

# The TIE-project : designing a knowledge-based system for the thermal indoor office environment

**Citation for published version (APA):**

Groot, de, E. H. (1996). *The TIE-project : designing a knowledge-based system for the thermal indoor office environment*. Eindhoven University of Technology.

**Document status and date:**

Published: 01/01/1996

**Document Version:**

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

**Please check the document version of this publication:**

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

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**The TIE -project,**  
**designing a knowledge-based system**  
**for the thermal indoor office environment.**  
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July 1996.

**CIP-gegevens Koninklijke Bibliotheek, Den Haag**

Groot, E.H. de

'The TIE-project, designing a knowledge-based system for the thermal indoor office environment'/  
Groot, E.H. de - Eindhoven: Stan Ackermans Institute. - I11.

Post-initial engineering course: 'Ontwerp-, Plannings- en Beheertechnieken van bouwen en de  
gebouwde omgeving' [OPB] (Design, Planning and Management of buildings and the built  
environment)

With ref.

ISBN 90-5282-650-1

Subject headings: thermal comfort, knowledge-based system.

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## Preface

The project described in this report is part of the post-initial engineering course 'Ontwerp-, Plannings- en Beheertechnieken van bouwen en de gebouwde omgeving' [OPB] (Design, Planning and Management of buildings and the built environment). The OPB-course is one of the courses of the post-initial engineering education given at the Stan Ackermans Institute [SAI] at the Eindhoven University of Technology.

The one year project started in 1995 and is executed by the student F.H. Louwers and I at the Fysische Aspecten Gebouwde Omgeving Section [FAGO] (Physical Aspects of the Built Environment) in the Architecture, Building and Planning Department. My tasks were:

*the project management of my part of the project,*  
*the literature surveys into knowledge-based systems, into Fanger's method to predict thermal comfort of an office room, and into two personal parameters which influence it,*  
*the development of a knowledge-based system called the TIE-system,*  
*the implementation of Fanger's method, the personal parameters and three environmental parameters into the TIE-system,*  
*the design of the user interface,*  
*the development of a test of the TIE-system*  
*the oral presentation of the results of the project, and*  
*the writing of this report.*

(mostly done with, or in consultation with, F.H. Louwers.)

The project is supervised by Prof.ir. P.G.S. Rutten, professor in *Indoor Environment*. Further, ir. F.E. Bakker, (scientific employee at FAGO), ir. C.E.E. Pernot, (scientific employee at Center for Building Research [CBO] at Eindhoven University of Technology), and dr. G.L. Lucardie, (head of the Advisory Group Knowledge-Based Systems of the Building & Construction Research department of the Netherlands Organization for Applied Scientific Research [TNO] in Delft), have contributed their expertise and support. My exam committee consisted of these four persons.

Ir. Ellie de Groot.

## 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 Advisory Group Knowledge-Based Systems of the Building & Construction Research department of the Netherlands Organization for Applied Scientific Research [TNO] in Delft.

The objective of the project was to develop a KBS capable of evaluating thermal indoor environments of existing or proposed office building 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 is a pilot-study for the long-term Building Evaluation research project being undertaken at FAGO that examines all aspects of office building performance, and in which KBS may play a major role.

As a more extensive abstract, the paper presented at the third Design & Decision Support Systems conference in Spa, Belgium August 1996, is added in Appendix VII of this report.

This report describes the work of the one-year project of ir. Ellie de Groot. Chapter 1 describes the context and background of the project, as well as the results of a literature survey into KBS's for thermal comfort. Chapter 2 explains KBS's in general and Chapter 3 explains AKTS. In Chapter 4 the knowledge on thermal comfort is introduced. The specifics of metabolic heat and clothing insulation are dealt with in Chapter 5. Chapter 6 describes the processes of designing and developing a KBS for thermal comfort in office buildings. The 7th, and final, chapter discusses the whole project and offers conclusions and recommendations.

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## 1. Introduction

This chapter describes the context and background of the TIE-project. The results of a literature survey of other Knowledge Based Systems, (from now on referred to as KBS's), are shown as well.

### 1.1 Context and background

The Physical Aspects of the Built Environment group [FAGO, or 'Fysische Aspecten Gebouwde Omgeving'] is a section of the Architecture, Building and Planning department at the University of Technology in Eindhoven. A main part of FAGO is the *Indoor Environment* Section, which investigates, among other things, the comfort of human beings inside buildings. This includes: thermal comfort, acoustical comfort, visual comfort and air quality. Some projects done at FAGO are consulted in the initial stage of the project described in this report: (Cox 1984), (Croes 1988), (Lammers et al. 1982), (Lammers et al. 1983), (Pas 1985), (Rats 1992) and (Velde 1993).

At FAGO it was 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 the Building Evaluation research project was started to examine all relevant aspects of office building performance evaluation, and which will probably lead to a KBS that can be used as a tool to check a design or evaluate an existing building.

Until now the system in use for that purpose is the information system BFIM (Bouw Fysisch Informatie Model = Information Model for the Physical aspects of Building). This was developed in the CBO, (Centrum Bouw Onderzoek = Center for Building Research), a cooperate program of FAGO and TNO, and has been in development for several years now. One of the goals of CBO is to get to know more about the physical phenomena and the comfort aspects that influence the indoor climate of office buildings. Furthermore, CBO would like that the use of knowledge on indoor environments become accessible for designers and engineers, so that the system can be used to show the consequences of design decisions on the indoor climate. Unfortunately BFIM has several practical problems, mainly caused by the underlying database Paradox, that uses a lot of computer-memory itself and has a continuous release of updates.

The TIE-project described in this report started in 1995 as a one-year pilot study for the Building Evaluation research project. The goal of the TIE-project was 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 by using traditional methods. Further, it should be checked if possibilities to adapt or expand the system can be provided to the user. After that, the TIE-system is designed, developed and tested to evaluate designs of office rooms and existing office rooms on thermal comfort. In this way this can be used as a support for making decisions in the design and management of office building environments.

### 1.2 Literature survey

A literature survey was conducted to find other KBS's that examine 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 ended with an unfinished KBS 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). This model is still in development.

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.

The main conclusions were:

- Systems based on human knowledge had better scores on organization and use than systems based on knowledge acquired from books.
- If goals are formulated clearly before the start of the project, successes concerning technique, organization and use might be guaranteed.
- When specialized knowledge engineers do the developing of a system with the help of users and domain experts, the results might be better then when users and domain experts do the developing themselves. (This might have been so in this project, too.)
- It is important to have good specifications of the future user. If possible, the user should be involved in an early stage of developing the KBS.
- The use of standardized hardware and software has large advantages. The system has to connect to existing systems as much as possible.
- It should be possible for the user to adjust or complete the knowledge stored in the system.

According to (Kwee 1987), concessions are made during the development of a KBS due to costs or time. These concessions cause restrictions in the system's depth, breadth, communication and speed. So, one has to choose between superficiality, restricted applicability, little user friendliness and long waiting times.

According to (Wognum et al. 1993), problems occur in existing KBS's in five main areas:

<i>Possibilities to generalize</i>	As the task is adjusted, the KBS should be revised.
<i>Reuse of knowledge</i>	Because no model of domain knowledge exists, one has to question experts repeatedly, in order to create a knowledge base.
<i>Handling new situations</i>	The knowledge is based on former experiences, so one cannot solve new problem situations.
<i>Size</i>	The maintenance of a large system is difficult.
<i>Economical value</i>	Costs of development and maintenance are high, because the possibility of re-use is limited.

Based on these observations it was felt that the TIE-system would have to:

- be well defined,
- represent knowledge logically,
- have an easily controllable way of inference,
- provide the possibility to store and load consultations, and
- provide the possibility to change one or more entered values without starting the consultation all over again.

The TIE-system is described in Chapter 6. Initial descriptions of KBS and of the KBS-building tool AKTS used to create the TIE system are given in Chapters 2 and 3. The knowledge collected on thermal comfort is reported in Chapters 4 and 5 (and in the report of F.H. Louwers, (Louwers 1996)). Conclusions and recommendations on how the TIE-system was implemented, can be found in Chapter 7.

## 2. Knowledge-based systems

This chapter shows various definitions for knowledge-based systems [KBS]. A knowledge-based system usually consists of a knowledge base, an inference mechanism, an user interface, a working memory and an explanation facility. The three first components are described in this chapter.

### 2.1 The definition of a knowledge-based system

Various definitions of KBS's are found in literature, but mostly they are very much alike. (Kwee 1987) describes KBS's as follows: "KBS's are computer programs in which knowledge is contained explicitly and which also have a mechanism to use this knowledge in solving problems". (Mars 1991) and (Wognum et al. 1993), of the Enschede University of Technology, give a more mathematical definition: "KBS's are computer programs in which as good as possible a separation is conceived between problem-specific knowledge and a problem-independent way of inference". Lastly, G.L. Lucardie provides the following definition: "KBS's are computer systems that embody knowledge to solve problems ordinarily addressed by humans", (Lucardie 1994).

A KBS that gives answers in one specific area as well as human experts would is called an artificially intelligent system. A computer program can be artificially intelligent in two different ways. Firstly, the computer program simulates human intelligent behaviour  $\Rightarrow$  artificially intelligent process. Secondly, the computer program provides the same results as those that can be reached using human intelligence  $\Rightarrow$  artificially intelligent product. A KBS is part of the second description.

The most important reason, according to (Witte and Kwee 1988), for developing a KBS 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. Building a KBS is only possible if one can demarcate the domain concerning the knowledge, i.e., reduce it to the most important issues. Methodical problem-solving in the demarcated domain should also be possible.

G.J. van Rossum lists characteristic functions of KBS's, from (Rossum 1992):

<i>Interpretation</i>	The deduction of descriptions of situations from observations.
<i>Prediction</i>	The determination of possible consequences from given situations.
<i>Diagnosis</i>	The deduction of defects from observations.
<i>Design</i>	The design of outlines of objects on basis of demands.
<i>Planning</i>	The determination of a list of actions to be taken.
<i>Monitoring</i>	The comparison of observations with the predicted or expected results.
<i>Debugging</i>	The prescription of remedies against disturbances in certain systems.
<i>Reparation</i>	The execution of ideas to apply to prescribed remedies.
<i>Instruction</i>	The analysis, the giving of remedies and the correction of the behaviour of persons.
<i>Control</i>	The guarding of the performance of systems.

The TIE-system will have the functions of *Prediction* and *Design*: the thermal sensation of employees in an existing or proposed office room design can be predicted, consequences of changes in the design can be shown.

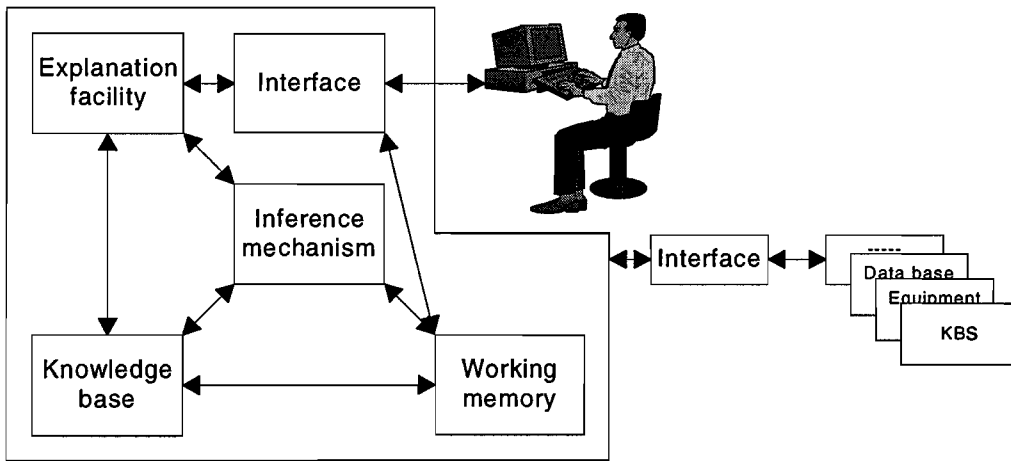


Figure 2.1: A typical structure of a KBS, from (Witte and Kwee 1988).

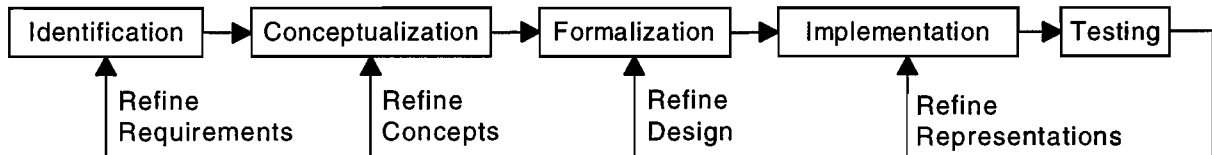


Figure 2.2: Systematic method for knowledge acquisition, from (McGraw and Harbison-Briggs 1989).

## 2.2 The structure of a knowledge-based system

According (Witte and Kwee 1988) a KBS consists of:

<i>One or more knowledge bases,</i>	containing knowledge and data needed to determine the goal of the KBS.
<i>An inference mechanism,</i>	making it possible for the computer to use the knowledge and data.
<i>A working memory,</i>	existing in every computer system.
<i>A user interface and an explanation-facility,</i>	making it clear to the user what he should do to let the program determine its goal.

Most of the time a KBS is linked with other KBS's, databases, or other facilities, (see Figure 2.1).

## 2.3 The knowledge base

### 2.3.1 The development of a knowledge base

The most important part of a KBS is the knowledge base itself. A knowledge base stores all the necessary knowledge in such a way that mechanical inference is possible. According (McGraw and Harbison-Briggs 1989), there are five stages in the development of a knowledge base, (see also Figure 2.2):

<i>Identification</i>	The identification of the characteristics of the problems which should be solved by using the KBS.
<i>Conceptualization</i>	The identification of the concepts used in the specific domain.
<i>Formalization</i>	The classification and organization of collected knowledge in an appropriate inference language.
<i>Implementation</i>	The development of inference rules.
<i>Testing</i>	The control and modification (when needed) of rules.

They also describe many extensive indications and directions that can be used to structure interviews in order to acquire knowledge from human experts.

(Mars 1991) describes two of the five stages, namely conceptualization and formalization. He states that during the conceptualization stage the domain should be demarcated. This is be done by developing a "*window of reflection*" in which one has to find solutions for problems. This window of reflection consists of a collection of objects on which knowledge is represented. Between two or more objects *relations* exist, which show corresponding characteristics of these objects. The window of reflection also contains *functions* that connect one object with a collection of other objects. An example of a conceptualization is given in the text frame: **An example of a conceptualization**. This shows that a conceptualization consists of:

- A window of reflection* (a collection of objects),
- A collection of relations* (between objects) and
- A collection of functions* (of objects).

A conceptualization is not unique and should be judged by its capability to solve a particular problem. The choice for some particular conceptualization influences the ease with which the KBS is solving problems.

### An example of a conceptualization, from (Mars 1991)

A collection of five blocks is drawn in the figure. A possible choice for a *window of reflection* in this case is to see the individual blocks as objects: the collection {a, b, c, d, e}. Each character stands for one particular block from the world of blocks, and not for a symbol itself.

Some pairs of blocks have a specific characteristic: one block is standing on the other. Such a characteristic can be represented by a *relation*. A relation represents a characteristic of a group of objects with one another. The same relation can exist for more groups of objects and one group of objects can have more than one relation.

In this case the relation **on** can be introduced to describe the characteristic of pairs of blocks mentioned above. The relation **above** can describe the characteristic of pairs of blocks from which one is above the other. It is also possible to introduce a relation of just one object, like **clear** that describes which blocks have a free top: {a, d}.

When a relation considers a combination of objects, sharp hooks are used to show this: < >. The *extension* of a relation is the collection of all combinations of objects that have that relation. So for the relation **on** the extension will be: {<a,b>, <b,c>, <d,e>}, and for the relation **above**: {<a,b>, <b,c>, <a,c>, <d,e>}.

A *function* is a rule, that (only) one object connects to every combination of objects. In the example of the world of blocks a function **support** can be introduced. This function describes of each object which unique object is supporting it:  $F_{\text{support}}(a) := b$  and  $F_{\text{support}}(b) := c$ .

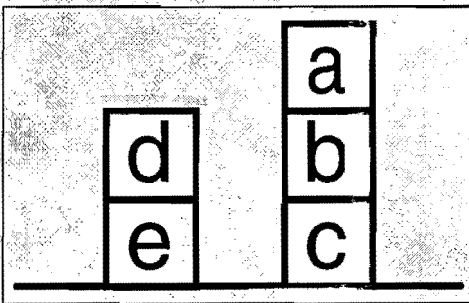


Figure: The world of blocks.

According to (Mars 1991), the collected knowledge is written in an appropriate language during the formalization stage. This language has a specific syntax and semantics. The syntax defines which sentences are allowed. The semantics indicate the relations between sentences in the language and a conceptualization of the world.

### 2.3.2 Knowledge acquisition

(McGraw and Harbison-Briggs 1989), (Mars 1991), (Mastrigt et al. 1987), and (Witte and Kwee 1988), all suggest three different methods to acquire knowledge:

- Consulting handbooks,*
- Re-using knowledge stored elsewhere, and*
- Retrieving knowledge from human experts.*

The later method can consist of interviewing the experts (asking for the ways experts handle different domain-specific problems), or the protocol-analysis (a human expert thinks aloud while solving a domain-specific problem and a knowledge engineer writes down the process).

After collecting a part of the knowledge there are three different ways of handling this:

- |                            |   |
|----------------------------|---|
| <i>KADS</i>                | Knowledge Acquisition and Documentation System, the KBS is not developed further until all relevant knowledge and methods for solving problems are carefully collected. |
| <i>Rapid Prototyping</i>   | In an early stage of knowledge acquisition a prototype KBS is built. After that, the knowledge is continuously expanded and validated.                                  |
| <i>Mechanical learning</i> | Inference rules are generated automatically from reliable examples of desirable behaviour.  |

### 2.3.3 Different kinds of knowledge

According to (McGraw and Harbison-Briggs 1989), there are four different kinds of knowledge:

- |                            |   |
|----------------------------|---|
| <i>Informal knowledge</i>  | Learned by imitation and observation. Difficult to represent, because how one executes a task is unknown.   |
| <i>Formal knowledge</i>    | Consists of laws and rules, superficial knowledge.  |
| <i>Technical knowledge</i> | Also called <i>domain knowledge</i> . Adopted from mathematical and physical theories. This is deep knowledge, which is easy to represent and therefore appropriate as a basis for the KBS. |
| <i>Strategic knowledge</i> | Knowledge about how one uses technical knowledge to solve problems.   |

The knowledge of experienced human experts consists of a combination of technical knowledge and strategic knowledge. This combination is the knowledge of the concepts and methods used in the specific domain, to solve problems. It is this knowledge that a KBS should represent. To represent knowledge, three possibilities are given:

- |                         |  |
|-------------------------|--|
| <i>Production rules</i> | Main rules, causal relations, prescripts.                        |
| <i>Semantic network</i> | Objects connected by relations.                                  |
| <i>Frames</i>           | Knowledge in modules handling the same characteristic or object. |

	Description	Decisions
Conditions	A	C
Actions	B	D

Figure 2.3: The basis representation of a decision table, from (Mors 1989).

**When is a year a leap year?** from (Verhelst 1972)

A year is a leap year if the year number is divisible by 4, but not by 100, except if it also is divisible by 400. However, the year is no leap year if the year number is divisible by 4000.

Year number is divisible by 4	YY	YY	YY	YY	NN	NN	NN	NN
Year number is divisible by 100	YY	YY	NN	NN	YY	YY	NN	NN
Year number is divisible by 400	YY	NN	YY	NN	YY	NN	YY	NN
Year number is divisible by 4000	YN	YN	YN	YN	YN	YN	YN	YN
A year is a leap year	-X	-	-	-X	-	-	-	-
A year is no leap year	X-	-X	-	-	-	-	-	-X
Impossible combination	-	X-	XX	X-	XX	XX	XX	X-

Some columns of this table can be joined, and the row 'Impossible combination' can be removed:

Year number is divisible by 4	Y	Y	Y	Y	N
Year number is divisible by 100	Y	Y	Y	N	-
Year number is divisible by 400	Y	Y	N	-	-
Year number is divisible by 4000	Y	N	-	-	-
A year is a leap year	-	X	-	X	-
A year is not a leap year	X	-	X	-	X



### 2.3.4 Decision tables

Decision tables provide a method to structure knowledge in such a way that a computer can understand it. It arranges related conditions and actions involved in the processing of data necessary to come to a decision. Decision tables make it possible to visualize complicated decision problems in a clear, controllable, and workable way. A decision table is a diagram of a decision process and has a matrix shape. The basis is represented in Figure 2.3.

In the decision table shown in Figure 2.3 the upper-left-side-part (A) gives the description of all relevant conditions and the lower-left-side-part (B) gives all the relevant actions or results of the decisions to be made. The upper and lower-right-side-parts (C+D) consist of columns with decisions. Every column describes an existing decision situation: within the upper-right-side-part (C), 'Yes' and 'No'-answers to the conditions; and within lower-right-side-part (D), an X behind every action to be taken in the specific case. An example of a decision table is given in the text frame: **When is a year a leap year.**

Special forms of decision tables are:

*The table with ELSE-column:* Combinations of actions that are not especially interesting and that occur twice or more times can be joined in one decision column, called the ELSE-column.

*The table with enhanced notation:* Rows are joined by writing the differences in similar conditions or actions instead of Yes/No/-. (when action is 'discount', values can be '5%', '10%' and '15%')

*Separation of one big table into smaller ones and iterations:* Big tables are divided into smaller ones that will be connected by:

*A jump instruction:* switch from one table to another,

*A subroutine:* before finishing one table switch to another, and after that switch back again,

*An iteration:* running through the same table twice or more often.

*Variation in order of succession of execution of actions:* All the actions in part B of Figure 2.3 have to be executed, but not always in the same order. The order depends on the decision situation.

*A decision tree:* Sometimes it is illuminating to draw a flow chart, which is called a decision tree.

A more detailed description about decision tables is given in (Lucardie 1994), (Mors 1993) and (Verhelst 1972).

## 2.4 The inference mechanism

### 2.4.1 The strategy of inference

According to (Wognum et al. 1989), the strategy to solve problems in a specific domain can be seen as a sequence of steps. Every step solves a little part of the problem by executing a task. The local strategy defines how this task should be executed to reach the desired result.

A task is called a *basis task* when it is executed by using technical knowledge (see section 2.3.3). For a basis task, the local strategy consists of one or more inference mechanisms and one selection mechanism. A *not-basis task* consists of a combination of basis tasks, and because of this, the local strategy of a not-basis task consists of a collection of strategies of basic tasks. The *main task* is the task the KBS itself has to execute, the goal of the system. This task consists of the total collection of all the tasks.

If in one step the task is done well, the next step or task is defined by the application of traditional knowledge on the basis of the obtained result of the accomplished task.

### An introduction into programming in Prolog.

The fact: 'John is a child of Mary', is represented as  
**child\_of(john, mary).**

Rules are represented by a :- in between the name of a predicate and its description.

For example, the rule for grandparent is represented as:

**grandparent(X,Z) :- child\_of(Z,Y), child\_of(Y,X).**

This can be read as: X is the grandparent of Z if Z is a child of Y and Y is a child of X.

The knowledge can be asked by a ?-.

To the question: Which X is a child of Mary?:

**?- child\_of(X,mary).**

Prolog will answer:

**X = john.**

All variables in Prolog start with a capital and all constants with a small character. Behind every statement must be a full stop. To organize objects, lists can be used:

**[edward, mary, john].**

Some signs often used in Prolog:

$\neg A$  denying fact A,

$A \cap B$  fact A and fact B are true,

$A \cup B$  fact A or fact B is true,

$A \Rightarrow B$  if fact A is true, fact B becomes also true,

$A \Leftrightarrow B$  fact A is equivalent to fact B.

### 2.4.2 Different kinds of inference

(Mars 1991) simply explains two different kinds of logic and inference mechanisms:

*Proposition logic*: the most simple form of logic. It is built around statements and logical connections with which the statements can be connected. In proposition logic, the only question regarding the statements is whether they are true or false.

*First-order predicate logic*: a complex form of logic. With it, the contents of the statements can be manipulated.

Mechanical inference is done in two ways: *forward* and *backward*. A forward inference strategy finds a solution by pulling conclusions from data. A backward inference strategy divides the problem into smaller sub problems that are solvable.

### 2.4.3 Prolog

The name of the programming language Prolog stands for **P**rogramming in **L**ogic. The language was developed in 1972 at the University of Marseilles in France. With Prolog, facts and rules about objects can be determined, as well as relations between objects. Prolog uses an efficient type of backward inference. This makes it useful for work with databases and for design programs, if one can define the design problems well and the conditions are stringent.

Programming in Prolog consists of three activities: state facts, determine rules based on these facts, and ask questions. The knowledge stored in Prolog has the form of facts and rules, both called predicates. Tree structures show the order of facts and the relations between facts. Some examples are given in text frame **An introduction into programming in Prolog**.

A more detailed description about Prolog is given in (Clocksin and Mellish 1987), (Leigh 1986), (Lucardie 1994), (Rowe 1988), (Saint-Dizier 1990) and (Walker 1987).

## 2.5 The user interface

A good user interface requires an understanding of:

people,

how to present information visually to enhance human acceptance and comprehension, and how physical actions must flow to minimize the potential for fatigue and injury.

The capabilities and limitations of the hardware and software of the human-computer interface must also be considered.

To get to know more about user-interfaces two recent books were consulted:

1. (Galitz 1994) describes that in designing an (graphical) user interface it is important to understand the user and the application. After this the method of showing information has to be chosen, as well as the layout of windows and the colors used. The messages, feedback and guidance to the user should be properly provided.

2. (Eberts 1994) describes that there exist four approaches to design a human-computer interface:

*The empirical approach*: a conceptual design is tested among possible users, and after that modified and again tested.

*The cognitive approach*: a design is made according to an accurate, consistent, and complete description of the computer system and knowledge on

how humans perceive, store, and retrieve information from short and long-term memory.

*The predictive modeling approach:* a design is made according to the predicted performance of humans interacting with computers.

*The anthropomorphic approach:* a design is made according to the process of human-human communication.

The user interface of the TIE-system is designed with an empirical approach.

### 3. Advanced Knowledge Transfer System

This chapter describes a KBS-building tool: Advanced Knowledge Transfer System [AKTS]. This was developed at the Advisory Group Knowledge-Based Systems of the Building & Construction Research department of the Netherlands Organization for Applied Scientific Research [TNO] in Delft. How AKTS is used to develop the TIE-system and its user interface is also described.

#### 3.1 Introduction to AKTS

The joint application of decision tables (section 2.3.4) and Prolog (section 2.4.3) offers a great amount of tools and techniques with which a formal, unambiguous description of real-world phenomena can be given. The Advanced Knowledge Transfer System [AKTS] developed by G.L. Lucardie is based on this concept. Further, AKTS allows automatic testing and simulation of a KBS. The necessary decision tables are easy to draw and to adjust, (Lucardie 1994).

AKTS allows a KBS-engineer to develop, design and maintain a KBS, because it meets the required demands for a language that can be applied on KBS's. These demands were:

*the language should represent knowledge logically,  
the way of inference should be easily controllable, and  
simulating previously specified knowledge should be possible.*

#### 3.2 How AKTS works

With AKTS it is possible to represent, reconstruct, validate and simulate knowledge, (see the AKTS user manual, (AKTS 1996)). To do this parameters are created. All of the parameters have properties that indicate whether its value is a real number, an integer or text, whether it is a goal parameter or not, and how it should be determined (this is done by editing the 'prompt-field' or the 'when needed-field'). There are three possibilities of determining parameters in an AKTS-KBS:

*Consulting a decision table:* the goal of a decision table is to determine one or more parameters. The values of these parameters, called actions, depend on the values of one or more other parameters, called conditions. The values of these conditions can be divided into various ranges, called alternatives. The values of the actions are determined, depending on the alternatives to which the values of the conditions belong. In this way more than a hundred tables and sub-tables can be created, describing the determination of hundreds of parameters.

*Extracting from the Prolog model:* in the Prolog model imbedded in AKTS Prolog predicates can be defined. To determine a parameter that depends on a Prolog predicate, it is needed to refer to the predicate's name in the 'when needed-field' of this parameter's properties. The predicate itself can depend on 64 other parameters, and the Prolog model can consist of 32 kilobytes of data. When more data is needed it is possible to load external data files.

*Asking questions:* if a parameter can not be determined by doing a decision table or by extracting it from the Prolog model it is asked to the user of the AKTS-KBS. These questions can be created in the 'prompt-field' of this parameter's properties. It is possible to explain the questions to the user by showing pictures or text.

When implementing knowledge in the AKTS-KBS is finished, or when the already implemented knowledge has to be tested, the KBS can be consulted. One of the goal-parameters will be determined, after which this particular consultation can be stored and printed. It is also possible to change one or more entered values by using a 'What if?'-function. During the consultation the way of inference can be followed.

## 4. Thermal comfort

This chapter provides an introduction on office building performance and thermal comfort. After a description of general thermal sensation and of local thermal discomfort, the three main design considerations for the thermal indoor environment of office buildings are discussed: Persons, Organizations and Society.

### 4.1 Introduction

Before designing the thermal environment inside an office building is possible, one should be aware of the whole process of designing an office building, see (Gunst 1984), (Harris et al. 1981) and (Hartkopf et al. 1993). This can be done by representing the building in terms of its performance requirements as shown in Figure 4.1 (after Rutten, 1995). Figure 4.1 shows that *health/ comfort* is one of the performance fields of the party *Person*. The demands of this performance field are acoustical comfort, air quality, visual comfort and thermal comfort.

For the TIE-project we are mainly interested in the demands concerning thermal comfort. Thermal comfort is often defined as *that condition of mind that expresses satisfaction with the thermal environment* (from Fanger, 1970). The design criteria involved in meeting this demand come from the areas of general comfort, local comfort and individual control. During the design process these criteria are matched to the various concepts that are involved.

Thermal sensation depends on several environmental parameters of the room and also on personal parameters of the people themselves. The dominant personal parameters are:

metabolic heat	(M-W)	[W/m <sup>2</sup> ], and
clothing insulation	$I_{clo}$	[clo].

The most important environmental parameters are:

air temperature	$t_a$	[°C],
mean radiant temperature	$\bar{t}_r$	[°C],
relative mean air velocity	$v_{ar}$	[m/s], and
relative humidity	$\phi$	[%].

*Total metabolic heat production* (M-W) is the total energy produced by the body: M (termed metabolic rate) minus the total work done by the body: W (termed external work).

*Intrinsic clothing insulation*  $I_{clo}$  is a property of the clothing itself and represents the resistance to heat transfer between the skin and the clothing surface.

*Air temperature*  $t_a$  is defined as the temperature of the air surrounding the human body, in which the heat flow between the human body and the air takes place.

*Mean radiant temperature*  $\bar{t}_r$  is defined as the temperature of a uniform enclosure. At this temperature a small black sphere at a test point would have the same radiation exchange, as it does with the real environment.

*Relative mean air velocity*  $v_{ar}$  is considered to be the mean air velocity intensity,  $v_a$ , during the exposure time of interest, and integrated over all directions, relative to a moving person:

$$v_{ar} = v_a + 0.3 \cdot \sqrt{\frac{M - 58.15}{58.15}} \quad [4.1]$$

Parties	Performance fields	Performance demands	Design criterions	Design process	Design concepts
Person	<ul style="list-style-type: none"> <li>• protection/ shelter</li> <li>• safety</li> <li>• health/ comfort</li> </ul>	- ... - ... - acoustical comfort air quality visual comfort <b>thermal comfort</b>	- ... - ... - ... - general comfort local comfort individual control	O F F I C E  D E S I G N	<ul style="list-style-type: none"> <li>• architecture</li> <li>• building physics</li> </ul>
Organization	<ul style="list-style-type: none"> <li>• image</li> <li>• recurrent costs</li> <li>• production support</li> </ul>	- ... - to finance to operate to redivide - office lay out workplace furnishing reliability efficient transport and communication system	- ... - ...		<ul style="list-style-type: none"> <li>• structure</li> <li>• building services</li> <li>• communication technology</li> </ul>
Society	<ul style="list-style-type: none"> <li>• durability</li> <li>• environment friendly</li> </ul>	- energy consumption flexibility - recyclable materials	- ... - ...		<ul style="list-style-type: none"> <li>•</li> <li>•</li> </ul>
Context, Climate, Regulation, etc.					

Figure 4.1: A first draft of a scheme of aspects of office building design, from (Rutten 1995).

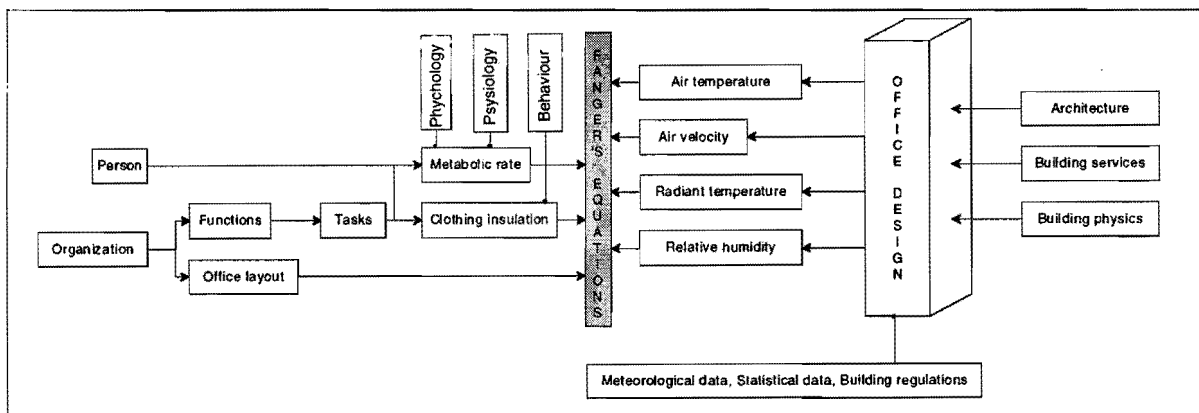


Figure 4.2: Schematic representation of designing the thermal environment inside an office room.



Relative humidity  $\phi$  is the ratio of the prevailing partial pressure of water vapour,  $P_a$ , to the saturated water vapour pressure,  $P_{sat}$ :

$$\phi = \frac{P_a}{P_{sat}}. \quad [4.2]$$

The interaction of these parameters influencing the thermal comfort of an office room is schematically represented in Figure 4.2, which is a derivation of the scheme of Figure 4.1. The 'Fanger equations' are described in section 4.2. The (personal) parameters on the left side of 'Fanger equations' are described in Chapter 5. The (environmental) parameters on the right side of 'Fanger equations' in Figure 4.2 are shortly described in Appendix I.

## 4.2 Fanger's equations

The objective of this project was to predict whether people would be satisfied with their thermal environment by evaluating an existing office building or a proposed office design. One of the methods to achieve this is determined by P.O. Fanger, (Fanger 1970), and also described in (ISSO 1990), (ISSO 1991), (McIntyre 1980) and (NEN-ISO 1989). To provide a method for evaluating and analyzing thermal environments, Fanger proposed that discomfort depends on the thermal load, which he defines as *the difference between the internal heat production and the heat loss to the actual environment for a man hypothetically kept at the comfort values of the mean skin temperature and the sweat secretion at the actual activity level*. In comfort conditions the thermal load will be zero. Fanger experimentally derived an equation that indicates the average thermal sensation of a group employees in a room: the Predicted Mean Vote [PMV]:

$$\begin{aligned} PMV = & \left( 0.303 \cdot e^{-0.036M} + 0.028 \right) \cdot \\ & \left[ (M - W) - 3.05 \cdot 10^{-3} \cdot (5733 - 6.99 \cdot (M - W) - P_a) \right. \\ & - 0.42 \cdot ((M - W) - 58.15) - 1.7 \cdot 10^{-5} \cdot M \cdot (5867 - P_a) - 0.0014 \cdot M \cdot (34 - t_a) \\ & \left. - 3.96 \cdot 10^{-8} \cdot f_{cl} \cdot \left( (t_{cl} + 273)^4 - (\bar{t}_r + 273)^4 \right) - f_{cl} \cdot h_c \cdot (t_{cl} - t_a) \right], \end{aligned} \quad [4.3]$$

where:

$$t_{cl} = 35.7 - 0.028 \cdot (M - W) - 0.155 \cdot I_{clo} \cdot \left[ 3.96 \cdot 10^{-8} \cdot f_{cl} \cdot \left( (t_{cl} + 273)^4 - (\bar{t}_r + 273)^4 \right) + f_{cl} \cdot h_c \cdot (t_{cl} - t_a) \right], \quad [4.4]$$

$$h_c = \max \left[ 2.38 \cdot (t_{cl} - t_a)^{0.25}, 12.1 \cdot \sqrt{v_{ar}} \right], \quad [4.5]$$

$$f_{cl} = \begin{cases} 1.0 + 0.2 \cdot I_{clo} & \longleftarrow I_{clo} \leq 0.5, \\ 1.05 + 0.1 \cdot I_{clo} & \longleftarrow I_{clo} > 0.5. \end{cases} \quad [4.6]$$

Equation [4.4] describes the clothing temperature  $t_{cl}$  in °C, and needs to be determined in an iterative process, because it depends, among other things, on  $h_c$ . The parameter  $h_c$  indicates the heat transfer coefficient of convection in  $W/m^2 \cdot ^\circ C$ , and depends on  $t_{cl}$ . The determination of this parameter needs to be embedded in the process of determining  $t_{cl}$ . The parameter  $f_{cl}$  gives the ratio of clothing area to body area and has no dimension.

The PMV is rated from -3 (cold) through 0 (neutral) to +3 (hot). The thermal sensation of the people in a room is good if the value of PMV is between -0.5 and +0.5.

Fanger also developed an equation for the *Predicted Percentage of Dissatisfied*, [PPD]. This provides the percentage of potential complainers:

$$PPD = 100 - 95 \cdot e^{-(0.03353 \cdot PMV^4 + 0.2179 \cdot PMV^2)} \quad [4.7]$$

The PMV and PPD are widely accepted 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 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. Moreover, the PMV and PPD equations are only valid in a certain domain:

metabolic heat:	between 46 and 232 W/m <sup>2</sup> ,
clothing insulation:	between 0 and 2 clo,
air temperature:	between 10 and 30°C,
mean radiant temperature:	between 10 and 40°C,
relative mean air velocity:	between 0 and 1 m/s, and
water vapour pressure:	between 0 and 2700 Pa.

### 4.3 Local thermal discomfort

Until now only whole-body thermal comfort is discussed. When a part of the body is too warm or too cold, it is called local thermal discomfort, see (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 following requirements for little local discomfort are for people in light clothing and sedentary activity:

*Temperature variations:* a method to predict whether humans will feel uncomfortable because of temperature variations is to calculate  $(\delta t_a)^2 f$ , where  $\delta t_a$  is the difference between minimum and maximum air temperature and  $f$  is the amount of temperature variations in one hour. When the calculation produces a number equal to, or bigger than 4.6, the percentage of dissatisfied people will be equal to or bigger than 10%, see (Hensen 1991).

*Vertical air temperature difference:* it is recommended that the vertical air temperature difference between 1.1 m and 0.1 m above the floor (head and ankle level) is less than 3°C.

*Draught risk:* the percentage of people dissatisfied due to draught, can be estimated by:

$$DR = (34 - t_a) \cdot (v_a - 0.5)^{0.62} \cdot (0.37 \cdot v_a \cdot T_u + 3.14), \quad [4.8]$$

where  $t_a$  is local air temperature in °C,  $v_a$  is the local mean air velocity in m/s and  $T_u$  is the local air turbulence in %, i.e., the ratio of the standard deviation of the local air velocity to the local mean air velocity. This equation is valid when the whole-body thermal comfort is close to neutral and should be as low as possible, see (Fanger 1987) and (Fanger 1988).

*Radiant temperature asymmetry:* the mean radiant temperature of cold vertical surfaces should be less than 10°C (in relation to a small vertical plane 0.6 m above the floor) and the mean radiant temperature of a warm ceiling should be less than 5°C (in relation to a small horizontal plane 0.6 m above the floor), see (Fanger 1985).

*Surface temperature extremities:* a floor temperature between 19 and 26°C (with floor heating systems 29°C) avoids discomfort due to surface temperature extremities.

*Relative humidity extremities:* actually, relative humidity extremities do not cause local thermal discomfort, though it is preferable to keep the relative humidity between 30% and 70%. It may cause tightness of the chest and allergic reactions if it is too high, or static electricity problems if it is too low.

## 4.4 Person

### 4.4.1 Behaviour

People's thermoregulation affects how they feel. This is partly behavioural and partly physiological. The behavioural part can consist of: put on or take off clothes, change posture, move, take shelter from sun, rain, wind, etc. Also personal taste for dressing, clothing behaviour, and a person's perception of how they appear to others in clothing are all very important for the individual thermal sensation, for more information see (Parsons 1993).

### 4.4.2 Physiology

The physiological part of human thermoregulation is controlled by the fact that the body has to maintain an internal temperature of around 37°C and cell temperatures all over the body at levels that avoid damage. If the body becomes hot, it loses heat by vasodilatation and sweating. If the body becomes cold, vasoconstriction preserves heat and shivering generates it.

Defining sensation in physical or physiological terms is not possible. The model of Fanger is based on an experimental study that correlated physical conditions and physiological response with thermal sensation.

### 4.4.3 Psychology

As stated earlier, thermal comfort is often defined as *that condition of mind that expresses satisfaction with the thermal environment*. This emphasizes that comfort is a psychological phenomenon. Thermal sensation is related to how people **feel** and is therefore a sensory experience. K.C. Parsons, (Parsons 1993), concludes that a great deal of evidence exists that thermal environments can significantly influence psychological responses, but the underlying mechanisms are not understood.

## 4.5 Organization

A business organization occupying an office building often has other interests in thermal environment than the persons working in it: The people who work for the organization should perform well and, at the same time, energy costs should be minimal. The organization indirectly influences the thermal environment by dividing the work space into units with a certain area, by providing furniture and plants, and by determining the amount of people in one work unit (influence human heat production and ventilation demands per unit area). They also decide what functions exist (indirectly influences the clothing choice), and what tasks people have to execute (influences the metabolic rate) and what equipment one should use to do so (mechanical heat production). With workload, job risks, fixed

(lunch) pauses, fixed working-clothes, etc., the organization can influence personal psyche and behaviour, as well, but these aspects are not taken into account.

Literature used regarding organizations: (Botter 1979), (Duffy et al. 1993), (Jansen and Bakker 1991) and (Wyon et al. 1982).

## 4.6 Society

The third party involved in the process of designing an office building is society. The major demands society has, are:

*do not damage the environment,*

*do save energy,*

*do make nice-looking buildings, and*

*do make buildings last for a long time.*

These demands of society have no direct influence on thermal comfort.

Literature used regarding society: (Duffy et al. 1993), (Nicol et al. 1995) and (Vaesen 1990).

## 5. Personal parameters

Persons and organizations influence the personal parameters metabolic heat production and intrinsic clothing insulation which, in turn, influence thermal sensation. Having good measurements or estimates of these is necessary to give a good prediction of the thermal comfort. In this chapter we describe how that can be done. Estimations are made according to ISO 8996 for metabolic rate and to ISO 9920 for intrinsic clothing insulation

### 5.1 Metabolic heat production (M - W)

Heat production within the body is related to the activity of the person, (see the international norm ISO 8996 (ISO 1990) and (Blaxter 1989)). In general, oxygen is taken into the body by breathing and is transported by the blood to the cells of the body, where it is used to burn food. Most of the energy is released as heat and, depending upon the activity, some external work is done. Energy for mechanical work,  $W$ , varies from about zero to no more than 20% of the total metabolic rate,  $M$ .

In an attempt to reduce the individual variability in estimates of metabolic heat production for a specific activity, the value is usually related to surface area of the body. The DuBois surface area,  $A_{DU}$ , estimates the area of the body:

$$A_{DU} = 0.202 \cdot \text{Weight}^{0.425} \cdot \text{Height}^{0.725}, \quad [5.1]$$

where Weight is body weight in kg and Height is body height in m. The unit of a metabolic rate is  $W/m^2$  or Met, 1 Met = 58.15  $W/m^2$ , which is the metabolic rate of a lying person at rest.

One could measure the metabolic heat production directly, called calorimetry, by observing total heat loss from the body in thermal equilibrium. With indirect calorimetry the metabolic rate is determined by measuring the oxygen consumption, the carbon dioxide production, and the energy released when food is burnt.

The metabolic rate has a linear relationship with the increase in the heart rate above a resting level for values between approximately 120 and 160 beats per minute [bpm]:

$$HR = HR_0 + RM \cdot (M - BM), \quad [5.2]$$

where HR is the heart rate in bpm,  $HR_0$  is the resting heart rate in bpm, RM is the increase in the heart rate per unit of the metabolic rate,  $M$  is the metabolic rate in  $W/m^2$  or Met and BM is the basal (minimal, at rest) metabolic rate in  $W/m^2$  or Met. This relation is determined experimentally for a person. After this it can be used in other situations.

In practice it is more convenient to obtain an estimate by matching a task description with that for which previous measurements or estimates have been made. One can find these in tables and databases, (see Table 5.1). When this table is used, inaccuracy is very high (approximately 15% in case of office work). This inaccuracy can be reduced by using tables for the estimation of the metabolic rate by task-components (still approximately 10% in case of office work). With this method, the metabolic rate is analytically determined by adding values of basal metabolic rate (the metabolic rate of a person lying down at rest under defined conditions) BM, the component for body posture PM, the component for type of work WM, and the component for body motion related to work speed MM.

Table 5.1: The metabolic rate based on a general description of kinds of activities

Kinds of activities	Metabolic rate [W/m <sup>2</sup> ]
lying/resting	58.15
sitting/resting	65
<b>low:</b> writing, typing, drawing, bookkeeping,	100
PC-work, hand work with small tools, inspection	100
assembly or sorting light materials, casual walking	100
<b>moderate:</b> sustained hand and arm work	165
handling of moderately heavy material	165
pushing or pulling light weight carts, walking 4 km/h	165
<b>high:</b> intense arm or trunk work	230
<b>very high:</b> very intense activity at fast to maximum pace	290

Table 5.2: The metabolic rate for body posture, values excluding the basal metabolism

Body posture	Metabolic rate [W/m <sup>2</sup> ]
lying	0
sitting	10
kneeling	20
crouching	20
standing	25
standing stooped	30

Table 5.3: The metabolic rate for different types of work, values excluding the basal metabolism

Type of work	Metabolic rate [W/m <sup>2</sup> ]		
	light	average	heavy
resting	0	0	0
hand work	15	30	40
one-arm work	35	55	75
two-arm work	65	85	105
trunk work	125	190	280

Table 5.4: The metabolic rate related to work speed, values excluding the basal metabolism

Type of body motion	Metabolic rate related to work speed [(W/m <sup>2</sup> )/(m/s)]
no motion	0
walking, 2 to 5 km/h	30
walking uphill, 2 to 5 km/h	
inclination 5°	60
inclination 10°	90
walking downhill, 5 km/h	
declination 5°	16
declination 10°	14
walking with a load on back, 4 km/h	
10 kg load	35
30 kg load	50
50 kg load	80
walking upstairs	540
walking downstairs	135

BM depends on body weight: Weight, body height: Height, person's age: Age, and gender:

$$\begin{aligned} BM_{\text{male}} &= \frac{0.04833}{A_{\text{DU}}} \cdot (66.473 + 13.7516 \cdot \text{Weight} + 500.33 \cdot \text{Height} - 6.755 \cdot \text{Age}), \\ BM_{\text{female}} &= \frac{0.04833}{A_{\text{DU}}} \cdot (655.0955 + 9.5634 \cdot \text{Weight} + 184.96 \cdot \text{Height} - 4.6756 \cdot \text{Age}). \end{aligned} \quad [5.3]$$

Sometimes, an approximation is used, based on international standard averages for human beings:  $BM_{\text{male}} = 44 \text{ W/m}^2$  and  $BM_{\text{female}} = 41 \text{ W/m}^2$ . Tables 5.2, 5.3 and 5.4 give the components for body posture, type of work and body motion related to work speed.

In practice, as stated earlier,  $W$  ranges from 0 to 20% of the metabolic rate and is difficult to measure. Because of inaccuracies in estimating both usable work and metabolic rate,  $W$  is often assumed to be zero. (ISSO 1990) gives an estimation, determined with bicycle experiments:

$$W = -8.623 \cdot 10^{-2} \cdot M + 1752 \cdot 10^{-3} \cdot M^2 - 3.152 \cdot 10^{-6} \cdot M^3 + 1.7695 \cdot 10^{-9} \cdot M^4. \quad [5.4]$$

## 5.2 Intrinsic clothing insulation

Human thermal balance is influenced by the clothing worn, see the international norm ISO 9920 (ISO 1995), (Cox 1984), (Havenith et al. 1990a), (Havenith et al. 1990b), (Lotens 1993) and (Nielsen et al. 1985). Clothing provides a thermal resistance between the human body and its environment, so one functional role of clothing is to maintain the body in an acceptable thermal state, in a variety of environments. However, a person's perception of how they appear to others in clothing is very important as well. The thermal behaviour of clothing is a complex interaction of, among other things, thermal insulation, transfer of moisture and vapour through clothing, heat exchange of body, clothing and environment, and air penetration. The only factors considered in this project are intrinsic clothing insulation and choice of clothing based on gender, function and activity of a person and on time of year.

Intrinsic clothing insulation  $I_{\text{clo}}$  represents the resistance to heat transfer between the skin and the clothing surface:

$$I_{\text{clo}} = \frac{(t_{\text{sk}} - t_{\text{cl}})}{H}, \quad [5.5]$$

where  $t_{\text{sk}}$  is the skin temperature in  $^{\circ}\text{C}$ ,  $t_{\text{cl}}$  is the mean surface temperature of clothing in  $^{\circ}\text{C}$  and  $H$  is the dry heat loss per  $\text{m}^2$  skin area in  $\text{W/m}^2$ . It is the reciprocal of clothing conductivity and the unit is  $\text{m}^2 \text{ }^{\circ}\text{C/W}$  or clo.  $1 \text{ clo} = 0.155 \text{ m}^2 \text{ }^{\circ}\text{C/W}$  is the thermal insulation required to keep a sedentary person comfortable at  $21^{\circ}\text{C}$ . This represents the insulation of a typical business suit.

Measuring the clothing insulation is possible by placing a sample of the material on standardized equipment or by using the clothing itself on a special heated copper man (manikin) with a temperature distribution across the body similar to that of a human being.

In practice it is more convenient to obtain an estimate by matching a clothing description with that for which previous measurements or estimates have been made. These can be found in tables and databases, see table 5.5 and 5.6 (inaccuracy is approximately 10%). Table 5.7 gives the intrinsic clothing insulation of individual clothing garments. To become  $I_{\text{clo}}$  of a clothing ensemble (inaccuracy is approximately 5%):

$$I_{\text{clo}} = \sum_i I_{\text{clu},i}. \quad [5.6]$$

Table 5.5: Intrinsic clothing insulation based on a general description of clothing ensembles

clothing ensembles	$I_{clo}$ [clo]
naked	0
shorts	0.06
tropical clothing outfit	0.3
light summer clothing	0.5
working clothes	0.8
indoor winter clothing	1.0
heavy business suit	1.5

Table 5.6: Often used averages of intrinsic clothing insulation  $I_{clo}$  [clo]

	male	female
summer	0.7	0.5
winter	1.0	0.85

Table 5.7: Individual clothing insulation of clothing garments

garment description	$I_{clu}$ [clo]			
	light	normal	heavy	special
underpants	0.03	0.06	0.10	
undershirt	0.04	0.09	0.12	bra: 0.01
shirt/blouse	0.20	0.25	0.30	short-sleeve: 0.15
trousers	0.20	0.25	0.28	Shorts: 0.06
dress	0.20	0.30	0.40	
skirt	0.15	0.20	0.25	
sweater	0.20	0.28	0.35	sleeveless: 0.12
jacket	0.25	0.30	0.35	
socks	0.02	0.05	0.10	pantyhose: 0.02
shoes	0.02	0.03	0.04	



## 6. The TIE-system

This chapter provides an introduction to the TIE-system and a description of the definitions involved, how the TIE-system was developed and tested, and how the user interface was designed.

### 6.1 Introduction to the TIE-system

The goal of this project was to build a KBS with knowledge on the thermal indoor environments of office buildings in the Netherlands. The name of this system was chosen to be the TIE-system, in which T.I.E. is an abbreviation of Thermal Indoor Environment, (and because a tie can make a difference for men (as a scarf can for women), not as much in feeling satisfied or dissatisfied with their thermal environment but more with their appearance. The later can have a large impact on a man's psychological sensation, and so influence his general well-being).

This system is designed to be used by non-experts in the field of building physics to help them determine whether an office room performs well on thermal comfort. Nevertheless, it can also be used by building engineers, controllers of building regulations (for example ARBO regulations) and managers of buildings or building services because it immediately shows the consequences of changing their design decisions.

### 6.2 Definitions of the TIE-system

The literature survey regarding KBS's identified five aspects that need to be known before any actual programming was done:

1. *the purpose or goal,*
2. *the functions,*
3. *the advantages in relation to already existing systems in the same field,*
4. *the risks involved, and*
5. *the future user.*

In other words, the five questions that need to be answered:

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 the use of specialized knowledge in the field of thermal sensation. It should 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 structure of the building and building services, organization and employees to the computer program it 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.
3. *What advantages the TIE-system can offer:* this computer program will not only complete the usual calculations, but it will also point out the problem areas in the design. It will also be possible to store knowledge from previous evaluations and adapt stored knowledge to recent developments in the field, however, this can only be done with help of knowledge engineers.

Further, it is very easy to change one or more entered values of a particular consult, when the user wants to see the consequences of these changes compared to the earlier result.

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, once it is 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 (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.).

### 6.3 Knowledge in the TIE-system

The knowledge that is implemented in the TIE-system has certain short-comings and therefore adaptations were made to the theories used. The inaccuracies that were taken into account are stated below.

To determine the performance of one particular office room the theories derived by P.O. Fanger are used. The PMV and PPD are widely accepted for predicting the thermal comfort of an office room in Western European climates. However, the PMV and PPD equations are only valid in a certain domain as can be read in section 4.2. The determination of the needed parameters can be done in two different ways: Either the user can enter the values directly, if those values were retrieved by measurement or by using another method of estimation (for example another computer program): Then the inaccuracies of these other methods should be taken into account. Or the user can make the TIE-system estimate the values of these parameters.

In the latter case the TIE-system derives the six parameters as follows (the predicted inaccuracies in PMV were found in ISSO Publication 19, (ISSO 1991)):

1. *Metabolic rate:* The metabolic rate is estimated by using different kinds of occupations or by calculation using body posture and specific tasks, according to ISO 8996, (ISO 1990). In the first case an inaccuracy of 15% causes an inaccuracy in PMV of 0.3, in the second case an inaccuracy of 10% causes an inaccuracy in PMV of 0.2.
2. *Clothing insulation:* The intrinsic clothing insulation is estimated by using standard ensembles, depending on gender and time of year or by adding the insulation values of various garments, according to ISO 9920, (ISO 1995). In the first case an inaccuracy of 10% causes an inaccuracy in PMV of 0.2, in the second case an inaccuracy of 5% causes an inaccuracy in PMV of 0.1.
3. *Air temperature:* In case of winter and in case of summer with mechanical cooling the user has to enter the designed air temperature. In the case of summer without mechanical cooling the air temperature is derived on an average day of the month at noon, according to the simplified dynamic method described in NEN 5067, (NEN 1985) and ISSO Publication 8, (ISSO 1985). This method is valid for typical construction in the Netherlands. Only conventional room types can be entered in the TIE-system. It also presumes that the office room is occupied from 9:00 am to 18:00 pm and that the lights are on during office hours. If

this creates an inaccuracy of 0.2°C, the inaccuracy in PMV will be 0.022. 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.

4. *Radiant temperature*: The radiant temperature is estimated using an area weight average of the surface temperatures in the room. In other words, the TIE-system presumes that the employee is in the center of the room. If a wall, floor or ceiling is on the inside of the building that particular surface temperature is estimated to be the same as the air temperature. If this creates an inaccuracy of 0.2°C, the inaccuracy in PMV will be 0.016.
5. *Air velocity*: The air velocity is fixed at 0.1 m/s, (knowledge on air conditioning installations, used to predict it more accurately, was not implemented). If this creates an inaccuracy of 0.09 m/s, the inaccuracy in PMV will be 0.03.
6. *Relative humidity*: To estimate relative humidity the water vapour production in the room is predicted (only that which is caused by persons), after which the water vapour pressure can be determined 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). If this creates an inaccuracy of 10%, the inaccuracy in PMV will be 0.05.

If the value for PMV is between +0.5 and -0.5 the causes of relative humidity extremities and local thermal discomfort are checked as well, see section 4.3. The causes of local discomfort that are considered in the TIE-system are, (see ISSO 1991):

- radiant temperature asymmetry,
- floor temperature extremities,
- draught,
- air temperature fluctuations, and
- vertical air temperature differences.

## 6.4 Developing the TIE-system

### 6.4.1 Parameter properties

When one of the parameters from a AKTS-KBS has to be determined, AKTS looks for the parameter properties of this parameter. There are three possibilities of gathering information for an AKTS-KBS, see section 3.2:

- asking questions,*
- consulting a decision table, or*
- extracting from the Prolog model.*

When the parameter should be extracted from a predicate in the Prolog model this predicate should be entered in the 'When needed'-field. When the 'When needed'-field is empty, AKTS will try to determine the parameter by consulting decision tables. If AKTS does not succeed it will ask the question stated in the 'Prompt'-field. If no question is stated AKTS will show the parameters name, and wait until a value is entered.

When the questions are not clear to the user the 'Explain' option in the consult window can be consulted. The text written in the 'Explanation'-field of the parameter properties will appear on screen.

<b>Parameter Name:</b>	Gender asked
<b>Explanation:</b>	The gender of the person(s) in the room, needed to estimate clothing insulation and basal metabolic rate.
<b>Prompt:</b>	What is the gender of the most employees in the room?
<b>When Needed:</b>	
<b>When Changed:</b>	
<b>Default:</b>	
<b>Domain:</b>	

Text       Multivalued       Module  
 Integer       Ask First       Goal  
 Real

Figure 6.1: The parameter properties of the parameter 'Gender asked' of the TIE-system.

Estimate clothing insulation								
Estimate clothing insulation		Estimation by using standard ensemble						Estimation by using single garments
C1	Method of determining clothing insulation	male			female			-
C2	Gender asked	male			female			-
C3	Month	January OR February OR March OR April	May OR June OR July OR August OR September	October OR November OR December	January OR February OR March OR April	May OR June OR July OR August OR September	October OR November OR December	-
A1	Estimate clothing insulation	1.0	0.7	1.0	0.85	0.5	0.85	{Clothing insulation under garments} + {Clothing insulation main garments} + {Clothing insulation over garments} + {Clothing insulation socks & shoes}
		R1	R2	R3	R4	R5	R6	R7

Figure 6.2: The decision table in which the clothing insulation is estimated.

An example of the parameter properties of the parameter 'Gender asked' is shown in Figure 6.1. In this case 'Gender asked' is a parameter containing text, and when it is needed the question stated in the 'Prompt'-field will show onto the screen.

In order to consult the knowledge inside an AKTS-KBS, the parameters considered should be indicated as 'Goal'-parameter. In the TIE-system 'Determine thermal sensation' is the main goal. Also the six parameters on which the PMV calculation depends and 'Determine local discomfort and humidity extremities' are goal-parameters, so these can be separately determined by the TIE-system. The 'Module'-option is needed to make decision-trees more clearly arranged, as can be seen in section 6.6.1.

#### 6.4.2 Consulting a decision table

As described in section 2.3.4, creating and editing decision tables could be done to implement knowledge. All decision tables have the same structure: On top of the table is the title of the table, which in general is the same as the goal that should be reached by consulting the table.

The left-side-part of the table, called the strip, contains the elements that determine the sort of the decision rules. The upper-left-side-part contains the **Conditions**, indicated with a "C".

The lower-left-side-part contains the **Actions**, indicated with an "A". The decision table shows the connection between conditions and actions. The right-side-part of the table contains columns, indicated with "R's". Every column contains one decision **Rule**.

In the upper-right-side-part of the table the state of every condition is exposed. This state has to be an elemental state, or a combination of different elemental states. If the state of a condition is indicated with a "-", (called "don't care"), it is irrelevant for the considered decision rule.

In the lower-right-side-part the states of all actions are exposed. They can contain text, a value or an X. An X indicates that the particular action should be executed.

An example of a decision table, in which the clothing insulation is estimated, is shown in Figure 6.2. The table in this figure can be read as follows:

- |    |   |
|----|---|
| R1 | If the clothing insulation should be estimated by using standard ensembles, and the gender of most employees is male, and the month is January, February, March or April, a value of 1.0 (clo) for the clothing insulation is estimated.      |
| R2 | If the clothing insulation should be estimated by using standard ensembles, and the gender of most employees is male, and the month is May, June, July, August or September, a value of 0.7 (clo) for the clothing insulation is estimated.   |
| R3 | If the clothing insulation should be estimated by using standard ensembles, and the gender of most employees is male, and the month is October, November, or December a value of 1.0 (clo) for the clothing insulation is estimated.          |
| R4 | If the clothing insulation should be estimated by using standard ensembles, and the gender of most employees is female, and the month is January, February, March or April, a value of 0.85 (clo) for the clothing insulation is estimated.   |
| R5 | If the clothing insulation should be estimated by using standard ensembles, and the gender of most employees is female, and the month is May, June, July, August or September, a value of 0.5 (clo) for the clothing insulation is estimated. |
| R6 | If the clothing insulation should be estimated by using standard ensembles, and the gender of most employees is female, and the month is October, November, or December a value of 0.85 (clo) for the clothing insulation is estimated.       |
| R7 | If the clothing insulation should be estimated by using single garments a value for the clothing insulation is estimated by adding four values determined in four other tables.   |

**Prolog Model**

```

humidity_production(Ta, Hum):-
    Hum is 12.9 -1.29*Ta+0.059*Ta^2.

saturated_water_vapour_pressure(Ta, P):-
    P is 545+58.9*Ta+0.336*Ta^2+0.0604*Ta^3.

estimated_water_vapour_pressure(AP, Hum, Ta, Ven, Paout, Pa):-
    Pa is (AP*Hum*0.000462*(Ta+273)/Ven)+Paout.

area_weight_average(A1, A2, A3, A4, A5, A6, T1, T2, T3, T4, T5, T6, AWA):-
    AWA is (A1*T1+A2*T2+A3*T3+A4*T4+A5*T5+A6*T6)/(A1+A2+A3+A4+A5+A6).
        
```

<b>Parameter Name:</b>	Water vapour pressure saturated
<b>Explanation:</b>	The saturated water vapour pressure, in Pa, needed to estimate relative humidity and water vapour pressure in the room.
<b>Prompt:</b>	
<b>When Needed:</b>	saturated_water_vapour_pressure({Determine air temperature}, {{Water vapour pressure saturated}})
<b>When Changed:</b>	
<b>Default:</b>	
<b>Domain:</b>	

Text       Multivalued       Module  
 Integer       Ask First       Goal  
 Real

Figure 6.3: The Prolog program, in which the saturated water vapour pressure is estimated, and the properties of the parameter 'Water vapour pressure saturated'.

### 6.4.3 Extracting from the Prolog model

Knowledge can also be implemented by programming in Prolog, described in section 2.4.3. In general, this is done for particularly cumbersome calculations. In the 'When needed' field of the parameter properties the needed predicate is called. Between the brackets the parameters are stated that are needed to execute the Prolog program, the last parameter(s) is (are) the parameter(s) that will be derived using the predicate. In the predicate itself these parameters are indicated with abbreviations. These has to be in the same order as in the 'When needed'-field.

An example of a Prolog program for calculating the saturated water vapour pressure and the parameter properties of 'Water vapour pressure saturated' are shown in Figure 6.3. In this figure can be seen that in the 'When needed' field of the parameter properties the predicate 'saturated\_water\_vapour\_pressure' is called. In this case 'Water vapour pressure saturated' Pa, only depends on 'Determine air temperature' Ta.

The total of Prolog programs can be found in Appendix IV, where the Prolog model of the TIE-system is shown. The Prolog model is divided into four parts.

1. The first part with the opening predicate: *knowledge\_base\_opened*, a little data base with average monthly temperatures for the Netherlands: *meteo\_NL*, and four left-over predicates. In the opening predicate four databases are loaded: *load\_files([heat\_sun, heat\_sun\_ceiling, accumulation, outdoor\_temp])*. These are needed to calculate the air temperature in the room in case of summer without mechanical cooling.
2. The second part is indicated with */\* Increase air temperature calculation \*/*. Here the predicates needed to calculate the air temperature in case of summer without mechanical cooling are programmed.
3. The third part is indicated with */\* PMV calculation \*/*. Here the predicates needed to calculate PMV are programmed.
4. The last part is indicated with */\* Local discomfort calculation necessities \*/*. Here the predicates needed to predict causes of local discomfort are programmed.

## 6.5 Designing the user interface of the TIE-system

Once all of the knowledge has been implemented, AKTS also provides good possibilities for the design of the user interface. For example questions that are asked of the user can be edited and explanations for these questions can be added.

When the TIE system is consulted a maximum of 150 questions are asked. All of the questions are edited to be as understandable as possible to the user. Explanations are added for most of the questions asked. They can be accessed by the user by clicking the 'Explain' button of the consult window, (see Figure 6.4).

The standard window of AKTS has one field where it puts all traced parameters and conclusions. In order to divide the various messages, the TIE-system has three distinct fields:

1. *a process-field* to show at what point of the consultation the user is entering values of parameters,
2. *a parameters-field* to show various important, traced parameters, and
3. *a conclusion-field* to show the conclusions gathered during the consultation.

In some cases, when the user makes a mistake or the entered values are beyond the domain of the used theories, an error message will be shown on the consult window. The conclusions that the TIE-system gathers during a consultation are shown simultaneously on screen as well.

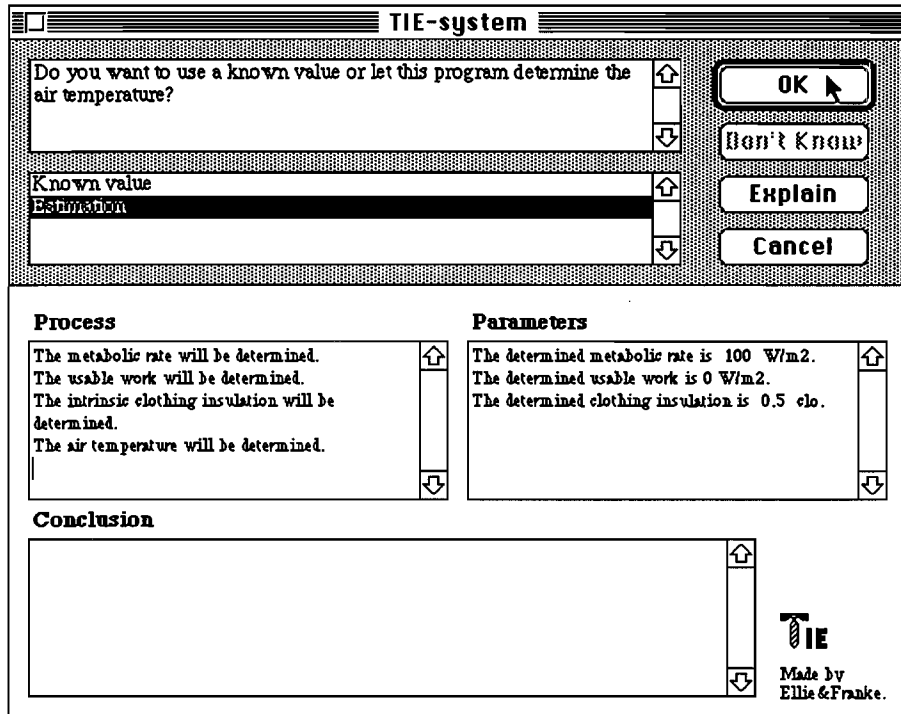


Figure 6.4: The consult window of the TIE-system.

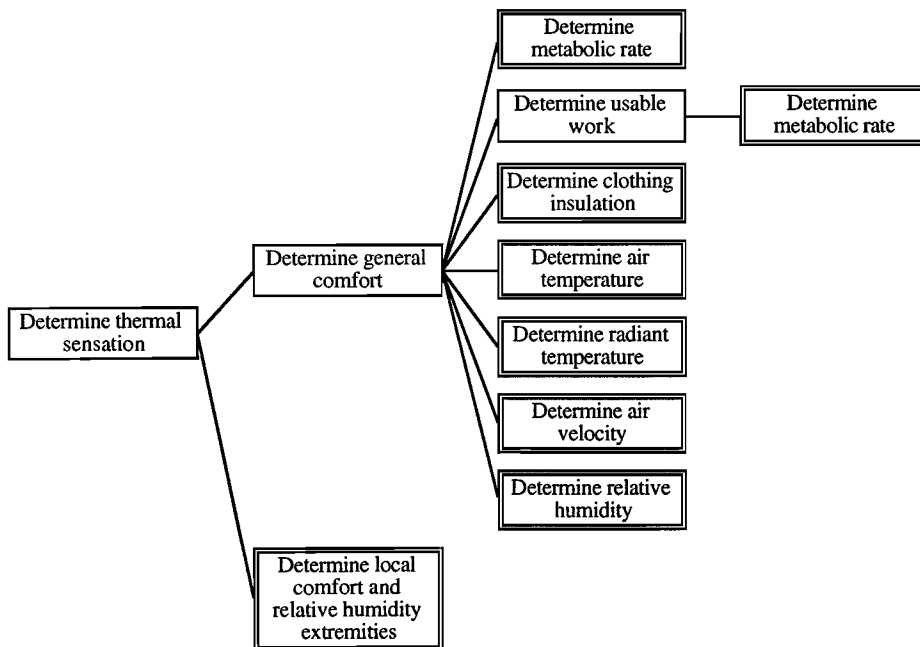


Figure 6.5: The decision tree of the goal parameter 'Determine thermal sensation'.



## 6.6 The structure of the TIE-system

To describe the total structure of the TIE-system, including all decision tables and Prolog programs, would take a large amount of space in this report. The structure is fairly consistent throughout the system. It was decided therefore to describe only one example here and to place the remainder in Appendix IV, the Prolog model in Appendix V and a summary of all tables in Appendix VI.

### 6.6.1 Decision trees in the TIE-system

A decision tree shows what tables should be consulted before AKTS is able to determine a certain parameter. The name of the table, in which this parameter is determined, is printed in a rectangle on the left side of the tree, the names of tables on which it depends are printed in other rectangles on the right side of the first one, and are connected to it with lines. When one of other tables depends on more other tables it is made into a module, and this is indicated by a rectangle with double lines. In this way the table tree becomes more clearly arranged.

### 6.6.2 Module 'Determine thermal sensation'

The first decision tree is the one for determining thermal sensation, (shown in Figure 6.5). It becomes clear that to determine thermal sensation first 'Determine general comfort' and 'Determine local comfort and relative humidity extremities' should be given a value. 'Determine general comfort' itself depends on seven other values: 'Determine metabolic rate', 'Determine usable work' (depending on 'Determine metabolic rate itself'), 'Determine clothing insulation', 'Determine air temperature', 'Determine radiant temperature', 'Determine air velocity' and 'Determine relative humidity'. Six of these are modules, as well as 'Determine local comfort and relative humidity extremities'. These modules are described in the following paragraphs.

The table 'Determine thermal sensation' has two conditions and two actions, (see Figure 6.6). The parameter 'Determine thermal sensation' will get the value *GOOD* if both parameters 'Determine general comfort' and 'Determine local comfort and relative humidity extremities' contain the value *Good*. The second action is meant to display the determined value in the *conclusion*-field of the consult window.

The table 'Determine general comfort' has only one condition: PMV, (see Figure 6.7). The value of PMV is printed in the *parameters*-field of the consult window. Depending on this value a different line is displayed in the *conclusion*-field of the consult window. The PMV-value is calculated in the Prolog model of Appendix V using all predicates under */\* PMV calculation \*/*. These predicates are based on the equations [4.3], [4.4], [4.5] and [4.6] in section 4.2: with the predicate *clothing*  $f_{cl}$  is calculated and with predicates *t<sub>clo</sub>* and *convection* the start-values of  $t_{cl}$  and  $h_c$  are calculated. These values are needed in the predicate *temperature clothing* with which  $t_{cl}$  is determined during an iterative process. During this process  $h_c$  is continuously adapted to the newly determined value of  $t_{cl}$  as well. When all values are known, and also all other parameters ( $M$ ,  $W$ ,  $I_{cl}$ ,  $T_a$ ,  $T_r$ ,  $V_a$  and  $P_a$ ), are determined the PMV-value is calculated with the predicate *predicted\_mean\_vote*. (The trick is needed to structure the question order to the user: in this way the personal parameters are firstly determined).

The table 'Determine usable work' shows that the value of the parameter 'Determine usable work' depends on the method of determining the parameter 'Determine metabolic rate', (see Figure 6.8).

Determine thermal sensation					
C1	Determine general comfort	Good		Bad	Probably bad
C2	Determine local comfort and relative humidity extremes	Good	Bad	-	-
A1	Determine thermal sensation	GOOD	global GOOD, local BAD	BAD	(probably) BAD
A2	COMMAND display(conclusion, [The thermal sensation of the employees in the entered room will be, [Determine thermal sensation], 'according to the used Fanger method.])	X	X	X	X
		R1	R2	R3	R4

Figure 6.6: The decision table of the parameter 'Determine thermal sensation'.

Determine general comfort					
C1	PMV	$X \geq -0.5, X \leq 0.5$	$X \geq -2, X < -0.5$	$X > 0.5, X \leq 2$	$X < -2$ OR $X > 2$
A1	Determine general comfort	Good	Bad	Bad	Probably bad
A2	COMMAND display(parameters, [PMV is', [PMV]])	X	X	X	X
A3	COMMAND display(conclusion, 'The room will be too cold.')		X		
A4	COMMAND display(conclusion, 'The room will be too warm.')			X	
A5	COMMAND display(conclusion, 'This is not between -2 and +2, therefore the results of the used Fanger model are unreliable.')				X
		R1	R2	R3	R4

Figure 6.7: The decision table of the parameter 'Determine general comfort'.

Determine usable work				
C1	Method of determining metabolic rate	Known value	Estimation by using kinds of activities	Estimation by using body posture and type of work
A1	Determine usable work	0	0	$\text{int}(\{(\text{Determine metabolic rate}) * (-8.623 * 10^{(-2)} + (1.752 * 10^{(-3)}) * (\text{Determine metabolic rate}) - (3.152 * 10^{(-6)}) * (\text{Determine metabolic rate})^2 + (1.7695 * 10^{(-9)}) * (\text{Determine metabolic rate})^3\})$
A2	COMMAND display(parameters, [The determined usable work is', [Determine usable work], 'W/m2.'])	X	X	X
		R1	R2	R3

Figure 6.8: The decision table of the parameter 'Determine usable work'.

Only if the more accurate method using body posture and type of work is chosen will the parameter get a non-zero value, according to equation [5.4].

## 6.7 Testing of the TIE-system

The TIE-system has been tested among ten FAGO-members, three of them were staff members and the other seven were students. The test itself can be found in Appendix II. The test was given after a short introduction on consulting in AKTS and the use of the 'What if?'-function, (see section 3.2). It took each participant 30 minutes to do the test. Predicting the performance on thermal comfort of the same room by using a calculator was done by one of the researchers. She needed three hours to estimate the air temperature.

The results of the test were that the FAGO-members were content with capabilities and the user-friendliness of the TIE-system. Nevertheless, they had recommendations on improving the TIE-system:

- the possibility to copy the structure of one wall to the others, and of the ceiling to the floor should be added,
- the possibility to draw graphics on the influence of one parameter on the PMV-value should be added,
- some of the questions could be improved to make them more clear, and
- instead of ventilation the ventilation rate should be asked for.

Some of these recommendations can be found in Chapter 7: Conclusions and recommendations.

## 6.8 Consulting the TIE-system

To start a consultation the user has to pull down the 'consult'-menu of AKTS. The user has to choose which goal-parameter he wants to trace:

- '*Determine thermal sensation*' if the thermal sensation of the employees in one office room needs to be determined.
- '*Determine metabolic rate*' if the metabolic rate of the employees in one office room needs to be determined.
- '*Determine clothing insulation*' if the intrinsic clothing insulation of the employees in one office room needs to be determined.
- '*Determine air temperature*' if the air temperature in one office room needs to be determined.
- '*Determine radiant temperature*' if the average radiant temperature in one office room needs to be determined.
- '*Determine air velocity*' if the relative air velocity in one office room needs to be determined.
- '*Determine relative humidity*' if the relative humidity in one office room needs to be determined.
- '*Determine local comfort and relative humidity extremities*' if the causes of local discomfort in the office room need to be checked.

By asking the user questions the missing parameters are determined and the TIE-system will derive the chosen goal-parameter. It is possible to change one or more answers given by using the 'What if?'-function of the 'consult'-menu. By using the 'Save case'-function the entered values can be saved. A saved case can be loaded with the 'Open case'-function. These functions, and other functions as well, are extensively described in the AKTS user manual, (AKTS 1996).

## 7. Conclusions and recommendations

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 works for cases that 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 layers;
- only common building materials, occupations, garments, window structures and light installations can be chosen;
- the air velocity is fixed at 0.1 m/s, because the knowledge for airconditioning installations, needed to predict the air velocity more accurately, is not implemented yet; and,
- the air temperature is determined with a simplified accumulation mass method and the radiant temperature is determined using an area weight average of surface temperatures, because the implementation of a more accurate methods was outside the scope of this study.

At this moment large memory problems are being encountered caused by AKTS or the underlying program Prolog. These memory problems would need to be solved before more knowledge can be added to improve the TIE-system. Some of the memory problems, which are caused by the size of the TIE-system might be solved if the linking of AKTS to existing commercially available software is made possible. 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. Before linking is made possible one should consider which programs can be linked to AKTS, without loosing already achieved goals. A combined system of the TIE-system with other software programs should still be kept easy to use.

After the memory problems are solved, the TIE-system can be completed and improved. To complete the TIE-system knowledge on airconditioning installations, standardized wall structures, and form-factor calculations (needed to improve the estimation of radiant temperature) can be added.

Further, the user friendliness of TIE-system can be improved by adding more explanation screens. Some screens are already designed and put in Appendix III. It was planned to let the first one appear on screen when the user started the TIE-system to explain when the TIE-system could be used. The others should appear on screen at the moment the user reached the point in the consultation where that particular parameter was determined. The user would read what questions could be expected. Another thing that will improve the user friendliness is to add the possibility to copy already entered wall characteristics to other similar, not yet entered, walls, and ceiling characteristics to the floor.

After completing the TIE-system the next step in research is to add the evaluation of visual comfort, acoustical comfort and air quality to make a system that considers all physical aspects of indoor environment. 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 such 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.

## List of symbols

$\phi$	relative humidity	[%]
Age	age of a person	[years]
$A_{DU}$	DuBois body surface area	[m <sup>2</sup> ]
BM	basal metabolic rate (at rest)	[W/m <sup>2</sup> ]
$BM_{male}$	basal metabolic rate (at rest) of a male	[W/m <sup>2</sup> ]
$BM_{female}$	basal metabolic rate (at rest) of a female	[W/m <sup>2</sup> ]
DR	percentage of people dissatisfied due to draught	[%]
f	amount of temperature variations	[-]
$f_{cl}$	ratio of clothing area to body area	[-]
Height	body height	[m]
H	heat loss per unit of body area	[W/m <sup>2</sup> ]
$h_c$	heat transfer coefficient of convection	[W/m <sup>2</sup> °C]
HR	heart rate	[bpm]
$HR_0$	resting heart rate	[bpm]
$I_{clo}$	intrinsic clothing insulation	[clo] = [0.155 m <sup>2</sup> °C/W]
$I_{clu}$	intrinsic clothing insulation of a single garment	[clo] = [0.155 m <sup>2</sup> °C/W]
M	metabolic rate	[W/m <sup>2</sup> ] = [0.017 met]
MM	component of metabolic rate due to body motion	[W/m <sup>2</sup> ]
$P_a$	partial pressure of water vapour	[Pa]
$P_{sat}$	saturated water vapour pressure	[Pa]
PM	component of metabolic rate due to body posture	[W/m <sup>2</sup> ]
PMV	predicted mean vote	[-]
PPD	predicted percentage of dissatisfied	[%]
RM	increase in heart rate per unit of metabolic rate	[bpm·m <sup>2</sup> /W]
$t_a$	air temperature	[°C]
$t_{sk}$	skin temperature	[°C]
$t_{cl}$	clothing temperature	[°C]
$\bar{t}_r$	mean radiant temperature	[°C]
$T_u$	local air turbulence	[%]
va	mean air velocity	[m/s]
var	relative mean air velocity	[m/s]
Weight	body weight	[kg]
W	usable work	[W/m <sup>2</sup> ]
WM	component of metabolic rate due to type of work	[W/m <sup>2</sup> ]

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## **Appendix**

**Appendix I: The equations for two environmental parameters**

**Appendix II: The test form**

**Appendix III: The explanation screens**

**Appendix IV: The structure**

**Appendix V: The programs**

**Appendix VI: The tables (summary)**

**Appendix VII: The DDSS-paper**

## Appendix I: The equations for two environmental parameters

### Equations used to determine radiant temperature:

To estimate the radiant temperature in °C:

$$t_{\text{radiant}} = \frac{1}{A_{\text{total}}} \sum_{i=1}^6 A_i \cdot t_{\text{surface},i}, \quad [\text{A.1}]$$

where  $A_{\text{total}}$  is the total area of all walls, ceiling and floor in  $\text{m}^2$ ,  $A$  is the area of one wall, the ceiling or the floor in  $\text{m}^2$ ,  $t_{\text{surface}}$  is the surface temperature of one wall, the ceiling or the floor, in °C, and  $i$  is a counter counting from 1 (wall1), to 6 (the floor).

To estimate the surface temperature of a construction in °C:

$$t_{\text{surface}} = \frac{1}{A_{\text{construction}}} \sum_{i=1}^6 A_i \cdot t_{\text{part},i}, \quad [\text{A.2}]$$

where  $A_{\text{construction}}$  is the total area of a wall, the ceiling or the floor in  $\text{m}^2$ ,  $A$  is the area of one construction part (window, door, heating device, building material) in  $\text{m}^2$ ,  $t_{\text{part}}$  is the surface temperature of one construction part, in °C, and  $i$  is a counter counting the amount of construction parts.

To estimate a surface temperature of a construction part in °C:

$$t_{\text{part}} = \frac{R_i}{R_i + R_{\text{part}} + R_e} \cdot (t_{\text{outdoor}} - t_{\text{indoor}}) + t_{\text{indoor}}, \quad [\text{A.3}]$$

where  $R_i$  is the heat transfer resistance on the inside of the construction in  $\text{m}^2 \text{°C/W}$ ,  $R_e$  is the heat transfer resistance on the outside of the construction in  $\text{m}^2 \text{°C/W}$ ,  $R_{\text{part}}$  is the heat transfer resistance of the construction part in  $\text{m}^2 \text{°C/W}$ ,  $t_{\text{outdoor}}$  is the outdoor air temperature in °C, and  $t_{\text{indoor}}$  is the indoor air temperature in °C.

To estimate the heat transfer resistance of a construction part consisting of several layers in  $\text{W/m}^2 \text{°C}$ :

$$R_{\text{part}} = \sum_i R_{\text{layer},i} + \sum_j R_{\text{airspace},j}, \quad [\text{A.4}]$$

where  $R_{\text{layer}}$  is the heat transfer resistance of one layer made of building material in  $\text{m}^2 \text{°C/W}$ , and  $i$  is a counter counting the amount of these layers.  $R_{\text{air space}}$  is the heat transfer resistance of one layer containing air in  $\text{m}^2 \text{°C/W}$ , and  $j$  is a counter counting the amount of these layers.

To estimate the heat transfer resistance of a layer in case of building material in  $\text{W/m}^2 \text{°C}$ :

$$R_{\text{layer}} = \frac{\delta_{\text{layer}}}{\lambda_{\text{layer}}}, \quad [\text{A.5}]$$

where  $\delta_{\text{layer}}$  is the thickness of a layer in m, and  $\lambda$  is the conductivity of a layer in  $\text{W/m}^2 \text{°C}$ .

To estimate a surface temperature of the floor (or ceiling) in case of floor heating (or ceiling heating) in winter in °C:

$$t_{\text{floor/ceiling}} = \frac{t_{\text{indoor}} - t_{\text{outdoor}}}{t_{\text{indoor}} + 10} \cdot (t_{\text{floor/ceiling,max}} - t_{\text{indoor}}) + t_{\text{indoor}}, \quad [\text{A.6}]$$

where  $t_{\text{floor/ceiling,max}}$  is the surface temperature of the floor (or ceiling) when maximum power is used in °C.

To estimate a surface temperature of a radiator in winter in °C:

$$t_{\text{radiator}} = \left( \frac{t_{\text{indoor}} - t_{\text{outdoor}}}{t_{\text{indoor}} + 10} \right)^{1/1.3} \cdot (80 - t_{\text{indoor}}) + t_{\text{indoor}}, \quad [\text{A.7}]$$

and to estimate a surface temperature of a convector in winter in °C:

$$t_{\text{convector}} = \left( \frac{t_{\text{indoor}} - t_{\text{outdoor}}}{t_{\text{indoor}} + 10} \right)^{1/1.3} \cdot (65 - t_{\text{indoor}}) + t_{\text{indoor}}. \quad [\text{A.8}]$$

### Equations used to determine relative humidity and water vapour pressure:

To determine the water vapour pressure in Pa:

$$P_a = \frac{P_{\text{sat}} \cdot \phi}{100}, \quad [\text{A.9}]$$

and to determine the relative humidity in %:

$$\phi = 100 \cdot \frac{P_a}{P_{\text{sat}}}, \quad [\text{A.10}]$$

where  $P_{\text{sat}}$  is the saturated water vapour pressure in Pa.

To determine the saturated water vapour pressure in Pa:

$$P_{\text{sat}} = 545 + 58.9 \cdot t_{\text{indoor}} + 0.336 \cdot t_{\text{indoor}}^2 + 0.0604 \cdot t_{\text{indoor}}^3, \quad [\text{A.11}]$$

this equation was derived using the smallest-squares-method on the data found in literature, see (Louwers 1996).

To estimate the water vapour pressure in Pa:

$$P_a = \frac{\Phi_p \cdot R \cdot T_{\text{indoor}}}{\dot{V}} + P_{\text{outdoor}}, \quad [\text{A.12}]$$

where  $\Phi_p$  is the humidity production caused by persons in kg/s,  $R$  is the gas constant: 462 J/kg K,  $T_{\text{indoor}}$  is the indoor air temperature in K,  $\dot{V}$  is the amount of ventilation in m<sup>3</sup>/s, and  $P_{\text{outdoor}}$  is the outdoor water vapour pressure in Pa.

To estimate the humidity production caused by persons in kg/s:

$$\Phi_p = N \cdot (12.9 - 129 \cdot t_{\text{indoor}} + 0.059 \cdot t_{\text{indoor}}^2), \quad [\text{A.13}]$$

where  $N$  is the amount of people. This equation was derived using the smallest-squares-method on the data found in literature, see (Louwers 1996).

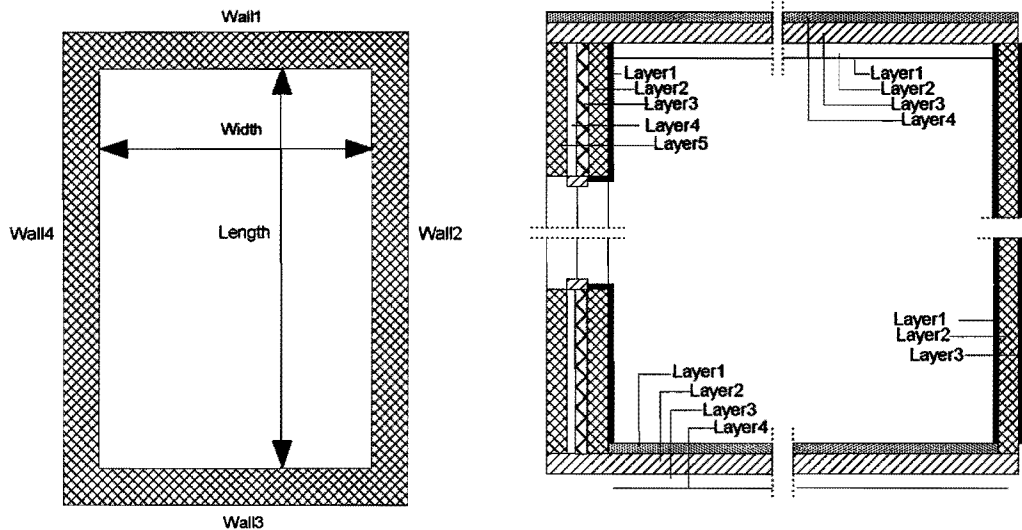
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## **Appendix II: The test form**

The following two pages show the test of the system, that was done by ten FAGO-members.

### Testing the TIE-system:

Choose for tracing 'Determine thermal sensation', and for the option 'Estimation' wherever possible. The geometry of the room we want you to enter is the following:



Width: 5 m., Length: 6 m., Height: 3 m.

Wall1 (outside wall, North-East):	Layer1: Plaster	1 cm.
	Layer2: Lime-sand brick	10 cm.
	Layer3: Insulation material	8 cm.
	Layer4: Air space	2 cm.
	Layer5: Masonry brick	10 cm.
Wall2, 3 & 4 (inside wall):	Layer1: Plaster	1 cm.
	Layer2: Lime-sand brick	10 cm.
	Layer3: Plaster	1 cm.
Floor (inside floor)	Layer1: Light concrete	5 cm.
	Layer2: Gravel concrete	10 cm.
	Layer3: Air space	5 cm.
	Layer4: Gypsum	2 cm.

Ceiling is as floor.

Wall1 has a window (double glass, inside sunshade, 5 m<sup>2</sup>), and a heating device (radiator 5 m<sup>2</sup>). Wall3 has a door (no glass, 2 m<sup>2</sup>). The room is lighted with built-in-TL-tubes, and the amount of ventilation by infiltration is 145 m<sup>3</sup>/h, no mechanical cooling available.

The work done in the room is ordinary office work, the 2 males wear ordinary office clothes. They all use a computer (with screen).

Begin with a test for the month July, after that change 'Month' into January by using the 'What if?' function. (Design-temperature 20°C).

When you finished the consultation you should save it under your own first name (in the TIE directory) by choosing the 'Save case' function under the 'Consult' menu.

Please answer these questions:

How long did the two consultations take? \_\_\_\_\_

What was the value for PMV in the month July? \_\_\_\_\_

What was the value for PMV in the month January? \_\_\_\_\_

Which conclusions could you make on the thermal comfort of the room without the TIE-system?

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Which additional conclusions could you make by using the TIE-system?

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Were the questions in the TIE-system easy to understand? Why?

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Was the TIE-system easy to use? Why?

---

---

---

How can the TIE-system be improved?

---

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---

### **Appendix III: The explanation screens**

The following examples of explanation screens were made during the TIE-project, but not yet implemented.



Welcome to the TIE-system,

Using this system the thermal comfort in one office room can be determined. For the determination of thermal comfort according to the whole body, the PMV-index of Fanger is used. This index can be determined when the values of six parameters are known. These parameters are metabolic rate, clothing insulation, air temperature, radiant temperature, air velocity and relative humidity. When thermal comfort according to the whole body is good, local comfort can also be determined.

The six parameters that are needed to determine thermal comfort can be estimated in the program, but it is also possible to enter a known or estimated value.

You can start the consultation by choosing the 'Reset & consult' function under the 'Consult' menu. If you have finished the consultation and you want to change any entered value, then choose the 'What if?' function of the 'Consult' menu. Change any entered value and consult again with the 'Consult' function (not 'Reset & consult', because this will delete all previously entered values). If you enter a wrong value, stop the consultation by choosing 'Cancel', then choose the 'What if?' and 'Consult' functions again (not 'Reset & consult').

We wish you good luck with the use of our program,

Ellie de Groot and Franke Louwers.



## Method of determining metabolic rate

### KNOWN VALUE

If you know the value for metabolic rate then you can enter it directly.

### ESTIMATION BY KINDS OF ACTIVITIES

The metabolic rate is estimated according to occupation. The occupation is selected from a list of fifteen examples based on ISO 8996.

### ESTIMATION BY BODY POSTURE AND TYPE OF WORK

The metabolic rate is estimated by calculating the basal metabolic rate (depending on body posture and age) of the 'average employee' in the room. Additional values will be used for sitting or standing and for arm or handwork, according to ISO 8996.

The first estimation is faster but is less accurate than the second one.

work	M [W/m <sup>2</sup> ]
resting	50
sitting	65 ± 5
low	100 ± 7.5
moderate	165 ± 10
high	230 ± 15
very high	290



## Method of determining clothing insulation

### KNOWN VALUE

If you know the value for clothing insulation then you can enter it directly.

### ESTIMATION BY USING STANDARD ENSEMBLE

The clothing insulation is estimated according to a standard value for male and female office employees, during summer or winter. In winter time these values are 1.0 clo for men and 0.7 clo for women. In summer these values are 0.85 clo for men and 0.5 clo for women.

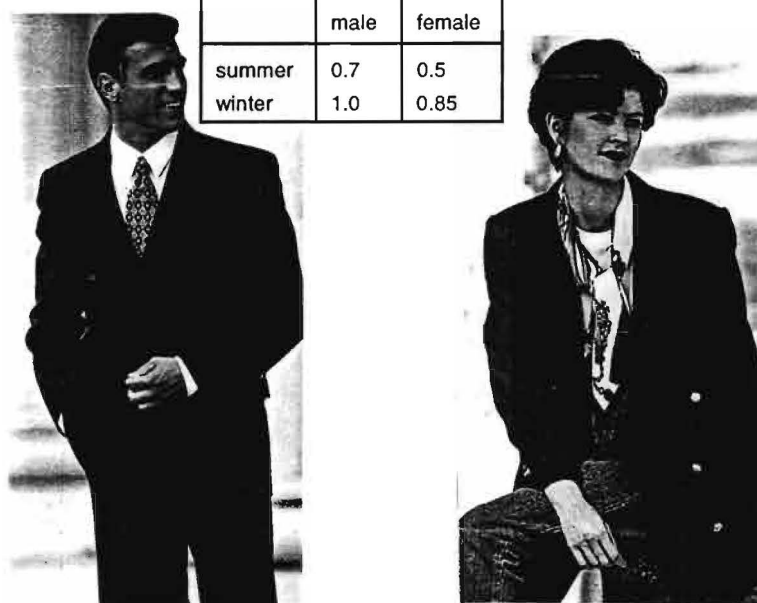
### ESTIMATION BY USING SINGLE GARMENTS

The clothing insulation is estimated by adding the values of the single garments of one 'average employee', according to ISO 9920.

The first estimation is faster, but is less accurate than the second one.

intrinsic clothing insulation  $I_{clo}$  [clo]

	male	female
summer	0.7	0.5
winter	1.0	0.85



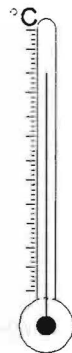
## Method of determining air temperature

### KNOWN VALUE

If you know the value for air temperature then you can enter it directly.

### ESTIMATION

The air temperature is estimated where there is no mechanical cooling in summer months. In winter months or summer months with mechanical cooling, a design temperature has to be entered by the user. The estimation for the summer months without mechanical cooling is done with a simplified cooling load method. This method is given by the dutch standards NEN 5067 and ISSO 8. The estimation takes a few minutes.



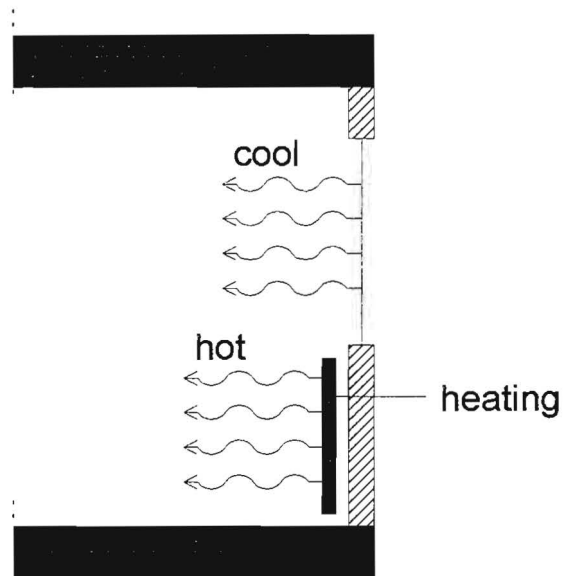
## Method of determining radiant temperature

### KNOWN VALUE

If you know the value for radiant temperature then you can enter it directly.

### ESTIMATION

The radiant temperature is estimated as an average of the surface temperatures of the walls, ceiling and floor. This takes a few minutes if the room geometry has not already been entered in relation to another estimating procedure.



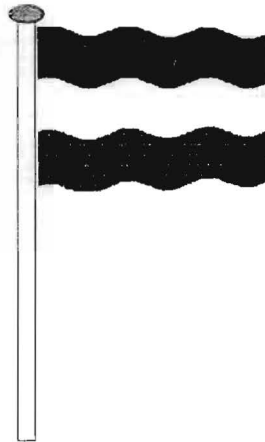
## Method of determining air velocity

### KNOWN VALUE

If you know the value for air velocity then you can enter it directly.

### ESTIMATION

The air velocity is estimated to be 0.1 m/s.



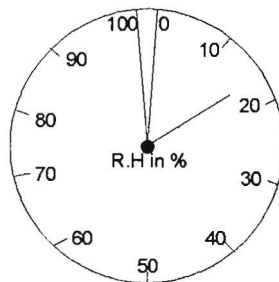
## Method of determining relative humidity

### KNOWN VALUE

If you know the value for relative humidity then you can enter it directly.

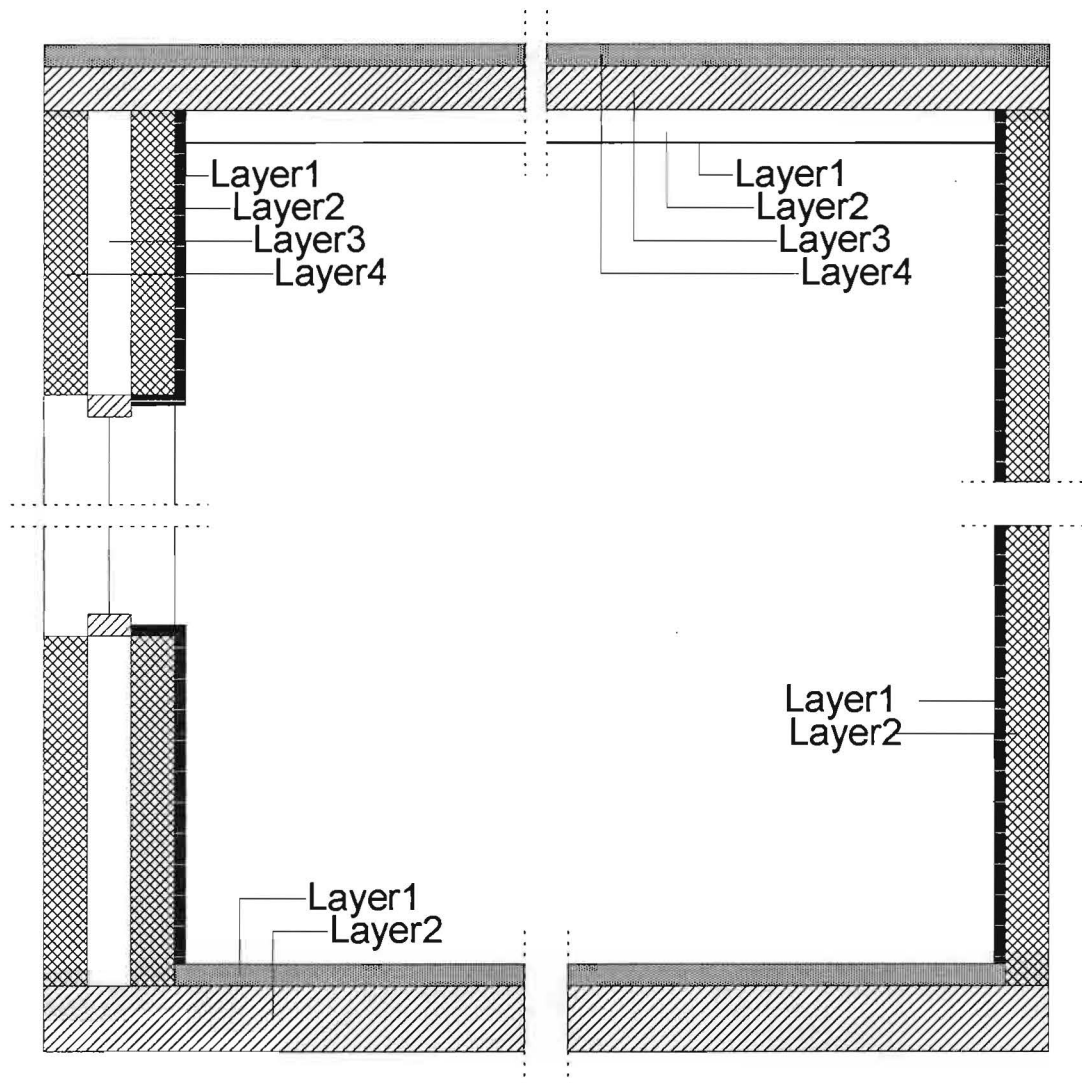
### ESTIMATION

The relative humidity is estimated by a stationary method. This method uses the humidity production in the room caused by people (and does not include other sources) as well as the relative humidity outdoors.



## Construction of the walls, floor and ceiling

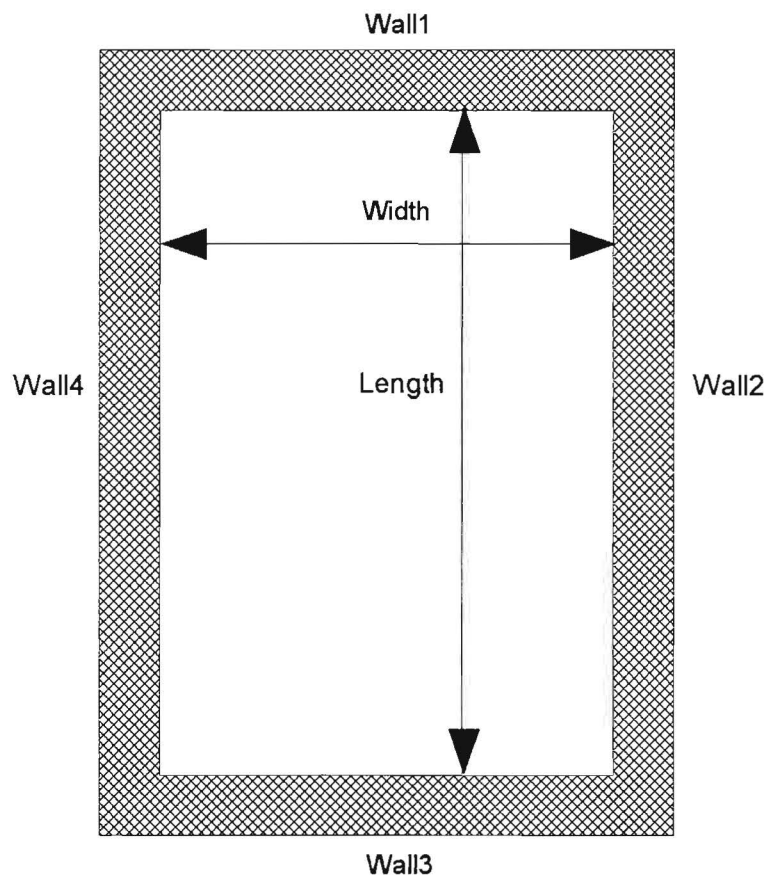
In choosing the construction layers of the wall, floor or ceiling the first layer is always considered to be the one on the inside of the room. The last layer is the one on the exterior of the building or forms the first layer of the adjacent room. An example is given below.





## Width and length of the office room

Please enter the width and the length as shown in the example below.  
The width of the room is the distance between the second and the fourth wall and the length of the room is the distance between the first and the third wall.



## Appendix IV: The structure

One part of the structure is already given in section 6.6.2: the module 'Determine thermal sensation'. The other modules are given here, the Prolog model in Appendix V and a summary of all tables in Appendix VI. The tables are referred to with their names, and can be found in the Appendix of the report of F.H. Louwers (Louwers 1996). The programs are referred to with the predicate's name and the part of the Prolog model in which it can be found, see Appendix V.

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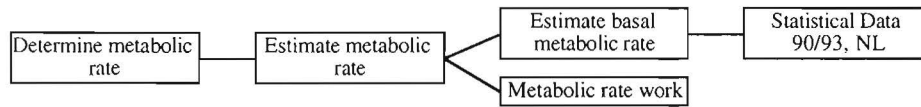


Figure A.1: The decision tree of the module 'Determine metabolic rate'.

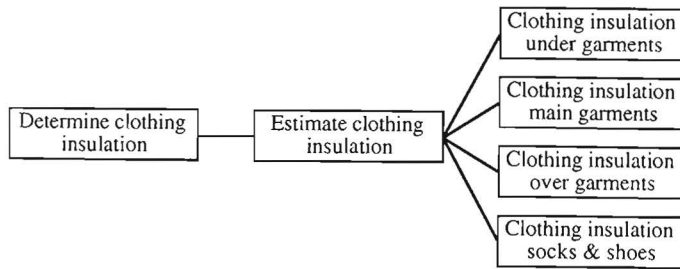


Figure A.2: The decision tree of the module 'Determine clothing insulation'.

#### A.IV.1 Module 'Determine metabolic rate'

The table-tree of 'Determine metabolic rate' is shown in Figure A.1. The table-tree shows that if the user decides to let the program estimate the metabolic rate four other tables may be needed: 'Estimate metabolic rate', 'Estimate basal metabolic rate', 'Statistical Data 90/93, NL' and 'Metabolic rate work'.

The table 'Determine metabolic rate' has three conditions: the first one indicates which method of determining this parameter will be used, the second and third one are added to control if the parameter's value is in the Fanger domain. If the value is out of this domain a warning will be displayed in the conclusion-field of the consult window. The value itself is rounded to zero digits, and is displayed in the *parameters*-field. This table's structure is used for all main parameters.

The table 'Estimate metabolic rate' is consulted if one of the estimation-options is chosen. At the first option, *Estimation by using kinds of activities*, one of fifteen occupations has to be chosen. At the other option, *Estimation by using body posture and type of work*, three more tables need to be consulted: the table 'Estimate basal metabolic rate', (in which the basal metabolic rate of a resting person is calculated according to equations [5.1] and [5.3]), the table 'Statistical Data 90/93, NL', to estimate a person's weight and height depending on their age), and the table 'Metabolic rate work', (in which two components of the metabolic rate are estimated, depending on a person's body posture and type and heaviness of work). These values will be added to the value of 'Estimate basal metabolic rate'. The total becomes the value of 'Estimate metabolic rate'.

#### A.IV.2 Module 'Determine clothing insulation'

The table-tree of 'Determine clothing insulation' is shown in Figure A.2. It shows that if the user decides to let the program estimate the clothing insulation five other tables may be needed: 'Estimate clothing insulation', 'Clothing insulation under garments', 'Clothing insulation main garments', 'Clothing insulation over garments', 'Clothing insulation socks & shoes'.

The table 'Determine clothing insulation' has three conditions: the first one indicates which method of determining this parameter will be used, the second and third one are added to control if the parameter's value is in the Fanger domain. If the value is out of this domain a warning will be displayed in the conclusion-field of the consult window. The value itself is rounded to two digits, and is displayed in the *parameters*-field.

The table 'Estimate clothing insulation' is consulted if the one of the estimation-options is chosen. At the first option, *Estimation by using standard ensembles*, a value for clothing insulation is determined depending on the person's gender and the month. At the other option, *Estimation by using single garments*, four more tables need to be consulted: The tables 'Clothing insulation main garments', 'Clothing insulation over garments', 'Clothing insulation socks & shoes' and 'Clothing insulation under garments'. The value of the parameter 'Estimate clothing insulation' becomes the total of clothing insulations of the ten single garments, determined in these tables.

#### A.IV.3 Module 'Determine air temperature'

In Figure A.3 the table-tree of 'Determine air temperature' is shown. It shows that seven other tables and nineteen modules may be needed, (actually this is only the case when an estimation needs to be made during summer in a room without mechanical cooling). Tables: 'Orientation wall2', 'Heat resistance windows', 'Heat computer', (depending itself on tables 'Heat printer' and 'Heat screen'), 'Determine heat light', (depending itself on table 'Estimate heat light'), 'Reduction factor light',

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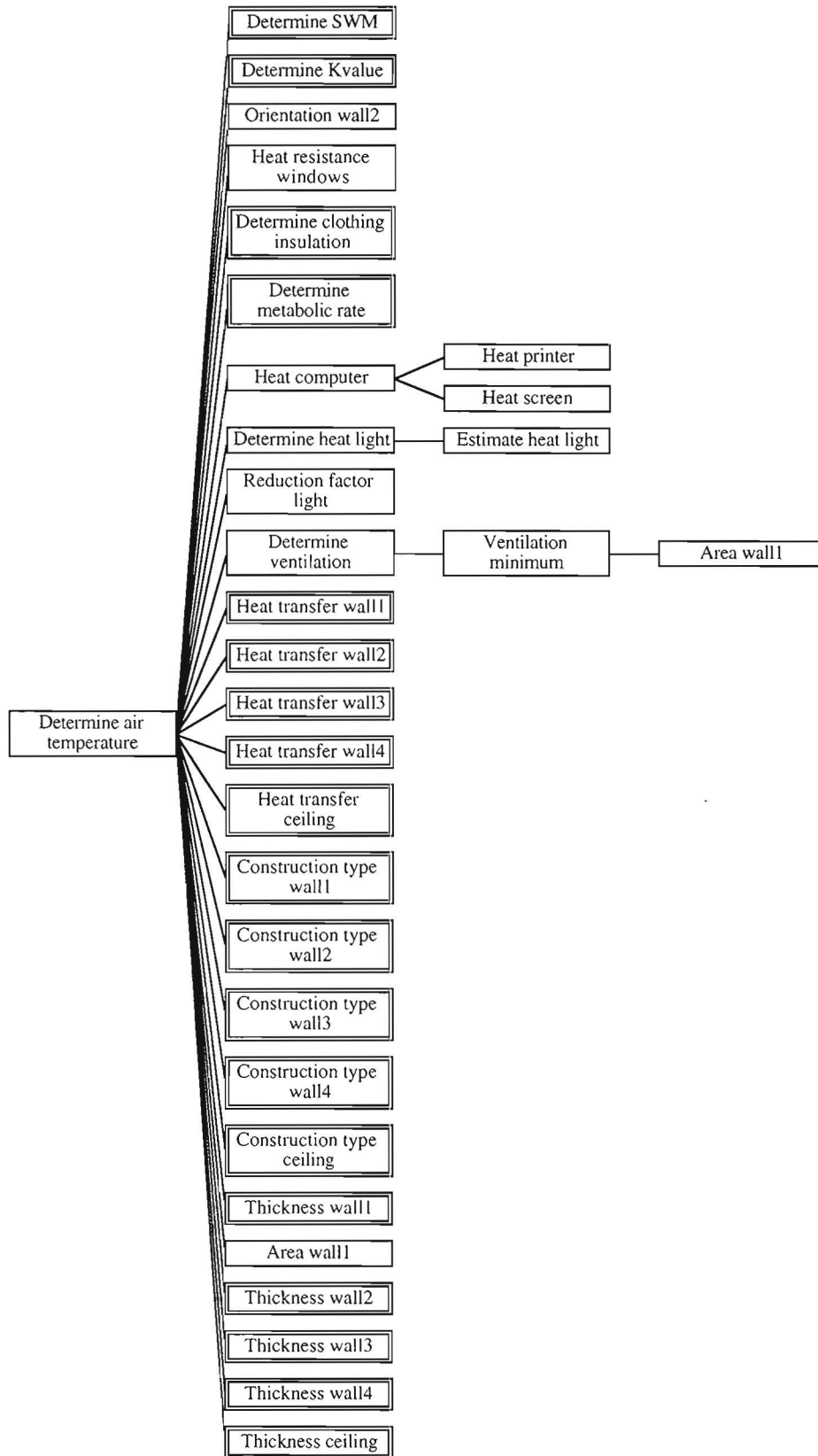


Figure A.3: The decision tree of the module 'Determine air temperature'.

'Determine ventilation', (depending itself on tables 'Ventilation minimum' and 'Area wall1'), and 'Area wall1'. Modules: 'Determine SWM', 'Determine Kvalue', 'Determine metabolic rate', (see section A.IV.1), 'Determine clothing insulation', (see section A.IV.2), five 'Heat transfer'-modules, five 'Construction type'-modules, and five 'Thickness'-modules.

The table 'Determine air temperature' has seven conditions: the first one indicates which method of determining this parameter will be used. The second and third one are needed to distinguish whether an estimation is needed (in summer without mechanical cooling), or asking for the design temperature will be enough (in winter and in summer with mechanical cooling). The fourth and fifth conditions are added to control if the parameter's value is in the Fanger domain. If the value is out of this domain a warning will be displayed in the conclusion-field of the consult window. The value itself is rounded to one digit, and is displayed in the *parameters*-field. (The sixth and seventh condition are added to make AKTS show these parameters in the table tree of 'Determine air temperature').

For an extensive description of the tables and programs to estimate air temperature is referred to the report of F.H. Louwers, (Louwers 1996). She implemented this part of the TIE-system, using the Dutch building code NEN 5067, (NEN 1985).

#### A.IV.4 Module 'Determine radiant temperature'

The table-tree of 'Determine radiant temperature' is shown in Figure A.4a. It shows that the table 'Area wall1' and six modules may be needed, (actually this is only the case when an estimation needs to be made). Modules: 'Estimate surface temperature wall1' (and also for wall2, wall3, wall4, the ceiling and the floor).

The table 'Determine radiant temperature' has three conditions: the first one indicates which method of determining this parameter will be used, the second and third one are added to control if the parameter's value is in the Fanger domain. If the value is out of this domain a warning will be displayed in the conclusion-field of the consult window. The value itself is rounded to one digit, and is displayed in the *parameters*-field.

The parameter 'Estimate radiant temperature' is determined, according to equation [A.1] of Appendix I, if the estimation-option is chosen. In the parameter properties of this parameter the predicate *area\_weight\_average* (first part Prolog model in Appendix V) is asked for. The values of the areas of wall1 to wall4, the ceiling and the floor are joined to A1 to A6, and the surface temperatures of wall1 to wall4, the ceiling and the floor are joined to T1 to T6. These areas are determined in table 'Area wall1' and the surface temperatures in the modules 'Estimate surface temperature wall1' and so on.

In the table 'Area wall1' the areas of wall1, wall2 and the ceiling are determined depending on the height, the length and the width of the room, (In the parameter properties of 'Area wall3' is its value determined equal to the value of 'Area wall1', the same for wall4 and wall2, and for floor and ceiling). Warnings will appear onto the *conclusion*-field if the entered value of the height of the room is less than 2.5 m or more than 4 m, or if the entered value of the length or width of the room is less than 2.5 m or more than 40 m.

The table tree of the module 'Estimate surface temperature wall1' is shown in Figure A.4b, (The table trees for wall2, wall3, wall4 and the ceiling would look alike, so these are not shown). It shows that the tables 'Area wall1', 'Determine outdoor air temperature', 'Heat resistance windows' and 'Estimate surface temperature heating device wall1' are needed, as well as the modules 'Thickness wall1', (shown in Figure A.4c; wall2, wall3, wall4, ceiling and floor look alike, so are not shown), 'Determine air temperature', (see section A.IV.3) and 'Heat transfer wall1', (shown in Figure

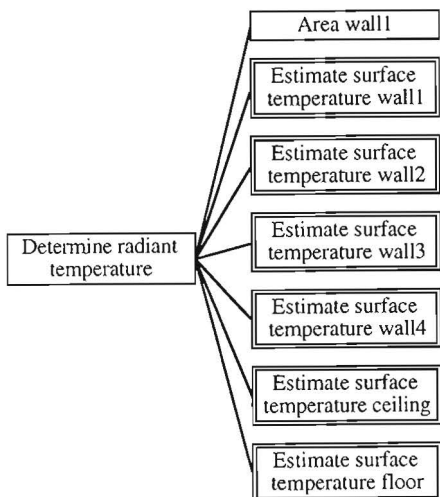


Figure A.4a: The decision tree of the parameter 'Determine radiant temperature'.

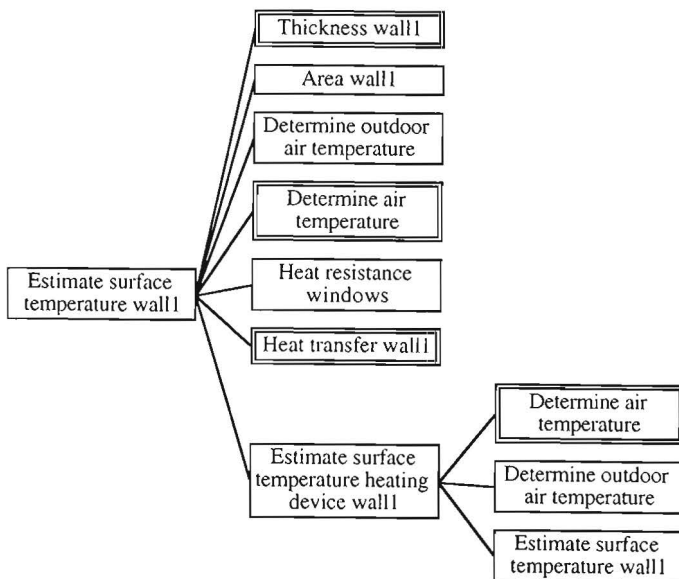


Figure A.4b: The decision tree of the parameter 'Estimate surface temperature wall1'.

---

A.4d; wall2, wall3, wall4, ceiling and floor look alike, so are not shown).

The table 'Estimate surface temperature wall1' shows that the surface temperature of indoor walls is determined to be the air temperature. Of outdoor walls the division of the walls in windows, heating device and building material has to be known before the surface temperature can be estimated using equation [A.2] in Appendix I, (It is emanated that no doors exist in a outdoor wall, in a ceiling or a floor, and no windows exist in a floor). The first two actions are needed to control whether the heat resistance of the outdoor wall is large enough (It has to be more than  $2.5 \text{ m}^2\text{K/W}$ , according to Dutch building regulations), and whether the entered area of the heating device is not larger than the area of the wall itself. If the heat resistance is too low or the area of the heating device is too large a warning appear onto the *conclusion*-field of the consult window. The third action determines the surface temperature of the building material, the fourth of the windows and the fifth of the wall itself. The latter can only be estimated as the surface temperatures of building material, windows and heating device are known, as well as the outdoor air temperature.

To determine the surface temperature of the building material the table 'Thickness wall1' is needed to provide the heat resistance of the building material. To calculate 'Heat resistance building material' the heat resistances of the single building material layers are added. The heat resistance of one layer depends on its material and on its thickness, and can be found in the tables 'Material layer1 wall1', etc. The entered thickness of each layer has to be between  $0.001 \text{ m}$  (= 1 mm) and  $0.3 \text{ m}$ . (This demand is programmed to make sure the user enters the values in meters.) Once the heat resistance of the building material is known the surface temperature of the building material can be estimated, using the equations [A.3], [A.4] and [A.5] in Appendix I.

To determine the surface temperature of the windows the table 'Heat resistance windows' is needed to provide the heat resistance of the windows, which depends on whether double glazing or single glazing is chosen. (The other actions are needed to determine the air temperature.) The table 'Heat transfer wall1' is also needed to provide the area of the windows, and an area check for the entered values of the area of the windows and doors, (The existence of a door and its area is asked although it is not needed. This is done to structure the question order to the user. The other actions are needed to determine the air temperature.)

The table 'Estimate surface temperature heating device wall1' shows how the surface temperature of a radiator or convector is determined. In winter the equations [A.6], [A.7] and [A.8] in Appendix I are used, in summer the surface temperature of the heating device is equal to the building material's surface temperature. For the floor heating and ceiling heating the equations of the surface temperature of the heating devices provide area temperatures of floor and ceiling itself.

The table 'Determine outdoor air temperature' has three conditions: The first one indicates which method of determining the parameters 'Determine outdoor air temperature' and 'Determine outdoor relative humidity' will be used. The second and third one are added to control if the parameters' values are realistic. If the value of 'Determine outdoor air temperature' is less than  $-20^\circ\text{C}$  or more than  $40^\circ\text{C}$ , or if the value of 'Determine outdoor relative humidity' is less than 0% or more than 100% a warning will be displayed in the conclusion-field of the consult window. Only the value of 'Determine outdoor air temperature' is needed to determine the radiant temperature.

#### **A.IV.5 Module 'Determine air velocity'**

The table-tree of 'Determine air velocity' is shown in Figure A.5. The module 'Determine air velocity' consists of only one table: 'Determine air velocity' and the module 'Determine metabolic rate' (see section A.IV.1).



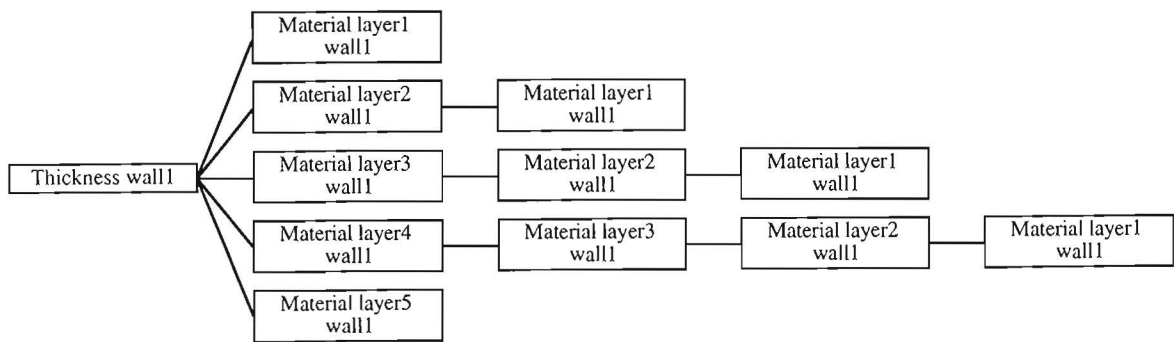


Figure A.4c: The decision tree of the parameter 'Thickness wall1'.

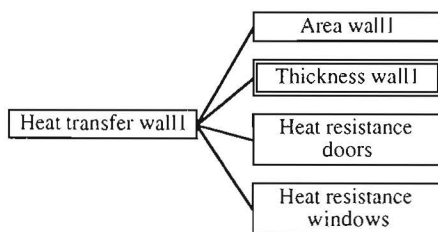


Figure A.4d: The decision tree of the parameter 'Heat transfer wall1'.

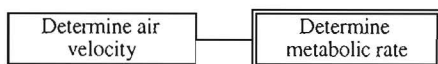


Figure A.5: The decision tree of the parameter 'Determine air velocity'.

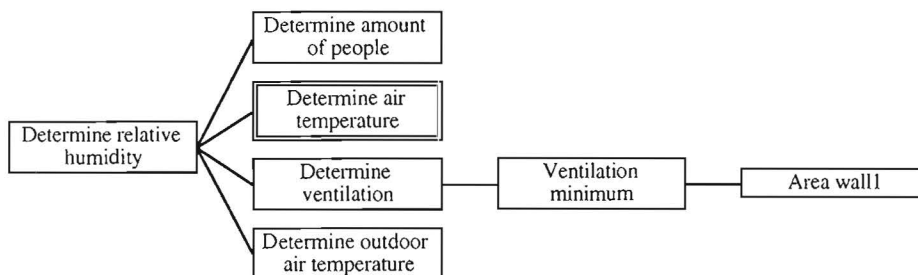


Figure A.6: The decision tree of the parameter 'Determine relative humidity'.

The table 'Determine air velocity' has only two conditions. The first one indicates which method of determining this parameter will be used. The second one is added to control if the parameter's value is in the Fanger domain. If the value is out of this domain a warning will be displayed in the conclusion-field of the consult window. The value itself is displayed in the *parameters*-field.

The value of 'Determine air velocity' is determined to be 0.1 m/s if the estimation-option is chosen. If the known-value-option is chosen the air velocity will be asked on screen. After the value is entered the relative air velocity is determined, according to equation [4.1]. This value is rounded to one digit.

#### A.IV.6 Module 'Determine relative humidity'

The table-tree of 'Determine relative humidity' is shown in Figure A.6. It shows that three other tables and the module 'Determine air temperature', (section A.IV.3), are needed, (actually this is only the case when an estimation needs to be made). Tables: 'Determine amount of people', 'Determine ventilation', (depending itself on tables 'Ventilation minimum' and 'Area wall1'), and 'Determine outdoor air temperature'.

The table 'Determine relative humidity' has three conditions. The first one indicates which method of determining this parameter will be used. The second and third one are added to control if the parameter's value is in the Fanger domain. If the value is out of this domain a warning will be displayed in the conclusion-field of the consult window. The value itself is rounded to zero digits, and is displayed in the *parameters*-field.

If the known-value-option is chosen the relative humidity will be asked on screen. After that the value of 'Determine water vapour pressure' is determined by using equation [4.2]. The saturated water vapour pressure is calculated with the predicate *saturated\_water\_vapour\_pressure* (in the first part of the Prolog model in Appendix V), according to equation [A.11] of Appendix I.

If the estimation-option is chosen the water vapour pressure will be estimated with the predicate *estimate\_water\_vapour\_pressure* (first part of Prolog model), according to equation [A.12] of Appendix I. To do this the values of 'Determine amount of people', (from table 'Determine amount of people'), 'Humidity production', (from predicate *humidity\_production* (first part of Prolog model), according to equation [A.13] of Appendix I.), 'Determine air temperature', (see section A.IV.3), 'Determine ventilation', (from tables 'Determine ventilation', 'Ventilation minimum' and 'Area wall1') and 'Determine outdoor air temperature' are needed. After that the value for 'Determine relative humidity' is determined, according to equation [4.2].

The table 'Determine amount of people' shows that the amount of people in the room is asked. If this value is less than 0 or more than 25 a warning is displayed in the *conclusion*-field of the consult window. In table 'Determine ventilation' can be seen that if the entered value for ventilation is less than the required minimum a warning is displayed in the *conclusion*-field as well. The height of this ventilation minimum is determined in the table 'Ventilation minimum', according to Dutch building regulations: the maximum of  $(0.0013 \times \text{the area of the floor}) \text{ m}^3/\text{s}$  and  $0.01 \text{ m}^3/\text{s}$ , (Because the area of the floor is needed the table 'Area wall1' is added to the table tree).

The table 'Determine outdoor air temperature' is needed for the outdoor water vapour pressure. This table is discussed in section A.IV.4.

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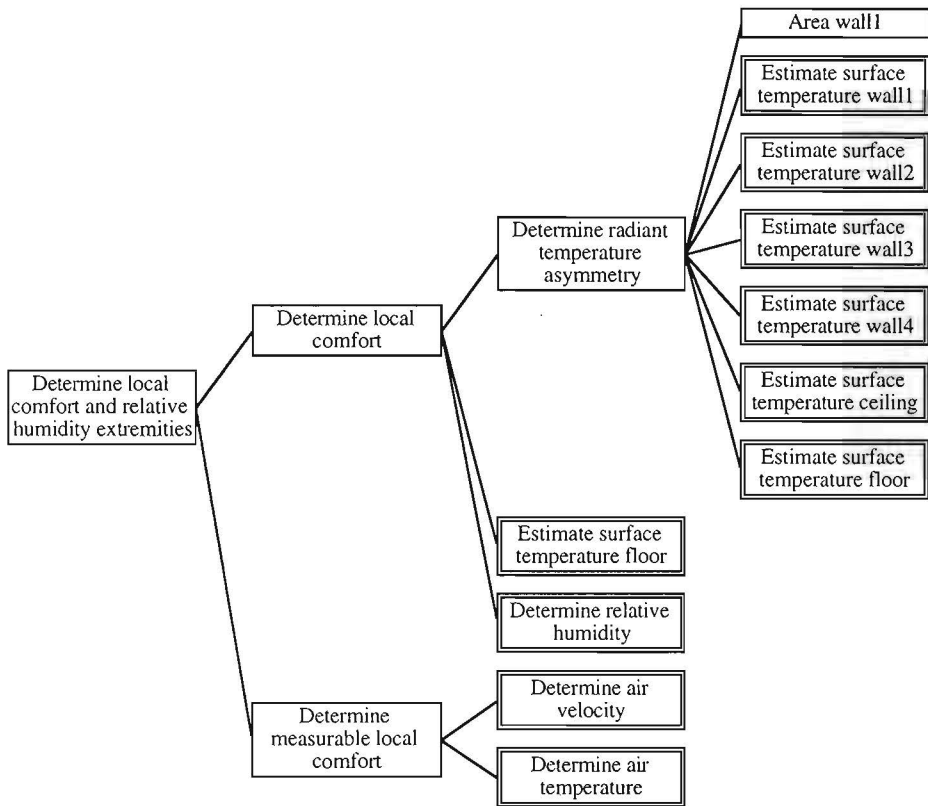


Figure A.7: The decision tree of the parameter 'Determine local comfort and relative humidity extremities'.

#### A.IV.7 Module 'Determine local comfort and relative humidity extremities'

The table-tree of 'Determine local comfort and relative humidity extremities' is shown in Figure A.7. It shows that two other tables are needed: 'Determine local comfort' and 'Determine measurable local comfort'. The first table depends on the table 'Determine radiant temperature asymmetry' (depending on the same table and modules as 'Determine radiant temperature', see section A.IV.4) and on the modules 'Estimate surface temperature floor', (see section A.IV.4), and 'Determine relative humidity', (section A.IV.6). The second table depends on the modules 'Determine air velocity', (section A.IV.5), and 'Determine air temperature', (section A.IV.3).

The table 'Determine local comfort and relative humidity extremities' shows that a division is made into two groups of causes of local discomfort: (normal) local discomfort and measurable local discomfort. The value of 'Determine measurable local comfort' only is needed if the value of 'Measurable local comfort determination' is *Yes*.

The table 'Determine local comfort' confirms that to complete this table no extra questions need to be asked. The first condition checks causes of radiant temperature asymmetry, for which table 'Determine radiant temperature asymmetry' is needed. The three conditions in this table refer to the predicates *trver* and *trhor* (in the fourth part of the Prolog model in Appendix V). In these predicates the differences in radiation of two opposite walls or of ceiling and floor is calculated by using the predicate *area\_weight\_average* again (first part Prolog model). The value of 'Estimate surface temperature floor' can indicate surface temperature extremities, and the value of 'Determine relative humidity' can indicate relative humidity extremities. In the table the values are compared with the maximums mentioned in section 4.3.

The first condition of the table 'Determine measurable local comfort' shows that values of the parameters 'Air temperature difference' (between minimum and maximum) and 'Amount of variations' are needed. These are needed to predict local discomfort caused by temperature variations. In order to predict 'Percentage dissatisfied draught' the predicate *pd* (fourth part Prolog model) is done, to perform equation [4.8]. Next to the already known parameters 'Determine air velocity' and 'Determine air temperature' the parameter 'Turbulence coefficient' is needed. The last condition in this table asks for the 'Vertical air temperature difference' (between head and ankle level), because this can indicate local discomfort as well. In the table the values are compared with the maximums mentioned in section 4.3.

---

## **Appendix V: The programs**

The following three pages provide the Prolog model of the TIE-system. In this model all programs made in Prolog can be found.



```

Qm is 0,
accumulation_light_constants(T, AF10, AF1100),
  AF1 is AF10+(AF1100-AF10)*SWM/100,
  Q1 is H1*RF1*((1-CV1)*AF1),
heat_sun_constants_wall(T,OsW1,EwW1,KofS,OrW1,CTW1, HsgW1100, HsgW10, HswW1),
heat_sun_constants_wall(T,OsW2,EwW2,KofS,OrW2,CTW2, HsgW2100, HsgW20, HswW2),
heat_sun_constants_wall(T,OsW3,EwW3,KofS,OrW3,CTW3, HsgW3100, HsgW30, HswW3),
heat_sun_constants_wall(T,OsW4,EwW4,KofS,OrW4,CTW4, HsgW4100, HsgW40, HswW4),
heat_sun_constants_ceiling(T,OsC,EwC,KofS,Ceiling,CTC, HsgC100, HsgC0, HswC),
  Qzg is Z1*AwW1*ZTA*( HsgW10+( HsgW1100- HsgW10)*SWM/100)+
        Z2*AwW2*ZTA*( HsgW20+( HsgW2100- HsgW20)*SWM/100)+
        Z3*AwW3*ZTA*( HsgW30+( HsgW3100- HsgW30)*SWM/100)+
        Z4*AwW4*ZTA*( HsgW40+( HsgW4100- HsgW40)*SWM/100)+
        AwC*ZTA*( HsgC0+( HsgC100- HsgC0)*SWM/100),
  Qzt is ACsW1*AW1* HswW1+ACsW2*AW2* HswW2+
        ACsW3*AW3* HswW3+ACsW4*AW4* HswW4+ACsC*AC* HswC,
outdoor_air_temperature(Month,T,Tout),
  Qtg is HTCg*(AwW1+AwW2+AwW3+AwW4+AwC)*(Tout-Tnom),
  Qv is V*1.2*1000*(Tout-Tnom),
Cooling is (Qp+Qm+Q1+Qzg+Qzt+Qtg+Qv),
temperature_respons_constants(T, A100, B100, C100, A0, B0, C0),
  TrSWM0 is A0+B0/(K -C0),
  TrSWM100 is A100+B100/(K -C100),
IncrTairTemp0 is Cooling*TrSWM0/Av + IncrTairTEMP0,
IncrTairTemp100 is Cooling*TrSWM100/Av + IncrTairTEMP100,
T1 is (T -1),
estimate_air_temperature(T1, Month, Av,OrW2,OrW1,OrW3,OrW4, SWM, KofS,ZTA,HTCg, Pp,Iclo,M, Hm,
H1,RF1,CV1, V,
AwW1,AwW2,AwW3,AwW4,AwC, OsW1,OsW2,OsW3,OsW4,OsC, EwW1,EwW2,EwW3,EwW4,EwC, Z1,Z2,Z3,Z4,
CTW1,CTW2,CTW3,CTW4,Ceiling,CTC, ACsW1,AW1,ACsW2,AW2,ACsW3,AW3,ACsW4,AW4,ACsC,AC,
Tnom, K, IncrTairTemp0,IncrTairTemp100,EstTair).

```

```

estimate_air_temperature(T, Month, Av,OrW2,OrW1,OrW3,OrW4, SWM, KofS,ZTA,HTCg, Pp,Iclo,M, Hm,
H1,RF1,CV1, V,
AwW1,AwW2,AwW3,AwW4,AwC, OsW1,OsW2,OsW3,OsW4,OsC, EwW1,EwW2,EwW3,EwW4,EwC, Z1,Z2,Z3,Z4,
CTW1,CTW2,CTW3,CTW4,Ceiling,CTC, ACsW1,AW1,ACsW2,AW2,ACsW3,AW3,ACsW4,AW4,ACsC,AC,
Tnom, K, IncrTairTEMP0,IncrTairTEMP100,EstTair):-

```

```

T=<18, T>=9,

```

```

Hp is 65.93 -20.76*Iclo+0.27*M -0.1*Iclo*M,

```

```

Qp is Pp*Hp,

```

```

Qm is Hm,

```

```

accumulation_light_constants(T, AF10, AF1100),

```

```

  AF1 is AF10+(AF1100-AF10)*SWM/100,

```

```

  Q1 is H1*RF1*(CV1+(1-CV1)*AF1),

```

```

heat_sun_constants_wall(T,OsW1,EwW1,KofS,OrW1,CTW1, HsgW1100, HsgW10, HswW1),

```

```

heat_sun_constants_wall(T,OsW2,EwW2,KofS,OrW2,CTW2, HsgW2100, HsgW20, HswW2),

```

```

heat_sun_constants_wall(T,OsW3,EwW3,KofS,OrW3,CTW3, HsgW3100, HsgW30, HswW3),

```

```

heat_sun_constants_wall(T,OsW4,EwW4,KofS,OrW4,CTW4, HsgW4100, HsgW40, HswW4),

```

```

heat_sun_constants_ceiling(T,OsC,EwC,KofS,Ceiling,CTC, HsgC100, HsgC0, HswC),

```

```

  Qzg is Z1*AwW1*ZTA*( HsgW10+( HsgW1100- HsgW10)*SWM/100)+

```

```

        Z2*AwW2*ZTA*( HsgW20+( HsgW2100- HsgW20)*SWM/100)+

```

```

        Z3*AwW3*ZTA*( HsgW30+( HsgW3100- HsgW30)*SWM/100)+

```

```

        Z4*AwW4*ZTA*( HsgW40+( HsgW4100- HsgW40)*SWM/100)+

```

```

        AwC*ZTA*( HsgC0+( HsgC100- HsgC0)*SWM/100),

```

```

  Qzt is ACsW1*AW1* HswW1+ACsW2*AW2* HswW2+

```

```

        ACsW3*AW3* HswW3+ACsW4*AW4* HswW4+ACsC*AC* HswC,

```

```

outdoor_air_temperature(Month,T,Tout),

```

```

  Qtg is HTCg*(AwW1+AwW2+AwW3+AwW4+AwC)*(Tout-Tnom),

```

```

  Qv is V*1.2*1000*(Tout-Tnom),

```

```

Cooling is (Qp+ Qm+ Q1+ Qzg+ Qzt+ Qtg+ Qv),

```

```

temperature_respons_constants(T, A100, B100, C100, A0, B0, C0),

```

```

  TrSWM0 is A0+ B0/(K -C0),

```

```

  TrSWM100 is A100+ B100/(K -C100),

```

```

IncrTairTemp0 is Cooling* TrSWM0/Av + IncrTairTEMP0,

```

```

IncrTairTemp100 is Cooling* TrSWM100/Av + IncrTairTEMP100,

```

```

T1 is (T -1),

```

```

estimate_air_temperature(T1, Month, Av,OrW2,OrW1,OrW3,OrW4, SWM, KofS,ZTA,HTCg, Pp,Iclo,M, Hm,
H1,RF1,CV1, V,
AwW1,AwW2,AwW3,AwW4,AwC, OsW1,OsW2,OsW3,OsW4,OsC, EwW1,EwW2,EwW3,EwW4,EwC, Z1,Z2,Z3,Z4,
CTW1,CTW2,CTW3,CTW4,Ceiling,CTC, ACsW1,AW1,ACsW2,AW2,ACsW3,AW3,ACsW4,AW4,ACsC,AC,
Tnom, K, IncrTairTemp0,IncrTairTemp100,EstTair).

```

```

/* third part: PMV calculation */

```

```

clothing(Iclo, Fcl):-
    Iclo =< 0.5,
    Fcl is 1.0+0.200*Iclo.
clothing(Iclo, Fcl):-
    Iclo > 0.5,
    Fcl is 1.05+0.100*Iclo.

tclo(Ta, Iclo, Tclo):-
    Tclo is (Ta+((35.5 -Ta)/(3.5*(6.45*0.155*Iclo+0.1)))).
convection(Ta, Tclo, Va, Hco):-
    X1 is Tclo -Ta, X2 is Ta -Tclo, X3 is max(X1,X2),
    X is (2.38*(X3)^0.25), Y is (12.1*(Va)^0.5),
    Hco is max(X, Y).
temperature_clothing(0, Tclo, _, _, _, _, _, Hco, _, _, Hc, Tcl):-!,
    Tcl is Tclo,
    Hc is Hco.
temperature_clothing(_, Tclo, _, _, Iclo, Fcl, _, Hco, _, _, Hc, Tcl):-
    Dfx is (1.0+0.155*Iclo*(3.96*10^( -8)*Fcl*4*(Tclo+273)^3+Fcl*Hco)),
    Dfx = 0, Tcl is Tclo, Hc is Hco.
temperature_clothing(N, Tclo, M, W, Iclo, Fcl, Tr, Hco, Ta, Va, Hc, Tcl):-
    N1 is (N -1),
    Fx is (Tclo -(35.7 -0.028*(M -W)
        -Iclo*0.155*(3.96*10^( -8)*Fcl*((Tclo+273)^4 -(Tr+273)^4
            +Fcl*Hco*(Tclo -Ta)))),
    Dfx is (1.0+0.155*Iclo*(3.96*10^( -8)*Fcl*4*(Tclo+273)^3+Fcl*Hco)),
    Dfx \= 0, Tc is (Tclo -(Fx/DFx)),
    X1 is Tc -Ta, X2 is Ta -Tc, X3 is max(X1,X2),
    X is (2.38*(X3)^0.25), Y is (12.1*(Va)^0.5), H is max(X, Y),
    temperature_clothing(N1, Tc, M, W, Iclo, Fcl, Tr, H, Ta, Va, Hc, Tcl).

predicted_mean_vote(M, W, Icl, Ta, Tr, Va, Pa, Fcl, Tcl, Hc, PMV):-
    Tric is (Va+Icl),
    Y is (0.303*aln( -0.036*M)+0.028)*
        ((M -W) -3.05*10^( -3)*(5733 -6.99*(M -W) -Pa) -0.42*((M -W) -58.15)
        -1.7*10^( -5)*M*(5867 -Pa) -0.0014*M*(34 -Ta)
        -3.96*10^( -8)*Fcl*((Tcl+273)^4 -(Tr+273)^4) -Fcl*Hc*(Tcl -Ta)),
    PMV is int(100*Y)/100 +0*Tric.

/* fourth part: Local discomfort calculation necessities */

trver(A1, A2, A3, A4, A5, A6, T1, T2, T3, T4, T5, T6, Trver):-
    area_weight_average(A1, 0.5*A2, 0, 0.5*A4, 0.5*A5, 0.5*A6,
        T1, T2, T3, T4, T5, T6, Tr1),
    area_weight_average(0, 0.5*A2, A3, 0.5*A4, 0.5*A5, 0.5*A6,
        T1, T2, T3, T4, T5, T6, Tr3),
    X is (Tr1 -Tr3),
    Y is (Tr3 -Tr1),
    Trver is max(X, Y).
trhor(H, A1, A2, A3, A4, A5, A6, T1, T2, T3, T4, T5, T6, Trhor):-
    X is (H -0.6)/H,
    Y is 0.6/H,
    area_weight_average(X*A1, X*A2, X*A3, X*A4, A5, 0,
        T1, T2, T3, T4, T5, T6, Tr5),
    area_weight_average(Y*A1, Y*A2, Y*A3, Y*A4, 0, A6,
        T1, T2, T3, T4, T5, T6, Tr6),
    Trhor is (Tr5 -Tr6).

pd(Va, Ta, Tu, PD):-
    Va > 0.05,
    PD is (0.37*Va*Tu+3.14)*(34 - Ta)*(Va - 0.05)^(0.62).
pd(Va, Ta, Tu, PD):-
    Va =< 0.05,
    PD is (0.37*0.05*Tu+3.14)*(34 - Ta)*(0.05 - 0.05)^(0.62).

```



## **Appendix VI: The tables (summary)**

The following four pages provide a summary of all tables of the TIE-system. The tables themselves can be found in the appendix of the report of F.H. Louwers.

---

## TABLE PROPERTIES

TABLE : Area wall1

TABLE : Clothing insulation main garments

TABLE : Clothing insulation over garments

TABLE : Clothing insulation socks & shoes

TABLE : Clothing insulation under garments

TABLE : Construction type ceiling

TABLE : Construction type ceiling asked

TABLE : Construction type wall1

TABLE : Construction type wall2

TABLE : Construction type wall3

TABLE : Construction type wall4

TABLE : Determine air temperature  
DO BEFORE : display(process, 'The air temperature will be determined.')

TABLE : Determine air velocity  
DO BEFORE : display(process, 'The air velocity will be determined.')

TABLE : Determine amount of people

TABLE : Determine clothing insulation  
DO BEFORE : display(process, 'The intrinsic clothing insulation will be determined.')

TABLE : Determine general comfort

TABLE : Determine heat light

TABLE : Determine Kvalue

TABLE : Determine local comfort

TABLE : Determine local comfort and relative humidity extremities

TABLE : Determine measurable local comfort

TABLE : Determine metabolic rate  
DO BEFORE : display(process, 'The metabolic rate will be determined.')

TABLE : Determine outdoor air temperature

TABLE : Determine radiant temperature  
DO BEFORE : display(process, 'The mean radiant temperature will be determined.')

TABLE : Determine radiant temperature asymmetry

TABLE : Determine relative humidity  
DO BEFORE : display(process, 'The relative humidity and water vapour pressure will be determined.')

TABLE : Determine SWM

TABLE : Determine thermal sensation  
DO BEFORE : clear\_display(conclusion)

TABLE : Determine usable work  
DO BEFORE : display(process, 'The usable work will be determined.')

TABLE : Determine ventilation

TABLE : Estimate accumulation mass ceiling

TABLE : Estimate accumulation mass floor

TABLE : Estimate accumulation mass wall1  
TABLE : Estimate accumulation mass wall2  
TABLE : Estimate accumulation mass wall3  
TABLE : Estimate accumulation mass wall4  
TABLE : Estimate basal metabolic rate  
TABLE : Estimate clothing insulation  
TABLE : Estimate heat light  
TABLE : Estimate metabolic rate  
TABLE : Estimate surface temperature ceiling  
TABLE : Estimate surface temperature floor  
TABLE : Estimate surface temperature heating device ceiling  
TABLE : Estimate surface temperature heating device floor  
TABLE : Estimate surface temperature heating device wall1  
TABLE : Estimate surface temperature heating device wall2  
TABLE : Estimate surface temperature heating device wall3  
TABLE : Estimate surface temperature heating device wall4  
TABLE : Estimate surface temperature wall1  
TABLE : Estimate surface temperature wall2  
TABLE : Estimate surface temperature wall3  
TABLE : Estimate surface temperature wall4  
TABLE : Heat computer  
TABLE : Heat printer  
TABLE : Heat resistance doors  
TABLE : Heat resistance windows  
TABLE : Heat screen  
TABLE : Heat transfer ceiling  
TABLE : Heat transfer floor  
TABLE : Heat transfer wall1  
TABLE : Heat transfer wall2  
TABLE : Heat transfer wall3  
TABLE : Heat transfer wall4  
TABLE : Material layer1 ceiling  
TABLE : Material layer1 floor  
TABLE : Material layer1 wall1  
TABLE : Material layer1 wall2  
TABLE : Material layer1 wall3  
TABLE : Material layer1 wall4  
TABLE : Material layer2 ceiling

TABLE : Material layer2 floor  
TABLE : Material layer2 wall1  
TABLE : Material layer2 wall2  
TABLE : Material layer2 wall3  
TABLE : Material layer2 wall4  
TABLE : Material layer3 ceiling  
TABLE : Material layer3 floor  
TABLE : Material layer3 wall1  
TABLE : Material layer3 wall2  
TABLE : Material layer3 wall3  
TABLE : Material layer3 wall4  
TABLE : Material layer4 ceiling  
TABLE : Material layer4 floor  
TABLE : Material layer4 wall1  
TABLE : Material layer4 wall2  
TABLE : Material layer4 wall3  
TABLE : Material layer4 wall4  
TABLE : Material layer5 ceiling  
TABLE : Material layer5 floor  
TABLE : Material layer5 wall1  
TABLE : Material layer5 wall2  
TABLE : Material layer5 wall3  
TABLE : Material layer5 wall4  
TABLE : Metabolic rate work  
TABLE : Orientation wall2  
TABLE : Reduction factor light  
TABLE : Statistical Data 90/93, NL  
TABLE : Thickness ceiling  
TABLE : Thickness ceiling to air space  
TABLE : Thickness floor  
TABLE : Thickness floor to air space  
TABLE : Thickness wall1  
TABLE : Thickness wall1 to air space  
TABLE : Thickness wall2  
TABLE : Thickness wall2 to air space  
TABLE : Thickness wall3  
TABLE : Thickness wall3 to air space

TABLE : Thickness wall4

TABLE : Thickness wall4 to air space

TABLE : Ventilation minimum

## **Appendix VII: The DDSS-paper**

The following ten pages provide the paper that was submitted in April 1996 for the Design & Decision Support Systems conference of August, 18-21 1996 in SPA Belgium. The TIE-project will be presented during this conference.

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

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**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 role.

# 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].

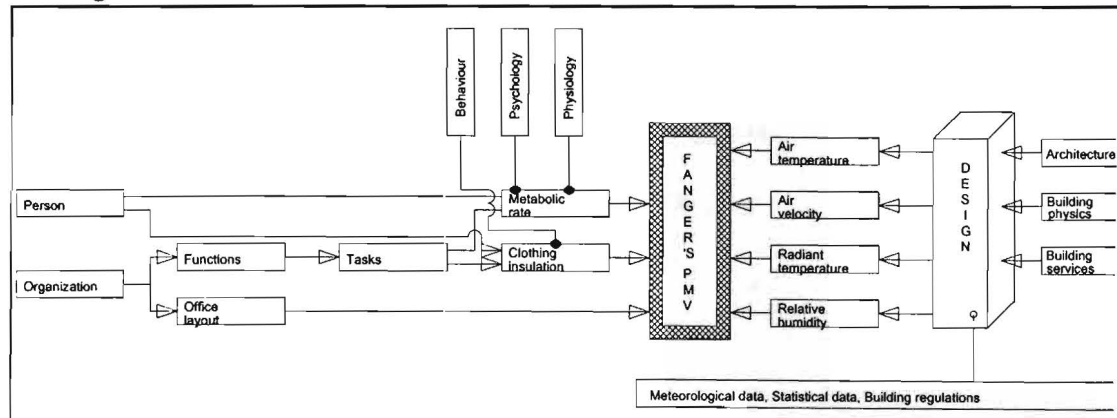
The dominant personal parameters are:

metabolic heat	(M-W)	[W/m <sup>2</sup> ] and
clothing insulation	$I_{clo}$	[m <sup>2</sup> °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 (Mastricht 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

- 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),

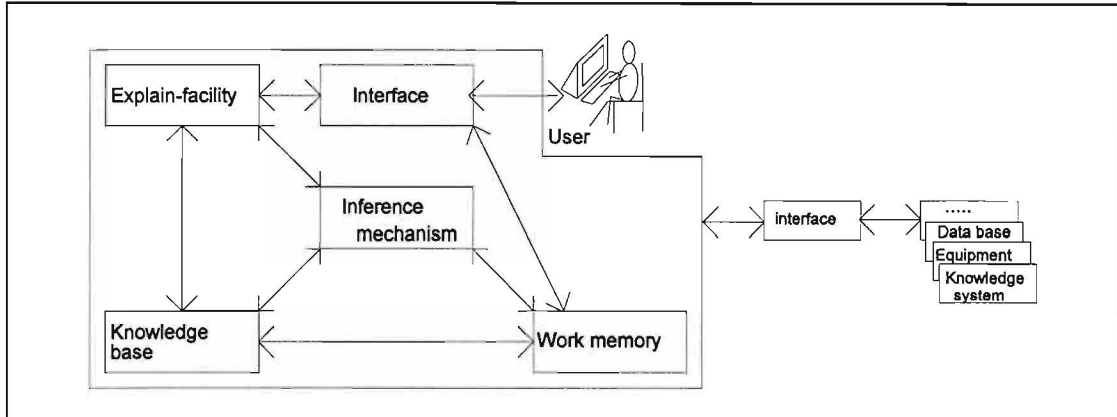
*an inference mechanism* (making it possible for the computer to use the knowledge to determine the values of those parameters and the PMV),

*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

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

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).

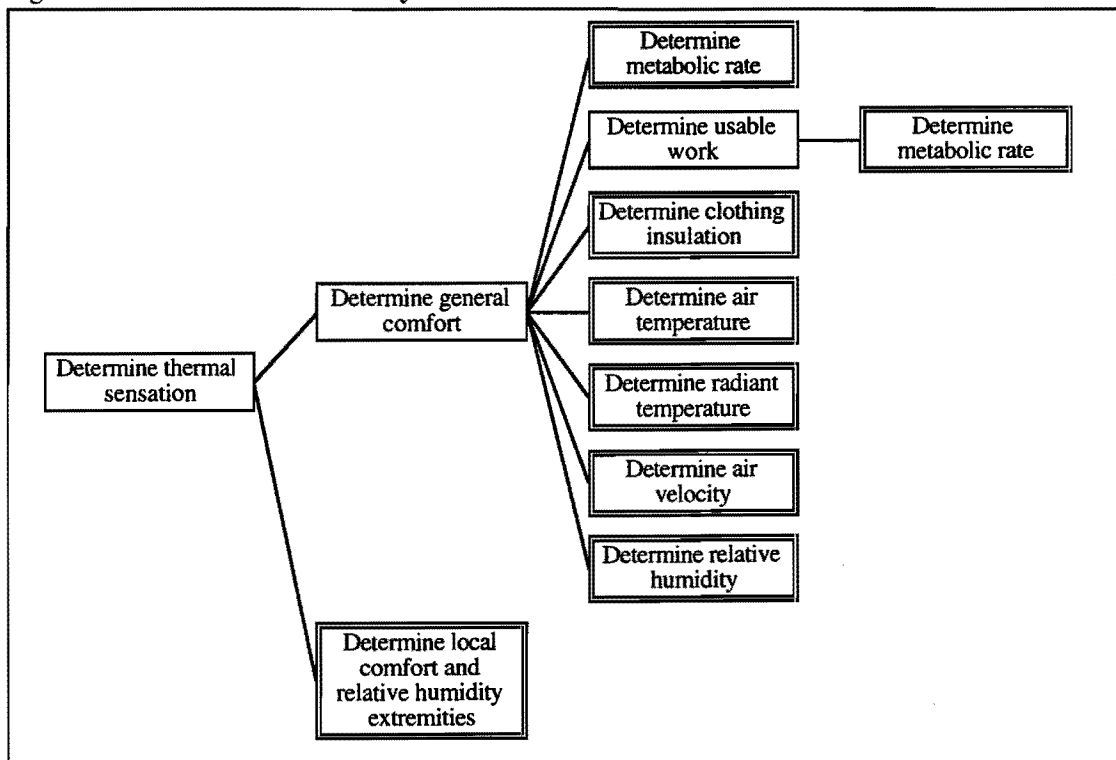
In the TIE-system also databases are stored. These databases are programmed in the underlying program language of AKTS: Prolog. Also some major calculation are programmed in Prolog. Literature used regarding Prolog: (Clocksin and Mellish 1987), (Leigh and Smith 1986), (Lucardie 1994), (Rowe 1988), (Saint-Dizier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



entered by the user in case of an existing building evaluation. In the case of an evaluation 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.

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