The TIE-system, a KBS for the Evaluation of Thermal Indoor office Environments.

E.H. de Groot, F.H.Louwers
University of Technology
Department of Architecture, Building and Planning
Section Physical Aspects of the Built Environment
Eindhoven
The Netherlands

ABSTRACT

A Knowledge-Based System [KBS] for the evaluation of Thermal Indoor office Environments [TIE] (in the Netherlands) was the product of a one-year project, undertaken by researchers of the Physical Aspects of the Built Environment group [FAGO] in cooperation with the Knowledge-Based System Section of the TNO-Building & Construction research Institute in Delft. The objective of the project was to develop a KBS capable of evaluating thermal indoor environments of existing or proposed office buildings designs. The approach used in this study was based on a traditional method of predicting thermal sensation by calculating Fanger's 'Predicted Mean Vote' [PMV]. PMV is influenced by four environmental parameters of a room: air temperature, radiant temperature, air velocity and relative humidity, and by two personal parameters of the employees: metabolic rate and clothing insulation. The knowledge required to determine these six parameters was placed in KBS-databases and tables using a KBS-building tool called Advanced Knowledge Transfer System [AKTS]. By questioning the user, the TIE-system is capable of determining the PMV for a particular office room. The system also provides conclusions and advice on improving the thermal comfort. The TIE-system was a pilot-study for the long-term Building Evaluation research project, being undertaken at FAGO, that examines in all aspects of office building performance, and in which KBS may play a major pole.

1 INTRODUCTION

1.1 Background

The Physical Aspects of the Built Environment section [FAGO] (= 'Fysische Aspecten van de Gebouwde Omgeving') is a department of Architecture, Building and Planning at the University of Technology in Eindhoven. A main part of FAGO is the *Indoor Environment* section, which investigates, amongst other things, the comfort of human beings inside buildings. This include: thermal comfort, acoustical comfort, visual comfort and air quality.

At FAGO they found that a method to store knowledge on evaluation and testing of the physical aspects of office building designs was needed to make knowledge-reuse of office building performance possible. This is why they have recently started the Building Evaluation research project, which will examine all relevant aspects of office building performance evaluation, (Rutten 1995).

The TIE-project, which is described in this paper, started in 1995 as a one year pilot study for the Building Evaluation research project. During the TIE project a new computer model for evaluating Thermal Indoor Environment in office buildings was designed, developed and tested.

1.2 Thermal indoor environments

Determining the thermal sensation of working people in an office room is difficult. Thermal sensation depends on several environmental parameters of the room and also on personal parameters of the people themselves. The most important environmental parameters are:

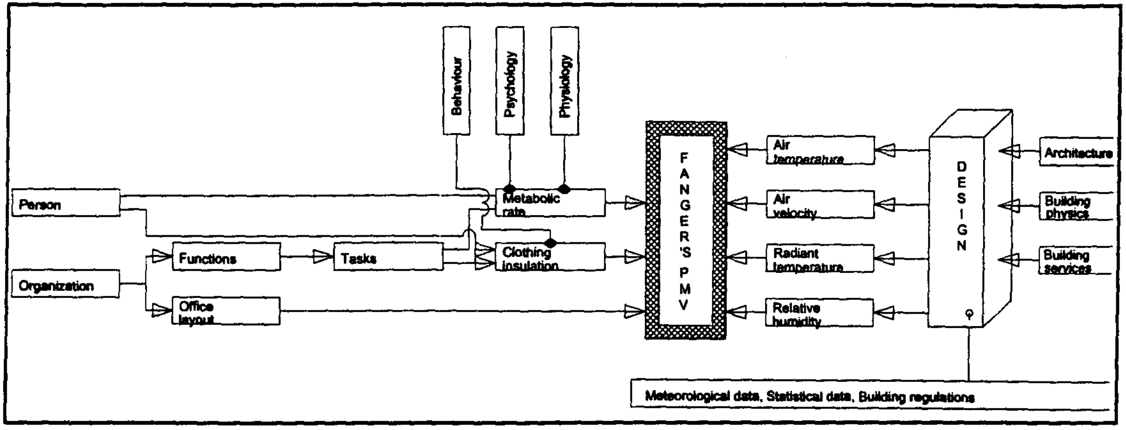
air temperature	t_a	[°C],
mean radiant temperature	t_r	[°C],
relative humidity	RH	[%] and
mean air velocity	v_a	[m/s].

The dominant personal parameters are:

metabolic heat	(M-W)	[W/m^2] and
clothing insulation	I_{clo}	[m^2 °C/W].

The objective of this project was to be able to predict whether people would be satisfied with their thermal environment by evaluating a proposed office design, or evaluating an existing office building. One of the methods to achieve this is determined by P.O. Fanger in 1970, described in (Fanger 1970), (ISSO 1990), (ISSO 1991), (McIntyre 1980) and (NEN-ISO 1989). P.O. Fanger experimentally derived an equation that indicates the average thermal sensation of a group employees in a room: the Predicted Mean Vote [PMV]. The interaction of the six parameters in this PMV-equation is represented schematically in Figure 1.1. The PMV is a widely accepted method for predicting the thermal comfort of an office in Western European climates. However, to use Fanger's method the relevant environmental and personal parameters have to be determined

Figure 1.1: **Schematical representation of designing the thermal environment inside an office building**



followed by a mathematically involved calculation. This is a rather cumbersome and time consuming procedure, especially when, in case of a plan-evaluation, the parameters have to be determined out of the building geometry and wall structures. Also local thermal comfort, the sensation of heat or cold on some particular part of the body, has to be considered. Discomfort occurs, of course, when a part of the body is too warm or too cold, as described in (ISSO 1990), (ISSO 1991), (Olesen 1993). This is usually considered in terms of draught, but can also be caused by temperature differences across the body, contact with cold or hot surfaces and high radiant temperature asymmetry.

The goal of the TIE-project is to determine whether it is possible to collect, structure and implement all of the relevant knowledge on thermal indoor environments of office rooms in such a way that the prediction of the thermal sensation of people in an office room can be done easier and faster than traditional methods. The TIE-system would then be designed, developed and tested to evaluate designs of office rooms and existing office rooms on thermal comfort. This tool could be used as a support for making decisions in the design and management of office building environments.

The following sections of the paper describe the development of the TIE-system including a brief description of KBS and existing applications in the field of thermal sensation, as well as a description of how the TIE-system was implemented.

2 LITERATURE SURVEY

2.1 The definition of a knowledge-based system

Knowledge-based systems are computer programs in which knowledge is contained explicitly. KBS's have a mechanism to use this knowledge in solving problems. When a KBS gives at least as good results in one specific area as a human expert, it is considered artificially intelligent and it is called an expert-system, as for example described in (Kwee 1987), (Lucardie 1994), (Mars 1991) and (Wognum et al. 1993).

The most important reason, according to J.J.S.C Witte and A.Y.L. Kwee, (Witte and Kwee 1988), for developing a knowledge-based system, is that one can describe, distribute and use precious knowledge with it. This knowledge will be accessible to other people and, if the system is flexible, can be kept up to date. This means that when knowledge on thermal comfort of offices is stored in a KBS, this KBS can be used as a support for making decisions in the design and management of thermal indoor environments of office buildings.

2.2 Examples of the use of KBS for thermal assessments

A literature survey was conducted to find other knowledge-based systems that examined the issue of thermal sensation. Three principle models were found as a result:

1. H. Rats developed an information model entitled: *The indoor environment of a habitation*, (Rats 1992). This model is a simple encyclopedia, on the physical aspects of building in general. The model does not provide any consultation.
2. ISSO in Rotterdam and the University of Copenhagen, Denmark, developed another model during an European Community-project in 1987. However, the project was closed with an unfinished knowledge-based system that dealt with complaints concerning thermal comfort. The reason for this disappointing result was that the domain of their system was not demarcated well enough, so that their model became too large to handle, (Hogeling and van Weele 1989).
3. K.C. Parsons developed an information model in 1989 at the University in Loughborough, described in (Keyson and Parsons 1990), (Parsons 1989), (Parsons 1993) and (Wadsworth 1989).

Some reasons why these models did not meet expectations of their developers are presented in (Mastrigt et al. 1989). This study examined the success and failure of KBS into common applications. Two of the main conclusions from this study were that if goals are formulated clearly before the start of the project, successes concerning technique, organization and use might be guaranteed, moreover it is also important to have a good specification of the future user.

Based on these observations it was felt that the TIE-system would have to be well defined, it has to represent knowledge logically, its way of inference should be easily controllable, it has to provide the possibility to store and load consultations and to change one or more entered values without starting the consultation all over again.

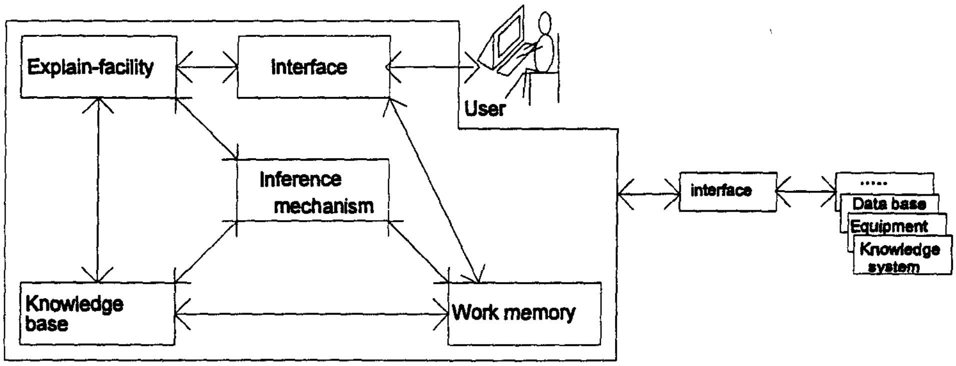
3 METHODOLOGY

3.1 Definitions according the TIE-system

The literature survey identified five questions that need to be answered before any actual programming was done:

1. *What the TIE-system will do*: the computer program should support the user's work during the design or evaluation of an office building, by providing easy and quick access to specialized knowledge in the field of thermal sensation. It should

Figure 3.1: **An often seen structure of a knowledge-based system, from (Witte and Kwee 1988).**



other facilities.

3.2.2 *The knowledge base of the TIE-system*

The knowledge is implemented in the KBS-building tool called Advanced Knowledge Transfer System [AKTS], which is developed at the TNO-Building & Construction research Institute in Delft. Results of this system were first published by G.L. Lucardie in 1994, (Lucardie 1994). In AKTS decision tables, a way to structure knowledge, and Prolog, a logical program language, are joined.

The joint application of decision tables and Prolog offer a great amount of tools and techniques that can give a formal, unambiguous description of real-world phenomena. With AKTS it is possible to represent, reconstruct, validate and simulate knowledge on thermal indoor office environments. Further, AKTS allows automatic testing and simulation of a knowledge-based system and the necessary decision tables are easy to draw and to adjust.

As a result of AKTS the knowledge in the TIE-system is mostly stored in decision tables. An example of these is shown in Figure 3.2. In the decision table shown the upper-left-side-part gives the description of all relevant conditions and the lower-left-side-part gives all the relevant actions or results of the decisions to be made. The upper and lower-

Figure 3.2: **An example of a decision table in which knowledge is stored**

Determine local comfort and relative humidity extremities							
C1	Determine local comfort	Good			Bad		
C2	Measurable local comfort determination	Yes		No	Yes		No
C3	Determine measurable local comfort	Good	Bad	-	Good	Bad	-
A1	Determine local comfort and relative humidity extremities	Good	Bad	Good	Bad	Bad	Bad
		R1	R2	R3	R4	R5	R6

also be possible to save and load previous evaluations.

2. *How the TIE-system will do it*: when the user offers relevant characteristics about the organization, the employees, the design of building and building services to the computer program, the program will compare the 'thermal performance' of a particular office room with the predicted demand of the employees. Then the program provides a list with positive and negative points in the design related to the field of thermal sensation. It will also offer recommendations for improvement.
3. *What advantages the TIE-system can offer*: this computer program will not only fulfil the usual calculations, but it will also point out the problem areas in the design and provide recommendations in solving these problems. It will also be possible to store knowledge from previous evaluations, and adapt stored knowledge to recent developments in the field.
4. *What potential problems the TIE-system will have*: the recommendations for improving the thermal comfort of the employees may have an impact on other design aspects, such as the acoustical comfort, the visual comfort, the air quality, the consumption of energy, the environment or the initial costs. These aspects will be added to the KBS during the Building Evaluation research project.
5. *Who will use the TIE-system*: the future user of the TIE-system, enlarged with knowledge of other physical aspects, will be a designer of office buildings, advisers to problems in the field of building physics, or those who make evaluations of office buildings in the field of building physics. These users have the disposal of (conceptual) drawings of the design of the building and the building services at their disposal, they are familiar with the organizational structure and the employees who (will) occupy the building and they know the context in which the building is or will be built (laws and regulation, climate, infrastructure, etc.).

3.2 The structure of the TIE-system

3.2.1 The overall structure

The TIE-system is made with the same basic components as any KBS (as described in (Witte and Kwee 1988), and as shown in Figure 3.1). This includes:

one or more knowledge bases (containing knowledge and data needed to determine the values of air temperature, radiant temperature, relative humidity, air velocity, metabolic rate and clothing insulation can be determined and the PMV-equation),

an inference mechanism (making it possible for the computer to use the knowledge to determine the values of those parameters and the PMV),

a working memory,

a user interface and an explanation-facility (making it clear to the user what he should do the let the program determine the values of the parameters and the PMV).

Most of the times a KBS is linked with other knowledge-based systems, databases, or right-side-parts consist of columns with decisions. Every column describes an existing decision situation: within the upper-right-side-part, 'Yes' and 'No'-answers to the conditions; and within lower-right-side-part, an X behind every action to be taken in the specific case. A more detailed description about decision tables is given in: (Lucardie 1994), (Mors 1993) and (Verhelst 1972).

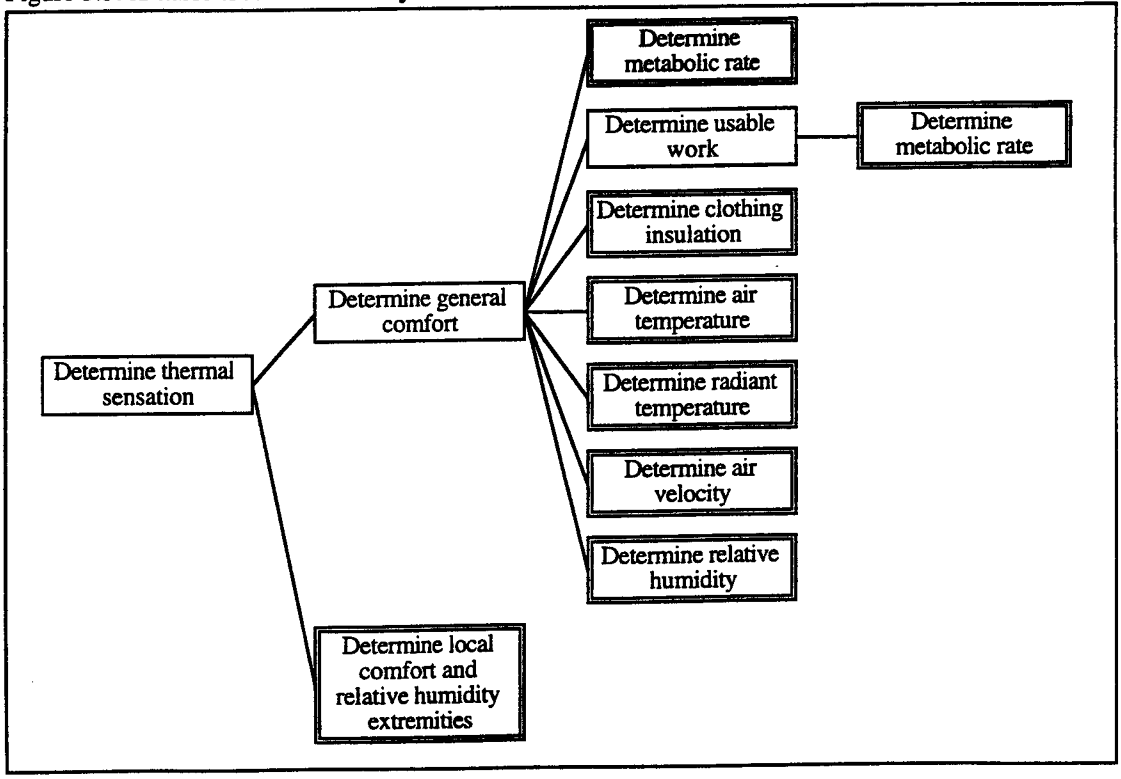
In the TIE-system also databases are stored. These databases are programmed in the underlying program language of AKTS: Prolog. Also some major calculation are programmed in Prolog. Literature used regarding Prolog: (Clocksin and Mellish 1987), (Leigh and Smith 1986), (Lucardie 1994), (Rowe 1988), (Saint-Dizier 1990) and (Walker et al. 1987).

3.3 The knowledge-based system for thermal sensation

Thermal sensation can be divided into two components: global and local thermal comfort. This division is also made in the TIE-system. First the global, or general, comfort of the room is determined. When this is good, local comfort is also checked. This ensures that smaller sources of discomfort are also dealt with. A graphic showing the evaluation path of the system is shown in Figure 3.3.

To determine global comfort the PMV-equation is imbedded in the system itself. The actual measurements of the personal parameters (the metabolic rate and the clothing insulation) and the environmental parameters (air temperature, air velocity, radiant temperature and relative humidity) which influence global thermal comfort, can be entered by the user in case of an existing building evaluation. In the case of an evaluation

Figure 3.3: **A table tree of the Tie-system**



of a design these parameters can be derived or estimated by the system.

In the later case the TIE-system estimates the two personal parameters:

1. *Metabolic rate*: The metabolic rate is estimated by using different kinds of occupations or by calculation using body posture and specific tasks.
2. *Clothing insulation*: The intrinsic clothing insulation is then estimated by using standard ensembles, depending on gender and time of year or by adding the insulation values of various garments.

Four environmental parameters can also be derived by the program:

1. *Air temperature*: In the case of winter the user has to enter the designed air temperature. In the case of summer the air temperature is derived on an average day in July at noon according to the accumulation dependant method. The user has to enter the geometry of the room, (including the amount and type of all heat producing machines and lamps), the wall structures and the orientation of the walls on the outside of the building.
2. *Radiant temperature*: The radiant temperature is estimated using an area weight average of the surface temperatures in the room.
3. *Relative humidity*: The water vapour pressure in the room is predicted and divided by the saturated water vapour pressure using the derived value for air temperature. The user has to enter the amount of ventilation and outdoor air temperature and relative humidity (monthly statistics of the Netherlands of outdoor air temperature and relative humidity are also available).
4. *Air velocity*: The air velocity is fixed at 0.1 m/s, (because the knowledge on air condition installations, needed to predict it more accurately, is not implemented yet).

4 CONCLUSIONS

The TIE-project demonstrated that it is possible to create a KBS capable of predicting the thermal comfort of office rooms. The use of AKTS helped meet most of the objectives set out at the beginning of the project. This included:

- logical representation of knowledge,
- easily controllable inference (way of solving problems),
- possibilities to store and load consultations and
- possibilities to change one or more entered values without starting the consultation all over again.

AKTS made it possible to collect, structure and implement the relevant knowledge on thermal comfort for the project.

The TIE-system is working for those cases which are most common. The current limitations of the system are:

- only office rooms in the Netherlands can be considered, this is because only local building regulations and meteorological and statistical data are implemented;
- only rectangular office rooms can be considered;
- walls, ceiling and floor can only consist of five or less cavities;

- only common building materials, occupations, garments, window types and light installations can be chosen;
- the air temperature is determined with a simplified accumulation mass method because implementing a more complex method would have been very time-consuming,
- the air velocity is fixed at 0.1 m/s, because the knowledge on air conditioning installations, needed to predict the air velocity more accurately, is not implemented yet; and,
- the radiant temperature is determined using an area weight average of surface temperatures because the implementation of a more accurate method was outside the scope of this study.

In the future it will be possible to link existing commercially available software with AKTS. This means that calculations, (for example to determine radiant temperature) need not be imbedded within the TIE-system itself, but can be performed by external programs specializing in these tasks.

After completing the TIE-system the next step in research will be to add the evaluation of visual comfort, acoustical comfort and air quality to make a system that considers all physical aspects of building. Obviously, these four aspects interact with one another, so thermal comfort alone will not be enough to judge the quality of the entire indoor office environment. When this system is completed it will contribute to decision support in designing indoor office environments. During the long-term Building Evaluation research project, other office building performances, such as use of energy, environment and initial costs will be added as well.

5 REFERENCES

Clocksin, W.F. and C.S. Mellish (1987) *Programming in Prolog.* (Third, revised and extended edition) Springer-Verlag, Berlin.

Fanger, P.O. (1970) *Thermal comfort.* Danish Technical Press, Copenhagen.

Hogeling, J. and A.M. van Weele (1989) *Expert system 'Comfort'.* (Two parts) Stichting ISSO, Rotterdam.

ISSO (1990) *Ontwerpbinnencondities en thermische behaaglijkheid in gebouwen.* (ISSO-researchrapport 5) Stichting ISSO, Rotterdam.

ISSO (1991) *Thermisch binnenklimaat: aanbevelingen.* (ISSO-publicatie 19) Stichting ISSO, Rotterdam.

Keyson, D.K and K.C. Parsons (1990) Designing the user interface using rapid prototyping, *Applied ergonomics* 3, pp. 207-211.

Kwee, A.Y.L. (1987) Kennissystemen in Nederland, *Informatie en informatiebeleid* 2, pp. 51-59.

Leigh, W.E. and A.N. Smith (1986) *Prolog; to expertsystems.* Mitchell Publishing Inc., Santa Cruz California.

Lucardie, G.L. (1994) Functional object-types as a foundation of complex knowledge-based systems, Ph.D. Thesis, Department of Architecture and Urban Planning, Eindhoven University of Technology, Eindhoven.

Mars, N.J.I. (1991) *Inleiding kennistechnologie.* Academic Service, Schoonhoven.

Mastrigt, B. et al. (1989) *Slagen en falen van expertsystemen.* Stam tijdschriften, Schoonhoven.

McGraw, K.L and K.H. Harbison-Briggs (1989) *Knowledge acquisition: principles and guidelines.* Prentice-Hall Inc., Englewood Cliffs New Jersey.

McIntyre, D.A. (1980) *Indoor climate.* Applied Science Publishers, London.

Milne, G.R. (1995) The energy implications of a climate-based indoor air temperature standard, from (Nicol 1995).

Mors, N.P.M. (1993) *Beslissingstabellen*, Lansa Publishing bv, Leidschendam.

NEN-ISO (1989) *Gematigde thermische binnencondities*, Nederlands Normalisatie Instituut, Delft.

Nicol, F. et al. (1995) *Standards for thermal comfort: indoor air temperature standards for the 21th century,* Chapman&Hall, London.

Olesen, B.W. (1993) Standards for design and evaluation of the indoor thermal environment, *ASHRAE Journal* **Aug.**, pp.20-25.

Parsons, K.C. (1989) Computer aided design of the thermal environment, *Proceedings of the human factors society 33rd annual meeting*, pp. 512-516.

Parsons, K.C. (1993) *Human thermal environments: the effect of hot, moderate and cold environments on human health, comfort and performance: the principles and the practice.* Taylor & Francis, London.

Rats, H. (1992) Het binnenmilieu van een woning: Het ordenen van binnenmilieu-aspecten t.b.v. het opstellen van een model van een informatiesysteem voor ontwerpers, Students report, no. 1764, Department of Architecture and Urban Planning, Eindhoven University of Technology, Eindhoven.

Rowe, N.C. (1988) *Artificial intelligence through Prolog.* Prentice-Hall Inc., Englewood Cliffs New Jersey.

Rutten, P.G.S. (1995) Personal communications.

Saint-Dizier, P. (1990) *An introduction to programming in Prolog.* Springer-Verlag Inc., New York.

Verhelst, M. (1972) *Beslissingstabellen*, Samson, Leuven.

Wadsworth, P.M. and K.C. Parsons (1989) The design, development, evaluation and implementation of an expert system into an organization, from: *Work with computers: organizational, management, stress and health aspects*, pp. 106-113.

Walker, A. et al. (1987) *A logical approach to expert systems: knowledge systems and Prolog.* Addison-Wesley Publishing Company Inc., Reading Massachusetts.

Witte, J.J.S.C. de, and A.Y.L. Kwee (1988) *Kennissystemen in de industrie.* Samson, Alphen a/d Rijn.

Wognum, P.M. et al. (1993) Wat is kennistechnologie?, *Klimaatbeheersing* **6**, pp. 9-13.