the analysis tools mentioned in chapter 2. Detection of climate effects is more complicated. In some cases, for instance temperature gradients, recognition can result from comparing temperatures at different locations. Other effects such as drafts and downdrafts from cold surfaces are far more difficult to recognize reliably using automated methods. Humans can best identify these types of effects.

To determine the correct appearance and applicability of indoor climate visualizations, we analyzed each of the factors with regard to their application in a user-interaction based system. Visualization of the factors with the purpose of quickly and effectively communicating the prominent consultations to designers using the system, give rise to several criteria. These criteria stem from both the characteristics of indoor climate factors and the abilities and preferences of designers in recognizing indoor climate characteristics. The fact that visualization in the Meta Design environment is aimed at the architectural discipline determines the precise purpose of the criteria. The criteria are intended to provide designers with a correct understanding of the indoor climate data in a straightforward manner.

When the available visualization types are analyzed using the same criteria, we obtain an indication of their matching against the first and second order climate factors. For instance, the indoor climate effect of draft is best communicated in combination with user interaction since the users can most accurately detect draft locations. In addition, draft requires an integration of three first order factors. Visualizing air velocities is best done dynamically, since this closely resembles the actual movement of air packets through spaces. We selected the following five criteria guide the application of visualization.

- Interaction
- Integration
- Interpretation
- Dimension
- Dynamics

5.3.1 Feedback criteria

Interaction is one of the most important criteria which should be used for the evaluation of visualization types. Interaction is desirable because many visualization types offer only a local representation of a given data set. Helman and Hesselink (Nielson e.a (ed.) 1990) state the following in this connection:

‘Even with the best display techniques, it is impossible to simultaneously display all of the quantitative information in a large data set in an understandable form. So when we require more precise information on some element or aspect of the data, we must specify it through user interaction.’

The interaction concept may be divided into three levels:

- Choice
- Viewpoint
- Positioning

Choice refers to interaction in the form of selecting a given type of visualization. *Viewpoint* refers to the position of the viewer in relation to the three-dimensional data model. *Positioning* refers to the positioning of a certain visualization type within the data set (e.g. origin of particle source). Interaction in the form of free positioning of the visualization type (e.g. plane, volume or source) is considered important because it allows the viewer/architect to actively investigate the data. This is considered important for spatially understanding the data set.

The *integration* criterion relates to the possibility of simultaneously displaying multiple dimensions of a given data set. Many dimensions within a data set are not independent but prove to be dependent on another factor in the data. Air speed is an example of this. Air movement with a speed of 0.15 meters per second is not experienced as an irritating draft at a temperature of 23 ºC, but it is at 18 ºC. In this instance it can be useful to integrate air speed and air temperature into the same visualization, so that the viewer can immediately judge whether a given air movement will be found objectionable or acceptable. Multiple dimensions can also be integrated. This is, for example, highly desirable in the case of visualizing the PMV (predicted mean vote) value.

The criterion of *interpretation* chiefly comprises the aspects of perception and cognition. Perception is mainly a matter of visual capacities. These possess pleasant and peculiar aspects, thus raising the possibility that matters will not be interpreted correctly. Cognition, by contrast, is based on mental capacity. Its principle task consists of the interpretation of the visual information. Ambiguity e.g. as to whether one thing is perceived as being in front of or behind another, is indicative of difficult interpretation. It must be noted, by the way, that difficult interpretation of a visualization type can generally be alleviated by the use of suitable tested methods.

The *dimension* criterion relates to the spatial character of a visualization type. One, two and three dimensional visualization types may be distinguished. An example of three-dimensional visualization is the isometric surface in the form of a volume. A cross-section or plan of the data set, on the other hand, is two-dimensional. The spatial quality of a visualization type is of considerable importance. The viewer is required to make a mental reconstruction of the spatial value distribution of the parameters if he is to obtain sufficient understanding. If only two-dimensional cross-sections of the data set are available to him, this may be considered disadvantageous to comprehensibility.

The *dynamic* criterion comprises what is sometimes termed the fourth dimension. It involves the introduction of the time concept, with the consequent possibility for animation (i.e. movement). For example, airflow is an important component of the indoor climate.
Designers may be unfamiliar with scientific representation of airflows. Therefore, it is advisable to appeal to the imaginative powers of the architect. Drawing similarities with the success of multi-dimensional Virtual Reality techniques in architecture, a 3D, dynamic display of airflow is very likely to meet this requirement.
It is not possible to introduce animation in every case, but stationary images can nonetheless have a strongly dynamic appearance. This may be done, for example, by giving a realistic impression of the course of a flow.

5.3.2 First order factors

First order factors are the basic elements of the indoor climate. They consist of the physical properties of the air, walls, floors and other material inside buildings. The Meta Design environment translates and communicates the effects of design decisions on shape and materials on the indoor climate to architects. In order not to overload designers with climate factors that have little relevance in this respect, we limited the indoor climate parameters in visualization to the following:

- Air pressure
- Air humidity

- Air velocity
- Air temperature
- Radiant temperature (of materials)

The choice for these five was determined by their immediate relation to early design e.g. with respect to building shape and window areas. Other factors such as pollution are more difficult to predict using conceptual data. Another consideration was the abilities of the analysis tools. In the case of indoor climate visualization, CFD simulations produce most of the results and place limitations on the amount of factors that can be used.

Air Pressure is a property that relates to the amount of air present inside a volume. An increase in the mass of air, for example by supplying air of higher pressure into a limited volume, results in an increase of air pressure. Air pressure is not extremely relevant to indoor comfort. Human physiology is able to function under various pressures. Still, feedback of pressure is relevant in this context. Designers need to determine whether large pressure difference exist inside a space as a result of ventilating. Moreover, rapid variations in pressure will cause for much discomfort among inhabitants.
The large amount of locations where pressure is calculated makes user interaction with the dataset necessary. This also requires making the dimensionality of the dataset clear. Integration with other first order factors is not relevant, however, the relation between internal and external pressures might prove interesting.

Air humidity is related to the composition of the air. Air is a mixture of several gaseous molecule types. Oxygen [O_2], Nitrogen [N_2], Water [H_2O] and Carbon dioxide [CO_2] are the most important. Air humidity figures express the amount of water vapor per volume unit. The Rgd criterion states a lower limit of 30% and an upper limit of 70% Relative Air Humidity. Humidity figures may vary among spaces which makes interaction such as producing sections at various locations and dimensionality important. Integrating humidity with air temperature or wall temperature can reveal condensation problems.

Air velocity refers to the movement that can be observed when following a (small) volume of air. Although the molecules inside such a volume move in all directions as a result of internal molecular forces, the volume as a whole can move in a particular direction. The distance it covers in an amount of time is the air velocity. Insight into air velocities is necessary for finding locations where discomfort due to drafts may occur. Visualizing velocities can also provide an indication for ventilation efficiency inside a space. The dynamic character of moving air necessitates a certain degree of dynamics in the visualization. In most cases this will immediately provide an oversight of the entire space. Determining the correct location for the illustrations may require interactive searching. Integration with other climate factors is required to display, for instance, the locations of drafts or downdrafts due to cold surfaces.

Air temperature expresses the internal energy of air. As the internal energy of a molecule increases, it will move more rapidly, thus reaching a higher temperature. The movements also lead to collisions among molecules which causes air pressure. Air temperature is one of the most well known properties of the indoor climate. In most buildings, the air temperature is the factor inhabitants relate to most closely and attempt to control. Air temperatures can be viewed instantly, daily and over an entire year. This makes interaction with the dataset recommendable. Placing time dependant variations on separate graph axis displays dynamics in most situations. Air temperature is often taken into account when visualizing other climate factors. However, feedback of temperatures themselves does not require integration with other factors.

Radiant temperatures of the surfaces that make up spaces are related to the internal energy of their materials. In indoor climate theory, the radiant temperatures of all surfaces are expressed in a Mean Radiant temperature which is a single figure. It combines the radiant influences of all surfaces with the space geometry to determine the radiant temperature for one location inside that space. Hot surfaces such as radiators deliver a large amount of radiant energy. Visualization of radiant temperatures can often be done through displaying the temperatures in degrees Celsius of the various surfaces of a space. Mean radiant temperatures are calculated when determining the PMV (a second order effect). Interaction is not relevant since the surface temperatures and view angles can be revealed in a single 3D model. This also excludes dimensionality and, apart from long-term effects, dynamics.

5.3.3 Second order factors

Second order indoor climate factors are effects that consist of specific combinations of first order factors. In most cases, an additional analysis of first order data is required to determine the presence and extent of second order effects. These effects are at least of equal importance than 1st order factors, since they often determine the actual quality of the indoor climate. Moreover, some indoor climate situations might seem to be acceptable when only viewing 1st order factors but prove to have climate hazards when 2nd order effects are retrieved. The climate effects we encountered during our research are contained in the following list:

- Temperature gradient
- Radiant asymmetry
- Draft
- Turbulence Intensity
- Airflow pattern
- Coanda effect
- Downdraft
- PMV

Temperature gradients describe the phenomenon that temperatures may vary over height inside spaces. The unit expresses the number of degrees Celsius the temperature varies over the length of one meter. One usually analyses the occupation zones of spaces when determining gradients. This applies to the area from ankle height to just above head level. Interaction and dimensions are hardly necessary for gradients since the automated routines can detect gradients and visualize them at their locations. Although integration with other factors is not required, an indication of occupation zones might prove useful.

Radiant asymmetry refers to the temperature differences between the surfaces of a space in relation to a person. Inhabitants experience the temperatures and their individual values may not vary largely. Especially windows can contain cold glass surfaces that can cause discomfort. In order to visualize the temperature differences between surfaces, a three-dimensional display is useful. Surface temperatures can be visualized separately and need not be integrated with other factors.

Turbulence intensity is the phenomenon that air velocities may display rapid fluctuations that at times even reverse the direction of the airflow. Predicting turbulence is difficult and most simulations work with mean figures (paragraph 2.2.3.2). However, the presence of turbulence has considerable influence on the indoor climate and feeding back general indication on turbulence can prove very useful. Interaction in this respect is recommendable in this respect because it can provide insight into the cause of turbulence. Turbulence has a dynamic and three-dimensional character that places additional constraints on feedback.

Draft is a combination of two of three instances of the factors: air of cold temperature, high air velocities and large velocity fluctuations (turbulence). The exact definition of draft is too extensive to mention here. In some cases, (warm days), drafts can even be pleasant since they cause an increase of sweat evaporation. However as a general guideline, in winter seasons, air velocities should remain below 0.15 $m^1 \cdot s^{-1}$ at maximum temperatures of 24 ºC. In summer seasons, air velocities should remain below 0.25 $m^1 \cdot s^{-1}$ at maximum temperatures of 26 ºC. The exact locations of drafts are hard to determine because of their dynamic nature. Still a three-dimensional display is important to locate workplaces correctly.

Airflow patterns entail the movement of air inside spaces. The influence of sources such as open windows and air inlets create typical flow patterns. Identification of these patterns is important when climate aspects such as ventilation efficiency and pollution distribution are assessed. Visualization of airflow patterns can also aid users in gaining a better understanding of fluid mechanics. Interaction with the dataset is leading and can reveal new insights in the relation between sources, disturbances (such as furniture) and the resulting flow patterns. Revealing relations also requires integration with other factors and a dynamic and three-dimensional image.

The *PMV* (Predicted Mean Vote) is the well-known abstract statement of indoor comfort. It combines the 1st order factors of air velocity, air humidity, air temperature, and radiant temperature with human bound factors such as metabolism and clothing insulation into a single figure that expresses a prediction of the measure of thermal comfort that will be experienced inside a building. This figure employs a 7 point scale that ranges from +3 to –3 PMV requires a visualization that allows users to make PMV measurements at locations of their choice. Since a single 1st order factor can shift PMV largely, it is necessary to integrate the 1st order factors that make up the PMV into the image.

The *Coanda effect* is often used in building ventilation. It refers to the phenomenon that air that is supplied parallel and in close vicinity to a surface tends to ‘stick’ to that surface. This allows building service designers to achieve large, revolving airflow patterns that otherwise involve much higher inlet speeds. Similar to airflow patterns, a three-dimensional image is required. Interaction is not necessary when automated routines detect and display the boundaries of the Coanda effect.

Downdraft as a result of a cold surface is a form of draft that occurs naturally. It stems from the phenomenon that the temperature of air is related to its density and to the amount of gravitational pull it experiences. As a result, cold air tends to drop to floor level. A well-known example of downdraft can be experienced for windows in cold outside conditions. Air in front of windows cools down and drops rather rapidly causing cold sensations for people sitting in front of the window. Detection of downdraft can be aided by three-dimensional dynamic visualization of the airflow patterns. The systems can facilitate this by generating images around the designed windows.

5.3.4 Results

The results of the indoor climate factor analysis in terms of user feedback criteria are collected into Table 18. This table can be combined with an analysis of available visualization types and form the starting point the development of Meta Design Environment visualizations.

Table 18: Visualization criteria

Key: o = not important, + = important

Criteria: / *Factors:*	*Interaction:*	*Integration:*	*Interpretation:*	*Dimension:*	*Dynamics:*
Air temperature	+	o	+	+	o
Radiant temperature	o	o	+	o	o
Air humidity	+	+	+	+	o
Air velocity	+	+	+	+	+
Air pressure	+	o	+	+	o

Criteria: / *Factors:*	*Interaction:*	*Integration:*	*Interpretation:*	*Dimension:*	*Dynamics:*
Temperature gradient	o	o	+	+	o
Radiant asymmetry	o	o	+	+	o
Turbulence	+	+	+	+	+
Draft	o	+	+	+	+
Airflow pattern	+	+	+	+	+
PMV	+	+	+	+	o
Coanda effect	o	o	+	+	+
Downdraft	o	+	+	+	+

5.4 Scientific Visualization

Scientific visualization is a discipline that has made huge advances in the scientific world during recent decades. This is largely due to the increased computing power available, which has made it possible to generate vast quantities of numerical data. A thesis by Richard Hamming is clearly applicable here: ‘The purpose of computing is insight, not numbers.’ (Hamming 1973).

The relevance of scientific visualization is that it is a collective term for aids and techniques that make new dimensions of insight possible in problem solving. The latest computational techniques in the areas of hardware and software are used in this connection.

One of the core features of scientific visualization is, as the name suggests, its visual aspect. The alternative term visual data analysis is also sometimes used. The goal is to obtain understanding and insight into the data by seeking a form of graphic representation that elucidates certain relations and correlations. The major difference between scientific visualization and graphic presentation is that the latter is concerned with portraying and communicating results which are already understood, whereas scientific visualization is a method of achieving understanding of results (Earnshaw e.a. 1992).

5.4.1 Application

Scientific visualization is applied in many branches of science. It is applicable wherever large volumes of data have to be represented. In chemistry, for example, it is used for visualizing molecular structures and reactions. In medicine, it is used for visualizing tumors or bone fractures detected in CT and MRI scans as three-dimensional models. In meteorology, scientific visualization methods are used for displaying weather patterns. In engineering, scientific visualization methods are a valued tool for representing simulated solutions.

What matters in the context of this study is the application of scientific visualization to the results of CFD calculations, the subject of VIA3D. CFD (Computational Fluid Dynamics) methods make it possible to calculate the various parameters of the indoor climate. The main ones are air velocity, air temperature, humidity, air pressure and radiant temperature. It is essential to visualize these factors in order to get to grips with the material. Since several different types of visualization are available, it is valuable to present an overview of the possibilities they offer and their advantages and disadvantages. This is necessary to give some prospect of a well-grounded choice of method in a given situation.

5.4.2 Types

Among the different applications of scientific visualization, various types of visualization may be categorized which can be applied to highly diverse situations. The individual visualizations thus look superficially similar even though they originate from entirely different disciplines (Brodlie e.a. 1992). In order to gain a comprehensive view with regard to the different types of visualization, several scientific attempts have been made towards a classification. Earnshaw and Wiseman (Earnshaw e.a 1992), for example, devised a classification based on the number of dimensions represented, with regard both to the computational domain and its representation, referred to as the visual domain.

Frühauf (Frühauf 1997) divides all types into the following three categories (taken from (Delmarcelle e.a 1994):

1. Order of data: scalar, vector, tensor
2. Definition area: point, line, surface, volume
3. Information level: elementary, local, global.

Brodlie’s classification (Brodlie e.a 1992) shares features of both the above mentioned examples: classification on the one hand according to spatial dimensions of the object of visualization, and the order of the data to be visualized on the other hand, i.e. points, scalars and vectors. Recent advances in computer technology have brought forward animation (i.e. series of stills played in rapid sequence) as an excellent way of visualizing *time dependant* feedback values. This is often referred to as feeding back the fourth dimension.

It is fairly easy to see that the above classifications are based on substantially different premises. The reasons for this lie primarily in differences in the goal and function of classification. Frühauf argues, for example, that classification can serve for the comparison of different visualization techniques, or as a scheme for identifying potential new visualization techniques.

The point of departure for determining a suitable classification is formed by the various indoor climate parameters that are to be visualized. These have been in more detail earlier in this chapter (paragraph 5.3) and earlier in this thesis (chapter 2). The five most important factors are: air temperature, air humidity, air pressure, air velocity and radiant temperature. Also relevant are the second order climate effects mentioned in paragraph 5.3.3.
Temperature and humidity are clearly scalars. They have a specific value for each point in the space. Air velocity is on the other hand a vector, because both speed and direction are involved. A combination of various scalars and vectors could be regarded as a tensor. This is not completely correct from a mathematical point of view, because scalars and vectors may indeed be derived from a tensor but arbitrary scalars and/or vectors do not produce a real tensor. However, the visualization of a tensor is not widely different from that of a scalar/vector combination (multidimensional visualization), so the term tensor is usable here.

In conclusion, we can create an overview of possible visualization techniques for depicting scalars, vectors, tensors and multidimensional forms in a three dimensional space. Types which are prima facie non-functional (hence impossible) are not considered. Proceeding from the trio of vector, scalar and tensor, the classification of Demarcelle and Hesselink (Demarcelle e.a. 1994) proves to be consistent with the points of departure based on the indoor climate factors. In that respect, it is worth filling in their classification with the possible visualization types that are eligible for this study (Table 19).

Table 19: Characteristics of Visualization types

Visualization technique:	*Order of data:*	*Definition area:*	*Information level:*
Color Coding	Scalar	Plane	Elementary
Contour Display	Scalar	Plane	Elementary, local
Color-filled Regions	Scalar	Plane	Local
Color Display	Scalar	Point, Line, Plane	Elementary, Local
Iso-surface	Scalar	Volume	Elementary, Local
Vector Field	Vector	Point	Elementary
Streamline	Vector	Line	Local
Vector Field Topology Plots	Vector	Plane	Global
Tensor	Tensor	Point	Elementary

Since the aim of carrying out the evaluation of the different visualization types by reference to the defined criteria is to produce an overview in which the advantages and disadvantages are clearly identifiable, the criteria must be associated with standard ratings. The evaluation of visualization types on the basis of the standard ratings will be explained further for each criterion, thereby providing insight into the reasoning followed.

5.4.3 Scalars

A scalar is a voxel (a 3 dimensional point) in space with a certain value. Temperature is for example a scalar - voxel (x) has temperature (y).

5.4.3.1 Color Coding

Color Coding is a way of producing a rapid overview of the values of scalars on given model surfaces. In the case of a room, for example, this will result in a color for a given surface (wall, floor, ceiling) related to a value of the scalar (Figure 44).

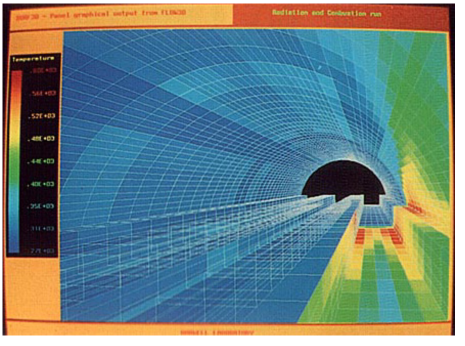

Figure 44: An example of a Color Coded visualization (source: Earnshaw e.a. (ed.) 1993)

Interaction
There is scarcely any prospect of interaction with a model which is visualized by means of color coding. The walls of the model are fixed, so it is impossible to achieve a good understanding of what is taking place in the space (Frühauf 1997).

Integration
Since color coding, uses color, it is not possible to integrate multiple scalars on the same wall surface of the model. Vectors on the wall surfaces of rooms are similarly largely uninteresting, regardless of whether we can expect a correct flow pattern on the wall as a consequence of the wall equations in CFD. However, it is perfectly possible to utilize other visualization types such as isometric surfaces, vector fields etc.

Interpretation
The interpretation of color coding does not present much of a problem. Since each wall of the model is colored in according the value of a certain parameter, it is not difficult to establish the relation between the model wall and the parameter value.

Dimension
Although color coding may be applied to all walls of the model and in this respect may be considered three-dimensional, this does not result in an optimal three-dimensional

impression of the varying value of the parameter. The image may be termed 2.5-dimensional. The remaining half dimension must be reconstructed mentally without further assistance from the visualization type.

Dynamics
Color coding offers no prospect whatsoever of a dynamic image. This is logical enough considering that color coding serves primarily as a means of visualizing scalars, which tend to be constant in a static simulation.

5.4.3.2 Contour Display

Another word for a contour is an *isometric line*, a line which connects points with identical values. Contour display is a widely used technique for representing results in a plane or on a surface (Figure 45). A familiar example of Contour Display is the use of contours on a topographical map, where the isometric lines indicate the height of the terrain.

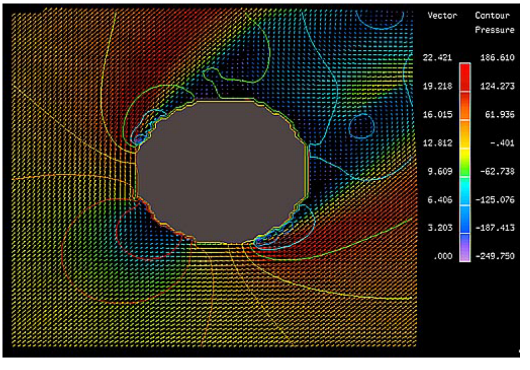

Figure 45: An example of a Contour Display

Interaction
Interaction with a plane on which data is represented by contours is limited to displacement of the plane, allowing the viewer to reconstruct mentally the path of the contours in space.

Integration
Contour display allows the integration of several parameters, because the contours can be visualized together with e.g. a vector field or even a color display.

Interpretation
The interpretation of contour displays can be difficult because although the position of the contours can be seen at a glance, the viewer is obliged to refer back repeatedly to the key in order to establish the exact transition visualized by a contour.

Dimension

Contour display can be applied only in a plane. It is therefore two-dimensional. Extension to the third dimension results into the isometric surface.

Dynamics
Dynamic properties cannot be represented by means of contour display.

5.4.3.3 Color-filled Regions

This visualization technique is an extension of the contour display. In the color-filled regions method, the spaces between the contours are filled with different colors. This improves the legibility of the representation (Figure 46).

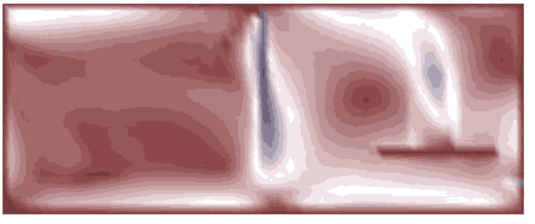

Figure 46: An example of a Color Filled Region

Interaction
Interaction with a plane on which color-filled regions are displayed is limited to displacement of the plane, allowing the viewer to reconstruct mentally the path of the contours in space.

Integration
Color-filled regions provide fewer possibilities (in comparison with contour lines) for the integration of multiple parameters in a visualization plane. Since a colored background has already been utilized, the only remaining possibility is the addition of a vector field.

Interpretation
The allocation of a color to a certain region between two contours makes the interpretation of color-filled regions much simpler than would be the case without the use of color or if continuous color shading without intervening contours were used.

Dimension
Like contour displays, the color-filled regions visualization type is applied primarily in a plane.

Dynamics
Dynamic properties cannot be represented by means of color-filled regions.

5.4.3.4 Color Display

An extension of the color-filled regions technique produces the color display. Instead of contour lines, the colors are interpolated over the surface. This produces more or less smooth transitions of color (Figure 47).

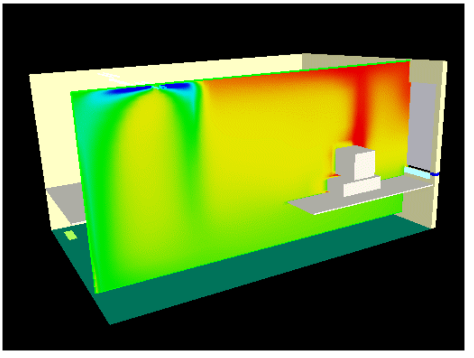

Figure 47: An example of a Color Display

Interaction
Interaction with a plane on which color display is used is limited to displacement of the plane, allowing the viewer to reconstruct mentally the changing values of the visualized parameter in the modeled space (Frühauf 1997).

Integration
It is not simple to integrate multiple scalars in color display planes, because the integration of scalars by means of color is impossible without losing the uniqueness and identity of the scalars concerned. It is however possible to integrate a vector field.

Interpretation
The interpretation of a color display is much of a problem assuming a suitable key is provided. There is however a minor disadvantage to this technique which is chiefly caused by the smooth color transition characteristic of the key of the color display technique (Frühauf 1997).

Dimension
Like contour displays, the color display visualization type is applied principally in a plane.

Dynamics
Dynamic properties of static simulations cannot be represented by means of color display.

5.4.3.5 Isometric surface

An isometric surface is formed by connecting points with a constant scalar value. This produces a volume in the space and a three-dimensional counterpart to isometric lines (Figure 48). Isometric surfaces are represented by means of shading techniques, which can produce a clear picture of the specific form.

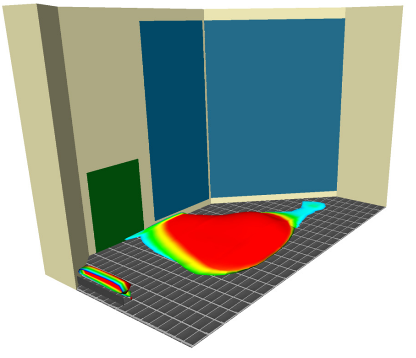

Figure 48: An example of an Isometric Surface

Interaction
Isometric surfaces are more effective than color displays in allowing a viewer to construct a mental image of the changing values of a given parameter in the space by traversing the parameter range.

Integration
Integration can be carried out effectively for isometric surfaces by mapping the color display of a different scalar onto the isometric surface. It is also possible to display vectors on the 'skin' of the isometric surface.

Interpretation
The interpretation of isometric surfaces is to some extent simple and unambiguous, but it is possible for one part of an isometric surface to pass in front of another, thus preventing the user from obtaining a full view of the surface. One solution to this is to use a degree of transparency.

Dimension
The isometric surface can be confidently classed as a three-dimensional visualization type.

Dynamics
Using the successive tones of all isometric surfaces within a given parameter range, not only gives insight into the disposition of the values through the space, but also conveys a certain impression of the dynamic character of the airflows in the space.

5.4.3.6 Icons

The icon is something of an oddity in the series of visualization methods for scalars. This is largely due to the fact that an icon makes it possible to visualize several dimensions in a single object, as stated by Crawford and Fall in (Nielson e.a. (ed.) 1990):

"We can use glyphs [icons] effectively, however, when we must encompass more than three dimensions in the display."

Well-known examples of multidimensional icons include the sunflower plot and the Chernoff face. The sunflower represents scalars as radial 'petals' lines of specific lengths. The Chernoff face is a schematic human faced in which the size and shape of features such as the eyes, nose and mouth represent values in the data set (Figure 49).

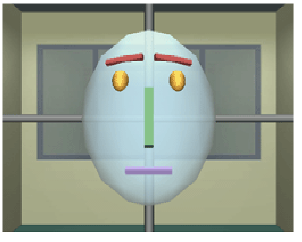

Figure 49: An example of an Icon

Interaction
It is sufficient to allow the user to move the icon freely through the space and thereby visualize the values of the variables at any point.

Interaction
Icons are an effective way of integrating multiple dimensions into a single object, as explained above.

Interpretation
The quality with regard to interpretation varies with the icon and depends strongly on the quality of its design. It is moreover impossible to fill the space with icons in a way similar to planar representation methods (Frühauf 1997). This problem can be overcome only by limiting the number of icons displayed to at most a few per space.

Dimension
Because it derives from the 'scatterplot', the icon is point-oriented or one-dimensional. It is however possible for the area represented by the icon to be much larger than a single point.

Dynamics

In principle, the icon as such is not particularly dynamic in a static data set. The addition of oscillatory motions may make it possible to impart a measure of dynamism to the icon.

5.4.4 Vectors

A vector is a voxel with a specific size and direction. Air velocity is a vectorial variable: voxel (x) has direction (y) and magnitude/speed (z) (Post e.a. 1994).

5.4.4.1 Vector Field

A usual method of representing vectorial data is the 'vector arrow'. The arrows are disposed on a grid and each given length and direction to present a picture of flow magnitudes and directions in a given plane (Figure 50). This is applicable to 2D planes and to some extent to 3D volumes.

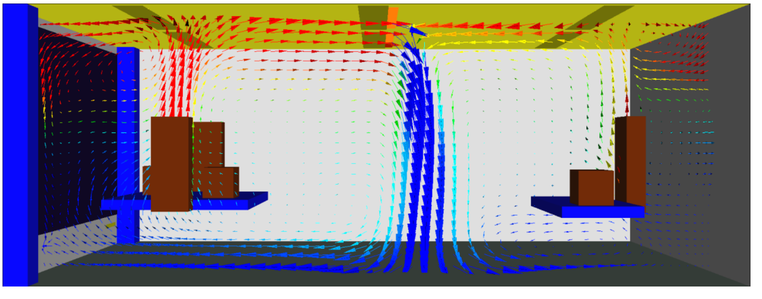

Figure 50: An example of a Vector Field

Interaction
Interaction with a plane on which a vector field is displayed is limited to displacement of the plane through the space.

Integration
A vector field allows the integration of multiple parameters because the vector arrows can be combined with scalar representations such as contours or even a color display.

Interpretation
The interpretation of a vector field has its strengths and weaknesses. An advantage is that it presents a clear picture of flow directions as well as their local and general magnitude. A disadvantage is that if the cell size widely varies, the small cells tend to dominate the display excessively due to the compression of the vectors.

Dimension
Vector fields are applicable only in two-dimensional situations, because in three-dimensional situations they are prone to occlusion (Frühauf 1997),

Dynamics
Since a vector field provides insight into the trajectory of airflows, a certain amount of dynamic information is legible from the image.

5.4.4.2 Streamlines

Linking certain properties of successive vectors with a polyline produces a ‘streamline’, which provides insight into the path of a flow. This makes it possible to visualize a complete trajectory or to show how far a stream reaches within a given time (Figure 51). It is also possible to link two streamlines and thus create a *streamband*. The streamband can be used to give an impression of the twisting of a stream.

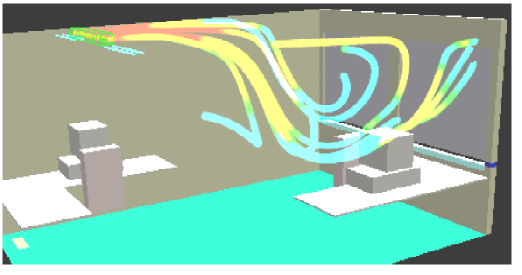

Figure 51: An example of visualization with streamlines

Interaction
Interaction with a set of streamlines will generally consist of the positioning of the origin from which the streamlines depart.

Integration
Coloring makes it possible to represent an additional scalar on the streamline.

Interpretation
The interpretation of the trajectory of streamlines can be severely impeded where streamlines cross because it is unclear which streamline passes behind the other (Sadarjoen 1999).

Dimension
A streamline may follow a path through the entire data set. They are thus fully three-dimensional.

Dynamics
Since streamlines follow air currents, they give a substantially dynamic picture of the data.

5.4.4.3 Particle Tracks

We can gain insight into the patterns of airflow by releasing ‘particles’ into the current and continuously calculating and displaying their individual positions. The particle track can be regarded as a dynamic form of the streamline, which takes on a definite form once calculated and is thus static. The particles appear, however, to flow through the space. The result is a very close approximation to the viewer’s natural image of a current. The particles are not subject to gravity or Brown’s motion but follow the flow-lines of the air.

Interaction
A common kind of interaction with particle track visualization is to allow the user a free choice of the source of particles. This offers a highly interactive way of exploring the data set.

Integration
The particles can be enhanced with scalar information by the addition of color. They also give a clear picture of the velocity of the current at a given position. The particles can be made to oscillate in order to represent turbulence. There are thus ample possibilities for integration.

Interpretation
Particle tracks visualize the otherwise invisible paths that packets of air follow when flowing through a space. It closely resembles the methods of real-life airflow analysis experiments where smoke or small fluid bubbles are released into an airflow. The simplicity of the method facilitates an easy interpretation while the display of the particles shows (relative) air velocity, direction and flow patterns in a single image.

Dimension
Particle tracks map the entire data set and thus provide an instructive 3D image of the flow in a space.

Dynamics
For particle tracks, the resulting picture of flows in the space is a highly dynamic in character since the velocity of the flow is converted directly and intuitively into the motion of the particle.

5.4.4.4 Topology Plot

One method of making vector fields more comprehensible is vector field analysis. This method involves identifying points in the field where the flow speed is zero. Helman and Hesselink, who both advocate vector field topology, describe it as follows (Nielson e.a. (ed.) 1990):

“In fluid flows, we can determine (assuming a particular frame of reference) critical points in the flow. These are points where the velocity vanishes. The critical points,

connected by principal lines or planes, determine the topology of the flow." (see also Figure 52)

In the same article, they explain why they intend to seek better methods of visualizing the flows in a data set as follows:

"Interpretation of large, multidimensional vector fields is a difficult task, and presently available techniques are not adequate. The difficulty stems from the inability of the human visual system to assimilate displays containing a large number of vectors or curves."

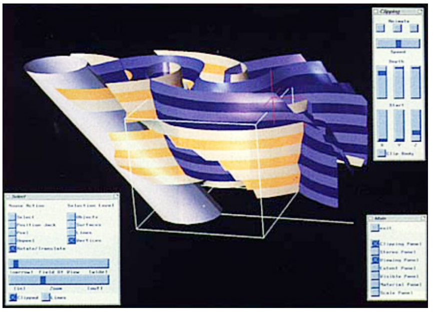

Figure 52: An example of a Topology Plot (source: Nielson e.a. 1990)

Interaction

Interaction with a topology plot is non-existent. The critical points are first determined, and the topology of the flow is then calculated by various algorithms. This produces a specific outcome with which further interaction is impossible. After all, the flow topology is fixed. However, interaction with a vector field topology plot is actually unnecessary. A good topology plot already displays the main features of the flow space, so the display of additional features - one of the motives for interaction - is largely unnecessary.

Integration

The integration of further parameters in a topology plot visualization is feasible because many other visualization types can be displayed simultaneously with the topology plot.

Interpretation

With regard to the interpretation of flow characteristics, the topology plot is superior to curve displays and, to a lesser extent, to particle tracks. The latter visualization techniques have obvious merits, particularly in displays of multiple curves or particle tracks, but the displays are more difficult to interpret. Topology plots avoid this drawback.

Dimension

Since the topology plot consists of three-dimensional planes and lines, it has powerful 3D qualities.

Dynamics
The topology plot presents a static picture of the dynamic properties of the flow. Particles could conceivably be deployed on critical lines to enhance the dynamic impression, but no examples of this have been found in literature. Without this technique, the topology plot is less than optimally dynamic.

5.4.4.5 Vortices

The vortex opens up an interesting phenomenon of fluid flow which plays a very significant part in many areas of science. It can therefore be useful to go into the detection and visualization of vortices more deeply here. Vortices are among the most important features in fluid flow engineering (Sadarjoen 1999) (Figure 53).

Vortices thus play an important part in the study of flow behavior. Minimization of vortices is important when designing e.g. and effectively streamlined car. The control of vortices is similarly important in the effectiveness of aircraft wings. Fluid dynamics research takes a considerable interest in the creation and interaction of vortices because they are important in the development of turbulence.

In interior climate control, too, the vortex is an important phenomenon. The presence of sufficient vortical motion in an air stream is necessary for the effective ventilation of a space. Evaluation of the properties of a vortex is thus highly recommended for designing environmental conditions in spaces.

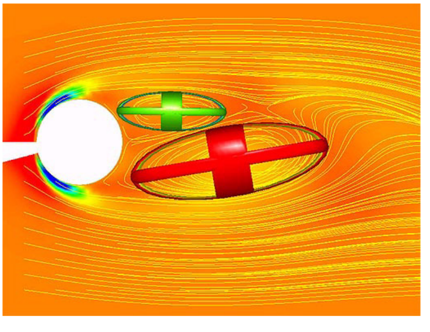

Figure 53: An example of a visualization of vortices (source: Sadarjoen 1999)

Interaction
From the point of view of interaction, the same applies in principle to the vortex as applies to the topology plot. Since a vortex is determined by physical, algorithmic or geometric methods, and is only changed if the flow pattern in the space is changed, no direct interaction is possible with a vortex. We can only choose whether to display vortices or not.

Integration
Although the visualization of vortices (for which there are many possibilities) leaves scarcely any room for the integration of other parameters, the simultaneous visualization of a vortex and other visualization types is realizable.

Interpretation
The interpretation of vortices depends strongly on the type of visualization used. A formal approach using a circulating flow of particles is also worth considering.

Dimension
Since a vortex can be considered as an elliptical form in space, a three-dimensional visualization is obviously suitable.

Dynamics
Although the vortex is a highly dynamic phenomenon, it does not generally make a strikingly dynamic impression when visualized. Accompaniment by particles or streamlines can enhance this considerably, however.

5.4.5 Tensors

A tensor, finally, is a vector that not only has magnitude and direction but several further degrees of freedom in relation to the surrounding voxels: a voxel (x) has deformation (y), tension (z) and curvature (a). The term ‘tensor’ originated in linear algebra, and is widely used in describing physical phenomena that have multiple degrees of freedom.

Tensor fields occur in e.g. CFD and in Finite Element Stress Analysis (Brodlie e.a. 1992). A feature of tensors is that multiple effects can be derived from them. In strength calculations, for example, torsion, bending etc. are termed second order effects (Figure 54). The visualization of such effects is very interesting but fairly complicated. The second order effects often have to be converted into scalars which are then displayed with several dimensions simultaneously.

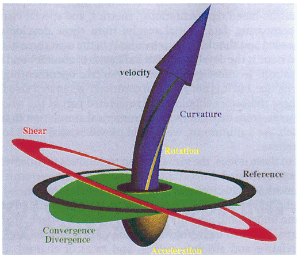

Figure 54: An example of a Tensor (source: Rosenblum e.a. 1994)

Although the visualization of tensors has interesting aspects, such as displaying multiple dimensions in an object, no evaluation can be accorded to the tensor in the context of Via3D. This is due, on the one hand, to the fact that tensorial properties (slip, deformation, etc.) are not found to occur in the indoor environment. On the other hand, the icon is considered to correspond adequately to the tensor, since it is capable of representing several dimensions of an object simultaneously.

5.4.6 Results

Table 20 summarizes the results of our evaluation of the various visualization types for comparison purposes.

Table 20: Qualification of Visualization types

Key: – – = very poor, – = poor, o = usable, + = good, ++ = very good

Criteria / *Visualization type*	*Interaction:*	*Integration:*	*Interpretation:*	*Dimension:*	*Dynamic:*
Color Coding	-	o	o	o	- -
Contour Display	o	+	-	o	- -
Color Regions	o	o	++	o	- -
Color Display	o	o	+	o	- -
Iso-surface	+	+	+	++	+
Icon	+	++	++	-	-
Vector Field	o	+	o	o	+
Streamline	+	+	o	++	+
Particle Track	+	+	+	++	++
Topology Plot	-	+	+	++	+
Vortex-icon	-	+	+	++	+

Notes:

Diversity

The evaluation of the visualization types using the various criteria reveals the strengths and weaknesses of many kinds of visualization. However, simply adding up and subtracting the positive and negative attributes will not produce an optimal set of visualization types. There are too many differences between them to allow direct comparison. An isometric surface, for example, is scarcely interchangeable with an icon, for while icons are outstanding from the point of view of integration, isometric surfaces excel on account of their good three-dimensional properties. If equal weight is also given to the weaknesses, the optimal visualization method will turn out to be a compromise which scores ‘good’ on all criteria but ‘very good’ on none.

Context

On account of the diversity, it is important to perform the evaluation in such a way that the context in which a visualization method is used is integrally considered in the eventual evaluation. This is the only we can do justice to the strong points of a visualization type, since it is quite conceivable that its weaknesses will not be relevant in a specific context.

Some conclusions that may be drawn as a result of the analysis of scientific visualization are:

- The isometric surface method and the particle track method stand out as performing well on all criteria.

- Different visualization methods can be assessed for their strong and weak points on the basis of precisely defined criteria.

5.5 Applied visualization of indoor climate

The goal of a combination of the analysis results from the two previous paragraphs (indoor climate factor and scientific visualization) is to provide insight into the merits of a specific visualization type for visualizing a certain factor of the indoor climate (either 1st order or 2nd order). On the basis of this synthesis it can be concluded which visualization types are broadly applicable and which are not. The relevant combinations of visualization types and factors will be accompanied by a revealing example.

The synthesis offers the possibility of drawing further conclusions with regard to three matters relating to the relation between *visualization type* and *factor.*

- Relevance
- Applicability
- Verification.

The synthesis is the outcome of combining the analysis of visualization types and of factors in the following manner (Table 21). In the factor analysis, it is decided per factor which criteria are relevant and which are not. Score of non-relevant criteria are not counted in the synthesis. The scores of the relevant criteria are summed up, with a '- -' score being converted into '-2', '-' equals '-1', 'o' equals '0', '+' equals '+1' and '++' equals '+2'. This modus operandi results in a total number which indicates the strength of a visualization type for the visualization of a given factor (NR= not a relevant combination.

Table 21: Matching of Visualization types with indoor climate

	Visualization type										
Climate factor	Color Coding	Contour Display	Color Regions	Color Display	Iso-surface	Icon	Vector Field	Streamline	Particle Track	Topology Plot	Vortex-icon
Air temperature	-1	-1	2	1	4	2	NR	NR	NR	NR	NR
Radiant temperature	0	-1	2	1	1	2	NR	NR	NR	NR	NR
Air humidity	-1	0	2	1	5	4	NR	NR	NR	NR	NR
Air velocity	-3	-2	0	-1	6	3	2	5	7	4	4
Air pressure	-1	-1	2	1	4	2	NR	NR	NR	NR	NR
Temperature gradient	0	-1	2	1	3	1	NR	NR	NR	NR	NR
Radiant asymmetry	0	-1	2	1	3	1	NR	NR	NR	NR	NR
Turbulence	-3	-2	0	-1	6	3	2	5	7	4	4
Draft	-3	-2	0	-1	5	2	2	4	6	5	5
Airflow pattern	-3	-2	0	-1	6	3	2	5	7	4	4
PMV	-1	0	2	1	5	4	NR	NR	NR	NR	NR
Coanda effect	-2	-3	0	-1	4	0	1	3	5	4	4
Downdraft	-3	-2	0	-1	5	2	2	4	6	5	5

When the corresponding score is more than 0 the visualization type should be relevant for the indoor climate factor. However, this would make a wide range of visualization types eligible, making it impossible to draw clear conclusions from the analysis. A reasonable solution for this situation lies in raising the relevance limit to a score of 4 in the total table. The choice of 4 as a limiting score is based on the assumption that a visualization type with a score of 4 must score positively on at least 3 criteria. Only then the *visualization type/factor* relation is really relevant.

This assumption may be verified by checking whether combinations with a score of 3 also score positively on 3 or more criteria. This proves to be true in only 23% of cases. The score on the remaining criteria is in these cases very poor. The last constitutes a good extension to the conditions for relevance. Those visualization types that score positively on 3 or more criteria and negatively on less than 2 become relevant. Verification of types scoring 4 or more shows that they satisfy this condition in 100% of cases. Relevance is a precondition for the elaboration of the visualization of a factor with an example. This does not however imply that less relevant types are not usable.

5.5.1 Applicability

Regarding the breadth of applicability of a visualization type, a limit must be defined above which it may be assumed that a visualization type is broadly applicable. This limit may be related to the total score of the various visualization types. This score is produced by summing the individual scores per factor.

Broad applicability means, on the one hand, that the visualization of multiple factors is feasible. On the other hand, it indicates that a visualization type is more than averagely applicable in relation to other types.

The average score for all types is 20 points. Types that score significantly higher than 20 may thus be regarded as broadly applicable. The visualization types concerned are as follows:

- Iso-surface (62)
- Icon (31)
- Streamline (30)
- Particle Track (44)
- Topology Plot (31)
- Vortex-icon (31)

5.5.2 Results

- With regard to relevance, all factor visualizations (combinations of visualization types and factors in the synthesis table) scoring 4 or more may be considered relevant. This implies that they will be subject to further verification as part of the Via3D study.

- With regard to applicability, the visualization types *icon, isometric surface, streamline, particle track, topology plot* and *vortex-icon* may be considered broadly applicable. This means that they can be applied more broadly than average (in relation to other visualization types) for visualizing factors.

5.5.3 Indoor climate visualization examples

The verification of relevant visualization types that can be applied for the visualization of factors involves checking whether a score of 4 or more in the synthesis table can indeed be transformed into a realistic visualization of a factor. A distinction must be made for this purpose between a direct and an indirect application. In a direct application, the factor can be displayed directly using the visualization type concerned. This is not possible for an indirect application. Integration must then be sought with the visualization of another factor in such a way that the integrated factor is nonetheless clearly visualized.

In cases where a factor can be visualized neither directly nor indirectly, it becomes necessary to seek an explanation for this. Various alternatives present themselves here. One possibility is that the criteria do not do justice to the specific properties of a visualization type. Consequently, no relevant application can be thought up although all criteria are met. Another possibility is that the criteria have not been correctly evaluated. This must be scrutinized critically, since it could make or break the method followed. It is also conceivable that although the synthesis suggests promising potential for certain visualization types, the present state of science and computational techniques do not make it possible to achieve a satisfactorily functional visualization. Finally, there is a possibility that a certain factor visualization seems ideal on the grounds of the synthesis table, but that on further exploration the results seem fairly unremarkable; or worse, that it becomes immediately obvious that the results will be disappointing.

5.5.4 Isometric surface

5.5.4.1 Air temperature

The isometric surface of air temperature presents a clear picture of varying temperatures throughout the space. In many cases it also reveals the principle airflows (Figure 55).

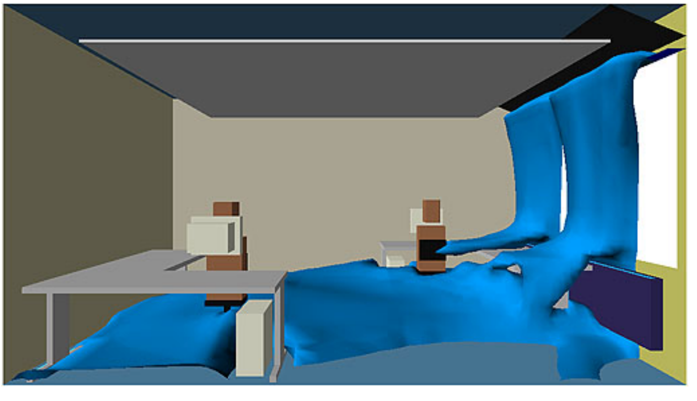

Figure 55: Visualization of Air Temperature using Isometric surfaces

5.5.4.2 Air pressure

The isometric surface of air pressure produces volumes which indicate where air pressure is, for instance, 0 (zero) $N^1 \cdot m^{-2}$. The limitation of this specific visualization lies in the ambiguity as to whether the zone between the two planes has higher or a lower pressure. Figure 56 combines an isometric surface with a color display and represents the pressure variations in the space.

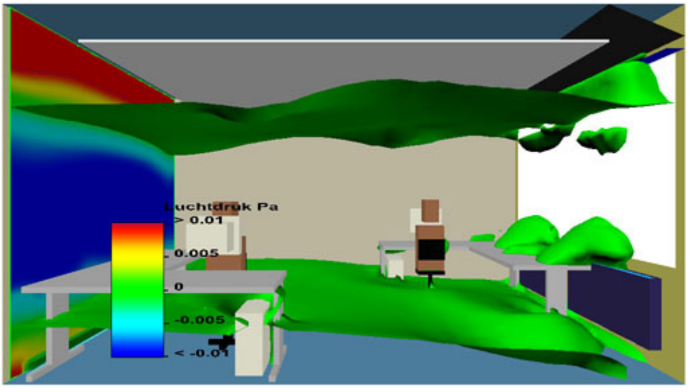

Figure 56: Visualization of Air Pressure using Isometric surfaces

5.5.4.3 Downdraft

Downdraft refers to airflow of relatively low temperature in a vertical direction. This occurs mainly adjacent to a glazed area in an external wall. Figure 55 shows that this can be effectively represented by an isometric surface.

5.5.4.4 Draft

The visualization of draft by an isometric surface is feasible, but the correct formulas must be used for this purpose (Figure 57). Draft is the combined result of a certain temperature and a certain air speed. Turbulence is also involved. It proved difficult to incorporate the necessary algorithms for this into VIA3D. It is therefore recommended that future research should go into this subject more deeply.

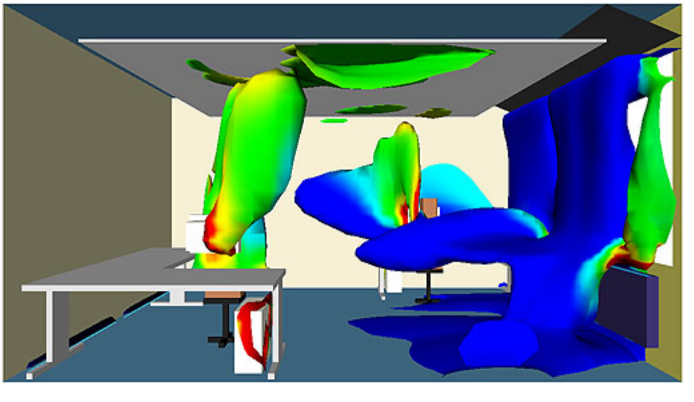

Figure 57: Visualization of Draft using Isometric surfaces

5.5.5 Streamline

5.5.5.1 Air velocity

Since air velocity is a vectorial datum, both its direction and its magnitude must be displayed by the visualization. Streamlines are not directly capable of indicating the magnitude of a vector. Displaying air velocity using streamlines can therefore only be done indirectly. Once indirect representation is accepted as an approach, various options are open. One of them is to represent air speed by the thickness of the streamline. The thicker the line, the slower the flow. The disadvantage of this approach is that adjacent streamlines could occlude one anther. It is therefore better to make use of color for this purpose. A given color denotes a given speed. With regards to the visualization key, color provides a more reliable instrument than thickness which is prone to perspective distortions (Figure 58).

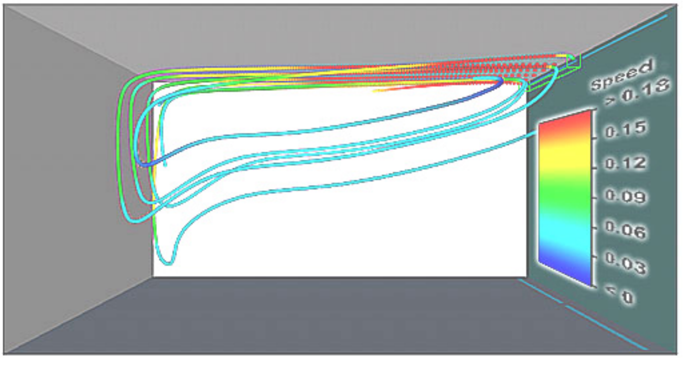

Figure 58: Visualization of Air Velocity using Streamlines

5.5.5.2 Turbulence

The same remark applies to the visualization of turbulence as to that of air velocity: streamlines are only indirectly capable of displaying turbulence in the space. Color is an excellent adjunct. A drawback is that the streamlines follow their own path through the space. Zones with high turbulence could thus remain invisible. Analysis is therefore required to determine the optimal placing of the streamlines (Figure 59).

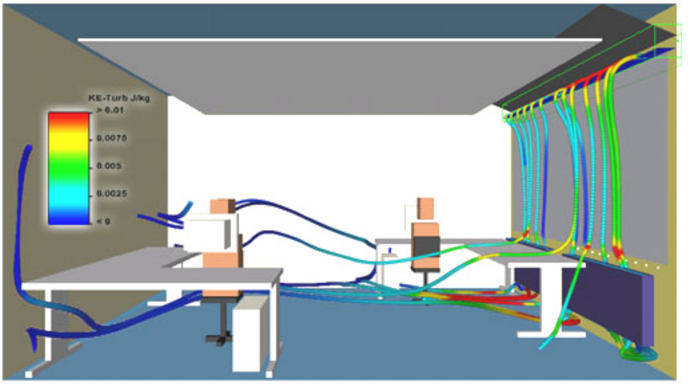

Figure 59: Visualization of Air Turbulence using Streamlines

5.5.5.3 Draft

Since draft is a second-order factor which depends on several other factors (air velocity, air temperature and turbulence), its visualization by streamlines could sometimes prove difficult. Streamlines are not well suited to the simultaneous representation of the multiple factors that contribute to draft. However, the separate visualization of the contributory factors is not strictly essential. Draft alone is sufficient, and color can convey something about the intensity of draft in a given zone in conjunction with the indirect use of streamlines (Figure 60).

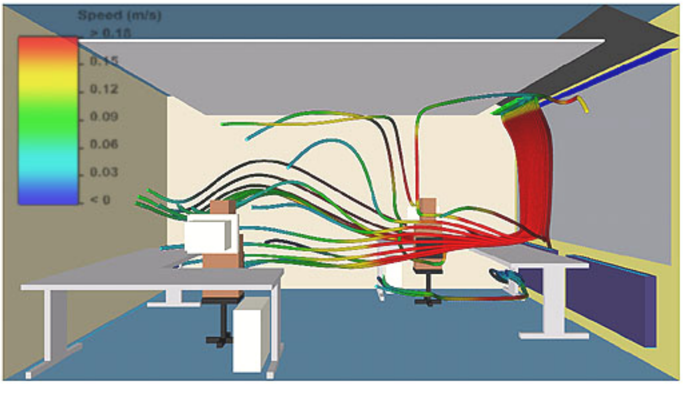

Figure 60: Visualization of Draft using Streamlines

5.5.6 Particle track

5.5.6.1 Air velocity

Air velocity can be visualized directly using particle tracks. This is possible because the distance between adjacent particles conveys information about the velocity of the airflow.

As for streamlines, the position of the particle source is essential for interpretation. It is generally sufficient to place the source in front of the air inlet. In many cases, however, matters will be less simple. Further research is required in these instances. The research could consist simply of trying out various positions for the source. Analysis methods could conceivably also be developed which would replace the trial-and-error approach and propose an appropriate place for the particle source on the basis of the properties of the data set.

5.5.6.2 Airflow pattern

Particle tracks are an excellent way of visualizing airflow patterns. This is principally due to the realistic quality of this visualization type. The idea of flowing particles is easily associated with the subjective experience of airflow.

For airflow patterns, as for the visualization of other factors, the positioning of the particle source is critical to correctly displaying the airflows in a space. The positioning of the source requires considerable experience, but manual positioning may be replaced in the future by analysis of the data set using suitable algorithms (Figure 61).

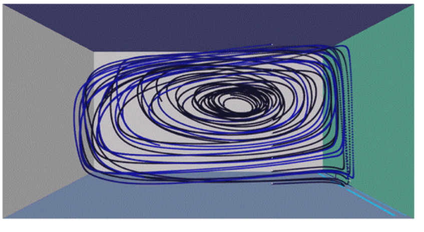

Figure 61: Visualization of Airflow Patterns using Particle Tracks

5.5.7 Icon

5.5.7.1 Air humidity

Air humidity is in the light of the analysis a suitable factor for visualization using icons. However, since no other examples of this are known, it was decided to design a personal variant. A water droplet was used as a metaphor for this purpose because it is readily associated with the idea of moisture. This has been colored green. The size of the droplet shape indicates the risk of condensation at the locus concerned.

5.5.7.2 PMV

An iconographic representation of the PMV in space was sought at an early stage in the Via3D study. Various possibilities for this proved available. The scientific literature presents several different icon forms, although it is of course possible to design ones own icon. Known examples of multidimensional icons are the *sunflower plot* and the *Chernoff face*. The sunflower visualizes scalars by assigning corresponding lengths to radial lines thus generating an image. The Chernoff face operates as follows (Nielson e.a. 1990):

"When displaying a scatterplot composed of such faces, each data point is a stylized drawing of a human face, with the size and shape of facial structure - nose, ears, eyes and so further - representing variables in the analysis." "The human gift for recognizing and integrating features associated with facial structure enables analysts to digest a scatterplot displaying a large number of dimensions."

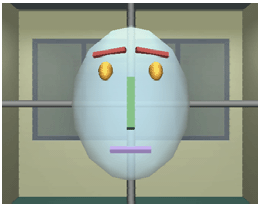

Figure 62: Visualization of the PMV using an Icon

The Chernoff face can be regarded for the above reason as one of the most powerful icon types. The Chernoff face is particularly in its element in datasets such as that represented in Figure 62. Localized deviations in the dataset can be quickly and effectively traced by the changing facial expressions. However, matters are rather more complicated in a three-dimensional environment. In this case it is not possible to fill the whole space with icons analogously to the plane display.

When we combine the necessity for user interaction with the Chernoff face icon, the result is an element in the form of a face that can be freely maneuvered through the space. The *Chernicon* (Chernoff face icon) a newly developed visualization type that combines the indoor climate parameters that make up the PMV. These parameters were linked to different facial features of the Chernicon, with an attempt being made to establish metaphorical connections between the image and the parameters. *Radiant temperature* is associated with the size of the eyes. This agrees with the human response to intense radiation, to close the eyes. *Air humidity* is associated with the nose. When the air is dry, it is primarily detected by the mucous membranes in the nose, producing a dry sensation. *Air velocity* is associated with the overall size of the face. In a strong wind, people tend to screw up their faces to protect themselves from flying sand or other matter. *PMV* is associated with the total form of the Chernicon itself. This was done consciously between the main shape is the first aspect of the Chernicon which will be conceived. It can thus communicate immediately whether the PMV is positive or negative. A disadvantage is that the ellipsoidal shape of the face can only be appraised properly in a frontal view, for when viewed diagonally from above it could resemble a sphere.

5.5.7.3 Airflow patterns: Vortexicon

The visualization of the indoor environment by means of Vortexicons is restricted to the factor airflow patterns. This is because interesting vortices occupy large zones of the space, since an effective vortex is of great value for efficient ventilation. Few architects presently take any interest in the small vortices that occur due to drafts and the Coanda effect. The visualization of these vortices cannot be considered worthwhile at present.

For the visualization of vortices, contact was sought with the Computer Graphics group of the ITS (TU Delft). Researcher F. Reinders provided an introduction to vortices, vortex visualization and automated detection methods that could be broadly employed (Reinders 2001). The detection of vortices is currently the subject of intensive research and is an area in which the ITS group has been successfully active. The detection methods have not however reached a level for application in practice such that our research could readily implement them. Rather, we make use of the theoretical approach that produces the detection and visualization.

For this purpose, we used streamlines which circulate for several rotations through the space. This can be checked analytically, making it possible to draw conclusions about the magnitude of the vortex. Figure 63 illustrates this approach. An evident next step would be to replace these streamlines by something else, e.g. icons. This opens up the possibility of abstraction, while at the same time it would be possible to communicate further properties of the vortex by means of color or shape.

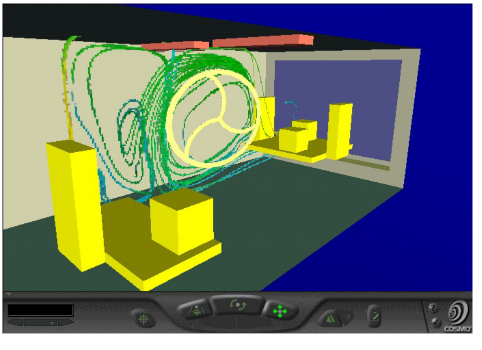

Figure 63: Visualization of Airflow Patterns using a specialized Icon

Since vortices in simple spaces usually have a reasonably constant cross-section, a two-dimensional icon has been adopted. The magnitude of the vortex is broadly indicated by the size of the icon. The revolving spokes (visible in animate versions of the figure) indicate the approximate speed of rotation and their curvature indicates the direction of rotation.

5.5.7.4 Climate and Services interaction: Identicon

It is important when viewing a visualized simulation to be able to see the actors such as air inlets, exhaust and sources. However, that alone is not enough. Their influence on the indoor climate is significant as well, since the actors jointly determine the factors of the indoor environment.

A type of icon known as an *Identicon* has been designed for the purpose of designating the identities of the actors in a given space and representing their effects. An identicon is an icon which represents the identity of an actor (air inlet, exhaust etc.). This is necessary in order to give designers better insight into the interaction between building and indoor environment.

The points of departure for an identicon are as follows:

1. Good visibility
2. Clearly related to a specific actor
3. Evidently distinguished from the interior of the space
4. Indication of the indoor climate factors influenced
5. Indication of the direction in which influence takes place (particularly with regard to radiation and air velocity)
6. Linkage to parameters of actor.

Relation to actor
The basic form of the identicon consists of a support in the shape of a bracket. The various elements are given a place on this. The shape of the bracket produces a clear relation between the identicon and the actor to which it is attached. For example, this could be a window pane, radiator or exhaust grille. In all cases, the identicon will start and end, by means of the bracket-shaped carrier, on one of the surfaces of the actor. This results in a clearly visible unity between them, so that there can be no confusion about the origin of the identicon.

Distinction from the space
Besides the face that a bracket establishes a clear relation with the actor, the parabolic support forms an obvious contrast with the generally orthogonal space. This is very important, because it must be clear in advance to the viewer that the identicon conveys

information about the function and influence of the actor, and the identicon must not be mistaken for an arbitrarily placed interior element.

Relation to the indoor environment factor

Sphere shape elements are mounted on the bracket and constitute the core of the identicon, for they are the intermediary between the function of the actor and the viewer's perception. The choice of the sphere shape was deliberate: it is the only conceivable form which presents the same image regardless of the angle from which it is viewed. The coloring of the spheres of the identicon is as follows:

- Air temperature: red
- Radiant temperature: orange
- Air velocity: purple
- Air humidity: green

Direction of influence

In the case of air velocity and radiation, it is important to establish in which direction they operate. The spheres, which represent scalars only, are, due to their uniformity with regard to direction, incapable of displaying vectorial information in the form of a direction. It is therefore necessary to provide additional elements to the basic identicon concept so that this important information can be displayed.

Link to parameters

When examination of the visualization reveals the influence of an actor on the indoor environment factors, it may become desirable to obtain more information about the parameters of the actor or to modify them, in order to clarify the spatial concept. Since the identicon is to be applied in a Internet environment, it is fairly simple to attach a link to each of the spheres. This link can lead to the input side of the Meta Design environment, where the parameters of an actor may be adjusted.

The design and application identicon is shown below. It can have various guises. This is very important because the identicon is intended to give the viewer insight into the influence and function of the actor to which it is attached. The representation of the influence of the various indoor environment factors is derived from what is termed the actor table, in which each influence is broken down by indoor environmental factors.

To give an impression of the possible visualizations which ensue, a number of variants have been combined in the figure below. Where no influence is exerted on a given indoor environment factor, the respective sphere is uncolored (grey). The more influence an actor exerts, the more saturated is the associated color. This enables the viewer to identify the main 'culprits' at a glance from the color. This is an important property with regard to design support, since this allows problems to be tackled at their sources.

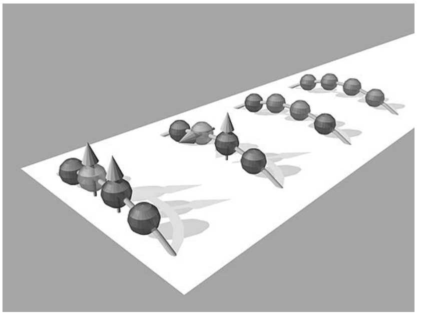

Figure 64: Visualization of Actor Properties using a specialized Icon

5.6 Findings

We concluded that the visualization types icon, isometric surface and particle track may be regarded as broadly applicable for the visualization of indoor climate. All three types have the flexibility to be configured according to the requirements of individual projects. The isometric surface and the particle track are the most relevant of all visualization types for visualizing the indoor climate. These two types have distinct geometric properties that provide a reduced view of complicated phenomena such as temperature distributions and airflow.

Icons are valuable for visualizing various abstracted and integrated statements of the indoor climate quality because of their capacity for integrating multiple dimensions. Icons can be designed to have geometric properties that facilitate specific project demands. An example is the Identicon (paragraph 5.5.7.4) which displays actor properties in a way that is closely linked to installation equipment. Another example of the Vortexicon that was designed to display the size and direction of the dominant airflow. The interpretation of these airflows in a space can be simplified by using the visualization of vortices. The linkage of color as an identity to an environmental factor produces a clear key visualization. Color can easily quantify the spatial representations produced by using isometric surfaces and particle tracks.

Local visualizations offer designers the possibility to determine the level of detail and the climate aspects that should be displayed. For example, using particle tracing, it is possible to identify both global and local airflow characteristics (Post e.a 1993). Placing particle sources for air-inlets, contamination sources and windows gives much insight in the three-dimensional behavior of air within spaces. This type of visualization also has the characteristic of pointing to relations between building properties and indoor climate aspects. 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 a prolonged period of time, 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 in important zones.

Visualization also provides presentation of multiple indoor climate aspects simultaneously. This compresses several or all performance parameters into a single image. The resulting image can help designers to quickly browse through all indoor climate performance aspects of their design. Higher order indoor climate effects such as draft and gradients can also be fed back using these integrated images. The visualization aids in identifying these aspects by finding and displaying the combinations of indoor climate parameters that typify these effects. This helps designers in determining which indoor climate aspects are present in their design.

As a recommendation, research into the visualization of air contamination in the indoor environment will be highly complementary to the present study. Also, the development of algorithms for the calculation of draft on the basis of the CFD results will enable a more precise visualization of draft. At present, turbulence is uncovered by using rules-of-thumb.

6 Design Analysis

This chapter will present a design method that can be used to use the benefits of the environment without adapting the entire design process to accommodate for indoor climate. Users should be able to employ this method parallel to the conventional design procedure. This means that an additional effort by architects is only required when the need to measure and steer the indoor climate arises. The Meta system will perform most of the laborious and time-consuming information processing tasks such as performing the necessary calculations and preparing the feedback. Still, because designers are on tight time schedules, they are likely to require some guidance on exactly which design aspects need evaluation in order to prevent them from meticulously trying all system possibilities.

The descriptive approach followed in the development of the Meta Design environment excludes the use of design directions or methods that exhaustively dictate how indoor climate related design moves must be made in the design process. Instead, we looked for ways to facilitate a broad range of design methods and approaches. The solution lays in common elements that can be found in many design processes. These common elements are objects or aspects that all buildings or spaces have and are very likely to be addressed in some way at some point in the process. The Meta design analysis method identifies these anchor points within the traditional design process and links them to common indoor climate issues. The combination of recognizable design elements with a limited set of indoor climate problems and issues could lower the threshold for performing analysis. Instead of randomly performing an analysis and searching the result for usable information, the analysis method quickly scans the design for indoor climate performance and provides conclusions whether indoor problems are to be expected. In addition, designers can choose individual aspects that they deem relevant and vary their designs to determine its sensitivity.

6.1 Climate analysis in building design

Climate factors

Chapter 5 argued that in order to support architectural design, a qualitative visualization of the indoor climate parameters is desirable. In order to provide these types of climate visualizations, the values of the indoor climate parameters of, for instance, thermal and olfactory comfort must be known. Chapter 2 introduced the tools that can be used to predict these parameters. It also made clear that manually producing these parameters during design is difficult and that performing laboratory experiments is expensive. For the early design stages, a more appropriate solution is using CFD en Thermal Simulations (TS) to predict the climate parameters of designs. Given the correct input, these simulation tools can provide projections of the thermal and olfactory parameters at any point in time or at any location in the building (Table 22).

Chapter 5 elaborated on the parameters of the indoor climate. In addition to the first order climate parameters that consist of physical properties of the air inside spaces and of wall material, second order climate *effects* also influence inhabitant comfort. These effects can consist of combinations of first order parameters and/or include dynamic (time-dependent) phenomena. The second order effects are usually not immediately clear from the basic simulation outcomes. It requires either a designer or a computer algorithm to infer the presence and severity of second order climate effects from the first order parameters. The detection of, for instance, temperature gradients involves temperature measurements at various locations in a space and finding a difference of several degrees. The temperature simulation software can automatically determine temperate exceeding during a certain length of time in a building. CFD simulation has the ability to assist the research of dynamic indoor climate phenomena such as temperature oscillations and turbulence. The most important indicator of the level comfort provides inside buildings, the Predicted Mean Vote (PMV), is best calculated using long-term (yearly) indoor temperature profiles. The PMV values can be used to determine code compliance such as the ARBO decree (paragraph 0).

Table 22: Indoor climate parameters and analysis

Key: CFD = Computational Fluid Dynamics, TS = Temperature Simulation

Indoor climate parameter:	*Provided by:*
Air Temperature (A_T)	CFD, TS
Radiant Temperature (R_T)	CFD, TS
Air Velocity (A_V)	CFD
Relative Humidity (RV)	TS
Ventilation Rate (N_V)	CFD, TS
Pollution concentrations (C_P)	CFD (when modeled)
Higher order climate effects:	*Provided by:*
Draft	CFD
Downdraft (cause: cold surfaces)	CFD
Temperature gradient	CFD
Ventilation efficiency	CFD
Temperature exceeding	TS
Radiant temperature asymmetry	CFD

The application of climate simulations in any area of expertise requires a fair amount of knowledge and experience with both the tool and the phenomena under investigation. Until recently, only indoor climate specialists held the amount of knowledge regarding building properties, services and calculation models that was needed to apply these simulation techniques in building design. However, in the past years some software companies developed applications aimed at less experienced users. These tools include advanced techniques that automated much of the data specification process for commonly used situations. Some examples were specifically developed for use in building practice and the built environment. Applications such as *Energy10* (Balcomp 1997) and *FLOVENT* (Flomerics 1995) showed functionality that automated the definition of building services and materials. This greatly reduced the amount of user operations and input information while still guaranteeing a sufficiently reliable simulation.

Conditions

The amount of information, knowledge and experience required to use the applied airflow and thermal simulations is at a level which demands the involvement of an expert. Compared to e.g. lighting simulation and structural analysis tools considerable knowledge of the fundamental aerodynamic and thermodynamic principles is required. This is especially true for airflow simulations where an initial guess of the outcome is crucial for the correct preparation of the simulation model. Another complication is striking a correct balance between preparation and calculation time on the one hand and required accuracy on the other. In architecture, fast order-of-magnitude calculations are much more desirable than accurate predictions that take days to compute. However, it takes knowledge of airflow mechanisms to determine at what point conceptual calculation models still have some degree of accuracy and at what point they cannot be used at all. Similarly for thermal analysis, attention for building properties such as window size and internal heat dissipation is crucial to obtain reliable results.

Scope

Modeling buildings into the analysis tools is subject to limitations. Abstraction of design geometry is most influential in this respect. The calculation procedures are built in such a manner that they require a reduction of complex shapes. In order to simulate airflow in a space using CFD simulation, the volume of this space needs to be divided into a grid of numerous cells (Figure 65). These cells usually have shapes that follow from geometrical principles such as tetrahedral or hexahedral configuration. Some grids wills have up to hundreds of thousands of cells which describe scenes in great detail. Because manual definition of this data would take far too much time, many automated grid generators have been developed.

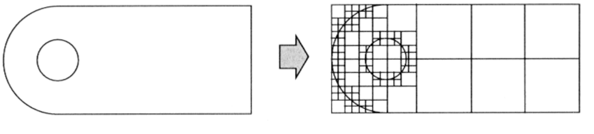

Figure 65: Transition between a free-form shape and a quadtree-based shape (source: Owen 1999)

For architectural purposes, grid techniques that require little effort to use are highly desirable. The staggered grid is a technique to define all geometry as orthogonal and build a grid of various sized, orthogonal boxes. To define a staggered grid, each axis of a particular domain is divided into multiple slices. When this is done for all three axes, a staggered grid of boxes remains. Defining this type of grid usually takes less than 15 minutes while only a few simple rules need to be observed. Some CFD codes use automated grid definition when working with orthogonal geometry thus completely eliminating the process of grid definition.

More advanced airflow simulations make use of techniques that define geometry in unstructured meshes. The smallest elements, the cells, can have a number of shapes such as triangular or hexahedral. The shape and topology of the cells allow for more freedom in the expression of geometry. The automated grid generators facilitate the conversion from the boundary represented CAD model to CFD geometry. The combination of unstructured grid and translation tools results in CFD models that represent even the most complicated designs. In spite of advancements in automated unstructured mesh generation techniques (Owen 1999), these types of grid require considerable more knowledge than orthogonal grids (paragraph 2.2.3.2).

Reducing the complex geometry found in building design to orthogonal grids is an abstraction that might experience some resistance from designers. Curved shapes and angled walls might be altered in the abstraction process resulting in a CFD model that looks different from the original design. Notwithstanding these limitations, CFD can still be most useful in predicting airflow in complex geometries. Due to the nature of the formulae it uses, CFD can treat curves and angles like they were build out of multiple smaller, rectangular shapes, without any notable effect on the calculation results.

Thermal simulations also make use of a conversion of geometry. Most thermal calculation engines use *nodes* to represent temperatures at significant locations in the building. The geometry that separates the nodes is translated into heat transfer coefficients. When design geometry contains more than 6 planes or faces, additional nodes have to be defined. The assumptions that are taking into the formulae can be applied to convex space shapes with regards to conduction and convection. For radiation, the procedure is more complex. The radiant heat exchange factors are more difficult to compute for convex shapes such as L and U shaped floor plans. Moreover, the calculation time increases exponentially with the addition of nodes.

ORCA uses several prototypical floor plans that can be selected and adjusted to fit the design by specifying measurements (paragraph 3.5.3, Figure 29). This allows users to abstract the layout of their design to fit the requirements of the design tool. Recently there have been developments that automatically define the nodes that corresponded with more complex floor plans (Wong e.a. 2000). These techniques could be combined with automated recognition techniques that abstract curved geometry. This would enable the Meta Design environment to connect design representations directly to thermal analysis.

6.2 Design Scenarios

The design of a building involves many instances where design parameters may be changed in order to achieve an effect. Most architects have mastered their design skills to the point where they will be able to make design moves or changes that optimize the performance of the product for the better. As mentioned earlier, the effects of these design moves on the indoor climate often remain unevaluated. One reason for this might be that it is difficult for designers to determine and implement those design changes that optimize the indoor climate. In most cases, the effects of design actions on indoor climate can only be revealed by specialist analysis. In others, designers might be familiar with the design moves that would improve climate conditions, but the possibly negative impact on, for instance, aesthetics prohibits them from taking action. It also requires an *awareness* of the interaction between the building itself and indoor climate, the presence of possible pitfalls in the application of (unusual) shapes or materials and the potential of building service in providing control over the indoor climate. We introduced *Design Scenarios* into the Meta Design environment in order to stimulate indoor climate awareness and the use of indoor climate performance predictions. Design Scenarios are a set of focus areas that isolate particular design aspects and facilitate investigation of their influence on the performance of the building.

These focus areas are building aspects that can have a large influence on indoor climate. In the research for a Meta Design environment, indoor climate specialists that supervised the project have identified design areas and their probable effects. A side effect of the exploration of a particular issue is the possible generation of design variants. The scenarios provide a means to generate design alternatives around the scenario's indoor climate aspects. These alternatives can be evaluated and compared providing a considerable amount of insight into design behavior.

The procedure to use the scenarios is as follows. First, designers select a theme that they feel is appropriate for the design stage and situation. Next, the Meta Design environment starts the corresponding simulation interface in which designers can make final adjustments and start the simulation. The Meta Design environment processes the information (input and output) surrounding the analysis. Finally, the visualized simulation results can be searched for occurrences of the issues related to the chosen scenario theme. The visualization is done in such a way that it can display several characteristics of the indoor climate simultaneously. Among these are the climate aspects that were at risk according to the design scenario. At the same time, it also permits identification of other indoor climate issues.

Architects may select scenarios at all stages of the process. Moreover, designers often operate alone in the early design stages. As a result, designers are responsible for engaging in the indoor climate with the help of the design scenarios. Using a structured CAD model and recognition techniques, it would be possible to couple design actions to specific scenarios. For instance, when designers create spaces with a height greater than 5 meter the systems could access encoded rules and trigger the activation of the related scenario, in this case the ‘height of space’ theme. However, this type of design support is quickly considered disturbing and unnecessary. Rather, the system may flag the spaces or building elements that require analysis (Koutamanis 2001). Still, this type of automated recognition of design features should be applied with care. Examples of scenario themes that can act as ‘triggers’ remain at the level of quantities that are measurable in the representation. As seen in paragraph 4.2.1, formalized design knowledge is not able to detect and solve all possible design problems. As a result, there may exist design situations where the indoor climate is compromised and that fail to trigger any of the scenarios.

In the application of scenarios, it is recommendable to use conditions that guard the overall performance of the design. These prevent over-optimizing towards a particular indoor climate goal. For instance, minimizing a building's heat load by applying sun shading, heat reflecting glass and awnings might be a very effective way of reducing solar irradiation, it will also completely alter the appearance of the building. However, the likelihood of design actions that accommodate for indoor climate objectives is not large. Architects are often reluctant to aesthetically alter their designs in favor of indoor climate. Still, in addition to limiting excessive design moves, the scenario conditions can also encourage cautious designers by showing them that in the Meta Design environment, achieving indoor comfort at the cost of design aesthetics or other qualities is not the ultimate objective.

Design scenarios can be defined for different building scale levels such as building, storey, space etc. These levels correspond with the way in which architects address particular issues in their design process. Some designers start with designing small items such as component details or typical space layouts and aggregate these products into larger building sections. Others define the shape of the entire building first and designate floors and typical and special spaces within this volume.
In both cases, the common building scale levels are likely to be addressed at some point during early design. For each of the scale levels, the design scenarios supply the relevant indoor climate issues that architects can work with.

From the viewpoint of building inhabitants, the level of individual spaces is most directly connected to indoor comfort. The space scenario addresses the climate characteristics of the individual space. It offers several themes that deal with building elements, building services and passive measures. Table 23 provides an overview of the themes that were defined during the development and testing of the Meta Design instruments. This table relates the scenario themes to indoor climate issues that could cause problems in spaces.

Table 23: Some Design Scenarios for spaces (see paragraph 6.4 for examples)

Scenario Theme:	*Indoor climate issue:*
Mechanical Ventilation:	
	Low ventilation efficiency
	Noise

Scenario Theme:	*Indoor climate issue:*
	Draft
Natural Ventilation through windows:	
	Low ventilation efficiency
	Low cooling capacity
	Draft
Mechanical Ventilation through climate façades / windows:	
	Low ventilation efficiency
	Draft
Size of façade glass area:	
	Downdraft
	Temperature exceeding
	Radiant asymmetry
Large space height:	
	Temperature gradients
	Draft
Exceptional space occupation:	
	Temperature exceeding
	Air pollution
Changing function of space:	
	Temperature exceeding
	Draft
Spaces at 2 façades, building roofs, underground:	
	Temperature exceeding
	Disturbance of control principle

The analysis tools presently contained within the Meta Design environment have been utilized to address the indoor climate of individual (office) spaces. However, airflow and temperature simulations can also be applied at larger building scale levels. At present, design specialists utilize a broad range of means such as thermal simulations that have the ability to address temperature and energy issues of entire buildings and CFD simulations applied at airflows around buildings. This type of applications has a similar potential in design support as the tools used in the space scenario. These new design scenarios could concentrate on climate issues that stem from the possibilities and problems related to building elements such as ventilation through climate façades or wind in pedestrian routing.

An additional scenario scale level could concentrate on the large spaces within buildings such as office landscapes or large atria. The size of these types of spaces is often a cause for indoor climate problems. Two prominent examples are drafts as a result of high spaces (higher than 6m) and temperature differences when thermal services need to cover large distances. It is important to realize that when these problems occur, they are usually locked in the shape and configuration of the design and, as a result of these extremes, are difficult to solve. Compensating drafts or reducing temperature differences through the application of building services often only relocates the problem.

The scale that addresses the entire building handles the interaction of the building with the immediate surroundings. An important example of these problems is the occurrence of large velocities in the air flowing around the building. High air speed can cause for problems for people entering the building or standing on balconies and can also complicate natural ventilation. Another design topic concerns the solar irradiation on the south side of the building. Sunlight is often an essential part of architectural design. However, it can also contribute considerably to temperature exceeding. It might be possible to use the shadows of other buildings or trees to reduce this.

In addition to being an organized index to indoor climate issues, the scenario themes also provide an excellent way of gaining access to the case-base of indoor climate precedents. As mentioned in paragraph 4.3.2, precedent representations should contain short descriptions of the indoor climate issues they address. When the content of one such field is taken from the scenario descriptions, it can be used to create an index of precedents. This index can contain the indoor climate issues from Table 23 where each of the issues is linked to the specific precedent projects that deal with this issue. It would enable designers to quickly learn about a particular problem by looking at some design situations. The Archie system has shown promising results using a similar approach (paragraph 4.2.2). It would also make browsing through the case-base more efficient and could even replace the case matching mechanism needed for case-based support as in, for instance, the CFD wizard (paragraph 4.3.5).

Conclusions
Design scenarios are shortcuts from building to indoor climate. Free from techniques, procedures and systems, the scenarios offer involvement and feedback. As is to be expected with shortlists, it is far from complete. The list is also an inaccurate way of indoor climate analysis if it is used to assess the occurrence of climate hazards. However, design scenarios can educate architects about the possibility of the common indoor climate problems and issues. In this regard, it provides a comprehensible overview of the climate issues common in architecture. Moreover, since the scenarios use building elements as their main index, designers will have less resistance in using them than for instance, aerodynamic rules-of-thumb.

The scenario themes and climate issues are accompanied by brief explanations that define the terms used more accurately. This might refresh the memory of users regarding indoor climate. The climate visualizations employed by the Meta Design environment produce a similar effect when the causes and effects related to the indoor climate issues are displayed graphically. These use separate and recognizable icons that indicate soft and invisible climate issues such as the Coanda effect.

The use of scenarios can help in determining whether designs hold fundamental weaknesses on the area of indoor comfort. This is especially useful in situations where designers consider design moves that imply large indoor comfort hazards such as atria and large glass façades. These types of decisions can have extensive consequences that cannot be easily countered by using a combination of passive measures on other building aspects. Instead of instructing designers to avoid architectural elements that are hazardous to the indoor climate, the Meta Design environment takes an alternative approach. It is ultimately the designers who make the choice for high-risk building shapes and elements. However, most of these types of choices come with an additional cost. The precedents can show the possibilities, extend and preferably the costs of the building services that can counter the unwanted climate effects caused by typical hazardous architectural elements. Moreover, they also contain cases where different types of design innovations have been successfully applied in complicated indoor climate areas.

It is not sensible to include all possible indoor climate problems in the scope of design scenarios. This would imply that designers meticulously evaluate the indoor climate of their designs. Although there might be some discussion possible to the desirability of this occurring, it is not likely that architects will reserve a major part of their time for scanning their design with the use of design scenarios. More realistic would be to place the design scenarios in the early stages to bring about an awareness of the two or three most prominent opportunities that a particular design could contain.

6.3 The Meta Design Method

The definition of the Design Scenarios forms the final step in the specification of the Meta Design environment framework. We will now describe the use of the environment in the design process. Using the Meta Design environment approach consists of the following steps: (see also Figure 66)

- Step 1: Create a representation of the design or building using the Meta Drawing Model.
- Step 2: Select a Design Scenario that applies to the design and select the part of the building (space) that is to be analyzed with the scenario.
- Step 3: Answer the queries of the corresponding analysis wizards and wait for the calculations to finish
- Step 4: Open the visualizations of the calculation results and determine the behavior of the design in relation to the scenario theme.
- Step 5a if needed: Improve the design by changing the design with regard to the scenario theme or on aspects mentioned in the feedback or precedent stories.
- Step 5b: Another option is to create several design alternatives by varying the design on the scenario theme.
- Continue with step 3

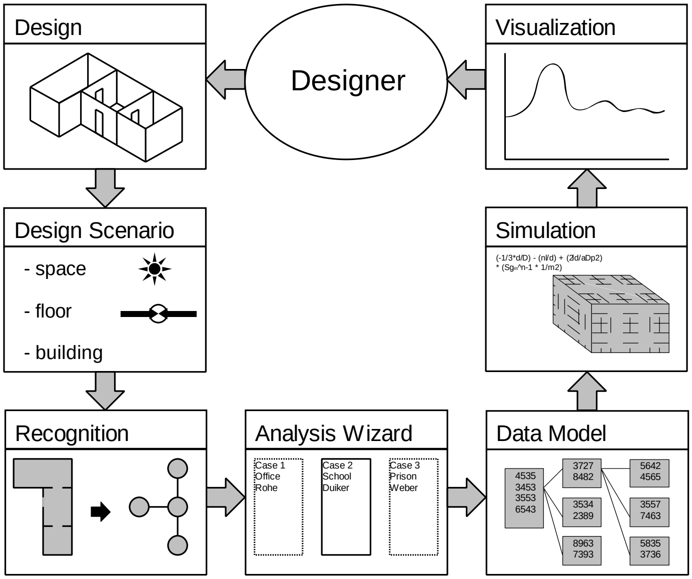

Figure 66: The Design Support process

Create representation

The Meta Drawing Model has been developed to have the ability to be implemented on many CAD platforms. Currently, the Meta Design environment uses AutoCAD to enable users to easily and efficiently input their design. The rules of the Meta Drawing Model (paragraph 3.4.2) are such that they require a minimum of geometric and functional information to allow easy transition from current building drawings to the Meta Design environment. The MDM models can easily be copied from the content of existing drawings which also permits to use the MDM as an enhancement without altering the current drawings models. In the later case, it would also be possible to create a MDM compliant representation of only the portion of the building that needs to be analyzed and to do this only at the moment the analysis is required. In the exceptional situation that creating 2.5D representations takes too much effort, the analyses could also be enabled to run with only 2D information in combination with a typical height for spaces and windows.

Select Scenario

The Meta Design Scenarios are developed to start the analysis portion of the design process. They appeal to the architect’s preference to engage in building design rather than indoor climate design. The design scenarios connect indoor climate aspects to specific building elements such as shape and location. The designer selects a scenario that applies to the design and is able to learn more about the related indoor climate issues. The selection of a specific scenario supports the system in determining which analysis to start and on which buildings services to concentrate. The scenario choice also facilitates the feedback process by suggesting the appropriate visualization method for each of the climate issues.

Complete wizards
After a scenario has been selected the system can start the corresponding user modules that precede analysis. In cases where these modules have been executed previously, the system remembers the settings and skips most of these steps. At present, the Meta Design environment contains two user interface modules. The CFD wizard allows users to design an airflow configuration for the design of enclosed spaces and control the execution of the airflow simulations. It offers users the ability to choose from a limited set of general ventilation principles and to apply one in their design. The ORCA tools cover the analysis of a typical space for temperature analysis. Again, the interface requests a small amount of additional building data and offers a limited set of climate control concepts that can be applied in the design at choice. Both tools offer a straightforward and simple way of specifying the most essential details required for analysis. During the first uses of these modules, users may access the help functions to receive explanations of unknown terms or procedures.

The CFD wizard also contains the support of precedents that can be used to provide suggestions at the various input items. Users can inspect sets of precedent projects that have been selected by the system and look for common principals in indoor climate control or typical solutions to the problems related to the design scenario themes. Entering information in the wizards in not similar to specifying a building service system. The information contained in the user interfaces can act as a guide for making decisions about the passive contributions of the building to the indoor climate. In addition, it can form the basis for discussions with design specialists.

View results
After the simulation tools have finished calculation, the Meta Design environment automatically visualizes the results. In the case of airflow data, the indoor air visualization environment is brought up. This contains a number of techniques to feedback airflow patterns and characteristics. The system couples each of the design scenario themes to the most appropriate visualization technique. In most cases this will concentrate on the indoor climate parameters mentioned in the indoor climate issue that was selected in the design scenario phase. The feedback has dynamic features that facilitate the attribution of indoor climate effects to the responsible building elements or services (paragraph 5.5.7.4) In the case of an indoor climate extreme, it is well possible that this points to the same building elements as was mentioned in the selection of the design scenario theme. Again, the explanations and precedent remain accessible for the designer to learn more about the identified problem. Alternatively, users may select other visualization methods or settings to further explore the contents of the indoor climate.

The visualization of indoor temperature in relation to building overheating and underheating uses diagrams to display the temperature profiles. This can be done on a daily or yearly basis. It can also be expressed in the number of hours each degree of indoor temperature occurs. The simulation also provides the energy used by the building installations. To show the influence of design decisions regarding building elements such as wall materials and installed capacities, the feedback also contains the results of the previous run. This enables users to change their design one aspect at a time and use the change in thermal performance as an indicator of the degree of influence of that building aspect on the thermal comfort.

Improve design or Create alternatives
The improvement of the design is the responsibility of the designer. The design scenarios can point to elements that have a strong influence on the indoor climate. It could even suggest particular actions and directions for change; however, the Meta Design environment will not carry out these modifications itself. This would require a mechanism that resembles the case adaptation techniques for which paragraph 4.2.1.4 concluded that application in architecture is not feasible.

The results of a CFD simulation currently take some time to compute. Together with the novelty of the instrument, this could lead to a time-consuming trial and error process when designers require specific feedback on design modifications. Therefore, it might be more efficient when designers create multiple design alternatives from the original situation. They could do this by varying the size, location or other properties of a building element or service in several, discrete steps. These steps should be defined within realistic boundaries and, if possible, be accompanied with an estimation of their effects. This prevents useless simulations and saves time. The variants can be executed in rapid succession by the system offering the possibility to compare the results of the variants. This in turn, can provide information on the amount of influence of the variation on the indoor climate. In addition, it might also reveal a design optimum for that specific aspect.

The temperature overheating results are available within a few second after the design modification. This enables users to directly experience the influence on thermal performance of all design parameters. Creating design variants is less useful in this regard. However, we have observed a positive effect on the knowledge of students of architecture regarding indoor climate thermal principles. Most of them indicated this was the result of experiencing the interaction between building and thermal performance. (Dijk e.a. 2002)

6.4 Meta Design Examples

6.4.1 CFD situations

In order to develop case entries for the precedent database and to acquire more knowledge on the application of CFD in building design, we performed several CFD simulations of design situations. These situations were found in the day-to-day practice of the educational activities of the chair of installations. Some of these examples are taken into this paragraph to illustrate the possibilities of CFD simulations.

Example 1: Gevers Deynoot Elementary School
Design Scenario: Natural ventilation through windows -> Draft

This project by van Reijzen en Verbeek architects concerns the design of an elementary school. The indoor climate consultants have attempted to realize an optimal and comfortable indoor climate for the students within the relatively low budget. This meant that mechanical cooling was too expensive. Instead, the design contained a hybrid ventilation system that consisted of a combination of mechanical air extraction and natural air entry. In the summer, this prevents overheating for a large part of the time while at the same time providing for sufficient ventilation. However, in winter conditions this system can quickly lead to discomfort as a result of cold drafts. The ceiling is designed in such a way, that air entering through the façade has the possibility to heat up to around room temperature. During this time, the cold air flows over the ceiling and mixes with warmer air. Figure 67 provided an overview of the situation.

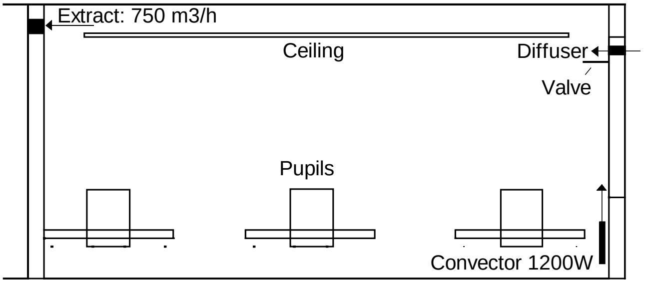

Figure 67: Gevers Deynoot problem specification

A simulation using the Meta Design environment was made to determine whether this system would work. The first variant contains two convectors with 1200 Watts power each. Also present is an air inlet facility in the façade (white) and a mechanical air extraction of 750 $m^3 \cdot h^{-1}$ (yellow). The intention was to have the air flowing up from the convectors to push up the air that entered through the façade until it flows on top of the ceiling. Figure 68 shows that this does not occur. The cold air flows below the ceiling and is able to reach the other side of the space as a result of the high ventilation amount.

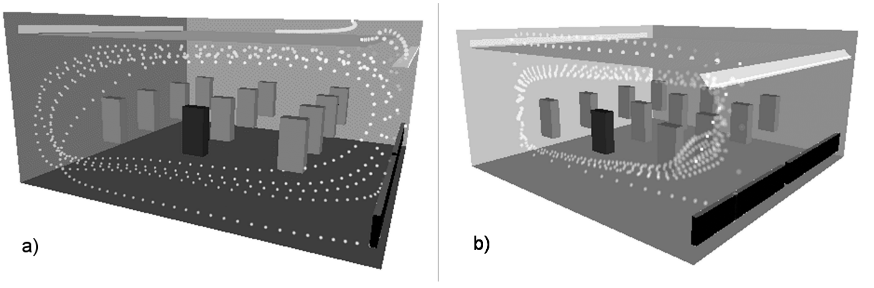

Figure 68: Gevers Deynoot simulation results

Design alternative (b) contained an angled valve below the air inlet facility. In contrast to the first variant, the valve is tilted upwards at an angle of 47 degrees. In addition, the valve is extended to 20 cm to reach closer to the edge of the ceiling. The simulation of this variant shows the air flowing over the ceiling till the other side of the space. The color index shows the cold air heating up until it reaches about 22 degrees before flowing down into the space.

Example 2: Office space 1
Design Scenario: Mechanical Ventilation -> Low ventilation efficiency & Draft

This example concerns a space that was designed for research. It is a space that has been built inside a laboratory environment by Peutz and associates consultants. The aim of the experiment was to determine the efficiency of a hybrid ventilation system. In addition to the measurements, we simulated the airflow in this space. Figure 69 shows the space that contains four air extracts located in the upper section of the hallway side of the space, four radiators located between the columns in the façade and two air inlet facilities located in the upper section of the façade. The part of the ceiling that should support the air entering the room is considerably smaller than in the previous example. This allows for a broader use of the ceiling.

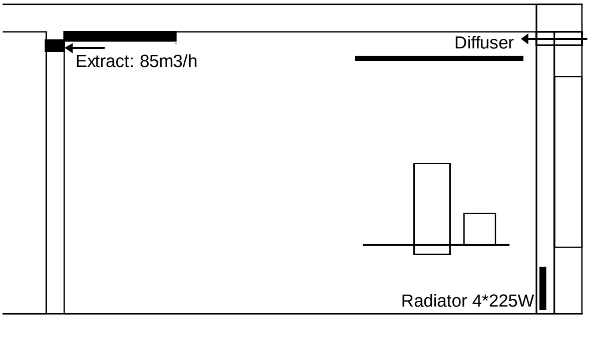

Figure 69: Office space 1 problem specification

Simulation revealed that cold air entering the space flows over the ceiling and reached the other side of the space before dropping down in the room. This is remarkable since the tendency of relatively cold air introduced in a warm room is to drop down quickly due to buoyancy. The Coanda effect is usually not enough to prevent this. In this case, the ceiling provides mixing of the cold air with warmer, induced air. At the edge of the ceiling, the air's momentum is large enough to have it reach the other side of the room without causing draft. At the hallway side of the space, a part of the air is extracted while the greater part flows down into the occupation zones and mixes with room air.

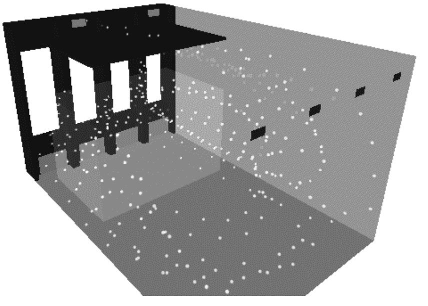

Figure 70: Office space 1 simulation results

Figure 71 provides a sketch that was made from laboratory experiments where smoke was released into the airflow. This indicated that predicted circulation matched the observations of the researcher. Comparing air velocities was difficult to do since the exact location of the measurements wasn't available. Although this type of airflow is relatively straightforward to predict, both analytically and numerically, it is a clear indication of the practical use of the simulation results. For instance, the fact that the air entering the room reaches the far (hallway) side of the space without dropping too soon, is an important condition for avoiding draft.

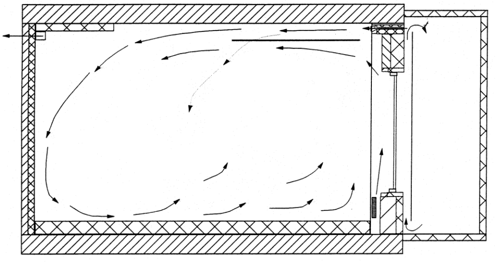

Figure 71: Office space 1 laboratory observation (source: Peutz 1996)

Example 3: Office space 2
Design Scenario: Mechanical ventilation through climate façade -> Draft

The third example also deals with a laboratory space. In this case, it is a test environment for the development of new HVAC configurations by Stork-Bronswerk. The space contained a fan-coil unit in the ceiling that supplied air directly down into the space. The air is extracted at the top of a second layer window that contained an opening for the space air at a height of 0.3m (Figure 72).

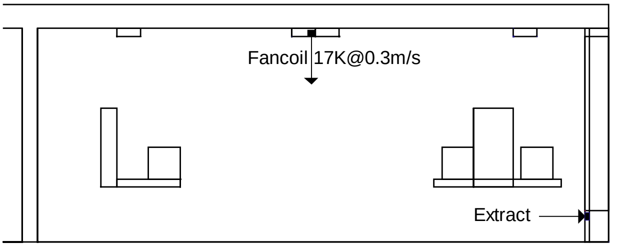

Figure 72: Office space 2 problem specification

This type of configurations has the hazard of causing for drafts in summer situations. The air with a temperature of 17 ºC is supplied directly down into the occupant zone. Inhabitants run the risk of exposure to this high velocity, cold airflow and therefore uncomfortable conditions. The layout of the space has been optimized to prevent this. However, the simulation revealed that the supply air does not mix completely with room air. Instead, air velocities remained high at considerable distance from the air inlet. This resulted in airflow at ankle height with relatively high velocity and low temperature (Figure 73).

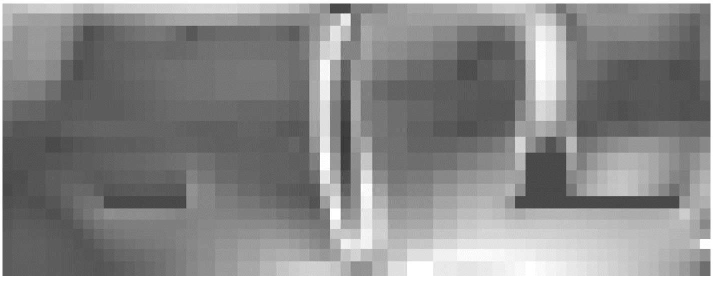

Figure 73: Office space 2 simulation results

The data on this space contained the results of the laboratory measurements. We visualized these results using a similar principle as the simulation results (Figure 74). In spite the limited amount of measurements it is clear that the general location and velocity of the airflow is relatively accurate predicted by the simulation. The maximum air velocity right under the air inlet matches the calculated equivalent. Also, presence of increased airspeeds over the surface of the floor appeared in both simulation and measurement. The dislocation of the area of high velocity induced by the air inlet is also interesting. Most likely this is due to the estimation of the air-inlet angle. A precise inlet angle could not be retrieved from the measurements logs. Instead, we deducted the angle from the fan-coil unit configuration.

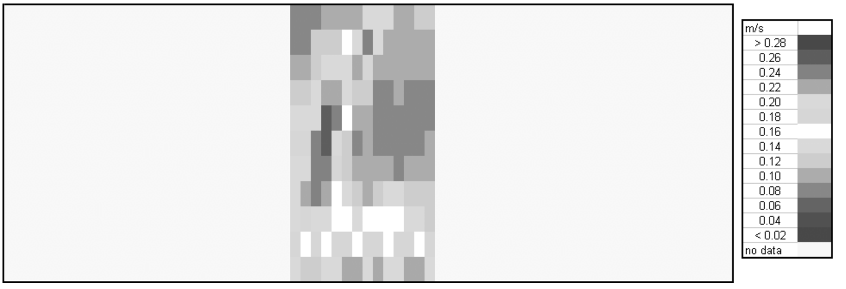

Figure 74: Office space 2 laboratory measurement

Example 4: Office space 3
Design Scenario: Size of glass area -> Downdraft, Mechanical ventilation -> low ventilation efficiency

This example contains an exercise performed as support for students engaged in a design assignment. In designing a ventilation configuration for an office space with an active façade, the question arose whether the ventilation efficiency was sufficient.
The building is fitted with an all-glass façade which prevented the placement of climate service in front of the façade. Instead, the idea was to distribute the supply and extract the air horizontally through the floor zones. Topologically it would be preferable to place the air in- and outlets near the façade as well (Figure 75).

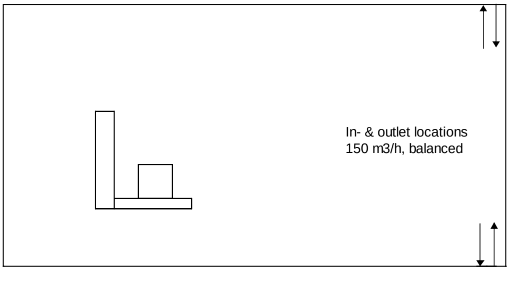

Figure 75: Office space 3 problem specification

The first simulation was done with air supply and extract located in the floor of the space. Air in- and outlet are placed alongside the façade in close vicinity of each other with the air inlet providing the air directly upwards. The ventilation amount was set at $150m^3 \cdot h^{-1}$. The small distance between in- and outlet caused for concern about the air 'short-circuiting'. The simulation showed that this effect didn't occur.
Instead, the Coanda effect ensures that the inlet air sticks to the window while flowing up.
As a result, the air circulated with the shape of a typical vortex through the space, eventually reaching the outlet. With regards to ventilation efficiency, this typically indicates a good configuration.

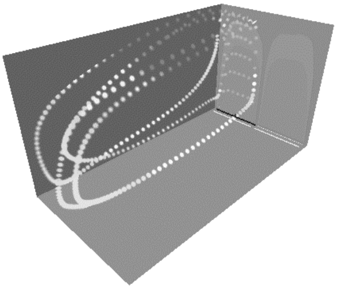

Figure 76: Office space 3 simulation results A

Shifting the location of the air inlet to the ceiling created an alternative design. The air outlet remained at floor level. Both were located near the façade. The inlet was angled at 90 degrees to supply the air horizontally in the space. Simulation of this configuration showed a different airflow pattern. Instead of covering the entire space with a single vortex, ventilation seemed to divide the space into smaller segments. Although the air velocities in the occupation zone and more specifically the facial zone are not likely to cause discomfort, ventilation efficiency is not guaranteed here.

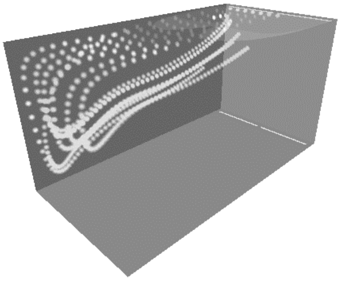

Figure 77: Office space 3 simulation results B

As often occurs in practice, the students also attempted to optimize use of their design budget by removing building services. In this case, the design alternative contained only one air inlet and one outlet. This reduction necessitated an increase in supply velocity to around $1m^{1} \cdot s^{-1}$ in order to maintain the ventilation rate objective. The simulation revealed an asymmetric airflow pattern that displayed high velocities in the occupation zones. Moreover, the crossover between left- and right-hand sides of the space makes the vortex unstable.

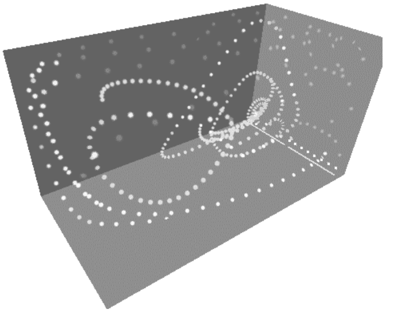

Figure 78: Office space 3 simulation results C

The examples show the ability of CFD simulations in the Meta Design environment to model real-life design situations. The design configurations and the simulation outcomes have been discussed with indoor climate experts to determine the validity and to find useful clues for design guidance. This process itself caused an increasing awareness of the presence of airflow phenomena in building design. The ability to model almost any type of space and airflow configuration has affirmed our belief in the applicability of CFD simulations in the design process. The rectangular abstractions required for the calculation grid did not prove to be a problem. The automated abstraction algorithms provide for most of the geometric modeling in the CAD input. In some cases with angled or curved walls, users had to make simplifications in the space shapes. This also did not cause for much difficulties.

Due to the straightforward way of using the analysis tools, the results may contain some inaccuracies. This prevents making too definitive decisions on the basis of this type of feedback. However, in most cases, the design queries in the early stages do not require a yes/no answer. An exception is formed by the design of innovative systems such as the Gevers Deynoot School. These simulations require a thorough understanding of aspects such as turbulence and buoyancy and additional fine-tuning of the input.

6.4.2 Design education

The introduction of ICT in architectural practice has stimulated a wider spectrum for computing in architectural education. In particular, computers are now an accepted part of the design studio. The necessity of computer skills in practice means that the use of computer modeling and visualization tools alongside analog media is becoming commonplace. And when the utility or innovative potential of tools such as CFD simulations become evident, educators may even show a preference to digital media. Reversely, design activities are currently deemed an essential part of CAAD courses. Consequently, the focus of CAAD courses has been shifting from technical skills and general theoretical issues to current, specific design issues, such as the relationship between geometric modeling and construction, design communication, information management and design analysis. Especially advanced CAAD courses increasingly attempt to introduce these issues and corresponding advanced ICT in a design framework that outlines the possibilities of these technologies and the underlying computational design methodology. This framework is essential for bringing research as well as practice closer to teaching (Koutamanis 1999).

CFD exercise

Advanced design computing courses, where students have sufficient understanding of geometric modeling, as well as of the complexity of the digital design process, form the starting point for the integration of CFD simulation in architectural design education. At the Faculty of Architecture, Delft University of Technology, this takes place in the D7 design computing course, in the form of a semi-independent CFD exercise. At the beginning of the exercise, students are asked to pick an enclosed space from their designs where information on airflow would form an interesting part of the design process. Areas where people reside for a considerable length of time were particularly relevant. The spaces should be connected with the outside environment only by means of doors and windows. In the event that designs do not have a separated space, the airflow around the building can be analyzed instead. Since the design assignment of the course deals with an exhibition building, the students are likely to choose the main exhibition space as their subject for CFD analysis.

In order to analyze the airflow within buildings effectively, the ventilation context of the space should be defined in advance. This means identifying the location and characteristics of the air inlets and outlets, as well as any pollution sources that exist with the space. In order to aid the students with this task, a quick reference scheme was developed. This scheme organizes the options for ventilation principles and offers simple formulae to determine ventilation characteristics. Consulting the scheme only takes a couple of minutes and is supervised by an indoor climate specialist. The aim of this step is to make students aware of the indoor climate of their designs and to provide a framework within which the simulations can be held.

A prerequisite to the simulation is a representation of the design in the CAD tools used within the course. Students represent their designs using a few simple rules to give the representation structure. One of those rules is to draw the boundaries of the spaces using closed, extruded polylines. Elements such as doors, windows and air inlets are also drawn using polylines and are placed on corresponding layers. Another requirement originates from the CFD calculation engine: all geometry, with the exception of angled walls, has to be abstracted to and represented by rectangles. This basic representation largely corresponds with the design representation used for most of the course. Creating the CFD representation essentially amounts to copying part of the design representation. This part includes only the design elements that are relevant to airflow simulation. Details such as door handles and small holes should be ignored. The ventilation concepts of the previous step can also be drawn in the representation using a component library.

In the exercise two different CFD engines can be used, *Flovent* and *WISHPC* (Lemaire (ed.) 1992, Flomerics 1995). Flovent has the advantage of a user interface for building engineers. However, the design needs to be input separately from the design representation. This takes a fair amount of time and must be guided by a teacher with CFD experience. WISHPC does not have a user interface. This makes monitoring and controlling the simulation progress harder. However, WISHPC has an open data format specification. This open format makes it possible to develop software that connects this CFD engine directly to the CAD tool. Using automated recognition, it is possible to generate the input needed for CFD analysis directly from the design representation in AutoCAD. The amount of time saved by this translation makes this engine very useful during early design. WISHPC also features an automated grid generator that further reduces the time needed for data preparation.

After the initial simulation, the results are presented using three-dimensional visualization. The airflow is illustrated by releasing small particles in the air and by tracing the path these particles follow (see student work examples). The particle tracing method can be combined with the use of color to represent air speed or temperature. These kinds of visualizations are useful to focus the attention on medium size local phenomena such as draft or ventilation inefficiencies. By analyzing and evaluating the initial simulation results, students identify possible indoor climate problems such as large air velocities. Subsequent design variants improve on the weak points identified in the first simulation. Simulating several design options with varying window sizes or inlet velocities can uncover optimal configurations where drafts are avoided or ventilation efficiency is improved.

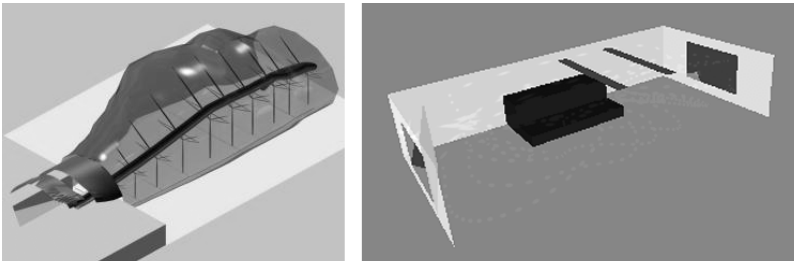

Figure 79: Example of student material

The CFD exercise was evaluated and graded by the students. Table 24 is an overview of the grades the exercise received after the first semester.

Table 24: Grades for CFD exercise, given by students

Key: 1 = low, 10 = high

Group:	*Knowledge:*	*Technique:*	*Educational value:*
A	8	-	6
B	4	6	4

C	8	8	8
D	7	8	7
E	8	-	-
F	8	8	9
G	8	8	8
H	8	9	9
I	9	9	5
J	10	10	8
K	7.5	8	8.5
L	8	7.5	7
M	8	8	8
Average	7.3	8.1	7.3

These figures indicate that the students appreciated the exercise and its educational value. The feedback received from the students was overall positive. Indoor climate specialists reviewed the students' work. From the examples of the students work can be seen that they produced results that showed an increased awareness with regard to indoor climate. This was most notable during subsequent design exercises when students started to request validations of their designs with the use of Meta CFD simulations.

ORCA exercise

Paragraph 3.5.3 described the ORCA project. Researcher E.J. van Dijk developed ORCA around an advanced temperature simulation program. It broadened the application area this complicated program in a way that made use by students possible. The primary use for this design tool that focuses on a high degree of interactivity and usability is mainstream architecture education. Van Dijk, together with the staff of the chair of Installations set up an exercise to teach students indoor climate design. Presently, the ORCA tool is being used in the MSc1 and BSc4 design courses on the faculty of architecture of the Delft University. These courses aim to familiarise students with a range of specialist disciplines that constitute an important part of modern design. One such a discipline is indoor climate design. Here, the ORCA exercise is used to teach students the basics of indoor climate control through passive and active means. The students are faced with design cases and are asked to carry out a series of tests. The test-questions address the performance of the design in relation to building parameters such as materialization and installations. The ORCA tool can be used to input the design situation and parameters and to provide answers in the form of temperature performance. Changes in the temperature performance graphs help students to isolate building *hot-spots*. Hot-spots are building parameters that, under certain conditions, can be a cause for building over- and underheating.

The results of this process could be surprising to students. For instance, many were hesitant to accept that situations with too much solar irradiation, single glazing is preferred above double glazing. It proved to be important that the results of the ORCA calculations could be validated with the VA114 building simulation program described in more detail in paragraph 2.2.2.2.

The test consisted of a series of questions that contained sub-optimal design objectives (Table 25). The example design was a straightforward office building that was placed in several situations. In addition, wall materialization, window size and configuration could be altered according to student preference. We included two scenarios and had the students research summer and winter conditions as well as the north as south façade of the building. The first calculations were done on a single office cell while subsequent tests broadened the scope to the entire building.

Table 25: Examples of ORCA exercise questions

	Exercise question:
B	Make a calculation for a summer period and evaluate the indoor climate.
C	Try to optimize the room comfort for the summer period without using installations.
D	Try to optimize the room comfort for exercise C for the winter, without installations.
E	Load your (reference) model from exercise A and change the orientation 180º.
F	Try to optimize the room comfort for the summer period without using installations.
G	Try to optimize the room comfort for exercise F for the winter, without installations.
H	Choose one model (among exercises A to G) that you think will do well in both summer and winter.
I	Optimize the room comfort and energy use with installations for the summer period using the model from exercise H
J	Optimize the room comfort and energy use with installations for the winter period using the model from exercise H

The students were asked to describe each exercise in terms of what design alterations were made, why were made (i.e. what were the expectations) and what was concluded from reviewing the actual simulation results. In their reports, the students included snapshots of the design situations and the simulation results produced with ORCA. These reports were reviewed and graded by the ORCA instructors.

The exercise proved informational for both students and instructors. One of the most intriguing effects noticed was the difficulty that students had with learning to make trade-offs. Primarily, they seemed to focus on design moves that had a quick pay-off in temperature results. When the same design moves turned out to have a negative effect in other situations, they questioned the reliability of the program first. This was most notable in cases where preference for aesthetics could have both a positive as well as negative effect on temperature performance. For instance, students seemed happy to learn that making windows larger meant that more heat from inside the building would radiate to the outside. In situations where temperatures inside are high and outside low, this has a positive effect on the temperature inside. Students were particularly fond of

the transparency this provided. However, in situations where solar irradiation is dominant, this effect is reversed and the building gains heat. Students that discovered the first effect, seemed to ignore the second.
Another typical finding is the reaction to the consequence of applying double glazing. In winter situations, double glazing 'keeps heat inside' the building. However, in summer situations, it does the same. Single glazing lets heat 'escape' more easily and has a positive effect on temperatures in summer. Technically, this implies a trade-off of the same category as the one mentioned above. However, students more quickly accepted this trade-off and used other considerations (such as cost) to make a decision. In this case, the absence of aesthetic variables might be the cause for this behavior.

We also found that in order to support the design process more adequately, ORCA needed to support more complex geometry. In some cases, students that wanted to take the exercise one step further, requested to input designs made in other exercises. In the current version of ORCA this means they had to abstract geometry to a box-like shape. Although most designs can be translated to orthogonal spaces in terms of areas and types, this often diminished enthusiasm. Another problem found was related to costs. Some students made design alterations regardless of the costs. The use of awnings was notorious is this respect. Some student reports mentioned double skin facades of more than one meter wide used with the sole purpose of providing an awning. Obviously, this was not among the intentions of the exercise.

7 Conclusions

This chapter will recapitulate the research questions from the research introduction and summarize the findings from the other chapters. It will also elaborate on other conclusions that were made during the course of the research.

7.1 Indoor climate analysis

The first research question was concerned with the usefulness of the advanced indoor climate simulation tools in architecture. We raise the question whether these tools had sufficient potential to be used in the architectural design process. We concluded the following.

The abstraction in building geometry required by CFD simulation does not conflict with architectural design. Architects define a space by surrounding it with solids (materials) or by describing a void that occupies the space's volume. CFD engines regard space as a collection of smaller volumes. When spaces contain more detail, reducing the size of the elements will increase the resolution. When the designed spaces are concave, their volumes can be modified straightforwardly by adding or de-activating space elements. From our experiences with the design examples in chapter 6 became clear that using low resolution meshing is not likely to be a bottleneck in the accuracy of the simulation results. More often, the accuracy in the specification of CFD source values is the limiting factor with regard to the level of realism. This observation provides a guideline when developing more advanced translation methods for more complex geometry.

With regards to CFD, mainly *steady state* simulations were used. However, it turned out that some design situations are difficult to assess with this technique. It predicts the airflow at only a single instant in the airflow process. For instance, in cases with natural ventilation in winter, the temperature differences between room air and outside air causes for dynamics effects in the airflow. These effects are hard to simulate, even in general sense, using steady state simulations. Therefore we recommend simulating these types of cases using *transient* simulations as was done with some of the design examples in chapter 6. Introducing several time steps into the simulation might introduce for additional input operations and cause for longer calculation times. However, apart from determining a typical length for the dynamic effects, transient simulations have little effect on the overall data input requirements and make the calculation more stable. Experiencing the dynamic interaction between building and airflow might require architect to develop a more profound understanding of airflow effects which is an objective of the Meta Design environment. However, given the current limitations with regard to computing power, this was not incorporated into the Meta Design environment. Moreover, we first need to develop knowledge on the occurrence of transient effects and the typical time-length associated with each of these indoor climate situations.

During the research, the question arose whether the availability of advanced design tools didn’t corrupt the design process. Users that are unskilled in the area of indoor climate but receive access to advanced climate analysis might see an opportunity to manipulate the results in their advance. This, of course, would assume unruly intentions from the side of the designer. The answer to this question came from the CFD exercises. A few students started the exercise with preconceptions of what their design should like and tried to have the simulation endorse these ideas. They tried to configure the input in ways that were beneficial for them. The indoor climate experts mentoring the exercise had no difficulties in spotting these cases. When confronted, the students turned out to have discovered more about airflow and airflow simulations than was expected. They did this in order to hide and 'motivate' their abuse of the simulation. In our experiences, designers that attempt to abuse climate analysis also gain a more thorough understanding of CFD simulation and climate behavior. In case of invalid simulations, specialists have little difficulty in finding the flaws in the simulation result and in using these aspects to convince designers of the correct procedures.

In conclusion can be stated that the available indoor climate analysis tools have sufficient potential to be used in architectural design. From results reported in several sources, we concluded that the existing indoor analysis techniques provided more accuracy than was required for architecture. In addition, the input and calculation procedures of indoor climate analysis techniques are extensively documented. Years of development have made these tools robust and accurate. In most cases, the input allows configuration of the tools to cater for rare situations.

7.2 Representation

The second research question considered possibility to use the output of design representations as the input for analysis tools. To answer this question, we analyzed the data present in design representations and related it the geometrical input of temperature and airflow simulation tools. We discovered differences in the level of abstraction between representation and analysis. Also, analysis requires topological data that often is not present in representations. We developed tools that created the required abstraction and recognized topological relations between design elements. The conclusions we made during these developments are included below.

Architectural design and building service analyses have different informational properties. The early stages of architectural design concentrate on the definition of shapes and materials and in later stages on detailed specifications and services. The analysis tools developed for predicting climate, building and building service interaction place a strong focus on correct modeling of building services and the operation of the building and the services. The precise specification of building materials influences the outcomes to a lesser degree. This contradiction between the sequential production of information in the design process on the one hand and the relevance of the various kinds of building information in analysis tools on the other can cause for problems. When the specialized tools are used early in the design process, the representations still lack some of the important calculation parameters. Another problem is that the tools have no provisions to deal with the dynamic changes in shapes and materials that typify the early design process. To overcome this disparity, we can use a variety of techniques such as automated recognition and case-based information transfer (paragraph 3.2.1).

We encountered an issue with regard to a common-used method for the development of computer systems called Object Orientation (OO). When this is used as the main method of data interaction between architects and their support systems, it can cause for difficulties. Object-oriented languages have considerable advantages in the development and maintenance of large information processing systems (Dijk 1988). Moreover, it would be almost impossible to create robust, complete design support systems without using OO. It's precisely the success of this method that has brought many system developers to use it as a model for man-machine interaction.
However, we found similar problems as Stouffs (Stouffs e.a. 2001) with regard to using OO approaches in architectural design. Despite much effort from the side of software developers and computer scientists, OO fails to support the dynamic creation, manipulation and reassignment of shapes and building elements as present in architecture. Design systems that are implemented using OO need an additional input translation layer that prevents users being confronted with the objects and methods from the data-structure. Using polymorphism in this respect might provide some additional access methods but does not cover the entire problem. If these types of support systems are to be accepted in practice, it is imperative that designers working with them can continue to use the drawing techniques they are familiar with (paragraph 3.4.3.3).

Several cases we represented using our system showed that the Meta representation method can model the basic shapes and elements of buildings in conceptual design (paragraph 3.4.2.8). The method can be used to rapidly produce conceptual representations that contain sufficient structure to be used for other purposes than visualization alone. For this purpose, designers indicate the outlines of spaces, windows, doors and possibly other building elements such as walls and services. However, detailed tender drawings are difficult to produce with the Meta representation. These types of documents contain many details in element descriptions that easily confuse the automated interpreters of the Meta system. However, the layer-structure and the Meta layer management tools enable creating Meta representations parallel to conventional CAD drawings by placing them in the same computer document.

The information structure of the Meta design environment is developed using object-orientation, however users do not notice this. Automated recognition routines detect hierarchy and topology between building elements (spaces, wall, windows etc.). This translates the designer oriented Meta representation to the necessary instances in the object structure of the database. The use of this architectural representation method in combination with automated recognition enables designers to draw in outlines, while this is translated into more structured information storage that has the benefits of OO.

During our research, cooperation with both The Netherlands *Organization for Applied Scientific Research* (TNO) and the *Association for Computerization in Building and Installation Technology* (VABI) was established. Mr. A.D. Lemaire of TNO developed the CFD application *WISHPC* and a CFD data protocol for the VABI. We received access to these information standards in order to link the calculation engines of both *WISHPC* and *VA114* to the prototype. This made it possible to use the design representation in AutoCAD as the basis for CFD simulation. The working model proved that an architectural design representation could be used to provide the geometric input of a CFD analysis. Furthermore, the clear definitions of the data protocols that connect the interfaces with the calculation engines allowed for a redefinition of the focus areas of the interfaces. The standards provided a solid basis for developing more abstract ways of inputting information since it was clear that the underlying calculations models would not be affected easily.

The connection of representations to the CFD simulations required an abstraction of geometry. In our experiment, we employed a structured-grid CFD solver. This necessitated the reduction of shapes to orthogonal geometry. In order to remain as close as possible to the designer’s intention, we use region-modeling techniques to approximate these shapes with rectangular blocks. Standard geometric Boolean operators in the Meta CAD application were employed to determine which parts of the content of the rectangle should be replaced by smaller blocks to represent obstructions and angled walls. It turned out that as long as the original geometry was close to orthogonal, the automated abstraction algorithms were able to reduce the complexity of space floor plans to fit the requirements of analysis tools (Figure 15). However, the treatment of large angled walls requires a different technique than Boolean operators. The adaptation of *plastering* techniques from unstructured mesh generators to fit the needs of convex footprints represented structured grids (Owen 1999) is recommended.

Simulation methods that employ unstructured grids have been surrounded by a number of techniques that convert boundary represented geometry (e.g. CAD) to Finite Element Method meshes (Owen 1998, 1999). Although these techniques require post-processing (by humans), the results are promising enough to consider their application in architecture. It is desirable when architectural CAD applications that concentrate on highly curved geometries (such as Alias Wavefront's *MAYA*) could be connected to CFD simulations without user intervention.

The development of the Meta_CML CFD extension and the ORCA project showed that the informational properties of the tools could be connected to architecturally oriented user-environments. However, we were concerned that the tools would require too much attention in design processes. After all, design is not primary for the use of computer tools. The educational exercises showed that the small amount of input together with the high calculation speed made the use of these tools in a design context possible. The easy-of-use of the tools left room for other considerations besides steering the instrument. With regards to accuracy, the main concern was whether the reduced complexity of the design input environments would not greatly degrade the level of precision of the output. Again, the developments from paragraph 3.5 showed that the Meta Design environment could be designed to make accuracy largely dependent on the significance of the user input.

7.3 Precedents

The third research question concerned the analysis input that lacked in our representation. We designed several experiments based on the applicability of precedent information in indoor climate analysis. The review of currently available Case-based Reasoning (CBR) tools has brought some aspects of the application of precedent information to light.

The results of Case-based Reasoning (CBR) research have not been broadly applied in architectural software. The reason for this is twofold. Firstly, most of the currently available products have been developed for research purposes and, as yet, lack the required robustness and scope to be employed in practice. Moreover, these tools need continuous customization of the users to keep the case-bases up-to-date. The possibilities for the development of global case-base standards and Internet database sharing are still remote. As a result of these difficulties, interest quickly fades away after the introduction of the instrument. The second reason is that the knowledge-based case-adaptation modules of case-based support tools fail to support design adequately. Because of the difficulties in formalizing design knowledge, the system cannot generate new designs (paragraph 4.2.1.3). Another option is to let architects modify the cases themselves. This raises questions with regard to originality and copyrights. Furthermore, the limited intrinsic drawing capabilities of CBR tools combined with the use of constraints results in a procedure that limits design freedom considerably.

Systems that avoid the use of Knowledge-based elements such as ARCHIE have potential in an educational context. These systems enable teachers to provide students with a limited but growing case-base of education projects. Compared to books with selections of famous designs, CBR-tools are easier to maintain and extend. CBR tools that employ genetic algorithms for case-generation are still in development. Therefore, it is difficult to assess the performance of these types of systems at present.

The CFD wizard uses a user-selected project from the Meta database to determine suggestions for the input of indoor climate concepts (paragraph 4.3.5). It does this by reading the parameters such as capacities and locations of the building services modeled into the projects. This automated interpretation of precedent representations relieves users from manually searching the representations. This showed that representations made with the Meta Drawing Model can provide information regarding conceptual climate systems that can be used to make CFD simulations. The CFD wizard that uses the automated interpretation of precedents demonstrated the possibility of re-using case-data as suggestions in the compilation of analysis input.

The production of reliable precedent projects is not straightforward. Case-based systems require consistent use of the structured databases for the retrieval of information. Often, this is a complex procedure since labels, relations and indexes have to be manually generated. Also, the accuracy and reliability of the precedent representation needs to be relatively high when these are used as textbook examples for students.
In the Meta design environment precedents can be generated with the same procedure of new drawings. Although this simplifies the production of precedents, it does not mean that architects will be able to produce entries for the case-base. In general, design sketches do not provide enough reliable information to be considered as precedents for other projects. This would require design specialists such as building service advisors to be engaged in the production of the drawings to provide them with sufficient reliability. It will take a considerable amount of additional research to develop multi-abstraction building service component libraries that allow the connection of documents with various kinds of completeness and levels of details. This needs further research before the use of precedents in climate design can truly be evaluated in practice.

7.4 Visualization

Simulation tools produce large amounts of numerical data that designers cannot easily connect to. Scientific visualization is a powerful technique that can condense this data into comprehensible pictures and animations that appeal to the visual cognitive abilities of humans. Our last research question was focused on finding an insightful and informative way of presenting analysis results.
The application of Scientific Visualization in the feedback of climate analysis results was researched. This produced the following results.

The first part of the chapter discussed the rules and legal regulations that guard to design of indoor climate in buildings in The Netherlands with regard to office buildings and dwellings. The three levels of rules, the Rgd guidelines, ARBO legislation and the Building Decree do not cover all indoor climate aspects to allow a complete assessment of indoor climate comfort. However, given the fact that comfort is a subjective statement, it remains a question whether conclusive regulations can ever be made. The Rgd guidelines come closest to this. They describe indoor climate parameters and effects in detailed terms and provide threshold values. The ARBO legislation has the intention of providing comfort for employees and bears some legal basis, but remains indecisive when actual values are required. The Building Decree only mentions ventilation criteria and proves inadequate as a guideline for thermal comfort.

Scientific visualizations can have a strong resemblance with photo-realistic renderings that architects often use as imagination aids. In a similar way, Scientific Visualization of the indoor climate can portray the otherwise invisible airflows and temperatures as an integral part of an imaginative building. At the same time, this allows for a transfer of building qualifications that helps architects to relate indoor climate performance to building shape and form.

Icons are valuable for visualizing various abstracted and integrated statements of the indoor climate quality because of their capacity to integrate multiple dimensions into a single statement.
Prolonged use of icons can train users to regard specific icons as symbols for a broad range of effects and phenomena that otherwise would be difficult to recognize. However, icons can also appeal to universal themes such as faces and building elements in case of untrained users. In fact, any clearly recognizable object (puppets, clocks, plants, arrows, numbers, etc) can be used as an icon in visualizations.

Icons can have any number of characteristics, depending on the chosen form. These characteristics can reflect various properties of the visualized dataset. In cases of aggregated statements such as the representation of the PMV by a Chernoff face, the iconic representation can feedback the outcome of post-processing computations of the dataset. When this doesn't eliminate the need for visualizations of the elementary values, icons can be of use too. The color of the icon could be linked to a legend that index the outcome, while the icon properties such as size and shape and indicate the values of the formulae parameters.
The interpretation of airflow patterns in spaces can be simplified by using the visualization of vortices. A two-dimensional icon can quickly reveals the presence, size and orientation of vortices (paragraph 5.5.7.3).

Isometric surfaces have a clear three-dimensional character. The parameters of the indoor climate such as temperatures and pressures do not contain strong variations within the content of spaces. This results in more or less concave shapes that indicate size and location of indoor climate parameters. For air velocity and turbulent energy, the resulting isometric surface can also reveal general direction and orientations.

Particle tracks display linear effects most effectively. Placing particle sources within an imaginary airflow and tracing the pathways of the particles over time can reveal airflow patterns, high velocity and vortices quickly and adequately. Animating the movement of the particles adds dynamics to the picture which greatly enhances legibility. It is impossible to convey this using a paper-based medium so interested readers might take a look at this internet URL: www.DesigningIndoorClimate.com and choose to access the visualization research for examples of dynamic particle visualization.

Concluding, the techniques of scientific visualization can be successfully employed in indoor climate design. Technically, the connection of climate analysis output and visualization tools was straightforward and often directly supported by the software. This allowed us to easily produce accurate results. Cognitively, the visualizations provided insightful schemes that often uncovered new patterns and relations (Figure 63 provides a good example). When feeding back specific climate parameters, we were able to develop specialized visualizations from the generic principles offered by scientific visualization. In this respect, employed techniques offer sufficient flexibility to facilitate future developments in the area of indoor climate.

7.5 General Conclusions

The hypothesis of the research stated that the execution of indoor climate analysis during early design would improve the performance of the designers on the area of indoor climate. The research budget did not allow for a full-scale experiment with groups of designers working with and without the Meta Design environment within the time-span of our research. Therefore, an educational exercises for our students that could be done with the Meta Design environment at the various stages of developments was set up. Even thought the student worked with various beta-releases, the results have been rewarding enough to recommend continuation of the underlying Meta Design environment research at the Delft University.

The Meta Design environment has characteristics that are designed to appeal to architects. Techniques such as CAD and visualization can make performing analysis easier and more entertaining. In fact, the advantages of these types of support might suggest that everyone can be enabled to design indoor climate. In the context of the Meta Design environment, this is not the case however. Architects and designers that have no concern for indoor climate and building services *at all* cannot expect a computer environment to solve indoor climate issues. The use of the Meta Design environment presupposes designers that have the intention to design buildings with healthy indoor climates. The Meta Drawing Method requires some effort from the side of the designers and will take some getting used to. The handling of the Meta analysis interfaces will also require some knowledge and successful application depends on an increasing awareness regarding the problems and principles of indoor climate control.

The response to the CFD exercise made clear that the use of the Meta Design environment did have a positive effect on the performance of students with regard to the indoor ‘awareness’ of their designs. The high rating the CFD exercise received during student evaluations and the design examples of the students work support this. The ORCA exercise received a similar response. A considerable amount of students expressed their appreciation for the way in which it introduced indoor climate. They also indicated that it helped them define and design indoor climate more effectively. From the exercise reports we could determine that this was true in a significant number of cases.

The success of the application of CFD in architectural design such as encountered in the CFD exercise, also gave rise to a concern. We noticed that advanced students of architecture have very limited knowledge regarding airflow and airflow related services. As a result, they tend to take on the principles used by the Meta system without critical assessment. This reminded of concerns regarding the knowledge level of students regarding these types of analysis (Schodek 1994). Schodek advises that the use of finite element techniques in education may over ask student capabilities.
Questions such as to the level of realism of conceptual systems and the simulation results were expected. Instead, most students stopped designing the building services after they had entered their designs. Subsequent exercises contained incentives to let students evaluate the results of Meta simulations more. As of yet, it is not clear whether more experienced architects would display similar behavior. Further research after this is recommended.

The table with Design scenarios with related indoor climate issues is an instrument that offers designers the quickest route from architecture to indoor climate. The scenarios simultaneously mention architectural issues and indoor climate hazards. This principle can be used for all indoor climate related information. We found that designers more easily accept indoor climate when it is linked to moves and procedures they use during the design process.
The use of scenarios is also the most inaccurate prediction of indoor climate performance in the Meta Design environment. This is in line with other findings of our research. Lowering the threshold for acceptance of indoor climate results in a reduction of the analysis accuracy. However, we also found that, in order to seize the attention of architects, an easy accessible design tool does not suffice. The use of the design tools such as the Meta Design environment must be directed and guided. Using Design scenarios can provide a point of entry into the architectural design process. At the same time, this allows designers to remain focused on the design and not be over-occupied with the tools.
In the Meta Design environment, the themes from the Design scenarios are accompanied by a calculation with one of the advanced analysis tools. These results offer more than a prediction of performance. Approximate as the results may be, they allow designers to interact with their design in a way that otherwise would require years of experience with indoor climate issues.

Still, the accuracy of the climate simulations is related to the input provided by architects. This leads to one of the most important conclusions of this research. The architect Verheijen stated that in the beginning of design processes: "Architects have to deal with uncertainty" (Verheijen 2002). This implies that anyone or anything involved with architecture at those early stages also has to deal with a degree of uncertainty. In the case of indoor climate analysis for architectural design support: "The cross is in the ballpark". Architects dealing with uncertainty can work with ballpark calculations. Sometimes it is all that is needed to falsify an idea. When designers require justification of an innovative concept, an indicative analysis might prove that a more dedicated investigation is obligatory. Either way, designers have more time to concentrate on what matters in architecture; the production of good buildings.

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Summary

The quality of the indoor climate of buildings is the result of design decisions that architects make. In order to have the ability to correctly design indoor climate, designers need feedback on the performance of the design. Indoor climate analysis may provide this type of feedback.
This research aimed to improve the design process on the aspect of indoor climate by providing architects with information. It attempted to develop a computer environment that stimulates integration of indoor climate analysis into architectural design. This environment linked the available design information to analysis tools in order to arrive at building performance predictions. Several techniques were researched and employed to reduce the gap between design and analysis.

Control over aspects such as temperature, air quality and light is important to the short-term as well as the long-term well being of humans. The domain of indoor climate researches the perception of indoor comfort and designs well being as a part of the built environment. In order to balance building and indoor climate, information on building behavior is compulsory. Currently available temperature and airflow analysis tools can provide design information on these aspects.

Designers often use CAD tools to make design representations. Our environment linked these representations to analysis tools to provide simplified access to these tools. Drawing methods and automated recognition algorithms were used to transform early representations into an organized information structures.

Most conceptual architectural designs contain little information on building services or service concepts. Service information however, is essential if the analysis is to support assessment of indoor comfort. The representations of completed projects contain information that can provide architects with ideas and solutions. In our environment, information from precedents is used to support the definition of building service concept for the calculations.

Indoor climate analysis results consist of large amounts of numbers for velocities, temperatures, etc. Designers find it hard to relate to this data and have difficulties in drawing conclusions from large tables of figures. Scientific Visualization can provide architects with information on the indoor climate in a comprehensible and abstract form. Visualization techniques such as particle tracing and isometric surface construction are used to provide overviews of climate parameters facilitate identification of problem areas. Designers can now interact with the analysis results instead of being confronted with data they do not understand.

The application of indoor climate analysis in design can be supported by design scenarios. These scenarios are a set of focus areas that isolate particular design aspects and link to predefined analysis scenarios. Architects are able to pinpoint various design aspects such as façade type and building mass and receive guidance in performing the corresponding indoor climate analysis and interpretation of results.

Various tests with students of architecture show that execution of indoor climate analysis during early design is possible. In the context of the exercise assignment, a small improvement in performance of the designs on the area of indoor climate was noticed. In most cases, the availability of design tools supported students in gaining knowledge regarding the relation of external factors and building behavior. Another exercise made clear that the use of our design environment did have a positive effect on the performance of students with regard to the indoor 'awareness' of their designs.

J.P. den Hartog

Samenvatting

De kwaliteit van het binnenklimaat van gebouwen is het resultaat van ontwerpbeslissingen die architecten maken. Om het binnenklimaat correct te ontwerpen, hebben ontwerpers informatie nodig over de prestatie van het concept ontwerp. Binnenklimaatanalyse kan deze informatie leveren. Dit onderzoek richtte zich op het verbeteren van het ontwerpproces op het aspect van binnenklimaat door de beschikbaarheid van deze vormen van informatie te vergroten. Een computeromgeving is ontwikkeld die de integratie van binnenklimaatanalyse in architectonisch ontwerpproces stimuleert. Deze omgeving verbond beschikbare ontwerpinformatie aan analyse instrumenten om eenvoudig en snel de prestatie van gebouwontwerpen op het gebied van binnenklimaat duidelijk te maken.

Controle over gebouwaspecten zoals temperatuur, luchtkwaliteit en licht is van belang voor het welzijn van mensen in gebouwen. Het vakgebied binnenklimaat onderzoekt de relatie tussen mensen en de gebouwde omgeving en ontwerpt het klimaat van gebouwen. Om gebouw en binnenklimaat goed op elkaar af te stemmen, is informatie over het gedrag van het gebouw noodzakelijk. Temperatuur- en luchtstromingsimulaties kunnen deze informatie leveren.

Ontwerpers maken vaak gebruik van CAD applicaties om hun ontwerpen weer te geven. Onze computeromgeving verbond deze tekeningen aan analyse instrumenten om op een eenvoudige manier toegang te geven tot de resultaten van de analyses. Tekenmethoden en geautomatiseerde herkenning werden gebruikt om schets ontwerpen in CAD naar gestructureerde informatie te transformeren.

De meeste schetsontwerpen bevatten weinig informatie over gebouwinstallaties. Deze informatie is van wezenlijk belang wanneer klimaatanalyse instrumenten een voorspelling van het welzijn en comfort moeten geven. De ontwerpdocumentatie van realiseerde gebouwen bevat informatie die architecten van ideeën en oplossingen kan voorzien. In onze computeromgeving wordt de informatie van precedenten gebruikt om het ontwerpen van gebouwinstallatie in concept te ondersteunen.

Binnenklimaat analyses produceren grote hoeveelheden van getallen die bijvoorbeeld snelheden en temperaturen weergeven. Ontwerpers hebben vaak moeite conclusies te trekken uit deze grote hoeveelheid informatie. Wetenschappelijke Visualisatie is een vakgebied dat architecten kan helpen om binnenklimaat informatie begrijpelijk en overzichtelijk te maken. In onze omgeving zijn visualisatie technieken zoals *particle tracing* en *isometric surface construction* gebruikt om overzichten van klimaat parameters te genereren en het identificeren van probleemgebieden te ondersteunen.

Ontwerpers kunnen deze vorm van informatie eenvoudiger en sneller onderzoeken en bewerken.

De toepassing van binnenklimaat analyses in het ontwerpproces kan versterkt worden door het gebruik van ontwerpscenario's. Deze ontwerpscenario’s bestaan uit de ontwerpdoel t.a.v. binnenklimaat en een verzameling gebouweigenschappen die met dit doel in verband kunnen staan. Op eigenschappen zoals geveltype en materialisering kunnen architecten ontwerpvarianten maken en deze varianten onderzoeken op binnenklimaat prestaties.

Verschillende ontwerpoefeningen met studenten architectuur lieten zien dat het uitvoeren van binnenklimaatanalyses gedurende de vroege ontwerpfases mogelijk is. In de context en de opdracht van de ontwerpoefening werd een kleine verbetering in prestatie van de ontwerpen op het gebied van Binnenklimaat opgemerkt. In de meeste gevallen ondersteunde de beschikbaarheid van het ontwerpinstrument de studenten in verzamelen van kennis aangaande de relatie tussen gebouw en gebouwgedrag. Een andere oefening maakte duidelijk dat het gebruik van onze ontwerpomgeving de prestatie en kennis van studenten op het gebied van binnenklimaat versterkte.

J.P. den Hartog

Curriculum Vitae

Peter den Hartog was born on October 10th 1972 in *Utrecht* (The Netherlands). He went to high school at the ‘Niftarlake’ College in *Maarssen* and received his Masters in Building technology in 1997 from de faculty of Architecture of the Delft University. During his studies, he also worked a research assistant for the departments of Urban Studies, Building technology and Building management. After his graduation, he started his PhD research under supervision of Prof. ir. Peter Luscuere and Dr. ir. Alexander Koutamanis. His research focused on the gap between architectural design on the one hand and controlling the indoor climate of buildings on the other. He developed a method (with corresponding computer instruments) that invited architects to get acquainted with indoor climate control and analysis. During his research, he supervised two graduate students who produced excellent results in connected studies. His list of publications includes papers and presentations for several national and international conferences and conventions. In 2002, he commenced his tasks as a consultant engineer for the Governmental Building Agency during which he also finalized his thesis.