With the decline of fossil energy resources, the necessity to change our way of energy usage is apparent. One solution commonly heard of is the reduction of demand through greater efficiency of the building system. This is at issue even in the residential building sector even though its demand depends strongly on the occupant behaviour as shown in previous studies. The research of occupant behaviour focuses on the analysis of general behaviour patterns not on the factors leading to individual differences in the behaviour, however it can be said that such differences are the reason for many variations in the energy used for heating and cooling. The objectives of this research are (1) the identification of those factors having a major influence on the occupant behaviour and its reference levels, (2) the analysis of the potential to influence the reference-level towards a change of occupant behaviour and (3) the evaluation of the exergy consumption for cooling and heating in relation to the differences in occupant behaviour.

The analyses presented in this dissertation are based on (1) a comprehensive literature review within the fields of built environmental research, neurology, psychology, control theory and behavioural ecology; (2) a field measurement conducted in an international student dormitory gathering quantitative physical data of 39 students in summer and 34 students in winter together with their answers given to an introductory survey and two interviews; and (3) an Internet-based survey conducted also during summer and winter seasons leading to a qualitative database of comfort votes, recent behaviours and personal background of 434 participants for summer and 845 for winter.
Occupant Behaviour and the Related Reference Levels for Heating and Cooling

– Analysis of the Factors Causing Individual Differences together with the Evaluation of their Effect on the Exergy Consumption within the Residential Built Environment –

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March, 2010
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Abstract

With the decline of fossil energy resources, the necessity to change our way of energy usage is apparent. One solution commonly heard of is the reduction of demand through greater efficiency of the building system. This is at issue even in the residential building sector even though its demand depends strongly on the occupant behaviour as shown in previous studies. The research of occupant behaviour focuses on the analysis of general behaviour patterns not on the factors leading to individual differences in the behaviour, however it can be said that such differences are the reason for many variations in the energy used for heating and cooling. The objectives of this research are (1) the identification of those factors having a major influence on the occupant behaviour and its reference levels, (2) the analysis of the potential to influence the reference-level towards a change of occupant behaviour and (3) the evaluation of the exergy consumption for cooling and heating in relation to the differences in occupant behaviour.

The analyses presented in this dissertation are based on (1) a comprehensive literature review within the fields of built environmental research, neurology, psychology, control theory and behavioural ecology; (2) a field measurement conducted in an international student dormitory gathering quantitative physical data of 39 students in summer and 34 students in winter together with their answers given to an introductory survey and two interviews; and (3) an Internet-based survey conducted also during summer and winter seasons leading to a qualitative database of comfort votes, recent behaviours and personal background of 434 participants for summer and 845 for winter.

The whole dissertation consists of four parts. In the first chapter of part 1 (chapters 2–4), the development of a theoretical occupant-behaviour model is described based on the comprehensive literature review. In this context, the reference level is introduced as the entity to which all input values deriving from the body’s sensory systems are compared. Therefore, the reference level has a special place in the model, because the decision whether to perform or not to perform a certain type of behaviour is based on the outcome of this comparison. Second, the nature of the reference level was analysed by looking at the success, the purpose and the ranking of occupant behaviour based on the data from the Internet-based survey. It was found that there must be a separate reference level for different input values such as thermal comfort and noise, which are independent of each other. Third, a first trial analysis on the human body exergy consumption (HBx) rate as reference level shows that the decision to sleep with an open or closed window could be partly explained with the current HBx rate in comparison to the HBx rate range during childhood.

In part 2 (chapters 5–7), the factors influencing on the reference levels for thermal comfort were elaborated and a method to quantify the relative importance of those factors were established. The first analysis of the data obtained from the measurement in the student dormitory showed the significance of individual factors in relation to differences in the behaviour. Examples for such individual factors are a preference for air-conditioned spaces and thermal background, which refers to the climate a person spent the majority of their first
10 years of life. In the next step, the influence of external factors such as temperature and humidity as well as various individual factors were evaluated according to their significance in describing the observed behaviour by the mean of multivariate logistic regression analyses. As a result, statistical models of occupant-behaviour prediction including an exponentially weighted running mean of the outdoor temperature during the night and 17 individual factors such as above mentioned preference and thermal background were presented. The factors included in these models were then judged by introducing an importance factor. It was found that, on the one hand, the running mean of the temperature has a similar impact to the individual factors in summer, while, on the other hand, the latter have a much higher influence in winter than in summer.

Part 3 (chapters 8–9) analyses whether and to what degree long-term or short-term experiences can influence the set-up or a change of the reference levels. Firstly, the effects of long-term experiences such as cultural influences are shown by comparing the stated behaviour with respect to sleeping conditions of those participating in the Internet-based survey. This revealed, on the one hand that the behaviour is influenced by the type of building as well as the surrounding, and on the other hand, it was shown by means of a detailed analysis of Germans living in Japan compared to those living in Germany that behaviour can be influenced by such external factors. Second, the influences of knowledge transfer methods on the reference levels, which can be regarded as short-term experiences, were evaluated. It was shown that the knowledge transfer methods can motivate the recipients to try out strategies not practised before, but there is a huge discrepancy between the stated intention immediately after the knowledge transfer and the actions performed in reality. With respect to the usage of AC-unit, the effect of knowledge transfer processes such as workshops or information papers could be quantified to lead to a reduction of up to 16% in the case of the workshop, but no significant change was detected in response to the information paper.

Part 4 (chapter 10) describes the effect of differences in the reference levels compared to building envelope improvements on the exergy consumption for heating and cooling. Based on a steady-state exergy calculation, the influence of the occupant behaviour was highly significant (more than 90% decrease of exergy consumption) when the difference between indoor and outdoor air temperature is small, which is the case for long periods in those regions with moderate temperatures during summer and/or winter. On the other hand, the building envelope improvements have a much higher influence wherever the difference in temperature between indoors and outdoors are larger. Nevertheless, both measures combined lead to a reduction of up to 95% and should be the final goal.

Overall, this dissertation highlights the importance of researching the individual’s behaviour in order to understand the differences in certain types of energy usage. Besides being limited to the cases of heating and cooling with an AC-unit for most of the analyses, the methodology presented can also be applied to other types of behaviours. It is in such a way, that this dissertation shows another possible solution of how to change the current paradigms of energy usage towards the one that permits well-being with less exergy.
概要

現在における生活水準の維持のためにエネルギーの使用方法を変える必要性は、化石燃料の枯渇が近づく時代には明白である。しばしば言及される解決方法のひとつは、建築環境システムの効率の向上によって住宅部門のエネルギー使用量を減らすことである。しかしながら、過去の研究により、住宅のエネルギー使用量は、住まい手の行動に大きく依存することがわかっている。住まい手の行動に関する研究は、その多くは多くの人々にみられる一般的な行動パターンを扱っているが、個人差についてはほとんど取り上げられてこなかった。しかし、個人差は、暖冷房のエネルギー使用量に大きな影響を及ぼす。そこで、本研究では、建築環境における住まい手の行動に着目して、(1)行動変化に影響する主要因の抽出と定量化、(2)行動変化の閾値に及ぼす長期経験と短期経験の影響の評価、(3)行動変化の違いが暖冷房エネルギー消費パターンに及ぼす影響を評価した。

本論文では、まず建築環境学・神経学・心理学・制御理論や行動生態学の分野について包括的な文献調査を行い、その上で、実際の建物（東京にある国際留学生会館）での温度測定と質問紙調査の結果、ならびに夏季と冬季のそれぞれについて、4ヶ国語を用いて行なった人々の日頃の熱環境調整行動や熱環境の好み・行動履歴などに関する動的インターネット調査の分析結果を述べる。

第1部（第2～4章）では、行動変化の閾値を含む住まい手行動の理論モデルの構築について、包括的な文献調査に基づいて論じ、さらに、行動変化の閾値の性質を明らかにするために住まい手の行動の目的・順序を、後述するインターネットによる行動調査のデータに基づいて分析した。その結果、熱的快適性に関わる行動変化の閾値が騒音レベルなどの他の入力からは独立していると想定できることを確認した。

第2部（第5～7章）では、住まい手の行動とその行動変化の閾値に影響を及ぼす要因について詳しく分析した結果を述べた。国際留学生会館での調査データに基づく多変量ロジスティック回帰分析によると、指数的に重み付けされた外気温度の移動平均の他、個人差を含む約18個の要素を変数とする住まい手の行動モデルを得ることができた。

第3部（第8～9章）では、行動変化の閾値への長期経験と短期経験の影響性について行なった分析の結果について述べた。インターネット調査の参加者が選んだ就寝中の室内環境調整方法について分析したところ、文化的な影響のような長期経験が閾値に影響を及ぼすことが明らかになった。次いで、室内環境の調整方法に関する情報パンフレットなどのような短期経験が閾値に影響を及ぼすか否かを評価したところ、短期経験は、新たな温熱環境調整行動を誘発する可能性はあるが、その影響はそれほど大きくなかった。

第4部（第10章）では、住まい手行動の違いが暖冷房エネルギー消費パターンに及ぼす影響を分析した結果について述べた。室内空気温と外気温の差が小さい場合、行動の違いは、暖冷房エネルギー消費に相対的に大きな影響を及ぼすこと、その一方で、室内空気温と外気温の差が大きい場合は、断熱材を厚くするなどの建築外皮の改良の方が、行動の違いに比べて、暖冷房エネルギー消費に大きく影響を及ぼすことが明らかになった。

これ以上のことから、住まい手の行動を理解するために、個人差を詳細に検討することは重要である。本研究で示した方法は、エアコンの利用という行動に限らず、他の行動にも適用することができると考えられる。
Introductory Chapters

“Doing just what comes naturally can only please those who are unable to imagine better worlds and better ways.”

(Damasio, 2005; p. 254)
1 Introduction

More and more we are confronted by a contradictory situation in the world. On the one hand, some people are wasting water, food, high quality energy and other resources. On the other hand, others cannot satisfy their basic needs of drinking or eating. In such conditions, the lack of resources affects mainly the health, well-being, or even survival of a human, but the waste of resources has a strong impact on the environment and the quality of life of current and future generations. As Wall and Gong state, “the present use of resources in industrial society is obviously not sustainable, at least not for a very long time. The situation is similar to a colony of bacteria living from a limited resource. The population may increase exponentially for a short period but after that it collapses from the destruction of its own environment” (Wall and Gong, 2001; p. 141).

One of the major threats in this context is the much talked about climate change expected to occur due to human activity since the industrial revolution. A high percentage of this human activity is related to the aim of a comfortable life within the residential built environment as can be see when looking at the percentage of energy use and CO₂ emissions related to the household sector as shown in Figure 1.

Figure 2 shows the percentage of energy used per household for Germany, Japan in general and three regions of Japan. It can be seen that in Germany nearly 80% of the energy is used for heating, while in Japan only about 30% is used for heating and cooling. The

![Fig. 1. Energy use and CO₂ emissions by sector (other includes construction and agriculture/fishing) (IEA, 2008).](image-url)
distribution shown for the three Japanese sub-regions signifies that the percentage of energy used for heating as well as the total amount of energy used depends strongly on the latitude of the region. Sapporo in Hokkaido area is situated around a latitude of 43°N, Tokyo in the Kanto area around 35°N and Fukuoka in Kyushu around 33°N. This tendency is supported by the distribution shown for Germany, because the latitude of German cities ranges from Munich in the south having around 48°N and Hamburg in the north around 53°N.

![Fig. 2. Distribution of energy use per household by type of usage (JPC, 2005).](image)

1.1 The Importance of Understanding the Occupant Behaviour

All over the world scientists know that there has to be a change in energy usage to be able to keep the actual living standard in times of fossil energy sources coming to the end. Different opinions about the solutions for the built environment can be heard such as saving fossil energy by improving thermal insulation of buildings or producing it alternatively by installing solar collectors. The Intergovernmental Panel on Climate Change’s (IPCC) Fourth Assessment Report shows that the potential to reduce the projected global baseline emissions from the residential and commercial building sectors by 2020 cost effectively is about 29% (IPCC, 2007). At the same time, the IPCC’s third working group mentions within the detailed analysis of the building sector that “the energy use in a building also depends on the behaviour and decisions of occupants and owners” (Levine et al., 2007; p. 394).

While, the Japanese Ministry of Foreign Affairs wrote already in 1992, “the awareness that resources must be used sparingly and the environment protected from abuse has become part
of daily life in Japan" (Ishi, 1992; p.2). Schmitz (2000) is claiming, “in the last years the energy demand of buildings continuously decreased, so the heat demand is now less than half of 20 years ago. If you look at the yearly energy flow of Germany, the energy demand does not decrease in the expected way. Obviously there are other factors counteracting the technical progress. Those factors have to be found in the occupant of the building” (Schmitz, 2000; p.1).

First studies found variations in the energy usage between identical houses with different occupants of more than a factor of two (Socolow, 1978). Some years later, the comparison of electricity and gas consumption in nine identical children homes in London showed a variation of 40% in the gas consumption and 54% in the electricity consumption (Levermore, 1985). Lately, a study conducted in nine identical low-energy social housing units found variations in the electricity consumption of up to 600% (Bahaj and James, 2007). This shows that there is certainly a strong need to have a closer look not only at the characteristics of the building envelopes’ thermal insulation level and the mechanical heating and cooling systems’ efficiency, which can be regarded as the buildings’ hardware, but also at the human behaviour, which can be regarded as the software.

For a long time it is well known that there is a huge gap between the scientific results and the knowledge of the occupant and even between the knowledge of the occupant and their behaviour. Fietkau already named in 1981 eight reasons for this gap (Fietkau, 1981). This has to be viewed critically because the occupant still has a significant influence on the amount of energy used in their building, e.g. by the time and type of window opening, the use of air-conditioning (AC) units or the chosen indoor air temperature. I found different reasons for this gap during the work on a seminar paper. On the one hand, the occupant does not like changing his habits for private reasons, because environmental behaviour always seems to deal with abandonment, and environmental problems seem to be far away. On the other hand, the occupant does not have a chance to change his habits, because there is no information available how to behave more environmental conscious (Schweiker).

At the same time, little is known about the real behaviour of the occupant. In reality, the occupant behaviour must be influenced by quite a large number of factors, both external, e.g. air temperature, and internal, e.g. personal background, attitudes, preferences. A detailed understanding would be crucial for the future for the following reasons:

- The results of energy demand simulations are important pieces of information not only for decision makers. However, due to the huge impact of the occupant behaviour, these energy demand predictions will have to incorporate the lifestyle of occupants and its future changes in order to be realistic.
The currently existing energy supply structure with stable running power plants for base loads, and more flexible ones for middle and peak loads will be sooner or later replaced with a more dynamic and fluctuating supply pattern with a high percentage of renewable energy sources as shown in Figure 3. This demands a better understanding of the processes leading to middle and peak demands under different weather conditions in order to be able to assure a stable electricity. One key element driving the demand is the occupant.

- Understanding the occupants behaviour and the factors triggering certain types of actions will be crucial for designing buildings, especially residential ones, which allow occupants having a low consuming lifestyle with sufficient well-being.

Fig. 3. Existing and future energy demand and supply structure.

1.2 Studies Concerning Occupant Behaviour Within the Built Environment

Occupant behaviour can be formulated as one aspect of human behaviour, which itself is studied by very different academic fields, from the social to natural sciences. Starting with the latter, in the area related to building science, occupant behaviour is related to indoor and outdoor thermal conditions. In early studies, the outdoor air temperature accounts for most of the variations in the interaction of the occupants with the elements of the built environment (Dick and Thomas, 1951; Brundrett, 1977). These “external factors” are being investigated by an increasing number of researchers (Haldi and Robinson, 2008; Nicol, 2001; Rijal et al., 2007; Andersen et al., 2009). Recently the most common approach to show the relationship between external conditions and behaviour is to make a logistic model, namely the stochastic approach that has been introduced for the prediction of the control of building components by Nicol (2001). The first model set the probability of an action in relation to the outdoor temperature and was subsequently extended by combining the effect of indoor and outdoor temperatures through the use of multiple regression analysis (Rijal et al., 2007).
While these studies focus mainly on the operation of windows in the working environment, research on the AC-unit usage was first conducted in the frame of studies about the use of electricity in residential buildings. Seligman et al. stated in 1977 that personal comfort and health concerns were the best predictors of electricity demand (Seligman, 1977). Up to now, especially in the Japanese research environment, the research on AC-unit usage is set in relation to general behaviour patterns (Asawa et al., 2005) and the lifestyle of the occupant (Habara et al., 2005). An exception is the article by Iwashita and Akasaka (1997), which analysed the AC-unit usage and window-opening behaviour of 8 dwellings in Japan and found large difference in the time and usage pattern between the dwellings.

A questionnaire survey with 554 responses on AC-unit usage during the sleeping hours in Hong Kong revealed that 83% of the occupants use their AC-unit for more than 5 hours during the sleeping period (Lin and Deng, 2006), but this result cannot be applied directly to different weather conditions. Tanimoto and Hagishima (2005) applied the Malkov model to relate AC usage to different time intervals of the day based on the data from eight observed dwellings (Tanimoto and Hagishima, 2005). Nicol and Humphreys (2004) presented a logit line for cooling in mixed mode office buildings. Hart and deDear (2004) calculated the probability of AC-units switched on as a function of mean hourly outdoor temperature.

In the field of social sciences, behaviour is set in relation with factors, such as preference, attitudes, cultural background and so on, which will be called “individual factors”. In addition to external factors, they must be influenced by a variety of cognitions and actions in a very complex manner. Research on the individual factors leading to one action rather than another has been conducted in the field of behavioural psychology, but it is either not focusing on occupant behaviour at all (Ajzen and Fishbein, 2005; Ajzen et al., 2004) or analysing behaviour in waste management (Goven and Langer, 2009; Refsgaard and Magnussen, 2009).

According to a comprehensive review over the existing work on the exergy consumption analysis of acclimatisation systems within the built environment as given by Torío et al. (2009), the common approach is the assumption of a standard behaviour pattern, simply by a fixed set-point room air temperature as done, e.g. by Angelotti and Caputo (2007). This is due to the fact that those papers are mostly focussing on the improvement of the building systems.

1.3 Aim of this Study

The global aim of this work is a computational model of occupant behaviour including the influencing individual and external factors as well as a set of guidelines to design buildings, which allow the occupant to achieve thermal comfort with low consumption. To achieve these goals the work is divided into several subtasks.
In the first step research is done with view on human behaviour aiming at thermally comfortable conditions in order to reveal those variables influencing on the behaviour. This is done by a qualitative analysis and categorization of different occupant behaviour patterns related to their personal background and the outdoor conditions, which will lead to new insights into the decision process and the magnitude of the factors.

In the second step, the influenceability of occupant behaviour is analysed by looking at cultural, long-term, influences and short-term influences such as one-time methods of knowledge transfer from the expert – the scientist – to the layman – the occupant. Therefore, adequate education and information tools are designed, implemented and their effect monitored. Basis of the education and information material will be the “exergy”-concept in its possibly easiest way, because there is a “need to use the thermodynamic concept, exergy, to articulate, what is consumed” (Shukuya and Hammache, 2002; p. 8). In any case, the aim of future strategies should not be the reduction of comfort in favour of less exergy consumption, but the development of measures, which lead to more comfort for more people with less work and resources in order to assure a comfortable life for future generations.

In the last step, the effect of such variables and influences on the exergy consumption for heating and cooling are demonstrated by modified exergy calculations.

Fig. 4. Aim of this research and relationship to state of the art.
This research project is thereby combining methods and findings of multiple scientific fields such as built-environmental research (comfort studies and exergy/energy simulation), social sciences and environmental education as shown in Figure 4.

The global aims cannot be reached within the 3-years period of this PhD-study; the steps to be completed within this dissertation are thus the evaluation and quantification of the influencing factors for single actions such as switching on the AC-unit. The derivation of the complete model, including multiple actions will be part of research to be accomplished in the future.

The advancements compared to the state of the art can be summarized as follows:

- The holistic approach, looking not only at the technical system, the hardware of the building, but also in detail at the occupant, the software, extends the current view and facilitates a better understanding of the whole system.
- Combining physical measurements with surveys, interviews and educational interventions enables the quantification of such interventions in order to evaluate their cost-benefit ratio and improve their design.
- A deep understanding of the factors triggering a certain type of occupant behaviour permits the design of advanced building structures and building management systems.

1.4 Outline of the Study

This dissertation summarizes the work done in the years 2006 to 2010 concerning the occupant's behaviour within the residential built environment. Three articles were published and several papers presented at conferences throughout this time, which are included in this work and listed at the end of this dissertation (p. 215). This results are based on an intensive literature review and two data bases; one consists of the data from three field measurements conducted in an international dormitory building described in Chapter 4.2 and 5.2.2, and the other one of that from an Internet based survey described in Chapter 3.3. Following this introduction (Chapter 1), the main part of this dissertation is separated into four parts. The flow of this dissertation together with the data base used for the analysis presented in each chapter can be seen in Figure 5.

In the first part, consisting of three chapters, the reference level of occupant behaviour is defined. This includes in Chapter 2, an intensive review of literature concerning behaviour and occupant behaviour, which is given as theoretical basis for the further research together with a theoretical occupant behavioural model that includes the description of the reference level. Chapter 3 deals with the purpose of behaviour and further outlines the nature of the
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**PART I. Defining the Reference Level Leading to a Change of Occupant Behaviour**

| A Theoretical Occupant Behavioural Model |                       |                 |
| (Chapter 2)                             |                       |                 |
| Success, Purpose and Order of Behaviour  |                       |                 |
| (Chapter 3)                             |                       |                 |
| Analysis on the Human Body Exergy Consumption Rate as Thermal Reference Level for Occupant Behaviour (Chapter 4) | |  |

**PART II. Analysis and Quantification of the Factors Influencing on the Reference Levels**

| Analysis of AC-unit Usage Patterns |                       |                 |
| (Chapter 5)                       |                       |                 |
| Effect of External and Individual Influences on the Behaviour |                       |                 |
| (Chapter 6)                       |                       |                 |
| Comparison of Imagined and Real Behaviours |                       |                 |
| (Chapter 7)                       |                       |                 |

**PART III. Influenceability of the Occupant Behaviour and its Reference Levels**

| Cross-Cultural Comparison of the Factors Influencing on the Occupants Choice of Sleeping Conditions (Chapter 8) | |  |
| Evaluating the Influence of Various Methods of Knowledge Transfer on Occupant Behaviour (Chapter 9) | |  |

**PART IV. Effect of Variations in the Reference Level on the Exergy Consumption for H&C**

| Effect of Occupant Behaviour on the Exergy Consumption | |  |
| (Chapter 10)                                         | |  |

**Concluding Chapters**

| General Discussion                                    |                       |                 |
| (Chapter 11)                                         |                       |                 |
| Conclusive Summary and Concluding Remarks             |                       |                 |
| (Chapters 12 +13)                                    |                       |                 |

*Fig. 5. Flow of dissertation*
reference level. Chapter 4 describes a trial analysis on the human body exergy consumption rate as reference level.

The second part is dealing with the factors influencing on the reference level in three chapters. A general analysis of behavioural usage patterns is given in Chapter 5 and extended to the analysis of external and individual influences in Chapter 6, which can be regarded as the core of this dissertation. Chapter 7 describes a comparison between the imagined behaviour as stated during a survey and real behaviour as it was observed with the measurements.

The third part analyses the influenceability of the reference levels and consists of two chapters. On the hand, Chapter 8 deals with the effect of long-term experiences on the reference levels by a cross-cultural comparison of the sleeping conditions chosen by the occupants. On the other hand, the effects of short-term experiences such as one-time knowledge transfer methods are evaluated in Chapter 9.

The fourth part consists of Chapter 10, which is showing the effect of variations in the reference level on the exergy consumption for heating and cooling by calculating the exergy consumption within the built environment for various types of occupants.

Two concluding chapters follow this; in Chapter 11, the theoretical occupant behavioural model described in Chapter 2 is compared to the findings obtained by the statistical analyses in the following chapters. Finally a conclusive summary including future research tasks is given in Chapter 12 and some concluding remarks in Chapter 13.
PART I
Defining the Reference Level Leading to a Change of Occupant Behaviour

“Definitions are useful for resolving disputes, but they can easily become intellectual straitjackets, tempting people into the mistaken belief that words have fixed or essential meanings which should be defended against cultural change and scientific progress. Any definition should be regarded as provisional and always open to revision.”

(Evans, 2001; p. 101)
2  A Theoretical Occupant Behavioural Model

2.1  Introduction

This chapter summarizes the literature found concerning behaviour itself. First a definition of behaviour is given, which is followed by the description of types and steps of behaviour as well as the decision process. Based on this literature review, a theoretical model of occupant behaviour, which was developed within the frame of this research, is described. This model serves as basis for later discussions.

2.2  Definition of Occupant Behaviour

Three out of the various definitions of the word behaviour shall be presented here in order to show their variety:

(1) “behaviour: A response to external and internal stimuli” (Science VSC Glossary, 2007);
(2) “behaviour (…) refers to the actions or reactions of an object or organism, usually in relation to the environment. Behaviour can be conscious or unconscious, overt or covert, and voluntary or involuntary” (Wikipedia, 2007);
(3) “behaviour is considered as the collection of decisive processes, by which individuals adjust their state and situation according to variations in their environment” (Danchin et al., 2008).

Transferring these definitions to the built environment, occupant behaviour is more than just the action of opening or closing the window and most of the occupant behaviour must happen without the occupant even knowing about it. Occupant behaviour can be defined as a human being’s unconscious and conscious actions to control the physical parameters of the surrounding built environment based on the comparison of the perceived environment to the sum of past experiences. The physical parameters can be thermal, visual, auditory, and so on. Beside mentioning other physical parameters in Chapter 3, this study is concerned with the occupant behaviour related to the thermal parameters of the built environment. The different types of occupant behaviour resulting out of this definition are described and categorized in the following.
2.3 Types of Occupant Behaviour

In general, behavioural actions cannot be regarded singular, because they continuously interact with each other and the borders cannot be distinguished in every case. However, there are several ways to categorize behaviour. One of the simplest categorizations would be the distinction between internal (not visible outside the body) and external behaviour (observable) (Damasio, 2005; p.89). From the viewpoint of the field of ethology, which was founded by Konrad Lorenz and Niko Tinbergen, there are four levels to describe different types of behaviour, which are also called “Tinbergen's four questions”. (1) Immediate causation describes the direct response of an organism to its internal state; (2) Ontogeny describes the behaviour of an organism in relation to the history/development of that organism; (3) Adaptive value describes the current utility in the organisms natural surrounding, meaning the consequences of the behaviour for the organism and its environment; and (4) Evolution of behaviour describes the part of the behaviour, which can be described by looking at the evolutionary history of that organism (Cézilly, 2008; p. 17f).

Throughout the literature concerned with occupant behaviour within the built environment, different types of behaviour are described and researched. Looking at the total of conscious and unconscious reactions of the human organism to the external thermal stimuli four basic types of occupant behaviour are defined according to the environment and dimension of space, they occur. Starting from the smallest to the largest scale, one can define, behaviour as related to the “thermoregulation” or “passive body adaptation”, the “active body adaptation”, the “adjustment of the environment”, and the “change of place”.

2.3.1 Thermoregulation and Passive Body Adaptation

As a human species we are born with a good working heating and cooling system – the thermoregulation system. Thermoregulation or passive body adaptation describe the processes occurring within the human body in order to keep the core temperature stable within small limits. These processes are e.g. for the case of cooling actions performed in hot conditions during summer: (1) increasing the heart rate, (2) start of sweating mechanism, and (3) increase of blood flow to the skin surface. The basic control of the thermoregulation system is done by the hypothalamus, which adjusts the body functions by discharging hormones into the bloodstream. All these actions are done unconsciously and cannot be actively influenced by thought alone.

The thermoregulation process is still believed to be similar in human beings around the world, only the amount of sweat glands of people grown up in hot & humid climates was
known to be higher compared to those growing up in a cold climate (Hori, 1995). Recent studies from Japan show a dramatic change in the regulatory system of school children partly due to the extensive perception of air-conditioned spaces within the first three years of their life (Masaki, 2002).

### 2.3.2 Active Body Adaptation

Active body adaptation includes the change of body posture, and the amount of clothes worn. Takahashi et al. (2000) found a difference in the active body adaptation between subjects who are sitting in a natural ventilated room and an air-conditioned room. According to their results, the former are more active in their behavioural patterns, concerning actions, such as “waving hands like a fan” or “making space under clothes with hands”. In contrast, the air-conditioned space made the subjects more passive.

The changes in clothing due to day-on-day changes in temperatures happen quite slowly and need up to one week to be completed (Humphreys, 1979; Nicol and Raja, 1996; Morgan and deDear, 2003). In naturally ventilated buildings, the outdoor conditions seem to have an influence on the clothing level, while the indoor conditions seem to have an influence on the change of clothing during the day. Gender seems to have no significant influence on the clothing level (deCarli et al., 2007).

### 2.3.3 Adjustment of Environment

As adjustment of environment can be regarded all actions related to the use of windows, heating- and cooling devices as well as other elements of the room. The analysis of this type of behaviour is the main objective of this research and will be dealt with in the following chapters. The application of passive strategies such as insulation material can reduce the overheated and/or overcooled periods of a room. When the temperature oscillates within the remaining variations, the thermoregulation system of the human body as described above gets fine-tuned, so that such strategies lead to a healthy system. In contrast, in stable conditions provided by air-conditioned spaces this fine-tuning may be lost, leading to unhealthy states of the human body. Such a relationship between stable conditions and health problems was found in a study with Japanese school children in a medium sized Japanese city. Out of those children grown up in air-conditioned spaces, two to three children die each year due to overheating when playing outside in summer (Masaki, 2004). Therefore, the interaction between built environment, human body thermoregulation system and health issues is an important issue to consider during the design of any built environmental system.
2.3.4 Change of Place

In case all other types of behaviour are not available or favoured, the change of place is a further option and consists of those actions related to the active movement within the room, the building or between building and outside. One study observing the choice between sitting outside or inside a bar in Kassel/Germany comes to the conclusion that people's behaviour in the open space is very much dependent on the thermal outdoor conditions. Additionally, the expectation of weather and the activity planned have an influence on this decision (Katzschner, 2006).

2.4 Steps of Behaviour – from Perception to Action

Several steps precede every behavioural action. First, internal or external sensations are perceived, which is followed by a feeling or emotion that something is “not normal”. Depending on the type and quantity of the sensation, a decision whether or not to perform any action will be formed based on multiple variables. The main components and steps of this procedure will be described in the following.

2.4.1 The Human Brain

According to findings in the field of brain sciences, “there is behaviour without brain, but in all complex organisms, spontaneous and reactive actions are caused by commands from a brain” (Damasio, 2005; p.89). Furthermore, “some organisms have behaviour and cognition. Some have intelligent action, but no mind. No organism seems to have mind but no action” (Damasio, 2005; p. 90). This means that the behaviour of such a complex organism as the human occupant must be controlled by the mind within a body. Therefore, even though this research is not conducted within the frame of neural studies and no further research was done dealing directly with the functioning of our brain, let us have a brief look at the human brain and the points we should remember when talking about human behaviour. This will permit the comparison of the following statements with the findings concerned about the observed occupant behaviour in the built environment later. It will then be possible to see, if the truly complicated processes within our human brain can support those findings.

The human brain did not develop at once, but is rather the result of more than 400 million years of trial and error (Wilson, 1998). Parts of the human brain can therefore be found in other animals as well, e.g. the parts controlling breathing and movement are shared with fishes, thermoregulation systems are shared with mice and even more parts are shared with apes. Only the prefrontal cortex is unique to human beings.
Looking at the evolution of the brain, the limbic system is older than the Cortex and descends possibly from other mammals. However, it is connected with the cortex and permanently sending information. Even older than the limbic system is the brain stem, which developed some 500 million years ago with the reptilian brain. The brain stem is formed by nerves coming from the body and transports information from the body to the brain and back (Carter, 1998). It can further be seen that newer additions to the brain are taking over the control from previous additions (Cziko, 1995). However, “the mechanisms for behaviour beyond drives and instincts use both the upstairs (new part of the brain, neocortex) and the downstairs (old part of the brain). Rationality results from their concerted activity” (Damasio, 2005; p. 128).

The brain is connected to the body by nerves (signals) and the blood stream (chemical substances, neurotransmitters). The brain sectors where signals from the body arrive continuously are called “input” sectors. They are anatomically separate and do not communicate with one another directly. On the other hand, motor and chemical signals arise from the “output” sectors, such as the brain stem, the hypothalamic nuclei and the motor cortices (Damasio, 2005).

The basic elements for creating brain activity are the neurons. They have several dendrites (branches leading information towards the neuron), but only one axon (branch leading information away from the brain). The neurons are connected with each other by synapses, which is the name for the connection between the axon of one neuron with a dendrite of another neuron (Carter, 1998). In the average brain each of the 10 billion neurons has around 1000 synapses forming neuron circuits, which are firing within tens of milliseconds. But not every synapsis is equally strong. Its strength decides whether and how easily impulses continue to travel to the next neuron (Damasio, 2005). Furthermore, it is important to know that a neuron only “fires”, i.e. sending an impulse through its axon, when a certain critical level (the threshold) is reached. This is called a “triggered, explosive, all-or-nothing event” (Nicholls et al., 2001; p.14). Looking at the way neurons are connected with each other, “the firing of a single neuron is not enough to create the twitch of an eyelid in sleep (…), millions of neurons must fire in unison to produce the most trifling thought” (Carter, 1998; p. 19). Additionally, it shall be noted that, “(1) whatever neurons do depends on the nearby assembly of neurons they belong to; (2) whatever systems do depends on how assemblies influence other assemblies in an architecture of interconnected assemblies; and (3) whatever each assembly contributes to the function of the system to which it belongs depends on its place in that system” (Damasio, 2005; p. 30).

Regarding the behaviour related to thermoregulation and thermal comfort, the important parts of the limbic system are: “(1) the thalamus, which is a kind of relay station, which distributes the incoming information to the corresponding part of the brain for further
processing, (2) the hypothalamus and the pituitary gland, which permanently adapt the body to the surrounding conditions, (3) the hippocampus, which is responsible for the storing of long term memory after the age of 3 years, and (4) the amygdala, where fear is registered and generated, and which is also responsible to store memories before the age of 3 years” (Carter, 1998; p. 15ff). “The brain structures involved in basic biological regulation (hypothalamus and the limbic system) are also part of the behaviour regulation and other cognitive processes, such as learning, recall and emotion” (Damasio, 2005; p. 122f).

2.4.2 Perception, Attention and Emotion

Every second our body receives millions of sensations from the inside and outside and all these sensations get to the brain as electric pulses (Carter, 1998). These sensations, e.g. the temperature of a surface we are touching or the skin temperature in our fingertips can be measured and quantified. However, still few is known about what an individual really perceives, which is commonly described with the fact that two people may agree that a certain colour is green, but neither of them can know how the green looks like for the other person.

This is called perception and means that every individual differently perceives the same stimulus; this is also valid for the thermal perception. Takahashi et al. (2000) found that there is a clear difference in the thermal perception of an indoor space due to a temperature difference in the walkway towards this space. They conclude that it is very important to consider both outdoor and indoor space together when designing the thermal environment. Also, the physiological reaction to a given heat-stimuli changes, if human beings are staying for continuous days in a warm environment (Parsons, 2003); this is called adaptation. Adapted persons are able to tolerate a hot environment better and are less affected of heat-caused problems. At the same time the stress for metabolism and cardiovascular system gets less (Armstrong, 1998).

Most of the sensations are sub-conscious without us knowing about them. The ability to focus on a particular thought or activity is called “attention” (Evans, 2001; p. 78) and most of the time visual processes make us unaware of the other sensations deriving from our body. However, “if pain, discomfort or emotion set in, attention can be focused instantly on body representations and the body feeling moves out of the background into the centre stage.” (Damasio, 2005; p. 233).

“The allocation and maintenance of attention and working memory are first motivated by preference inherent in the organism and then by preferences and goals acquired on the basis of the inherent ones” (Damasio, 2005; p. 198). This means that the attention towards an object depends very much on the importance of this object for our goals, which can be easily proven by
observing our own awareness of different commercials when walking through a street. In case, we just decided to do an exchange year abroad, we are much more sensible towards commercials for language schools and automatically will direct more attention towards those commercials.

The question how a sensation gets conscious is still leading to heated discussions and is not yet answered. One element influencing on our attention are emotions, which “distract us from one thought only in order to make us pay attention to another, maybe in that moment more important one for survival” (Evans, 2001; p. 77). Additionally, Carter states that there is no decision without emotions (Carter, 1998). Therefore, let us have a brief look at emotions.

First of all, one has to distinguish between basic or primary emotions and higher cognitive emotions. Basic emotions are supposed to be universal and innate, but scientists still argue which of the emotions we know are basic emotions. Out of the emotions included into this discussion, joy, distress, anger, fear, surprise, and disgust are considered as basic emotions by most of the scientists (Evans, 2001; p. 5).

Emotions arise in the limbic system; together with appetite and other needs and urges, which secure our lives (Carter, 1998; p. 15ff). “Higher cognitive emotions are more placed in the neo-cortex and therefore capable of being influenced by conscious thoughts” (Evans, 2001; p. 20). According to Evans (2001), emotions are double useful. First, our internal feelings and bodily changes of emotions result in continuing or avoiding certain actions. Second, our external expressions of emotions are giving useful information to others and thereby enable them to learn from our experiences.

Damasio (2005) distinguishes between emotion and the feeling of the emotion, whereby former always precedes the latter. According to his definition, “a feeling of an emotion is the experience of changes in comparison to the mental images prevailing before the emotion started” (Damasio, 2005; p. 145).

2.4.3 Decision Formation

Aristotle is cited with the phrase: “The origin of action is choice, and that of choice is desire and reasoning” and (Danchin et al., 2008a; p. 98) states that “the study of behaviour can thus be viewed as the study of decision-making”.

Studies of any kind of choice include two different areas, which are (1) studies about information gathering behaviour; and (2) studies about the decision rules, an organism is following with the gathered information (Boulinier et al., 2008; p. 302). In the frame of this dissertation, the interest was more in the second area and the question, what influences on the decision to interact with the built environment. However, decisions are based on information, which have to be gathered and processed before (Danchin et al., 2008a; p.98).
When we want to talk about an organism choosing between alternatives, this implies that this organism is using some information about the alternatives; with the minimum information being the one that there exists a certain choice (Boulinier et al., 2008; p. 290). At the same time, individuals may make different use of the same information due to different gene combinations (Boulinier et al., 2008; p. 299) or preferences. In other words, “deciding implies that the decider has knowledge a) about the situation, b) about different options (responses) and c) about consequences of each of those options (outcomes)” (Damasio, 2005; p.166). This fact may seem to be trivial, but even though one might think that occupants know that their toilet is equipped with a flush stop to save water, a study among owners of sustainable houses in The Netherlands, which would be expected to know such things, revealed that “a reasonable share of residents did not know that their toilet had a flush stop” (Derijcke and Uitzinger, 2006; p. 119).

The basic model of decision-making can be explained with the following example when we encounter a feeling of discomfort. First, the brain detects the threat of overheating or cooling, generates a few response options such as opening/closing a window or switching on a heating/cooling device, selects one or none of them, and acts on it, which (hopefully) reduces or eliminates the detected risk.

“When faced with a decision, a huge diversity of actions is generated” (Damasio, 2005; p. 196), which is similar to what Darwin is saying about the evolution. In evolution only few of the developed alternatives survive. According to (Damasio, 2005; p. 199) the process to decide which of the diverse actions is performed happens as follows: (1) if order is to be created among different options, they must be ranked; (2) if they are to be ranked, certain criteria are needed; (3) those criteria are provided by somatic markers, which express the cumulative preferences we have both received through our genes and acquired through lifetime. This means that in case we have many very good experiences with air-conditioned rooms, we most probably rank the option of switching on the air-conditioning unit higher than in case we have several experiences of catching a flew after staying in air-conditioned rooms.

According to the somatic-marker hypothesis by Damasio (Damasio, 2005; p. 173f), somatic markers (from soma: Greek for body) lead to an unpleasant gut feeling, when thinking about a non-preferable option. This helps deciding faster and sorting out those actions leading to future losses. In conclusion, the somatic markers can be called a negative feedback, which rather lets you not choose a bad option than shows you, which is the right option. Additionally, there are positive somatic markers, e.g. you can only suffer now (by going jogging) if your body tells you that you will be rewarded later (by a good feeling, better health) (Damasio, 2005; p. 175).

Another way to describe the process leading to an action is Lorenz’s ‘psychohydraulic’ model, which describes the relationship between internal motivation, external stimulus and
behaviour in a more descriptive way. He suggests that the strength of internal motivation is increasing within an organism as long as a certain response behaviour is not expressed. This is represented by water flowing constantly into a reservoir. At the same time, an external stimulus, represented by a heavy or a light weight, is reacting on the organism. Between reservoir and weight is a valve, which is kept closed by the pressure of a spring. This state, representing that no behaviour is performed, is kept like this as long as either (1) the pressure of the reservoir is strong enough to open the valve (representing a high motivation); or (2) the stimulus is heavy (strong) enough to open the valve; or (3) the combination of reservoir and stimulus opens the valve. The intensity of the resulting behaviour is then determined by the amount of water flowing out of the reservoir (Lorenz, 1950).

2.5 A Proposed Model of the Occupant's Decision Cycle

The development of the theoretical occupant behaviour model was based on the theoretical discourse described above together with an additional literature review starting with the books of Czik (1995) and Damasio (2000), in which the former combines ideas emerging from biology, cybernetics and psychology and the latter explains recent findings in the field of neural science. In order to make it easier to follow the description of the model, an overview is presented first, followed by a more detailed description of its components.

Figure 6 shows the conceived model. This is a kind of a negative feedback system that can be found as well in the control of AC-units. The upper half represents the inside of the body and the lower the environment. Three sub-systems were assumed: “sensory sub-system” to observe the surrounding and internal conditions leading to an input value; the “control sub-system” to compare the input value from the sensory system to the “reference level” given from the memory in the brain and to form a decision to adjust the internal or external settings; and the “adjustment sub-system”, which drives the actual action according to the internal or external settings given by the control sub-system in order to keep the conditions within the required limits. The arrangement of the sub-systems with arrows should not be interpreted as if one sub-system is waiting for the foregoing to finish, but in a way that all sub-systems are performing their work simultaneously (McClelland, 1994).

Being very simple as a model compared to the multiple facets of human behaviour, it should be noted that in human behaviour there is not only one sensor-control-action cycle happening at any one time, but numerous of those cycles for various controlled parameters of internal and external environment working on different levels at the same time and interacting with each other (Powers, 1973) or as stated by Damasio, “behaviour of an organism is the result of several biological systems performing concurrently (...), like an
orchestra” (Damasio, 2000; page 87). This will be shown in more detail in the next chapter. A second important remark on this kind of control system is that it “does not control what it does; it controls what it senses. The word control is used here in its precise technical sense of maintaining some variable at or near specified fixed or changing values regardless of the disturbances that would otherwise influence it to vary” (Cziko, 1995; page 111). The same theory exists about vision, in that respect that vision is also only an action to control the environment (Noë, 2002).

This approach is called “perceptual control theory” and means, in the case of occupant behaviour that the action is performed in order to keep the sensed values within the limits of the reference level. The action is not a result of the external or internal input. As it will be discussed further down, this has some implications for the model components and the interpretation of the results.

As described above, looking at conscious and subconscious behaviours of the human organism with respect to the indoor thermal environment, four basic types were recognized and were grouped according to the “thermoregulation” or “passive body adaptation”, the “active body adaptation”, the “adjustment of the indoor environment”, and the “change of place”. Which of those actions are performed individually or simultaneously by the

![Fig. 6. A theoretical model of human behaviour.](image)
adjustment sub-system will be determined by the output of the control sub-system. The actions chosen will result in a change of the environmental conditions and hence the input value is renewed. Humphreys and Nicol stated a fifth type of behaviour called "adaptation (...) as a set of learning processes" (Humphreys and Nicol, 1998). I agree that adaptation plays an important role in human sensation and behaviour. Nevertheless in the case of the proposed model, adaptation is not a fifth type of behaviour, but rather a name given for the continuous updating of the reference level taking place in the brain.

The sensory sub-system tirelessly sends the input values to the control sub-system. As stated in the introduction, recent papers about occupant behaviour in the built environment discuss the best predictor of occupant behaviour (see Haldi and Robinson, 2008; Rijal et al., 2007) to be the outdoor or indoor air temperature. From the viewpoint of perceptual control theory (McClelland, 1994), the best predictor would be the controlled value. However, occupants cannot control the outdoor temperature, which depends on the weather conditions. Also the indoor temperature alone cannot be the value to be controlled by the full range of occupant’s behaviour, because e.g. comfort depends also on mean radiant temperature, air speed, relative humidity, clothing insulation and metabolic rate (CEN, 2007; Fanger, 1970). This means that the value to be controlled by the occupant’s behaviour and therefore used for the prediction should be some value reflecting all of the surrounding and internal conditions.

The control sub-system and the reference level are the most complex components of the model. In the case of an AC-unit, they are located within the memory and CPU and in the case of human occupants, they are considered to be within the brain. Basically speaking, the input value received from the sensory sub-system is compared to the reference level in the memory of the brain, followed by a command to the adjustment sub-system to perform as before or to change some settings of the internal or external conditions (McClelland, 1994). Though the number of factors influencing this process is relatively small in the case of an AC-unit and the capacity of the CPU can thus be relatively small as well, it is very much larger for the processes within the human brain. Being aware that even within the disciplines of neural science or behavioural psychology, there is so far no final conclusion about these processes, I do not want to claim that I know the answer for the occupant behaviour. Nevertheless two remarks based on the findings of these areas should be raised and compared to the findings of the studies with respect to the built environment. This should be interesting and challenging for the better understanding of the occupants’ behaviour.

One remark given by Cziko is that the reference level to which the input values are compared within the human brain is not the same for all human beings but a combination of initial values given by the genes and adaptation through life experience (Cziko, 1995). This can be easily confirmed for the case of thermal comfort studies looking at variations between
individuals (Fanger, 1970). Furthermore the reference level, called by Cziko (2000) and Damasio (2000) a part of the “milieu interior”, is not fixed at a certain point in life but is continuously adapting to the prevailing conditions. This again can be confirmed by the studies showing differences in the thermal comfort votes of the same individual in different seasons (Umemiya, 2001) or even different times of the day (Zeiler et al., 2008). Both aspects will be further discussed along with the findings of the present research in the next chapters.

The other remark concerns emotions and feelings and was given by Damasio. He states that most of the processes leading to the occupant’s behaviour are happening subconsciously and explicitly distinguishes between subconscious feeling and the conscious knowledge of this feeling (Damasio, 2000). An example is the difference between sweating and realizing one is sweating. Furthermore, Bechara et al. (1997) claim that non-conscious processes influence the behaviour before conscious knowledge. These statements can neither be proven nor rejected in this study, but they should be kept in mind to be investigated in the future in order to improve the proposed theoretical model.

2.6 Conclusions

A comprehensive literature review was described concerning the theoretical background of behaviour. The knowledge acquired through this process was used to develop a theoretical model of occupant behaviour, which contained a reference level to which all input values deriving from the body’s sensual system are compared. Therefore, this reference level is of special interest and will be dealt with in the following chapters.
3 Success, Purpose and Order of Behaviour – Requirements for a Behavioural Model

3.1 Introduction

Danchin et al. (2008b), who are looking at behaviour from an evolutionary perspective, state that the purpose of behaviour is – beside the survival of the individual – the survival and replication of the genes carried by that individual (Danchin et al., 2008b; p. 35). In case of occupant behaviour, there is in general no immediate danger of passing away due to a not performed behaviour. However, conditions with very high or very low temperature prevailing for a longer period can lead to a damage of the human organism. Some examples of injuries caused by heat are (1) heat oedema, (2) heat syncope, (3) heat cramps, and (4) heat stroke (Lee-Chiong and Stitt, 1995). The last one is caused by the failure of the regulation system in the hypothalamus due to which the sweating stops and the core temperature rises dramatically, so that one has no chance to reverse this process by oneself. Even though not all of the named injuries are as dramatic as the last one and some of them have no permanent effect, they should be avoided as mentioned in Chapter 2.3.1 and 2.3.3. Additionally, conditions with the lack of oxygen can lead to performance losses or even damages, which together with the thermal aspect leads to two basic purposes of occupant behaviour: (1) staying in conditions thermally favourable for the human body, and (2) staying in conditions with sufficient fresh air. These can be summarized in thermal comfortable conditions and conditions with a high indoor air quality (IAQ).

Past studies got to the conclusion that the outdoor air temperature accounts for most of the variations in the interaction of the occupants with the elements of the built environment (Dick and Thomas, 1951; Brundrett, 1977), and consequently, as already mentioned in the introduction, the behaviour is set in relation to the outdoor and/or indoor air temperature by recent studies (e.g., Haldi and Robinson, 2008; Nicol, 2001; Rijal et al. 2007). However, little is known about how often the behaviour was performed for one of the two explained purposes and how often other reasons were decisive.

This chapter presents the result of asking occupants about the success of their past behaviour concerning five factors, namely thermal comfort, noise, illuminance, air quality and humidity, their purpose of behaviour and the order of their behaviours when facing thermally not comfortable conditions. This knowledge of the main purposes as well as the order of behaviours will lead to a better understanding of occupant behaviour as well as insights into the type and nature of the reference level introduced in the previous chapter.
3.2 Thermal Comfort and IAQ

3.2.1 Thermal Comfort

The ASHRAE Standard 55 defines human thermal comfort as the state of mind that expresses satisfaction with the surrounding environment (ASHRAE, 1992). Even though there exist several models of thermal comfort derived from different scientists all over the world (see e.g., Fanger, 1970; Gagge et al., 1972; Humphreys and Nicol, 1998; Fiala et al., 1999; Shukuya, 2009), all of them concern at least six basic parameters stated as being important to determine the comfort level:

a) four indoor parameters
   • the room air temperature
   • the relative humidity of the room air
   • the mean surface temperature of the surrounding walls, windows, furniture, etc.
   • the air velocity of the air surrounding the human being

b) two parameters related to the human being
   • the rate of metabolic heat production
   • the level of clothing insulation

Additionally, Koppe (2005) states that the degree of acclimatisation of an individual should also be considered when judging the thermal environment.

To feel comfortable, there must be three basic conditions satisfied: (1) the fulfilment of the heat balance according to the 1st Law of Thermodynamics, (2) the skin temperature at every point above a certain value, and (3) a sweat secretion rate below a certain value.

The SCATS survey conducted in five European Countries showed that the running mean of the daily mean outdoor temperatures has the best correlation to indoor comfort and that this relation can be expressed for European offices by the linear relationship $T_c = 0.33T_m + 18.8$, where $T_c$ is the optimal indoor operative temperature for comfort and $T_m$ is the running mean of the daily mean outdoor temperature (McCartney and Nicol, 2002). At the same time, it is known that comfort depends on context, e.g. people in AC-buildings expect uniformity, while people in natural ventilated buildings are used to seasonal changes (Brager and deDeAr, 2001).

The adaptive approach to thermal comfort (Humphreys and Nicol, 1998) is based on the findings that in daily life people tend to adjust their thermal environment in order to feel comfortable by changes in clothing, activity, posture and settings of their thermal
environment, like windows and temperature controls (Nicol and Pagliano, 2007). This process is supported by the possibility to control the thermal environment, e.g. by fans or operable windows in summertime or by temperature control in winter (Baker and Standeven, 1996).

Saito and Shukuya (2001) investigated the relationship between the human body exergy consumption rate and thermal comfort. They found out that the thermal comfort, the thermally neutral condition, is provided with the lowest exergy consumption rate as far as the conditions from slightly cool to slightly warm are concerned. Further studies related to the human body exergy consumption rate suggest that the use of radiant warm exergy is more effective than the use of convective warm exergy for a heating purpose to realize both thermal comfort and as low exergy consumption within the human-body as possible (Isawa et al., 2002).

3.2.2 Indoor Air Quality (IAQ)

For reason that the main part of this dissertation is not concerned about IAQ, only a few words shall be given here to explain the concept and its importance.

IAQ refers to the air quality within buildings, which concerns not only the CO₂ concentration of the room air, but also other contaminations, e.g. from micro-organisms such as mould. In doing so, it is related to the health of the occupants. Not treated sufficiently a bad IAQ due to an inappropriate ventilation system or ventilation behaviour can become a more severe health risk than outdoor air. The best-known risk is called “sick-building syndrome”, causing economical and personal damage due to illness of workers (Bas et al., 2005).

3.3 Methodology of Data Acquisition

The analysis for this chapter was based on data deriving from an Internet-based investigation, which was conducted during the winter period of 2008/09 and summer period 2009. While the surveys and information related to summer could be conducted only during the northern-hemisphere summer-period, those concerning winter were conducted both in the northern-hemisphere winter 2008/09 and the southern-hemisphere winter 2009. The survey was announced by electronic mail via friends and colleagues with the request to forward it to their colleagues and friends; and also by a few organizations, who kindly sent the announcement to their mailing lists members most of whom are Japanese or Germans.

Summer and winter investigations of the Internet-based survey consisted of three steps each. First, interested persons filled out an introductory survey, which questions were similar to the one used during the first conducted investigation in the dormitory building described in Chapter 4.2, but the style was transferred to the Internet. Figure 7 shows a screenshot of
one of the question pages. The questions concerned the actual state of the heating devices and
the windows; the frequency of interaction with the heating devices, the windows, and
curtains during the last 14 days before the questionnaire; preferences and attitudes towards
or against certain interactions; and detailed questions about the current living conditions as
well as those prevailing during the childhood of the participants. The medium of the Internet
allowed the survey design to be dynamically, in such a way that following questions were
based on answers given to previous questions, e.g. the question “Please choose the current
state of your window.” was followed either by “When did you open the window?” or “When
did you close the window?” according to the state of window chosen before. This allowed the
adjustment of questions to be suitable to the conditions present at the participants place.

Fig. 7. Screenshot of one question page of the Internet-based surveys’ English version.
Second, those persons, who answered all questions and entered their e-mail address, received an access code for an information area, which is out of scope here and will be described in Chapter 9.3.2.

Third, four to eight weeks after the initial survey, the participants were asked to fill out a second survey, dealing with the information gathered, the strategies tried and the current behaviour. All these materials were presented in four languages: English, German, Japanese and Spanish.

3.4 Results

Due to the fact that the total number of e-mails sent to announce the survey is unknown, it is not possible to state the response rate here. Out of the 854 persons in winter and 435 in summer who started participating in the survey, 686 persons (80%) and 390 (90%) completed it, respectively. The answers of the participants were written into the database in between the completion process, so that answers of incomplete questionnaires could also be partly used for this analysis.

![Fig. 8. Age distribution, education level and gender of the participant in the Internet-based investigation.](image-url)
The basic statistics of the participants are shown in Figure 8. It can be seen that there is a majority (71%) in the age from 20 to 39 years old and most of them (70%) have a university degree, which is probably due to the way of announcement and media of the survey. The genders are well distributed.

Table 1 shows the number of observations for the heating/cooling devices as well as the windows during summer and winter surveys, which shows that only few persons have no heating device, but more than half do not possess any cooling device. As one would expect, most windows are closed during wintertime, while nearly half of the windows are opened in summer.

<table>
<thead>
<tr>
<th>Table 1. Number of observations for each state.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Heating/Cooling device</td>
</tr>
<tr>
<td>Running</td>
</tr>
<tr>
<td>Stopped</td>
</tr>
<tr>
<td>No device</td>
</tr>
<tr>
<td>No idea</td>
</tr>
<tr>
<td>Window</td>
</tr>
<tr>
<td>Opened</td>
</tr>
<tr>
<td>Closed</td>
</tr>
<tr>
<td>No window</td>
</tr>
</tbody>
</table>

3.4.1 Success of Behaviour

Figure 9 shows the comfort votes given by the participants divided by survey period and whether those persons were at home or at work in the moment of answering the questionnaire. It can be said that this shows the success of the adjustments of the built environment previously done. The votes were given by clicking at a place on the continuous bar whose ends show either of the extreme statements such as “too bright” and “too dark” for all cases, except the 7-point scale for thermal comfort.
Fig. 9. Comfort votes for thermal environment, IAQ, noise, illuminance and humidity (W1 and S1 are the introductory surveys in winter and summer; W2 and S2 are the follow up surveys in winter and summer; Numbers above the bars show the total number of participants answering the respective questions).
Fig. 10. Past and future reasons for interacting with the built environment. (The numbers in brackets give the total number of participants answering the question in winter and summer, respectively. Two bars for the respective categories are shown: one for winter (past/future) and the other for summer (past/future).)
The three middle votes of the 7-point scale for thermal comfort are regarded as representing a state of thermal comfort (deDear and Brager, 2002). Considering this, 10% to 20% of persons stated a feeling of discomfort in winter, while only 1% to 5% stated the same in summer. Except a small number of persons feeling too warm at work in winter, many claim discomfort due to coolness in both seasons, which suggests that a wrong utilization or setting of cooling devices is highly probable in summer.

With respect to the IAQ, 20% to 75% of persons stated to have a bad IAQ, with the highest value of dissatisfied in winter at work and the lowest value in summer at home. In general it can be seen that a higher percentage of participants managed to achieve satisfactory IAQ-conditions at home compared to work and in summer compared to winter. The former can be explained with the lower density of persons and equipment and the latter with the higher percentage of windows open in summer compared to winter.

The illuminance level is judged by 50% to 60% as neutral, i.e. in this case as comfortable, while there is a small tendency that it is a bit too bright at work and too dark at home.

The noise level is perceived by 40% to 60% as neutral, whereby this percentage is a bit higher at home compared to work.

Lastly, the humidity level is found to be neutral by less than 40% of the persons. In winter and thereby especially at work is judged as dry or too dry by some 50% of the persons, which is due to the dried air by the heating devices. In summer, 30% to 40% feel it to be humid at home while the same percentage of persons feels it dry at work, which can be explained with the higher percentage of cooling devices at work compared to home.

3.4.2 Purpose of Behaviour

The purpose of behaviour was analysed in two ways. On the one hand, the reasons for an interaction were analysed in order to see what kind of external influences such as temperature, humidity, and noise are triggering certain behaviours. On the other hand, the expectation was analysed in order to see the individual judgement how a change in the prevailing condition would affect external factors such as the energy used within the built environment as well as internal factors such as health.

Figure 10 shows the distributions of the reasons stated for the last interaction with the window, heating or cooling device as well as the reasons stated to interact with the same elements in the future. The former are concerning the already performed action, while the latter are concerning the possible future interactions. Besides being combined into one graph, the nature and style of the corresponding questions are different and needs to be kept in mind for the interpretation.
Furthermore, the former were asked as closed-ended questions giving the options “It was warm”, “It was cold”, “It was humid”, “I needed fresh air”/”It was noisy outside”, “I wanted more light”, “I don't remember” and the possibility to answer “other” and specify the reason by a free text input. “I needed fresh air”/”It was noisy outside”, and “I wanted more light” was shown only for the questions concerning the operation of the window. The latter, on the other hand, were asked as open-ended questions. According to Woods (2008), the difference is that closed-ended questions can create a feeling of being prompted to answer in a positive manner.

Fig. 11. Evaluation of a possible change in the state of window or heating/cooling device with respect to overall goodness, thermal comfort, health, energy use and easiness.
way, i.e. there is a high probability that some of the participants stated more reasons than there were in reality. On the other hand, participants will not think of all possible reasons in an open-ended question. The combination of both questions therefore balances the advantages and disadvantages of using one method alone, even though the magnitude of the options presented in the closed-ended questions might be overestimated, while those of the open-ended questions a bit underestimated.

Keeping these limitations in mind, opening the window is in both seasons mainly related to the wish for fresh air, followed by ventilation in winter and temperature related factors in summer. While fresh air is clearly a matter of IAQ, ventilation could mean either a matter of IAQ or a temperature related reason. A more detailed analysis was done for this case in order to analyse whether there are possible differences between the two major groups of this survey consisting of 223 and 74 Germans as well as 105 and 46 Japanese citizens participating in winter and summer, respectively. In winter, the percentage of those stating temperature as well as the combination of those stating fresh air or ventilation did not show a significant difference between these two groups. However, in summer, the percentage of Germans stating fresh air as reason to open the window is significantly higher than the percentage of Japanese stating the same reason.

Closing the window in winter is mainly related to uncomfortable thermal conditions. In summer, temperature regulation is the main reason besides being responsible for less than 50% of the interactions. Apart from the reason that the window is closed because the person is leaving the room, noisy, rainy or windy conditions outside the room account together for the same percentage as temperature does.

Switching on the heating or cooling device is to a great extent related to temperature. It is surprising that humidity accounted for less than 20% in summertime although being considered by many as important factor for such behaviour. In fact, of the 84 persons living in Japan and having the AC-unit switched on, only one person stated humidity as the reason for switching it on and of the 92 persons who are living in Japan and had the AC-unit switched off, seven stated humidity as reason for switching on the AC-unit in the future.

As the purpose for stopping the heating or cooling device several factors have equal proportions. These are temperature, leaving the room and going to bed for winter and temperature, leaving the room and the fact that the cooling device is not used at all in summer.

In general it can be said that the control of the prevailing temperature is the main purpose for closing the window and starting the heating and cooling device, while the control of IAQ is the main purpose for opening a window.

Figure 11 shows the distribution of persons evaluating the possibility that a change of the window state or heating/cooling device state would lead to a certain outcome as positive,
Fig. 12. Distribution of votes given for the actions to be performed first, second, and third in the case of thermal discomfort.

Fig. 13. Distribution of votes given for the actions to be performed first, second, and third in winter the case of thermal discomfort for separate groups.
neutral or negative. It can be seen that a majority of persons evaluates a change of the current conditions in nearly all cases as bad and leading to less comfortable conditions. Closing the window in summer has the highest percentage of votes with respect to a negative outcome. Additionally, in all cases around 80% or more of the participants judged that it would be easy to change the state.

However, looking at the question concerning healthy or unhealthy conditions a majority of persons stated that an open window would be healthier than a closed one. In the case of the heating/cooling device, it is interesting to see that one half believes that a running device is healthier, while the other half believes the opposite. This shows that people are able to distinguish between thermal comfort and health aspects and that they evaluate the thermal comfort to be more important in winter than the health aspect.

The question why people do not change the condition in the case they believe a change would lead to better conditions needs to be investigated further in the future.

3.4.3 Order of Behaviour

In this section, the analysis of the question related to the order of the first three actions the participants would perform to combat thermal discomfort are discussed. It should be kept in mind that this order is hypothetical and not based on any observation. That is, there may be some differences between imagination and reality as they are also shown in Chapter 7 below. However, for the first overview it must be interesting to see if any tendencies can be found in the type of actions believed to be performed first.

The question about the order of the performed behaviour in order to combat thermal discomfort was asked a little bit differently in the summer and in the winter survey. In the summer survey, the starting conditions were fixed to be window closed, cooling device off and summer clothes in the description of the question, but in the winter survey, no such starting conditions were described. The distribution of answers given in summer and winter are shown in Figure 12.

The ranking of the first action to be done in winter clearly shows a structure from the easiest to perform to the most difficult to perform, i.e. most people first put on more clothes, the second biggest group would first close the window and a third group would switch on the heating device first. In summer, a half of the persons stated to open the window first and another 37% stated to take off some clothes.

Figure 13 shows the same analysis as Figure 12a), but for four different cases. In Figure 13a) the distribution of those who stated closing the window as one option is shown and can be compared to those where this is none of the options, whose distribution is shown in
The former group thereby clearly considers an open window to be possible, while the latter either believes that an open window is no possible starting condition in winter or that closing it is none of the first three actions they believe to perform. Looking at those stating “closing the window” as one option more than 60% would perform this action before all other alternatives followed by 25% who would rather put on more clothes than closing the window. 5% would first switch on the heating device before closing the window. 60% of those not stating “closing the window” as one option would put on clothes and 30% switch on the heating device first.

The same appeals for the comparison of those stating the heating device as option, shown in Figure 13c), and those not stating it, shown in Figure 13d). Looking at the former group, around 40% each would either put on more clothes or close the window before switching the device on. Of the latter group, who might also believe that a heating device must be always switched on, 50% put first on clothes while less than 40% would first close the window.

Figure 14 shows the summer case separated into those stating to switch on their cooling device as one of the options, shown in Figure 14a), and those who did not state this option, shown in Figure 14b). In both cases it can be seen that most people would open a window or take off some clothes in order to regain thermal comfort. For those stating the cooling device as an option, it seems to be mainly the third option in case the other two failed.

In general it can be seen that there is not one single action performed by more than 60% of the persons first. This leads to the conclusion that the order of action is highly different from individual to individual. Especially whether a person switches on the heating device first, second, or third leads to very different energy usage patterns.

![Fig. 14. Distribution of votes given for the actions to be performed first, second, and third in summer in the case of thermal discomfort for separate groups.](image-url)
3.5 Discussion on the Reference Levels Nature

As mentioned during the explanation of the theoretical occupant behaviour model, the input values deriving from the body’s sensory system are compared to a reference level. A decision is formed based on the outcome of this comparison, for or against a certain action. Taking the results presented above, the nature of the reference level can be made more concrete and thereby we may come up with a purpose-rank based occupant behavioural model.

As shown with the results concerning the purpose of behaviour, on the one hand, the decision seems to depend on the type of input value so that there must be a separate reference level either for each input or a combination of related input values, which is symbolized in Table 2 by the different capital letters of the reference levels’ indices. On the other hand, as shown with the results concerning the order of actions, there must be also a separate reference level for each alternative, which is shown by the change in the minor letters.

The reference levels having different capital letters are independent from each other and one can only observe the percentage of actions related to each purpose as shown above. In contrast, the reference levels having different minor letters are dependent from each other, one can observe them by field measurements or questions asking about the order of actions performed in reaction to one input value being out of the limits as also shown above.

Each of these reference levels is different from individual to individual and also not fixed at one point in one’s life, but rather (1) partly given by the genome (human biological nature)

<table>
<thead>
<tr>
<th>Thermal comfort</th>
<th>Air quality (IAQ)</th>
<th>Sound</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>- Core temperature</td>
<td>- CO₂ concentration</td>
<td>- Noise level</td>
<td></td>
</tr>
<tr>
<td>- Skin temperature</td>
<td>- Odours</td>
<td>- Type of sound</td>
<td></td>
</tr>
<tr>
<td>- Air current</td>
<td></td>
<td>&quot;...&quot;</td>
<td></td>
</tr>
<tr>
<td>- Overall comfort</td>
<td></td>
<td>&quot;...&quot;</td>
<td></td>
</tr>
<tr>
<td>- HBx-rate</td>
<td></td>
<td>&quot;...&quot;</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Open window</th>
<th>Ref.-level Aa</th>
<th>Ref.-level Ba</th>
<th>Ref.-level Ca</th>
</tr>
</thead>
<tbody>
<tr>
<td>Close window</td>
<td>Ref.-level Ab</td>
<td>Ref.-level Bb</td>
<td></td>
</tr>
<tr>
<td>Start heating</td>
<td>Ref.-level Ac</td>
<td>.</td>
<td></td>
</tr>
<tr>
<td>Stop heating</td>
<td>.</td>
<td>.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>.</td>
<td>.</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Reference levels.
and (2) constantly adapted and changed by personal experience(s), e.g. experience of seasonal changes (see also Chapter 6), changes in the surrounding culture (see also Chapter 8) or knowledge transfer methods (see also Chapter 9).

Additionally, in the field of cognitive mapping, it was found that persons distinguish indoor scenes from outdoor scenes. This means, e.g. at the basic level, people categorize outdoor scenes into beach scenes, city scenes, or forest scenes and categorize indoor scenes into schools, restaurants, or grocery stores (Tversky and Hemenway, 1983). Scenes seem to be so important to human behaviour that a region of the parahippocampal cortex appears to be dedicated to their recognition (Brewer et al., 1998; Epstein and Kanwisher, 1998). This means that the human mind has a different pattern of behaviour, e.g. when eating out in a public restaurant or eating at home, which we can easily be proved by observing our own behaviour in those situations. Following those findings, one could add a third dimension to Table 2 by defining another set of reference levels, for home, work and other places. Whether this is sensible and true has to be found by well-designed measurements, which would be beyond the scope of this dissertation.

3.6 Conclusions

In this chapter, the importance of temperature compared to other purposes was evaluated for six different interactions. It was shown that temperature alone does not necessarily cause the majority of them and that especially the indoor air quality plays an important role for window opening behaviour. Furthermore a first ranking was derived showing the order of interactions performed by the occupants to combat the feeling of thermal discomfort and it was shown that this ranking is different for individuals.

Both findings support the previously introduced theoretical model of occupant behaviour and the results with regard to the reference level. Based on these findings the concept of reference levels was concreted by defining one reference level for each input value or purpose and each possible interaction with the built environment.

Further research is recommended in order to quantify the “when” of an interaction for indoor air quality and other factors, such as noise. Together with further research about the order of the interactions, this can lead to a better understanding of occupant behaviour and a powerful purpose-rank based occupant behavioural model. For this dissertation the decision was made to concentrate on the reference level related to thermal comfort and the use of the heating- and cooling device.
4 Analysis on the Human Body Exergy Consumption Rate as Thermal Reference Level for Occupant Behaviour

4.1 Introduction

As introduced in the previous chapters, there must be several reference levels for each input value or group of input values. One such group of input values could be the human-body exergy consumption rate (HBx rate), which is combining the six influencing factors described above with outdoor temperature and humidity and showing good relations to thermal comfort votes in first comparisons (Saito and Shukuya, 2001).

This chapter describes some results of a trial analysis of human behaviour combining questionnaires, measurements and the calculation of the HBx rate in order to know the relationship between present and past thermal environments of the occupants and their behaviours and to see if the HBx rate can be one of the reference levels for occupant behaviour.

4.2 Outline of the Investigated Building and Measurement

A trial measurement was conducted at an international student dormitory opened in 1989 in Tokyo area, which is a 5-storied building with 320 identical single rooms (see Figure 15) and made of concrete with single glazed windows and little thermal insulation. The single rooms of 15m² each including the bathroom are oriented to east, south or west. Each room has one door facing to the corridor and one window with a curtain on the opposite side, and is equipped with one air-conditioning unit for heating and cooling.

Figure 16 shows the view from the entrance door of one of the 320 single-occupant rooms, which are identical in layout and equipment. The residents were allowed to use electrical

Fig. 15. Floor plan of a student room and placement of the sensors.
fans, stoves or other measures to keep their rooms as comfortable as possible without using the air-conditioning unit at their own discretion. This setting allowed the observation of the individual occupant’s behaviour in a laboratory-like setting.

Ten rooms were chosen for the measurement for fifteen days starting on 25 September 2006. All chosen rooms are orientated to the south. One of those rooms for reference was used to measure the temperature and humidity at five points each, the air-current velocity and globe temperature at one point each as shown in Figure 15. The other nine rooms were inhabited by one student each from a different country and each of those rooms were equipped with a small temperature and humidity sensor. The equipment for measurement should not influence the occupants’ normal behaviour, so the sensor was installed hardly visible in the rooms. Not observed at this stage of the project was the usage of electric fans or the change in the amount of clothes. The outdoor temperature, humidity, solar radiation and wind speed were also measured in front of the building. After the measurement, interviews were made to collect data about the personal background and preferences.

Fig. 16. One of the measured dormitory rooms seen from the entrance door.
4.3 Thermal Condition in Student Rooms

As mentioned above, each student room is equipped with one air-conditioning unit and one window opposite to the door. Therefore the inhabitants have different options to adjust the indoor thermal conditions. Table 3 shows the result of the interview about the student’s behaviour in their home countries and that at present in Japan. It was found that 22% are taking exactly the same methods as they did in their home countries, 33.3% are taking fewer and 44.5% are taking more in Japan. It is quite obvious that those students taking more methods added the use of the air-conditioning unit at the Japanese hot and humid summer conditions, to which their accustomed methods in their home countries are not applicable. It seems that the usage of air-conditioning units is an easy and effective technique to learn and therefore applied before other methods. Within this pilot study, there was no questioning of the reasons for such behaviour.

<table>
<thead>
<tr>
<th>Student</th>
<th>Behaviour at home</th>
<th>Behaviour in Japan</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Electric fan(^1) Air-conditioner(^2)</td>
<td>Air-conditioner</td>
</tr>
<tr>
<td>B</td>
<td>Opening window or air-conditioner(^*)</td>
<td>Opening window or air-conditioner(^*)</td>
</tr>
<tr>
<td>C</td>
<td>Air-conditioner</td>
<td>Opening window or air-conditioner(^*)</td>
</tr>
<tr>
<td>D</td>
<td>Opening window + electric fan</td>
<td>Opening window + electric fan</td>
</tr>
<tr>
<td>E</td>
<td>Electric fan(^3) (^1)</td>
<td>Opening window or air-conditioner(^*)</td>
</tr>
<tr>
<td>F</td>
<td>Opening door &amp; window + shading devices(^3) (^1)</td>
<td>Opening door &amp; window or air-conditioner(^*)</td>
</tr>
<tr>
<td>G</td>
<td>No adjustment</td>
<td>Opening window + electric fan or air-conditioner(^*)</td>
</tr>
<tr>
<td>H</td>
<td>Opening door &amp; window or electric fan</td>
<td>Opening door &amp; window</td>
</tr>
<tr>
<td>I</td>
<td>No adjustment</td>
<td>Opening window + using curtain or air-conditioner(^*)</td>
</tr>
</tbody>
</table>

\(^1\) At home; \(^2\) At work; \(^3\) Climate without hot summer

* Depending on temperature
Figure 17 shows the measured air temperature and humidity prevailing in three different student rooms together with outdoor air temperature and humidity. During the period of measurement, student A is using the air-conditioning unit, but students B and C are regulating their indoor climate by opening and closing the window, with which the air temperature inside their rooms was kept lower than 28°C for 95% of the time, even though the outdoor temperature reached up to 33°C. Some students like C seem to have felt still comfortable above 25°C of air temperature, otherwise they would have switched on the air-conditioning unit to lower the temperature as stated during the interviews. This result is consistent with other studies showing that people tend to accept higher temperature, if they are in a naturally ventilated room and have their own control about the adjustment (Brager and deDear, 2001).

The thermal conditions in the room of student A are quite similar to that of student B so that within this time of year it is possible to achieve the same conditions without using air-conditioning units. The fact that there is a difference in the thermal conditions between students B and C, both of whom did not use air-conditioning unit, suggests that the behaviour has a significant influence on the thermal condition of a room under the same weather conditions.

![Figure 17. Distribution of measured indoor temperature and humidity of selected students.](image)
4.4 Nighttime Behaviour and Preferred Conditions

Within the period of measurement, the nine students changed the mode of their window from opened to closed or vice versa all together for four times only. This shows that people react less with their building environment during nighttime and that the decision to sleep with opened or closed window is done before going to sleep and only seldom revised in between.

4.4.1 General Observations

Figure 18 shows the percentage of opened windows during nighttime compared to the daily highest and lowest air temperatures. The outdoor air temperature during nighttime varied between 16°C and 21°C, while the percentage of students who opened their window ranged from 15% to 85%.

![Diagram](image)

Fig. 18. Relationship between the percentage of windows opened during night and outside temperatures.
The decision to sleep with the window open seems to depend, on the one hand, on the experienced temperatures during daytime. On the other hand, as can be seen at point 1 and 2, a foregoing cold night seems to lead to fewer opened windows, even though the temperature during daytime increased. This result is supported by the finding that the actual thermal perception is not only related to long-term acclimatization, but also to the thermal conditions of the recent past (Koppe, 2005).

### 4.4.2 Individual Analysis

The fact that 56% of the windows were opened during nighttime suggests that there must be other reasons for sleeping with an open or closed window to achieve the individual thermal comfort. In order to find these reasons, a trial was done to calculate the range of HBx rate considering the individual personal background, the climatic background and previous habits.

<table>
<thead>
<tr>
<th></th>
<th>Student B</th>
<th></th>
<th>Student C</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Summer</td>
<td>Winter</td>
<td>Summer</td>
<td>Winter</td>
</tr>
<tr>
<td></td>
<td>Shading./ nat. vent.</td>
<td>Rad. heat. panel</td>
<td>Air- cond. 24h</td>
<td>Air- cond. 24h</td>
</tr>
<tr>
<td>Habit in hometown&lt;sup&gt;1)&lt;/sup&gt;</td>
<td>Outdoor air&lt;sup&gt;2)&lt;/sup&gt;</td>
<td>21°C</td>
<td>1°C</td>
<td>24°C</td>
</tr>
<tr>
<td></td>
<td>Indoor air&lt;sup&gt;3)&lt;/sup&gt;</td>
<td>24°C</td>
<td>20°C</td>
<td>25°C</td>
</tr>
<tr>
<td></td>
<td>MRT&lt;sup&gt;3)&lt;/sup&gt;</td>
<td>24°C</td>
<td>20°C</td>
<td>26°C</td>
</tr>
<tr>
<td></td>
<td>Indoor humidity&lt;sup&gt;3)&lt;/sup&gt;</td>
<td>40%</td>
<td>30%</td>
<td>60%</td>
</tr>
<tr>
<td></td>
<td>Outdoor air&lt;sup&gt;2)&lt;/sup&gt;</td>
<td>36°C</td>
<td>10°C</td>
<td>33°C</td>
</tr>
<tr>
<td></td>
<td>Indoor air&lt;sup&gt;3)&lt;/sup&gt;</td>
<td>28°C</td>
<td>24°C</td>
<td>26°C</td>
</tr>
<tr>
<td></td>
<td>MRT&lt;sup&gt;3)&lt;/sup&gt;</td>
<td>25°C*4</td>
<td>24°C</td>
<td>29°C</td>
</tr>
<tr>
<td></td>
<td>Indoor humidity&lt;sup&gt;3)&lt;/sup&gt;</td>
<td>40%</td>
<td>30%</td>
<td>60%</td>
</tr>
<tr>
<td></td>
<td>Outdoor humidity&lt;sup&gt;2)&lt;/sup&gt;</td>
<td>38%</td>
<td>85%</td>
<td>89%</td>
</tr>
</tbody>
</table>

<sup>1)</sup> According to the answers during interview  
<sup>2)</sup> Average values according to BBC (2006)  
<sup>3)</sup> Assumed values based on their answers at the interviews  
<sup>4)</sup> Due to high thermal capacity of thick brick walls
In the calculation of the HBx rate, recent findings on individual characteristics of the human body such as height, weight and age, as well as the resulting body surface area, the maximum sweat rate and blood flow were implemented (Havenith, 2001).

Since the globe temperature and air-current velocity were not measured in the nine student rooms, the mean radiant temperature (MRT) was estimated from the measured room air temperature and calculated MRT based on the measured globe temperature, air-current velocity and air temperature in the reference room. The MRT of each of the nine rooms were estimated using the average of the foregoing eight measured data of the respective room air temperature. The standard error of the MRT estimated from the empirical equation using the average of room air temperature in the reference room was 0.41°C, compared to the MRT calculated using the measured globe temperature, air temperature and air-current velocity.

The air-current velocity was assumed to be less than 0.1 m/s for the situation both of a closed window and of an opened window since the measured air-current velocity for those situations in the reference room was not so different. The body posture was assumed to be sedentary in the middle of the room. These assumptions could lead to less accurate results, but if a higher accuracy is to be sought, the occupants normal behaviour and privacy could be disturbed by various instruments for measurement. It is necessary for us to establish a method to measure in-situ environmental conditions with fewer instruments.

Table 4 shows the summer and winter average values of daily maximum and minimum outdoor temperature and humidity in the home towns of students B and C and the assumed indoor conditions based on their answers in the interviews about cooling and heating behaviour at home. The assumption was made that the individual students used to live for the first 10 to 20 years of their life within the maximum and minimum values of HBx rate calculated in this way. Student B and C were chosen to demonstrate the effect of combined climatic and behavioural background in this chapter, because their climates differ extremely. Student B grew up in a climate with hot dry summers and cold winters. He was used to shading and natural ventilation in summer, and radiative heating panels in winter. Student C grew up in a tropical climate and air-conditioned spaces for nearly 24 hours a day.

Figure 19 shows the respective status of the window chosen by student B and C in relation to the minimum and maximum outdoor temperature, the average of the calculated HBx rate during nighttime from midnight to six o’clock in the morning as well as the estimated range of HBx rate in their home countries in summer and winter.

HBx rate of Student B is below the bottom of the HBx-rate range, to which he was used during summer, but student C experiences HBx rates within and above the HBx-rate range to which he was used during summer and winter in his home country.
Fig. 19. Nighttime behaviour in relation to outdoor temperatures, actual HBx rate and estimated HBx-rate range in home country (SR; WR: summer and winter ranges).
Their behaviours clearly represent the relationship between the current HBx rate and the HBx-rate range at home. Student B is sleeping mainly with an opened window and only twice with a closed one within the period of measurement, while student C slept only once with an opened window and for all other nights with the window closed.

These exceptions in their behaviours can be explained by looking at the HBx rate. Student B experienced the night of 26 September with an HBx rate, which is within his summer and at the bottom of his winter range. He may have realized the decreasing temperatures during the following daytime and therefore he closed his window to lower, maybe unconsciously, his HBx rate during an even colder night. The next day he might have sensed the increasing temperatures and therefore he decided to open the window at night again. The same behaviour is found in his behaviour in the following week, when the temperature drops again below 17°C during nighttime.

Student C experienced a low HBx rate during the night of 28 September and also the temperatures increasing during the following daytime. Therefore he may have decided to sleep with an opened window for the night of 29 September. A sudden drop of maximum temperature on the following day led to the decision to close the window again and thereafter for all other nights in the period of measurement.

4.5 Analysis of Human Interactions together with Human Body Exergy-Consumption Rate

Following the nighttime behaviour, the students' interactions during daytime were analysed. In this context, what was detected as human interactions is a series of moments when the occupants open or close their respective window and also switch on or off the air-conditioning unit.

Figure 20 shows an example of two interactions detected from the variation of temperature and humidity. At the time denoted by circle 1, the difference between inside and outside, both in temperature and humidity starts to decrease; this is due to the outdoor air entering the room by opening the window. At the time denoted by circle 2, the difference starts to increase; the reason for this is that the window was closed, since there is no solar radiation at this time of the day. Four hundred interactions of the students in their rooms were detected in this way. The maximum error of detected time is within the range of five minutes.

Thermal sensations were not monitored, but the moment of interaction must represent either a conscious or unconscious behaviour reflected by the feeling of discomfort. What follows is focussed on the result of an analysis of the “closing window” interaction. The “closing window” interaction is considered to represent such a condition that the occupant felt the room temperature as too low.
Fig. 20. Detection of human interaction using the variation of inside/outside difference in air temperature and mixing ratio.

Fig. 21. HBx rate before and after closing the windows.

Fig. 22. Comparison of HBx rate before and after closing the windows together with the range of estimated HBx rate in their hometowns.
4.5.1 General Observations

Figure 21 shows the variation of average HBx rate from 30 minutes before till 10 minutes after the window was closed, using the same assumptions as for the calculation during nighttime. The HBx rate tends to increase towards the time of interaction and then to decrease afterwards. This suggests that the behaviour to lower discomfort is consistent with lowering the HBx rate by interaction. The fact that the range of HBx rate is quite wide, from 2.9 to 4.3 W with a standard deviation of 0.29, indicates that it is not possible to define one single value for the moment when the occupants start to interact with their built environment.

4.5.2 Analysis of Individual Interactions

In order to understand such distribution of the HBx rates, the relationship between the HBx-rate ranges in the student's home country and at the moment of interaction was considered again.

Figure 22 shows the HBx rate of students B and C in their rooms at the dormitory in Tokyo and the estimated HBx-rate ranges in their home towns. The HBx-rate range for student B is very wide compared to that for student C. The line with closed circles represents the HBx rate of student B in his room at the dormitory and that with open circles student C. The respective lines are close to the bottom edge of the estimated HBx-rate ranges. During the period of ten minutes, five minutes each before and after closing the window, the values of HBx rate come closer to and enter the estimated HBx-rate range.

4.6 Conclusion

According to the present analysis, the occupants’ behaviour is strongly related not only to the current thermal conditions, but also to their personal thermal background, short-term and long-term. The method described above seems very helpful to understand the occupants behaviour regarding the choice to sleep with opened or closed window as well as when to close the window, through which cool air is entering the room, though all interactions may not be explained using the HBx rate only.

What was discussed above seems to be very convincing, but the results are limited by the small number of participants with little additional information about their personal background. By surveying one student, using an air-conditioning unit instead of opening a window or vice versa, it is not possible to compare a behavioural pattern based on the preference of an air-conditioned space with a behavioural pattern based on natural ventilation.

A future study has to deal with a larger number of students and a deeper investigation of the personal background and preference to define the reasons leading to the decision of opening, closing a window or switching on an air-conditioning unit.
Therefore a more intense study aiming at discovering other factors for the occupants thermal interaction with their built environment must be conducted asking in detail for the reasons and preferences leading to an interaction and at the same time aiming to find out how those preferences develop within the lifespan of the occupant. Knowing those will lead to the design of suitable and effective built environment and also the related education tools focusing on the most effective aspect to intervene the decision process towards a more healthy and responsible life not only inside but also together with a building and its facilities.

Finally, the HBx rate looks promising to be one of the reference levels of occupant behaviour, but it alone already represents a complex interrelated combination of several factors and the calculation model is at the moment of this research not yet fully developed for dynamic application. Additionally, it would be necessary to measure not only air temperature and humidity, but also MRT, and air velocity as well as the clothing level in order to calculate the HBx-rate. The necessary measurement devices and questions would very likely cause a great disturbance of the occupant and might change their normal behaviour pattern. Therefore, the following deals with simpler and more easily observable factors, such as the temperature directly. However, in the future the extension of above introduced approach should be pursued very much.
PART II
Analysis and Quantification of the Factors Influencing on the Occupant Behaviour and its Reference Levels

第 2 部
行動変化の閾値に影響する要因の定量化と分析

“Nothing is as simple as we hope it will be.”

(Horning, 2004)
5  Analysis of AC-unit Usage Patterns

5.1 Introduction

Although the Kyoto protocol is coming into effect, many countries are facing difficulties in fulfilling their promises so that the governments and industries are looking urgently for solutions. The amount of exergy consumption of a certain built-environmental system is influenced not only by the characteristics of hardware, such as the thermal insulation level of the building envelopes and the efficiency of mechanical heating and cooling systems, but also much by that of software whose central determinant is human behaviour. “Exergy consumption” is used here, because the concept of exergy enables us to articulate what is really consumed by active and passive building systems. Exergy is defined to be the usable part of energy that can irreversibly dissipate in any working system including the building system (Shukuya and Hammache, 2002). Over the last few decades the hardware has been researched intensively, while on the other hand the software has not been yet researched well enough, though a number of articles have appeared these days (Murakami, 2007; Rijal et al, 2007).

Recent studies on thermal sensation investigated the relationship between individual parameters such as weight, height and body constitution and thermal sensation (Havenith, 2001; Sassa et al., 2001), and a strong relationship between climatic background of a person and its thermal sensation during the experiments was found (Matsuyama et al., 2006). On the other hand, those researching about the occupant behaviour concentrate on finding general behaviour patterns in relation to the outdoor environment (Asawa et al., 2005) or the lifestyle of the occupant (Habara et al., 2005).

In reality, except a few days of extreme hot or cold weather situations, the occupants have different options to achieve comfortable conditions in their indoor environment and will choose different ways at comparable conditions. Which of the options they take, e.g. whether switching on an air-conditioning unit or opening a set of windows for cross ventilation influences significantly the exergy consumption pattern of the built-environmental system. For this chapter the observed occupants were grouped according to different behaviour patterns and then it was tried to find those factors, which seem to have a significant impact on the belonging to a group consuming more or less exergy for maintaining comfortable conditions. Furthermore two statistical analysis methods for small sample groups are introduced and used in order to judge the significance between different groups of occupants.
5.2 Surveyees and Their Thermal Environment

Even though field studies are not as accurate as laboratory experiments, they seem to be more relevant to the normal living and working conditions (Nicol and Pagliano, 2007) and were therefore chosen for this investigation. For the following analysis, data from a survey together with a physical measurement, which were conducted during summer 2007 at the same international student dormitory as described in Chapter 4.2, were taken.

5.2.1 Outline of the Investigation and the Questionnaire Surveys

As the first step, a questionnaire survey was conducted consisting of 35 questions written in English about the students’ current and past cooling and heating behaviour, thermal background, lifestyle, behavioural background, their preferences, knowledge about alternative methods to keep the room cool in summer, and personal evaluation of the effectiveness of those strategies. The questionnaire sheets were passed directly to a limited number of students and also posted into the mail boxes of the rest of the students. In total 310 questionnaires were distributed at the dormitory; 82 of them were given personally in the entrance lobby and the others put into the mailbox. In order to increase the return rate, a postbox and a poster were placed visible in the entrance lobby of the dormitory. Nevertheless only 71 questionnaires filled-out were returned: 56 of those were the ones distributed personally. The percentage of return was 23% as a whole and 68% of the personally distributed questionnaires. This shows clearly how effective personal contact is for this kind of project.

The reason for the low return rate can also be described by two other factors. First, the foreign students studying in Japan are very busy in their own studies and part-time jobs. Many of them leave the dormitory before 9 am in the morning and return after 11 pm so that there is not much time left to fill out the questionnaires given. Secondly, the majority of the students originate from countries where English is not spoken very much. Therefore they might have judged that a questionnaire sheet written in English looks very time-consuming to fill out.

In the second step, the 39 students who agreed to participate in a physical measurement as described below were invited to a short interview asking in more detail about their actual behaviour and strategies to keep their room comfortable in summer. Afterwards they received two sensors: one wireless sensor collecting temperature and humidity values; and the other one, which can indicate if the window is open or closed. In order to prevent a disturbance of privacy, these students were asked to install those sensors themselves.

In the first step the personal background- (e.g. climate in home country) and the actual behavioural-data is collected by questionnaires and one-to-one interviews, which were
designed to find out about the conscious aspect of the occupant behaviour and his personal background. A first small pre-survey was conducted in October 2006 to find out about potentials and difficulties for this method as described in Chapter 4.

5.2.2 Experimental Facility and Subjects

The residents of this dormitory were foreign students originating from countries other than Japan. The 39 students who agreed to participate in the measurement were having all different majors in social or natural sciences and were originating from 26 different countries from all continents, with the majority from Asia (39%) and Europe (29%) as shown in Table 5. They were aged between 20 and 34 with the average at 26.5 years old and 56% being male. The period the students are allowed to live in the dormitory is limited up to two years so that most students came to Japan within three and twenty months before the measurement.

For the physical measurements, one wireless temperature and relative-humidity sensor and another wireless sensor logging the times the window was opened or closed were installed in each of the 39 observed rooms as shown in Figure 23. As well as this, additional sensors were installed to measure the outdoor air temperature, relative humidity, solar irradiance and wind speed (wind speed was only measured for the summer case).

The sensor shown in Figure 24, which is logging the times of window opening, had to be developed especially for this investigation. The version used for this measurement consisted of two switches, which were placed at each side of the sliding window. A closed window and therefore a pressed button led to a small current, which was detected by a voltage meter including a data logger, which could be accessed wireless from outside the room.

| Table 5. Country of origin of the students participating in the physical measurement. |
|---------------------------------|----------|----------|-----------------|
| Country                        | Students | Countries | Students per country |
| Africa                          | 1        | 1        | 1               |
| Asia                            | 17       | 10       | 1.7             |
| Europe                          | 13       | 9        | 1.4             |
| North America                   | 2        | 2        | 1               |
| Oceania                         | 2        | 2        | 1               |
| South America                   | 4        | 2        | 2               |

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Fig. 23. Floor plan of a student room and placement of the sensors.

Fig. 24. Sensor used to log the times the window was opened or closed.
The occupancy could not be explicitly recorded during the daytime, but the students stated the nights they were not sleeping in their rooms as well as continued absence for more than a day. The measurement took place in all observed rooms at the same time with a logging interval of 2 minutes. These measurements of room air temperature, humidity and window opening of the individual rooms related to the outdoor air temperature and humidity will lead to qualitative data about the occupant behaviour inside rooms. In total 30325 data sets were garnered for each room for the six-week summer measurement.

Figure 25 shows the outdoor conditions during the measurement period together with the inside conditions of two student rooms and the adaptive comfort zone for Tokyo. The adaptive comfort zone is the range of ±2°C around the comfort temperature, which is most likely to be evaluated as comfortable and is given by an empirical formula proposed by Nicol and Humphreys (2002)

\[ t_c = 0.54 t_o + 13.5 \]

where \( t_c \) is the comfort temperature (°C) and \( t_o \) is the mean of daily maximum and minimum outdoor air temperature (°C). The difference in the interior conditions between student room A and B is the result of student A not using the air-conditioning unit and student B using it frequently. While the first two weeks were still relatively moderate as a Japanese summer, the last ten days were with the daily highest temperature of above 30°C and the relative humidity of over 70% so that the investigation was made both under moderate and extreme weather conditions.

Table 6 shows the average, maximum and minimum temperature and humidity of the rooms on each floor and for respective orientation together with the overall average of inside and outdoor values. The indoor conditions are even worse than the outdoor conditions due to the density of occupancy, lights, and electrical appliances in combination with the little thermal insulation of the building envelope.

### 5.3 General Behaviour Patterns

In order to articulate the behavioural patterns of the students with respect to the usage of the air-conditioning unit, first it was analysed when each student turns on the air-conditioning unit and how long they kept it on. This was judged by looking at the variations of the room air temperatures as described in Chapter 4.4.2. Due to the fact that most students are not in their room during daytime and some of them are still outside during the evening period, the data was divided into daytime (8am-6pm), evening (6pm-0am) and nighttime (0-8am).
Fig. 25. Thermal conditions during the measurement period and adaptive comfort zone for Tokyo (Student A did not use the AC unit, Student B did).
The usage of air-conditioning units was analysed in relation to the outdoor air temperature following a procedure described by Nicol (2001). Figure 26 shows the relationship between the percentage of persons using the air-conditioning unit and the mean outdoor air temperature and Figure 27 the percentage of hours the air-conditioning unit was switched on. Percentage of hours is defined to be the ratio of the number of hours that all of the air-conditioning units were on to the product of the number of students and the total number of hours for the respective four periods of time: night (12am – 8am); daytime (8am – 6pm); evening (6pm – 12am); and the whole day (24hrs):

\[
\text{percentage of hours} = \frac{\sum \text{hours each AC unit was running}}{\text{number of students} \times \text{hours of period}}.
\] (2)

Table 6. Comparison of inside and outside conditions during the period of measurement.

<table>
<thead>
<tr>
<th></th>
<th>Temperature (°C)</th>
<th>Humidity (%rh)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Avg(^1)</td>
<td>Max</td>
</tr>
<tr>
<td>1(^{st}) floor</td>
<td>28.1</td>
<td>33.9</td>
</tr>
<tr>
<td>2(^{nd}) floor</td>
<td>27.4</td>
<td>33.4</td>
</tr>
<tr>
<td>3(^{rd}) floor</td>
<td>28.2</td>
<td>35.4</td>
</tr>
<tr>
<td>4(^{th}) floor</td>
<td>28.9</td>
<td>36.2</td>
</tr>
<tr>
<td>5(^{th}) floor</td>
<td>29.4</td>
<td>38.3</td>
</tr>
<tr>
<td>East</td>
<td>27.7</td>
<td>38.3</td>
</tr>
<tr>
<td>South</td>
<td>28.6</td>
<td>37.4</td>
</tr>
<tr>
<td>West</td>
<td>28.4</td>
<td>35.4</td>
</tr>
<tr>
<td>Inside</td>
<td>28.2</td>
<td>38.3</td>
</tr>
<tr>
<td>Outside</td>
<td>24.3</td>
<td>33.4</td>
</tr>
</tbody>
</table>

\(^1\) “Avg” stands for average and “Var” for variance
Fig. 26. Percentage of persons using air-conditioning unit at different outdoor air temperatures and periods of day. The plots are observed values and the four curves represent best-fit to the respective group of plots.

Fig. 27. Percentage of hours air-conditioning units are running at different outdoor air temperatures and periods of day. The plots are observed values and the four curves represent best-fit to the respective group of plots.
Comparing Figures 26 and 27, the former gives an overview how many people tend to switch on the air-conditioning unit at a certain outdoor air temperature, while on the other hand, the latter shows the length of time the air-conditioning unit stayed switched on during the respective period. The plots represent the average of all students for each of the 43 measured days and corresponding periods. The lines represent the best-fit of these plots using the logit model (Nicol, 2001), the probability that an action occurs, p, to be a function of mean outdoor air temperature, \( t_{\text{av}} \):

\[
p = \frac{1}{1 + e^{-\beta t_{\text{av}}}}
\]  \( \text{(3)} \)

Table 7 shows the values of the constants \( \alpha \) and \( \beta \) derived from the analysis and used in eq. (3) to draw the curves in Figures 26 and 27. The determination of the constants was made using the software package R (R Development Core Team, 2005).

The percentage of usage tends to be higher during the nighttime, in which most students are sleeping in their rooms, than during the daytime. The occupancy from a person to another varied largely, but any further analysis of daytime and evening would not be very reliable since there was no sensor detecting the occupancy. The following analysis is therefore focused on the nighttime period. Some students stayed out of their rooms overnight, but they reported this so that the exact number of the students during the nighttime is known.

The formulae obtained from the method described above may be used to predict the occurrence of an event in building simulation as shown by Rijal et al. (2007). Nevertheless, the formulae are valid only for an imaginary average person. Figure 28, in which each student is represented by one line, shows that there are huge differences between individual persons.

<table>
<thead>
<tr>
<th>% of persons (Fig. 26)</th>
<th>% of hours (Fig. 27)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha )</td>
<td>( \beta )</td>
</tr>
<tr>
<td>Day (24hrs)</td>
<td>2.08x10³</td>
</tr>
<tr>
<td>Daytime (8am-6pm)</td>
<td>5.34x10²</td>
</tr>
<tr>
<td>Evening (6pm-12am)</td>
<td>1.94x10³</td>
</tr>
<tr>
<td>Night (12am-6am)</td>
<td>1.46x10⁴</td>
</tr>
</tbody>
</table>
In order to take a deeper look at the differences between individual persons and to find certain usage-patterns of the air-conditioning units, the students were divided into four groups “N”, “E”, “L”, and “A” based on their actual usage of the air-conditioning unit. The grouping process was as follows. Group “N” consists of those never using the air-conditioning unit; when the conditions get unbearable, they prefer to stand the heat or change the place to stay. Group “E” are those using the air-conditioning unit in case the conditions get unbearable for them and other measures such as the use of a fan have failed. Group “L” are those trying not to use the air-conditioning unit, but are likely to use it before trying other strategies. Finally, group “A” are those using the air-conditioning unit all the time, even when it should not be necessary.

Using the data of the indoor conditions in the rooms of the students together with the outdoor conditions, the measurement period was divided into three categories. If the indoor air temperature inside the rooms where no air-conditioning unit is used is within the limits of the adaptive comfort zone, this usage pattern of an air-conditioning unit was called “not-necessary.”

![Fig. 28. Probability of each student using his air-conditioning unit at different outdoor air temperatures. The average curve represents best-fit for all.](image)
(“NN”). If the room air temperature is lower than 1°C above the upper limit of the comfort zone and the outdoor air temperature within the comfort zone, the usage of the air-conditioning unit is called “necessary unless applying other strategies” (“NW”), because comfortable conditions could be reached by opening a window. If the room air temperature exceeds the upper limit of the comfort zone more than 1°C or the outdoor air temperature is above the comfort zone, the usage is called “necessary even with other strategies” (“N”). The relative frequencies of groups “NN”, “NW” and “N” are 54%, 15% and 31% respectively. For the grouping process, the students never using the air-conditioning unit during the measurement period were first placed in group “N”. The period and frequency of air-conditioning usage of the other students were then judged according to the three categories mentioned above. Those students using their air-conditioning unit in period “NN” were placed in group “A”, those using it beginning with period “NW” were placed in group “L” and those only using the air-conditioning unit in the periods marked as “N” were placed in group “E”.

Figure 29 shows the respective plots and best-fit lines for each group. The respective values for the constants $\alpha$ and $\beta$ are given in Table 8. As can be seen, those belonging to group “A”
Fig. 30. Relationships between four groups of persons with respect to the usage-pattern of AC-units and seven factors: a) preference of the AC unit; b) effectiveness of the AC unit; c) effectiveness of opening windows; d) effectiveness of closing windows; e) climatic background (h&h = hot & humid; h&d = hot & dry climate); f) number of alternatives they know; and g) gender. The symbol ‘(>)’ denotes that this portion is significantly higher in group than in average and ‘(<)’ that it is significantly lower.
use the air-conditioning unit more likely than those belonging to group “L”, “E”, or “N” for a certain outdoor air temperature. Due to no data for conditions above 33°C, it is not clear how students belonging to group N will react as the outdoor air temperature becomes higher. As a whole, the plots show that this kind of grouping process gives useful information to increase the reliability of such formula as eq. (3).

5.4 Factors Influencing the Decision Process

To have a better understanding of these four groups of persons with respect to the usage of air-conditioning unit, it was further analysed how the answers obtained from the questionnaires relate to the behavioural patterns of a respective group. The results of this analysis are displayed in Figure 30-a) to g). Each of the seven charts in Figure 30 represents one of the seven factors considered for the present analysis. Let us take a closer look at Figure 30-a) to show how to read each chart.

The vertical axis shows the number of persons belonging to group “N”, “E”, “L”, or “A” with the relative heights downwards. The horizontal bar at the top represents the average for all groups. The horizontal axis shows the percentage of persons in each of four groups. In case a), this is whether they like or dislike the usage of air-conditioning unit. For example, the percentage of those who like the usage of air-conditioning unit is 40% as can be seen at the bar for average.

The symbols such as “0.01(>)” or “0.05(<)” appearing in the portions of the bars indicate that the portion is significantly higher or lower in the group compared to the overall average. Taking a look at group “E” in case a) for example, one can be sure with 90% of probability that a student belonging to group “E” tends to like the air-conditioning unit less (<) than the average person, and one can be sure with 95% that a student belonging to group “E” dislikes

<table>
<thead>
<tr>
<th>Group</th>
<th>% of persons (Fig. 29)</th>
<th>α</th>
<th>β</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group N (“never”)</td>
<td>11.2x1011</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>Group E (“emergency”)</td>
<td>9.56x105</td>
<td>0.52</td>
<td></td>
</tr>
<tr>
<td>Group L (“likely”)</td>
<td>3.86x104</td>
<td>0.47</td>
<td></td>
</tr>
<tr>
<td>Group A (“always”)</td>
<td>55.1</td>
<td>0.33</td>
<td></td>
</tr>
</tbody>
</table>
the air-conditioning unit more (>\text{}) than the average person. The significance levels are obtained from the calculation of the hyper-geometric probability, a method especially designed for small samples, and also from a one-tailed test of hypothesis as described below. The portions having the number with the symbol "(<)" or "(>)" are those that both methods give the statistical significance.

The hyper-geometric probability is the probability that within an experiment the number of successes is exactly \(x\), when there are \(N\) items in the population with \(k\) successes and \(n\) items in the sample. For the purposes of this study, \(N\) is the number of students taking part in the measurement and \(n\) the number of students belonging to a certain behavioural group. Then, \(x\) is the number of all students supporting a feature, e.g. to like the air-conditioning unit, and \(k\) is the number of students in the respective group who support the same feature. The hyper-geometric probability is then calculated by

\[
h(x;N,n,k) = \frac{kCx}{N\binom{N-n}{x}}
\]  

(4)

where \(kCx\) represents the combination

\[
kC_x = \frac{k!}{x!(k-x)!}
\]  

(5)

The level of significance is the cumulative probability, which is the sum of the hyper-geometric probabilities from 0 to \(x\). This means, in case that there are four students of one behavioural group supporting one feature, the significance level is calculated by the sum of the hyper-geometric probabilities, with \(x = 0, 1, 2, 3, \text{ and } 4\) (Stat Trek, 2007).

A hypothesis test starts with the assumption that the probability of an event happening in one sample is different from the population. To test this hypothesis, a \(z\)-score indicating different significance levels is calculated by

\[
z = \frac{x-nP}{\sqrt{nP(1-P)}}
\]  

(6)

where \(x\) is the number of successes in the sample, \(n\) the sample size and \(P\) the probability that a success occurs in the population. For this study, \(n\) is the number of students belonging to a certain behavioural group and \(x\) is the number of students within this group, supporting a feature. \(P\) is the percentage of all students taking part in the measurement, who support the same feature (Spiegel, 1998).
In this case, the students belonging to one behavioural group can either support a feature more likely or less likely. A one-tailed test was used, because the only concern was if the probability in the sample is higher than in the population. The significance levels of 0.1, 0.05, 0.01, and 0.002 therefore correspond to the z-scores of 1.28, 1.645, 2.33, and 2.88 respectively.

What can be seen from Figure 30-a) is that, if a person likes or dislikes the air-conditioning unit at night has a significant influence on how frequent they turn on the air-conditioning unit in reality. This may seem to be very obvious, but so far there have been very few comparable studies.

The subjective evaluation of the effectiveness of air-conditioning units might affect the preference, but the answers given to the questionnaires show that the students who dislike the air-conditioning unit evaluated it comfortable in the same way as the students who like it. This implies that the students were able to distinguish between preference and effectiveness. Therefore, they are treated as two independent influences.

Figures 30-b) to d) show the results of the analysis in the subjective evaluation of the effectiveness of using the air-conditioning unit, opening the window and closing the window. The students in groups “L” and “A” believe fully in the comfort provided by the air-conditioning unit and less in alternatives such as opening the window, while on the other hand, those students in groups “N” and “E” believe in the opposite to be more comfortable. Interesting also is that the students never using the air-conditioning unit seem to evaluate positively the effect of closing a window. This result must be reflecting the fact that they have quite a lot of experience in regulating the thermal conditions with their windows. The analysis of other strategies such as the usage of a fan or wearing light clothes resulted in the same tendency, but is not shown here because the differences were not significant.

The reason for what is described so far is that those persons often using the air-conditioning unit have less experience using alternative strategies. Therefore they cannot imagine the effect of an increased airflow by opening windows or other strategies and might not be able to believe that it helps provide with more comfortable conditions.

For the analysis of the climatic background shown in Figure 30-e) the students were grouped according to the climate map of Köppen (Kottek, 2006). This resulted in four groups. The analysis of climatic background in relation to the actual behavioural patterns shows diverse results. Those students from regions with hot and humid climate, who must be used to the thermal environmental conditions occurred during the measurement period are more likely to be found in group A. The reason for this is possibly the high distribution rate of air-conditioning units in those areas and those students from Asia and the north of South America tend to evaluate air-conditioned places as upper class.
Fig. 31. Percentage of persons using air-conditioning unit at different outdoor air temperatures for each preference. The plots are averages of observed values and each curve represents best fit.

Table 9. The constants $\alpha$ and $\beta$ in eq. (3) for Figure 31.

<table>
<thead>
<tr>
<th></th>
<th>$\alpha$</th>
<th>$\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Like AC</td>
<td>$2.59 \times 10^4$</td>
<td>0.44</td>
</tr>
<tr>
<td>Dislike AC</td>
<td>$2.36 \times 10^4$</td>
<td>0.37</td>
</tr>
</tbody>
</table>

Table 10. Preference and measured average room air temperature during AC-unit usage.

<table>
<thead>
<tr>
<th></th>
<th>Dislike AC</th>
<th>Like AC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>26.8</td>
<td>25.7</td>
</tr>
<tr>
<td>Highest</td>
<td>29.1</td>
<td>28.8</td>
</tr>
<tr>
<td>Lowest</td>
<td>24.9</td>
<td>20.7</td>
</tr>
<tr>
<td>Variance</td>
<td>1.3</td>
<td>4.1</td>
</tr>
</tbody>
</table>
Those students from hot and dry countries are more likely to be found in groups “N” and “E”. Looking at the countries those students are originating from in detail, this can be explained due to a more traditional lifestyle those students grew up with. The students from a cold climate are more likely to be found in group “L”, though there is no significant difference in the students from a moderate climate. This can be explained that they are not used to the thermal environmental conditions during the measurement period and never learned alternative strategies in their home countries. Therefore switching on the air-conditioning unit must have been easy for them to learn in order to avoid the hot and humid conditions in Japan.

According to Figure 30-f), there seems no significant difference between the groups in relation to the knowledge of alternatives such as natural ventilation, external sun shading and evaporative cooling by spraying water. This result might have been influenced by the way of asking directly if those strategies are known or not. Generally speaking, people do not like to admit their lack of knowledge so that the knowledge stated would be different from the real knowledge. This has to be investigated further in future surveys.

Even though one might expect that females and males act differently, Figure 30-g) shows that both genders are distributed evenly to each group. The circumstance that there is no female student in group “N” is not significant according to the statistical evaluation and might be due to the small size of the sample.

In order to visualize the difference in the behaviour due to preference, the students were divided into two groups according to their answers in the questionnaire survey. The first group (L) consists of those who answered that they like sleeping within an air-conditioned space; the second group (DL) are those who answered to dislike it. Figure 31 shows the respective plots and best-fit lines for the two groups and Table 9 the respective values for the constants $\alpha$ and $\beta$ to be used in eq. 3. It can be easily recognized that those who like the air-conditioning unit tend to use it earlier than those who dislike it. Looking at Figure 31, it can be seen that at a mean outdoor air temperature of 25°C only about 32% of the students in group DL tend to switch on the air-conditioning unit, while on the other hand, more than 73% of group L do the same.

In order to clarify if there is a further relationship between the preference and the room air temperature set via remote control (named set-point temperature), the prevailing temperatures during the time of usage were analysed. Though it is difficult to know the set-point temperature the students used and it was neither recorded nor asked directly, the data from the student rooms were analysed according to the room air temperature during the use of the AC-unit. For each student and each period of AC-unit usage the lowest room air
Fig. 32. Difference in individual exergy consumption rate due to the difference in indoor air temperature alone.

Fig. 33. Difference between exergy consumption of 100 persons due to difference in room air temperature and percentage of persons using their AC-unit.
temperature was taken and then manipulated in that way that first an average air temperature value was calculated for each student, because even the same person did not set the AC-unit to have the same temperature all times. Second these average values for each student were taken to get the average, highest, lowest and variance for the like and dislike group respectively, which are shown in Table 10.

Those who like the AC-unit not only use it for a condition of lower outdoor air temperature as was seen in Figure 31, but also use it to achieve in average a 1°C lower room air temperature than those who dislike the AC-unit.

The findings regarding the differences with respect to the frequency and temperature of usage can be used as input values to calculate the exergy consumption for cooling. The procedure of this calculation is described in detail in Chapter 10. Basically, two types of calculation can be made: (1) a calculation for one person considering the differences in the chosen set-point temperature alone, and (2) a calculation for 100 persons considering both, the differences in the chosen set-point temperature and the frequency of usage. In the following the results are presented for two cases of outdoor-air temperature.

The result of the first calculation, which was done to compare one person from the like group with one group of the dislike group, is shown in Figure 32. The exergy consumption pattern itself is not different between the four cases, but the exergy input to the power plant for the case of 31°C of outdoor air temperature is different from that for 24°C. This is due mainly to the difference in Carnot efficiency to be multiplied to the cooling energy load. The difference between the person of the dislike group to the one of the like group results only out of the different room air temperature chosen.

Figure 33 shows the result of the second calculation, which considers 100 persons of each group and therefore adds the fact that at the same outdoor air temperature, there are different percentages of persons within both groups using the AC-unit. Much more differences can be seen among the four cases, which is due mainly to the difference in the percentage of AC-unit usage, but partly also due to the different room air temperature chosen.

Table 11 additionally gives the total amount of exergy necessarily supplied to the power plant for the eight cases together with the ratios between the like- and the dislike group. The results of the calculations show that, looking at the individual level, the preference may account for an exergy consumption rate up to 15% higher for a student belonging to the like-group compared to one of the dislike-group. Looking at the behaviour of a community of people, the exergy consumption rate of the like-group is up to three times larger than that of the dislike-group due to the huge differences in the percentage of persons using their AC-unit. For all cases it can be seen that the higher the outdoor air temperature, the higher the
total amount of exergy supplied is due to the larger difference in temperature between indoors and outdoors, but at the same time the higher the outdoor temperature, the less is the resulting difference between the two groups. Further analyses on basis of the exergy calculation are presented in Chapter 10.

5.5 Conclusions

The results of this investigation show that the Logit model introduced by Nicol can also be applied to the usage of an air-conditioning unit. Starting from this, it is shown that there exist different behavioural patterns, which can be presented with characteristic best-fit curves.

The analysis of the measured behaviour resulted in two distinctive logit curves showing that those preferring the AC-unit use them more likely than others do. Additionally, they prefer lower temperatures provided by the AC-units. The exergy analysis showed that, at the individual level, preference accounts for an exergy consumption rate up to 15% higher when comparing the persons who like the AC-unit with those who dislike it, while on the other hand, at the community level of one hundred persons, the exergy consumption rate of those preferring the AC-unit is up to three times larger than that of others.

Although the relationships between personal factors such as preference, the likelihood of the usage of AC-units and the resultant exergy-consumption patterns, were rather easily found in a limited case described here in this chapter, they must be more complicated in other cases such as ordinary residential buildings, in which we are actually very much interested.

For measures to reduce the exergy consumption within the built environment, this chapter shows that the preference has a highly significant influence on how often a person uses the

<table>
<thead>
<tr>
<th>Temperature</th>
<th>1 person dislike</th>
<th>1 person like</th>
<th>100 persons dislike</th>
<th>100 persons like</th>
</tr>
</thead>
<tbody>
<tr>
<td>24°C</td>
<td>225.2 W</td>
<td>257.4 W</td>
<td>5178 W</td>
<td>15445 W</td>
</tr>
<tr>
<td>Ratio of like/dislike</td>
<td>1.14</td>
<td></td>
<td></td>
<td>2.98</td>
</tr>
<tr>
<td>31°C</td>
<td>438.8 W</td>
<td>465.0 W</td>
<td>35104 W</td>
<td>45102 W</td>
</tr>
<tr>
<td>Ratio of like/dislike</td>
<td>1.06</td>
<td></td>
<td></td>
<td>1.28</td>
</tr>
</tbody>
</table>
air-conditioning unit. The subjective evaluation of the effectiveness and the climate in their home countries influence on the amount of air-conditioning usage. No significant influences were found between the knowledge of alternative strategies and the actual behaviour as well as between gender and behaviour. A more detailed analysis of the factors influencing on the occupant behaviour is presented in the next chapter.

In addition to the findings given in this chapter, it must be interesting to investigate whether it is possible for one to change a certain behavioural pattern towards a less exergy consuming one, namely the one that the air-conditioning unit is used less often, but the alternative strategy, namely natural ventilation with solar control is used more often naturally. A first analysis of this kind will be shown in Chapter 9.
6 Effect of External and Individual Influences on the Behaviour

6.1 Introduction

These days more scientists than ever before have recognised occupant behaviour together with its relation to the energy used within the built environment as being very important. Additionally, decision makers and politicians have started to look at occupant behaviour in order to reduce the energy use of a country. Recently the German Minister of Economics, Michael Glos, commissioned the verification of a bonus for those who can prove they used less energy than in the foregoing year (SpiegelOnline, 2008).

In order to clarify the variety of possible reactions between individuals towards the outdoor conditions, the significance of several individual factors on the usage pattern of AC-units was analysed as presented in Chapter 5. It was shown that, amongst others, the preference of AC-unit and also the thermal background of occupants have a strong influence on their behaviour. Preference in this context meant whether a person answered that he or she likes or dislikes working/sleeping in an air-conditioned space. Furthermore, it was shown that the impact of preference can be expressed by two distinctive logit lines, i.e. there is a difference in the percentage of persons using their AC-units at the same outdoor temperature of up to 40% (see also Schweiker and Shukuya, 2008a).

In reality, the occupant behaviour must be influenced by quite a large number of factors, both external and internal. This chapter describes an empirical determination of the external and individual factors and their constants for models to predict the air-conditioning usage in a residential setting under Japanese climatic conditions.

6.2 Methodology

6.2.1 The Data Base Used for the Investigation

The database used for the present investigation came from two measurements in the same international student dormitory as described in Chapters 4.2 and the procedure described in Chapter 5.2. The two measurements were conducted around the hottest weeks of Japanese summer from 29 June to 13 August 2007 and the coldest weeks of winter, from 11 January to 11 February 2008. Figure 34 shows the frequency of the prevailing outdoor air temperatures for both summer and winter.
Table 12. Country of origin of the students participating in the physical measurement in wintertime.

<table>
<thead>
<tr>
<th></th>
<th>Number of students</th>
<th>Number of countries</th>
<th>Students per country</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asia</td>
<td>17</td>
<td>10</td>
<td>1.7</td>
</tr>
<tr>
<td>Europe</td>
<td>12</td>
<td>8</td>
<td>1.5</td>
</tr>
<tr>
<td>North America</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Oceania</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>South America</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

Fig. 34. Distribution of outdoor air temperature during the summer measurement in 2007 and that during winter in early 2008.
The summer measurement is the same as described in Chapter 5.2 in which 39 students participated. In the winter measurement 34 students took part of which 53% also participated in summer. Their country of origin is shown in Table 12. The four-week winter measurement garnered 22,080 data sets for each room including the air temperature, the humidity and the period of open windows together with the length of the openness.

This was achieved with a sensor, as shown in Figure 35, which is different from the one developed for the summer measurement as described in Chapter 5.2.2. The new sensor consisted of a 50cm long linear potentiometer (see Spectrasymbol, 2007), which is a type of variable resistor, and a button. The potentiometer is placed on one side of the window and the button is placed on the other side. The button is always in contact with the potentiometer so that there is a constant current. Depending on the position of the button on the potentiometer, the resistance of latter differs and thereby does the current. A voltage meter was used again to log the change in the current.

Fig. 35. Elements and set-up of the window sensor used for the winter measurement.
While the time of opening and closing of the windows could be read using the data from the second wireless sensor directly, the time of the usage of AC-units could not be recorded by any sensor. In order to obtain these values, the measured indoor and outdoor air temperature and absolute humidity was compared as described in Chapter 4.4.2. Due to the relatively small volume of the rooms, especially the observation of the difference in absolute humidity between indoors and outdoors made it possible to identify the times of AC-unit usage with such accuracy that only periods of less than five minutes were not observable. The data of four students reporting the existence of other heating devices during the winter measurement were excluded from the presented analysis.

The model development consisted of three steps, resulting in models called standard, advanced and final models for winter and summer season, respectively.

For the standard models, the use of the AC-unit for cooling and heating in relation to the mean outdoor air temperature was analysed using the logit model (Finney, 1964), with

![Graph](image)

**Fig. 36.** Difference from one night to the other in the percentage of persons using AC-units during the summer measurement from 30 June to 1 August, despite similar average outdoor air temperatures.
reference to the recently published papers on occupant behaviours by Rijal et al. (2007) and Haldi and Robinson (2008). The analysis was done again for the whole day period of 24 hours, and then for three different periods within the day, namely daytime (8am to 6pm), evening (6pm to 12am) and night-time (12am to 8am). The parameters of the model were calculated with the statistical software package R (R Development Core Team, 2005) as a function of the mean outdoor air temperature, based on the two-minute data points of the respective period of time.

The starting point for the advanced models was Figure 36, which shows the average outdoor temperature during night-time for most of the six-week summer period and also the percentage of persons using the AC-unit for ten nights whose mean outdoor temperatures were from 21.5°C to 22.2°C. Despite the fact that the outdoor air temperatures during these randomly-distributed nights were more or less the same, the reactions of the occupants showed considerable differences. The same was true for ten similar nights in winter. Therefore, the analysis described as follows was conducted in order to see whether these differences are random or if they can be explained by factors other than the outdoor air temperature during the night in question.

The general form of a logistic model is expressed as follows:

$$p_{log} = \frac{1}{1 + e^{-\alpha + \sum \beta_j x_j}}$$  \hspace{1cm} (7)

where, $p_{log}$ is the probability that the AC-unit is used, $T_{av}$ is the mean outdoor temperature of the respective night, $x_i$ are additional factors and $\alpha, \beta_i$ as well as $\beta_j$ are constants to be determined by statistical analysis. The simplest model, which was used for the standard model, is the one with a single parameter of mean outdoor temperature only, namely the model with $\beta_j = 0$ except for $j=1$. For the advanced models, more complex models needed to be set up, though retaining simplicity. To find such moderate models, Pearson’s correlation coefficients for the AC-unit usage during night-time with respect to various external factors were calculated first. Those factors having a coefficient signalling an above-average linear relationship with the AC-unit usage, shown in Table 13 were used as the starting point for the selection process of a rational statistical model.

As the decision criterion during the selection process, Akaike Information Criterion (AIC), which was developed for model selection not for hypothesis testing, was used to determine whether the alternative model is better than the current model. The AIC is based on the
Table 13. Percentage of persons using AC-units and its correlation coefficient values with respect to time-averages of outdoor air temperature.

<table>
<thead>
<tr>
<th></th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Variance</th>
<th>Pearson Correlation Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of Persons using AC-unit</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Summer</td>
<td>11.1</td>
<td>33.3</td>
<td>20.7</td>
<td>37.2</td>
<td>1.00</td>
</tr>
<tr>
<td>Winter</td>
<td>45.5</td>
<td>61.8</td>
<td>56.0</td>
<td>40.1</td>
<td>1.00</td>
</tr>
<tr>
<td>Maximum during daytime (^1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Summer</td>
<td>23.8</td>
<td>29.2</td>
<td>25.4</td>
<td>3.3</td>
<td>0.66</td>
</tr>
<tr>
<td>Winter</td>
<td>3.3</td>
<td>10.0</td>
<td>6.9</td>
<td>4.1</td>
<td>-0.050</td>
</tr>
<tr>
<td>Mean during daytime</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Summer</td>
<td>22.5</td>
<td>26.6</td>
<td>24.2</td>
<td>1.8</td>
<td>0.68</td>
</tr>
<tr>
<td>Winter</td>
<td>2.2</td>
<td>7.2</td>
<td>4.9</td>
<td>2.3</td>
<td>-0.60</td>
</tr>
<tr>
<td>Minimum during daytime</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Summer</td>
<td>20.6</td>
<td>24.0</td>
<td>22.58</td>
<td>1.4</td>
<td>0.73</td>
</tr>
<tr>
<td>Winter</td>
<td>1.3</td>
<td>4.4</td>
<td>2.5</td>
<td>1.7</td>
<td>-0.45</td>
</tr>
<tr>
<td>Maximum during evening (^1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Summer</td>
<td>22.0</td>
<td>26.4</td>
<td>24.0</td>
<td>1.6</td>
<td>0.53</td>
</tr>
<tr>
<td>Winter</td>
<td>1.7</td>
<td>7.8</td>
<td>3.8</td>
<td>3.7</td>
<td>-0.79</td>
</tr>
<tr>
<td>Mean during evening</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Summer</td>
<td>21.6</td>
<td>24.1</td>
<td>23.1</td>
<td>0.5</td>
<td>0.52</td>
</tr>
<tr>
<td>Winter</td>
<td>1.2</td>
<td>6.9</td>
<td>2.8</td>
<td>3.4</td>
<td>-0.76</td>
</tr>
<tr>
<td>Mean one night before</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Summer</td>
<td>19.6</td>
<td>22.1</td>
<td>26.0</td>
<td>3.3</td>
<td>0.78</td>
</tr>
<tr>
<td>Winter</td>
<td>1.0</td>
<td>4.7</td>
<td>1.8</td>
<td>2.1</td>
<td>-0.33</td>
</tr>
<tr>
<td>Mean one day before</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Summer</td>
<td>20.5</td>
<td>23.1</td>
<td>26.8</td>
<td>3.0</td>
<td>0.67</td>
</tr>
<tr>
<td>Winter</td>
<td>1.2</td>
<td>9.3</td>
<td>5.9</td>
<td>5.1</td>
<td>-0.47</td>
</tr>
<tr>
<td>Mean two nights before</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Summer</td>
<td>19.2</td>
<td>24.6</td>
<td>22.2</td>
<td>2.9</td>
<td>0.53</td>
</tr>
<tr>
<td>Winter</td>
<td>-0.2</td>
<td>3.3</td>
<td>1.7</td>
<td>1.6</td>
<td>0.06</td>
</tr>
<tr>
<td>Mean two days before</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Summer</td>
<td>19.1</td>
<td>26.7</td>
<td>23.3</td>
<td>6.2</td>
<td>0.39</td>
</tr>
<tr>
<td>Winter</td>
<td>1.2</td>
<td>7.2</td>
<td>5.2</td>
<td>3.4</td>
<td>-0.53</td>
</tr>
<tr>
<td>Mean three nights before</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Summer</td>
<td>18.0</td>
<td>26.0</td>
<td>21.9</td>
<td>6.0</td>
<td>0.61</td>
</tr>
<tr>
<td>Winter</td>
<td>0.1</td>
<td>4.5</td>
<td>2.2</td>
<td>2.0</td>
<td>-0.57</td>
</tr>
</tbody>
</table>

\(^1\) daytime is from 8:00 to 18:00; evening is from 18:00 to 0:00.
concept of entropy in the information theory by offering a relative measure of the information lost when a given model is used to describe reality and is calculated by

\[ AIC = 2K - 2 \ln(L) \]  
(8)

with \( K \) being the number of parameters and \( L \) the maximized likelihood value of the estimated model (Akaike, 1973). The formula itself represents the basic concept underlying its development, namely the compromise between precision and the complexity of the model. In other words, the AIC is calculated by taking into account the fit between the model and the data together with the number of variables used in the model.

The AIC is beside the Bayesian Information Criterion (BIC) the most commonly used penalized model selection criterion, which were developed because standard tests are unsuitable for comparing models and provide little guidance to judge between different nested and non-nested models (Kuha, 2004). While the BIC is used in order to find the real model, which perfectly describes the reality, the AIC is based on the assumption that there is no real model, but one model best describing the data gathered (Burnham and Anderson, 2004). Additionally, the AIC can lead to models with more parameters than the BIC. It was decided to use the AIC, since the scope was the development of a model representing the data gathered in one building and the purpose was to have a look at various possible factors and their impact on occupant behaviour.

The lowest AIC-value is supposed to be calculated for the model, which best describes the measured data with the minimum number of variables necessary. When comparing two models, only the absolute difference \( \Delta AIC \) between their AIC values should be evaluated and not the absolute values. In order to define one model as being better than the other, \( \Delta AIC \) should be greater than 2 (Burnham and Anderson, 2004). Because of quite a few possible combinations of variables to define a model, the “stepAIC” function within the software R, which automatically selects the model with the smallest value of AIC, was used (Venables and Ripley, 2002). Additionally, Nagelkerke’s \( R^2 \) index, which was adapted to mimic the \( R^2 \) analysis for logistic regression (Nagelkerke, 1991), was calculated to have a second index when comparing the different models.

For the final models, having the same form as shown in eq. (7), the advanced models were amended with individual factors in order to show their influence on the behaviour of AC-unit usage at night-time following the findings so far as presented in Chapter 4 and in Schweiker and Shukuya (2008b). For a first overview, the students were divided into two groups according to their usage of AC-units. The first group consisted of those using their AC-unit
more often than average and the second group of those using their AC-units less often than average. The former group was called “A” and the latter group “B”. Taking the data on the individual factors from the survey, it was analysed whether or not they are related to the difference in AC-unit usage.

Due to the fact that none of the students grew up in Japan, it was possible to group them into different climate groups related to their region of origin. This was called “thermal background”. Using the climate map of Koeppen (Kottek, 2006), they were sorted into four groups: hot and dry, hot and humid, moderate, and cold climates. No student originated from a polar climate region, the fifth type of climate defined by Koeppen.

The “stepAIC” function was used again in order to reduce the number of variables implemented into the logit model for predicting the percentage of AC-unit usage in relation to external and individual factors.

To cross check the selection process performed by the automatic procedure of the statistical software, factors presented in Table 13 were manually added and it was also tried to reduce the number of factors further, e.g. by disregarding the mean outdoor temperature of the night before. This lead in all cases to a higher AIC-value and demonstrated the validity of the automated selection process.

<table>
<thead>
<tr>
<th>Table 14. 2 x 2 table according to Cornfield (1951).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposed</td>
</tr>
<tr>
<td>Unexposed</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 15. Values of the Logistic Regression Model.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Independent variable (X)</td>
</tr>
<tr>
<td>------------------------</td>
</tr>
<tr>
<td>Exposed (x = 1)</td>
</tr>
<tr>
<td>p(1) = ( \frac{e^{b_1+b_0}}{1 + e^{b_1+b_0}} ) (A)</td>
</tr>
<tr>
<td>Unexposed (x = 0)</td>
</tr>
</tbody>
</table>
6.2.3 Explanation of Odds Ratio

In Chapter 6.5 below, the odds ratio is used to compare different models. Some explanations of the concept of odds ratio shall be given here in order to facilitate the interested reader the application to their own datasets.

The difference between “odds” and probability is as follows: Taking the case, one gambles for money, the probability to win is 1/3, and that to loose 2/3, then the odds to win is 2 and the odds to loose is 1 (Allingham, 2002).

In general, the odds of success is defined as

\[
\text{odds (success)} = \frac{p}{q},
\]

with p being the probability of success and q the probability of failure (q = 1 – p).

The odds ratio (OR) is a popular measure of the strength of association between exposure and disease and is expressed as the ratio of the number of cases (successes) to the number of non-cases (failures) in two different groups (e.g. the exposed and unexposed groups) and can be expressed as

\[
\text{OR} = \frac{\text{odds (success exposed)}}{\text{odds (success unexposed)}} \quad (\text{Hailpern and Visintainer, 2003}).
\]

Another way of calculating the odds ratio was introduced by Cornfield (1951), who introduced a 2 × 2 table such as Table 14 for this method. Implementing eq. (9) into eq.(10) and using the letters given in brackets in Table 14, the OR can be calculated as follows:

\[
\text{OR} = \frac{\text{odds (success exposed)}}{\text{odds (success unexposed)}} = \frac{\frac{p_e}{q_e}}{\frac{p_u}{q_u}} = \frac{\frac{A}{B}}{\frac{C}{D}} = \frac{A \times D}{B \times C}.
\]

In case of logistic regression analysis, the independent variable, \( x \), is set in relation to a dependent variable \( y \) in the form of:

\[
y = \frac{e^{b_0 + b_1 x}}{1 + e^{b_0 + b_1 x}},
\]

which is just another way of presenting eq. (3) or (7) given above. Parallel to Table 14, the possible values of the logistic probabilities are shown in Table 15.
Following the same procedure as shown before, i.e. replacing the letters in eq. (11) with the probabilities presented in Table 15, leads to:

\[
\text{OR} = \frac{\left(\frac{e^{b_1}}{1 + e^{b_1}}\right) \times \left(\frac{1}{1 + e^{b_1}}\right) \times \left(\frac{1}{1 + e^{b_1}}\right) \times \left(\frac{e^{b_1}}{1 + e^{b_1}}\right)}{\left(\frac{1}{1 + e^{b_1}}\right) \times \left(\frac{e^{b_1}}{1 + e^{b_1}}\right) \times \left(\frac{1}{1 + e^{b_1}}\right) \times \left(\frac{1}{1 + e^{b_1}}\right)}
\]

\[
= \frac{e^{b_1}}{e^{b_1}}
\]

\[
= e^{b_1}
\]

Therefore, the relationship between the odds ratio and the regression coefficient is for logistic regression analysis

\[
\text{OR} = e^{b_1} \quad \text{(Hosmer and Lemeshow, 2004).}
\]

6.3 Differences in the Usage of the AC-unit between Different Periods of the Day and Seasons – the Standard Models

Figure 37 shows the relationship between the average outdoor air temperature and the percentage of persons using the AC-units for cooling. Each plot represents the average of all students for each of the 43 measured days in summer. The lines represent the best-fit of the raw data and are similar to those presented in the foregoing studies for window opening behaviour (Haldi and Robinson, 2008; Rijal et al., 2007). Compared to the curve presented by Nicol and Humphreys (Nicol and Humphreys, 2004), where the value of temperature resulting in half of the persons using AC-units \((T_{50})\) is around 29°C, a similar value was revealed for the case of daytime, but a much lower value of \(T_{50}\) 23 to 26°C for all other periods of the day, which in turn means a more frequent use of the AC-unit.

Looking at the difference between the times of the day, it is clearly visible that the AC-unit is used more during night-time than daytime. This can be explained by the lifestyle of the students, who have to leave their rooms in order to go to university or work. Due to the circumstances of this study that the real occupancy was known only for the night-time, the lines for other periods must be too low if one assumes an occupancy rate of 100%. For the
prediction of a similar type of building, these lines can be used as combination of occupancy and behaviour. The analyses of all other models to be described later were based only on the night-time period, where the true occupancy rate was known.

Figure 38 shows the logit lines for the heating case. While the logit curve presented by Nicol (2001) for heating with general heating devices approaches 100% around a value of mean outdoor temperature of 2°C, the curves shown here are much flatter. Especially the flatness of the curve for the night period shows that around 40% of people sleep without any heating system regardless of the outdoor temperature and adjust themselves with additional layers of clothes and blankets. This statement can be partly supported by the answers given to the questionnaire survey. The question whether one prefers to sleep in a room a) heated with an AC-unit, b) heated with other means than an AC-unit or c) not heated at all, was answered by more than 33% of the students with c). This number is a bit lower than the 40% obtained from the measured data, but still in the same range.

![Figure 37](image)

Fig. 37. Relationship between outdoor air temperature and percentage of persons using AC-units for the case of cooling in summer time. The outdoor air temperature is the value for respective period as shown inside the graph. The thin dotted lines along with the bold lines in between show the limits of the 5% confidence interval of the respective line.
By comparing Figures 37 and 38 it can be seen that the percentage of AC-unit usage is much more dependent on the outdoor conditions during summer time than winter time. The most obvious reason is the greater possibility of clothing adjustment during wintertime than in summer time, although clothing adjustment was not part of the survey. Further reasons are the special conditions within this dormitory, which has in general a higher indoor temperature than other buildings due to the high density of people, lights and electronic appliances as shown for the summer case already in Table 6 of Chapter 5.2 (p. 63). The latter reason also applies to the comparison with the logit lines presented by Nicol and Humphreys (2004).

Fig. 38. Relationship between outdoor air temperature and percentage of persons using AC-units for the case of heating in wintertime. The thin dotted lines along with the bold lines in between show the limits of the 5% confidence interval of the respective line.
6.4 The Usage of AC-Units in Relation to Outdoor Air Temperature during Night-Time – the Advanced Models

The following results were derived from a closer look at the decision to sleep with the AC-unit on or off. This was in particular interesting to investigate, as it is a decision made before knowing how the thermal conditions will change during the sleeping period and results in a different amount of exergy consumption for cooling and heating during each period.

The standard model can be expressed by

$$P_{\text{logStandard}} = \frac{1}{1 + \alpha e^{-k T_{\text{ov}}}}.$$

(14)

According to the statistical analysis of various external factors and their influence on the AC-unit usage, the best prediction was achieved by considering the mean outdoor air temperature of the night in question $T_{\text{ov}}$, the mean outdoor temperature of the first and third night before, $T_{\text{ov} - n1}$, $T_{\text{ov} - n3}$, and only for the winter case the mean outdoor temperature during daytime just before the night in question $T_{\text{ov} - \text{dt}}$. The corresponding advanced model can be expressed by

$$P_{\text{logAdvanced}} = \frac{1}{1 + \alpha e^{-k (T_{\text{ov}} + T_{\text{ov} - n1} + T_{\text{ov} - n3} + T_{\text{ov} - \text{dt}})}}.$$

(15)

The omission of the second night before the night in question in these models looks a bit illogical and irritating, but might be due to the co-linearity between the temperatures of consecutive days, which is supported by a medium Pearson correlation coefficient between the night before and two nights before (0.48) and a large one between two nights before and three nights before (0.63). In order to overcome this irritation, further models including different types of various running means (see CEN, 2007; Fanger, 1970) were compared according to their AIC-values and Nagelkerke's $R^2$-values. It was found that an exponentially weighted running mean of the outdoor air temperatures during night, $T_{\text{mean}}$, expressed by

$$T_{\text{mean}} = α (T_{\text{ov}} + α T_{\text{ov} - n1} + α^2 T_{\text{ov} - n2} + α^3 T_{\text{ov} - n3} + ... )$$

(16)

with the value of $α$ being 0.5 leads to the best models according to above criteria. The corresponding mean model can be expressed by

$$P_{\text{logMean}} = \frac{1}{1 + \alpha e^{-k T_{\text{mean}}}}.$$

(17)
Table 16. Comparison of standard and advanced models to predict the percentage of persons using their AC-units during night-time in summer and winter.

<table>
<thead>
<tr>
<th></th>
<th>α</th>
<th>β₁</th>
<th>β₂</th>
<th>β₃</th>
<th>β₄</th>
<th>AIC²)</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Summer</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>9369±2.0</td>
<td>0.37±0.03</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1550</td>
<td>0.177</td>
</tr>
<tr>
<td></td>
<td>(&lt;0.001)³)</td>
<td>(&lt;0.001)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Advanced</td>
<td>47058±2.2</td>
<td>0.26±0.04</td>
<td>0.11±0.04</td>
<td>0.07±0.03</td>
<td>–</td>
<td>1538</td>
<td>0.190</td>
</tr>
<tr>
<td></td>
<td>(&lt;0.001)</td>
<td>(&lt;0.001)</td>
<td>(0.01)</td>
<td>(0.03)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>56392±2.2</td>
<td>0.45±0.03</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1534</td>
<td>0.191</td>
</tr>
<tr>
<td></td>
<td>(&lt;0.001)</td>
<td>(&lt;0.001)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Winter</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>0.888±0.1</td>
<td>-0.03±0.04</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1250</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>(0.21)</td>
<td>(0.44)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Advanced</td>
<td>0.657±0.2</td>
<td>0.02±0.04</td>
<td>-0.02±0.04</td>
<td>-0.04±0.03</td>
<td>-0.05±0.04</td>
<td>1252</td>
<td>0.007</td>
</tr>
<tr>
<td></td>
<td>(0.04)</td>
<td>(0.76)</td>
<td>(0.63)</td>
<td>(0.27)</td>
<td>(0.21)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>0.833±0.1</td>
<td>-0.06±0.05</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1249</td>
<td>0.002</td>
</tr>
<tr>
<td></td>
<td>(0.11)</td>
<td>(0.21)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

¹) All of βᵢ are related to the mean outdoor temperature: β₁ for respective night in case of standard and advanced model and for the exponentially weighted running mean for the mean model; β₂ for one night before; β₃ for three nights before; β₄ for daytime

²) ΔAIC for summer: |1550.0 – 1534.3 | = 15.7; ΔAIC for winter: |1250.1 – 1249.1 | = 1

³) The numbers in brackets show the significance levels of the respective variable. However, they are not used to judge whether a variable is included in the models (see Kline (2005) for a summary of the debate about statistical test). The measures used for this judgement were the AIC-value and Nagelkerkes-R² index as described in Chapter 6.2.2.

Fig. 39. Logit lines for the case of cooling and heating with the AC-units for the group using them more often than average (group A) and less often than average (group B) together with the average usage during night time for summer (right) and winter (left). The dotted lines show the variation in probability distribution of individual occupants.
Table 16 shows the corresponding values of constants ($\alpha$, $\beta_1$-$\beta_i$) and the comparison between the standard models, the advanced models, and the mean models. The advanced model for the summer case shows a better fit to the measured data compared to the standard model; the difference in AIC value, $\Delta$AIC, is 12 and also the $R^2$-index is a little bit higher, even though it is still very low. However, the mean model can be regarded as the best model, because both, AIC and R2-index are having the best values. The $\Delta$AIC between advanced and mean model is 4, which is enough to declare the mean model as being better.

In the case of winter, the advanced model has a little higher AIC value compared to the standard model and the mean model a little lower AIC, meaning it is a bit better. However, it is not possible to conclude which model describes the data better, since the differences in AIC values between standard and advanced model, 2, as well as between standard and mean model, 1, are too small. The $R^2$-index is also extremely small. Nevertheless, it was decided to use the mean model also for winter due to reasons of contingency.

6.5 Individual Factors Influencing the Usage of AC Units – the Final Models

Figure 39 shows the logit lines for group A, consisting of those using their AC-unit more than average, and group B, consisting of those using their AC-unit less than average, in the cases of cooling and heating with the AC-unit. Additionally, some lines representing the variety of individual behaviour patterns are presented. The difference in the percentage of AC-unit use between the two groups exceeds 55%-points for the conditions of outdoor temperature of 5°C in winter and 25°C in summer. Additionally, the odds ratio for the two groups, which is an index to measure how different they are, was calculated. In case of logistic regression, the odds ratio is the value of e (Napier number) powered by the logistic coefficient alone as described above. In this case the temperature-adjusted odds ratio for group A versus group B is 11.98 for winter and 11.76 for summer. This means that at the same outdoor air temperature the odds of someone belonging to group A using the AC-unit is 11 times higher than the odds of someone belonging to group B using the AC-unit; namely, there is a clear difference between both groups.

The results of the analysis to get a first overview, which individual factors are possibly influencing on the AC-unit usage behaviour, are displayed in Figure 40. The horizontal bars indicate the difference in the percentage of the persons between groups A and B for the respective individual factor. A bar in the left of the centre shows that more persons in group B have a positive relation to a certain individual factor, while on the other hand, a bar in the right shows the opposite, namely more in group A have a positive relation to that corresponding factor. For example, according to the factor “prefer working with AC-unit”
Fig. 40. Difference in the surveyed individual factors between groups A and B.
shown at the top, those in group A prefer working with the AC-unit compared to those in
group B both in summer and in winter and also use their AC-units more often. The largest
differences between both groups are seen in the individual factors such as “a) Preference”
and “b) Subjective evaluation of effectiveness”.

These factors were used as starting point for the final models, which therefore include the
running mean of the outdoor air temperature as already shown in eq. (17), (βi), and several
individual factors, (βj - βk), and can be expressed by

\[ P_{\text{logfinal}} = \frac{1}{1 + \alpha e^{-\beta_j \text{temp} + \beta_k \text{hum} + \beta_l \text{sun} + \ldots + \beta_n \text{wind} - d}} \]  

(18)

The variables and parameters of the final models for summer and winter resulting out of
the multivariate logistic regression analysis are shown in Table 17 and Table 18 respectively.
They will be discussed below in the order they are presented in Figure 40.

The “a) preference” of the AC-unit either for working or for sleeping leads to a higher
usage both in summer and winter. This is consistent with previous findings presented in
Chapter 4 and in Schweiker and Shukuya (2008b) and may be related to a shift of the
reference level. Someone for whom natural light is very important might have in general the
curtain wider open than someone for whom it is not so important, so that it seems to be
logical that this person needs more cooling by the AC-unit in summer and less heat in winter,
because of a rather large amount of solar heat gain at least during the daytime.

In the group of “b) subjective evaluation of effectiveness”, which means the effect of
actions such as switching on AC-units one expects to have on thermal comfort, also seems
logical. Someone who believes that the AC-unit provides more comfort also uses it more
often. In winter, it looks somewhat illogical, since the result is that someone who believes an
open window provides him with more comfort will use the AC-unit more often. This might
be due to the fact that the room gets colder in general by the opened windows and thereby
results in a higher usage of the AC-unit at night-time.

The influence of “c) current thermal environment” in workspace looks logical in summer,
since the result shows that a person being used to a conditioned space during daytime will
have a lower reference level of temperature than a person working in a non-conditioned
space and will therefore be more likely to use the AC-unit at night-time. But it looks illogical
in winter, since the model states the opposite as described in the result of b).

Looking at “d) thermal background”, it can be seen that, in summer, those originating
from hot and dry as well as from moderate climates seem to need less cooling, while those
from hot and humid as well as cold climates seem to need a bit more. Since those from hot
and dry as well as moderate climates are normally used to a wider range of temperature and
Table 17. Factors, coefficients for the logit model usable to predict the percentage of persons using their AC-unit during night-time in summer, and importance values (AIC of the model = 1195.9, Nagelkerke’s $R^2 = 0.48$).

<table>
<thead>
<tr>
<th>Coefficient and estimated standard error</th>
<th>Importance value$^1$</th>
<th>Rank$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$ $7.361\times10^{-2} \pm 1.29$</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Factors leading to a higher usage of the AC-unit

| T) Running mean of outdoor air temperature at night | $\beta_1$ $0.581\pm0.04$ | 5.81 | 1 |
| a) Prefer sleeping with AC-unit on | $\beta_6$ $1.852\pm0.25$ | 1.85 | 4 |
| Natural light is very important | $\beta_7$ $1.157\pm0.28$ | 1.16 | 10 |
| b) Switching on the AC-unit leads to more comfort | $\beta_8$ $2.316\pm0.57$ | 2.31 | 3 |
| c) Current workspace is always cooled | $\beta_{11}$ $1.940\pm0.24$ | 1.94 | 5 |
| e) AC-unit used at home during childhood | $\beta_{16}$ $0.471\pm0.33$ | 0.47 | 14 |
| f) Originating from Middle Eastern country | $\beta_{20}$ $0.485\pm0.27$ | 0.49 | 16 |
| g) Male | $\beta_{23}$ $1.887\pm0.35$ | 1.89 | 6 |
| h) South orientated window | $\beta_{27}$ $1.033\pm0.28$ | 1.03 | 11 |

Factors leading to a lower usage of the AC-unit

| b) | Switching on the AC-unit leads to less comfort | $\beta_9$ $-1.538\pm0.81$ | 1.54 | 9 |
| d) | Originating from a hot & dry climate | $\beta_{13}$ $-0.644\pm0.42$ | 0.64 | 12 |
| e) | Slept as child with window opened | $\beta_{18}$ $-0.608\pm0.22$ | 0.61 | 13 |
| f) | Originating from East-Asian country | $\beta_{21}$ $-0.278\pm0.27$ | 0.28 | 17 |
| h) | Living in the 1st floor | $\beta_{25}$ $-2.820\pm0.44$ | 2.82 | 2 |
| Living between 2nd and 4th floor | $\beta_{26}$ $-1.571\pm0.34$ | 1.57 | 7 |

$^1$ The importance value is the product of the absolute value of coefficient value and the range of the variables, which is from 0 to 10 for temperature related factors (T)) and 0 or 1 for other factors (a) to h)).

$^2$ The larger the importance value, the higher the rank is.

$^3$ The p-values of the coefficients are below 0.001 except for the following: $\beta_{16} : 0.15$; $\beta_{20} : 0.07$; $\beta_{24} : 0.08$; $\beta_9 : 0.06$; $\beta_{13} : 0.13$; $\beta_{18} : 0.01$; $\beta_{21} : 0.31$ (see also comment to Table 16).
humidity, their reference level might also be broader and they are able to adapt easier to the hot and humid conditions prevailing in Japanese summer. Those from cold climates seem to have problems of adapting due to their little experience of such conditions and therefore a lower reference level. Looking at hot and humid countries, the distribution of the AC-units is the highest around the world and because of this, they must be already accustomed to the use of AC-units and with this also their reference level got lower; this explains the higher usage by the students from those climates. In winter, those from moderate as well as from cold climates need less AC-units due probably to their lifelong experience of a little lower temperature and their lower reference level, while those from tropical countries have less experience with cold conditions, a higher reference level and therefore need more heat provided by AC-units.

The effect of “e) behavioural background”, which was taken out of the questions concerning the childhood of those students can also be seen; those who grew up much within an air-conditioned space in summertime still use it more often in Japan, while on the other hand, those who have more experience sleeping with an open window need the AC-unit less often. In winter, the same tendency can be seen for those who are used to a heated school environment versus those who slept with an open window. In general, it looks as if the way people grow up during their childhood affects their behaviour and reference level quite strongly.

The tendencies shown in Figure 40 and the coefficients in the statistical models given in Tables 17 and 18 of the factors related to “f) geographical background” are not always consistent, whereby the tendencies shown in Figure 40 seem to be more logical than those in the statistical model. This discrepancy might be explained by the close relationship between d) thermal background and f) geographical background, so that the coefficients for the factors related to geographical background might reduce overestimations due to the coefficients of thermal background.

Looking at “g) demographic factors”, males seem to use the AC-unit both in summer and in winter more often than their female colleagues, while those studying natural science use it a bit more frequent in summer but far less in winter, than their colleagues from the social sciences. These tendencies cannot be explained by the authors and need to be investigated with further research.

The characteristic found in relation to factors describing “h) individual characteristics of the rooms” is quite consistent with what one can expect from the micro-climatic conditions. Those who live in either the 2nd, 3rd, or 4th floor are more likely to be protected by the surrounding trees, which can shade solar radiation effectively and need the AC-units less often in summer. Those living in rooms orientated south need to use their AC-units more often in summer and less in winter due to the solar heat gain through windows.
Table 18. Factors, coefficients for the logit model usable to predict the percentage of persons using their AC-unit during night-time in winter, and importance values (AIC of the model = 799.9, Nagelkerke’s $R^2 = 0.56$).

<table>
<thead>
<tr>
<th>Coefficient and estimated standard error</th>
<th>Importance value$^1)$</th>
<th>Rank$^2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>0.015±0.03$^3)$</td>
<td>–</td>
</tr>
</tbody>
</table>

Variables leading to a higher usage of the AC-unit

<table>
<thead>
<tr>
<th>Variables</th>
<th>Coefficient $\beta$</th>
<th>Importance value $^1)$</th>
<th>Rank$^2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Prefer working with AC-unit on</td>
<td>$\beta_5$ 1.860±0.34</td>
<td>1.86</td>
<td>9</td>
</tr>
<tr>
<td>Prefer sleeping with AC-unit on</td>
<td>$\beta_6$ 0.115±0.71</td>
<td>0.12</td>
<td>18</td>
</tr>
<tr>
<td>b) Switching on the AC-unit leads to more comfort</td>
<td>$\beta_8$ 2.907±0.53</td>
<td>2.91</td>
<td>5</td>
</tr>
<tr>
<td>Opening window leads to more comfort</td>
<td>$\beta_{10}$ 2.599±0.47</td>
<td>2.6</td>
<td>7</td>
</tr>
<tr>
<td>d) Originating from a hot &amp; humid climate</td>
<td>$\beta_{12}$ 1.282±0.58</td>
<td>1.28</td>
<td>12</td>
</tr>
<tr>
<td>e) School was always heated during childhood</td>
<td>$\beta_{19}$ 1.728±0.41</td>
<td>1.73</td>
<td>10</td>
</tr>
<tr>
<td>g) Male</td>
<td>$\beta_{23}$ 1.921±0.40</td>
<td>1.92</td>
<td>8</td>
</tr>
</tbody>
</table>

Variables leading to a lower usage of the AC-unit

<table>
<thead>
<tr>
<th>Variables</th>
<th>Coefficient $\beta$</th>
<th>Importance value $^1)$</th>
<th>Rank$^2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>T) Running mean of outdoor air temperature at night</td>
<td>$\beta_1$ -0.120±0.06</td>
<td>1.2</td>
<td>16</td>
</tr>
<tr>
<td>a) Natural light is very important</td>
<td>$\beta_7$ -4.316±0.61</td>
<td>4.32</td>
<td>2</td>
</tr>
<tr>
<td>c) Current workspace is always heated</td>
<td>$\beta_{11}$ -1.111±0.36</td>
<td>1.11</td>
<td>13</td>
</tr>
<tr>
<td>d) Originating from a moderate climate</td>
<td>$\beta_{14}$ -2.881±0.55</td>
<td>2.88</td>
<td>6</td>
</tr>
<tr>
<td>Originating from a cold climate</td>
<td>$\beta_{15}$ -0.558±0.53</td>
<td>0.56</td>
<td>17</td>
</tr>
<tr>
<td>e) Slept as child with window opened</td>
<td>$\beta_{18}$ -0.837±0.35</td>
<td>0.84</td>
<td>15</td>
</tr>
<tr>
<td>f) Originating from East-Asian country</td>
<td>$\beta_{21}$ -3.468±0.55</td>
<td>3.47</td>
<td>4</td>
</tr>
<tr>
<td>Originating from European country</td>
<td>$\beta_{22}$ -4.144±0.73</td>
<td>4.14</td>
<td>3</td>
</tr>
<tr>
<td>g) Studying natural not social science</td>
<td>$\beta_{24}$ -4.443±0.53</td>
<td>4.44</td>
<td>1</td>
</tr>
<tr>
<td>h) Living in the 1st floor</td>
<td>$\beta_{25}$ -1.420±0.31</td>
<td>1.42</td>
<td>11</td>
</tr>
<tr>
<td>South orientated window</td>
<td>$\beta_{27}$ -0.924±0.35</td>
<td>0.92</td>
<td>14</td>
</tr>
</tbody>
</table>

$^1)$ The importance value is the product of the absolute value of coefficient value and the range of the variables, which is from 0 to 10 for temperature related factors (T)) and 0 or 1 for other factors (a) to h)).

$^2)$ The larger the importance value, the higher the rank is.

$^3)$ The p-values of the coefficients are below 0.001 except for the following: $\beta_6 : 0.87$; $\beta_{12} : 0.03$; $\beta_1 : 0.06$; $\beta_{15} : 0.29$; $\beta_{18} : 0.02$; $\beta_{27} : 0.01$ (see also comment to Table 16).
In order to be able to judge how much one factor in the model influences the AC-unit usage behaviour, one has to understand the structure of eq. (18). As shown in Figure 41, the outdoor air temperature of the night in question (x-axis) where the logit curves cross the horizontal line representing 50% of persons using the AC-unit can be called $T_{50}$. Having this in mind, the value of $\alpha$ determines the tangent of the curve at the point $T_{50}$, while the exponent of $e$ (Napier number) determines the distance of the point $T_{50}$ to the y-axis. While the value of $\alpha$ is constant within each model, the value of the exponent changes according to the factors. As can be seen in Table 17 the absolute value of the coefficient for “Running mean of outdoor temperature at night” is 0.581. If we extract the part of the mean outdoor air temperature one night before, this leads to a value of $(0.581 \times 0.25 = 0.145)$, which is much smaller compared to the one assigned to “Prefer sleeping with AC-unit on” (1.852). This would imply that the former is less influential than the latter.

Looking at the three example cases shown in Figure 41, it can be seen that the value of $T_{50}$ is 30.2°C in case a), 25.2°C in case b), and 23.9°C in case c). This means that 50% of those who like to sleep with the AC-unit on (case c) tend to switch on their AC-unit around 23.9°C while 50% of those who prefer not to sleep with the AC-unit on (case a) tend to switch on their AC-unit around 30.2°C. At the same time, if the mean outdoor temperature one night before was 30°C (case b), 50% of the latter group also tend to switch on their AC-unit around 25.2°C. The difference in the value of $T_{50}$ between cases a) and c) is 6.3 and the difference for the same value between cases a) and b) is 5.0. The effect of both factors on the horizontal position of the logit line is similar. Therefore the importance of one factor compared to the others can be calculated as the product of the absolute value of the coefficient (the respective value of $\beta$) and the range of the variable. This product was called the “importance value” and the validity of the presented models was set between temperatures of 0°C and 10°C in winter and 20°C and 30°C in summer. These represent 90% of temperatures prevailing during a typical year in the Tokyo area during night-time (Akasaka et al., 1999). Therefore the range of the temperature-related variables is 10. All other variables are binary meaning either 0 or 1 and their range is therefore 1.

Comparing the AIC values of the models, the difference in AIC values $\Delta$AIC between the advanced models and the final models as well as between the standard models and the final models are exceeding 300 in the case of summer and 400 in the case of winter. As stated above, a value of 2 is necessary to be able to declare one model as better than another, therefore the result shows that the advanced model leads to a much better prediction of the individual occupant behaviour by considering various individual factors. This is also supported by the $R^2$-indices that are both in a range between medium and large.
The results of summing up the importance values of the respective factors shown in Tables 17 and 18 are presented in Figure 42. Quite different results were found for summer and winter. In summer, the most important groups are “T) temperature related factors” (β₁), which is the running mean of the outdoor air temperature, and “h) individual differences in rooms”, while on the other hand, the least important are “e) behavioural background” and “f) geographical background”. In winter the most important are “f) geographical background” and “g) demographic data”, while the least important are “T) temperature related factors” (β₁) and “c) current thermal environment”. This shows that the external factors have a strong influence on the behaviour in summer, but a very small in winter. Similar findings are present in the design of the new European Standard EN 15251, where there is no further change in the comfort limits below an outdoor temperature of 10°C (CEN, 2007).

The sum of importance values of “T) temperature related factors” together with “h) individual differences in rooms” and that of all other factors turned out to be 11.2 and 13.1 for summer and 3.5 and 33.1 for winter, respectively. This shows that factors generating from experience, attitude and origin affect the reference level as much as the external conditions in summer and even much more in winter.

![Diagram](image)

Fig. 41. The meaning of the “importance value” obtained from the constants of the summer model given in Table 17.
6.6 Discussion on the Validity of the Results

Due to the indirect logging of the AC-units state, it was not possible to detect a usage lasting less than five minutes. For the winter case, this had no implications, because the period of use was at least 20 minutes long. In the case of the summer, three students stated during the interviews that they used their AC-units sometimes for periods of around 10 minutes just to cool the room air temperature until they feel comfortable again. The analysis of those student's data was done very carefully, but all such short usages may not have been identified. This implies that the usage might be a little higher in summer than stated. For the advanced and final models, this had no implication in either season, because during the sleeping periods, the state of the AC-unit was not changed frequently.

Despite a high variation in relative humidity between 46% and 99% during the measurement period, the tested factors concerning humidity, namely the mean relative humidity of the respective night, the evening and daytime before as well as the night beforehand, did not show any linear or other correlations with the usage of the AC-unit.

Fig. 42. Comparison of the sum of importance values of the respective factors given in Tables 17 and 18.
Additionally, the Pearson correlation coefficient between the mean outdoor air temperature and the humidity is 0.39 for the measured data and therefore only medium. In addition to the above presented aggregated logistic regression analysis, i.e. all data were taken together, an individual analysis was performed for the data of each student using the AC-unit in order to analyse whether the omission was caused by the methodology. Half of the 30 individual models showed a negative relation with humidity, i.e. the lower the humidity, the higher the usage of the AC-unit and the coefficient for humidity of those models showing a positive relationship between humidity and the outdoor air temperature had only in five cases a significance level lower than 0.1. Therefore, according to the statistical analysis, humidity can be disregarded, which is also supported by the analysis concerning the purpose of behaviour presented in chapter 3, where humidity was stated as reason for less than 20% of the cases. This signifies that the need to use the AC-unit does not derive out of humidity alone, which can easily be proven when looking at the winter case with relative humidities above 80% not feeling humid. Moreover other studies suggest that only the combination of humidity together with a mean temperature of the surrounding surfaces (MRT) and a low air current leads to a feeling of discomfort (see e.g. Iwamatsu et al, 2008).

A further comment should be given to the statistical analysis based on logistic regression. Using this method, it was assumed that all observations are independent from each other. Nevertheless, the data was derived from 39 individuals, whose behaviour was influenced by their own personality, preferences and habits. This means that probably not all observations are independent. In order to justify the results, the same analyses as presented above were done for small data sets consisting solely of one observation for each student chosen randomly. The following points have been confirmed by these sub-datasets, which are consistent with the main findings presented above:

- The $R^2$-indices get larger from the standard to the final model.
- The best model chosen by the stepAIC-function consists of a combination of temperature related factors and individual factors, even though the total number of factors was reduced, because the AIC-criterion favours a much smaller model than the final model presented above due to the smaller amount of data.
- The importance of the individual factors compared to the external factors is much higher in winter than in summer.
6.7 Conclusions

What was found due to the presented analyses focusing on the occupant's behaviour is summarized as follows.

1) Following the general approach to set the occupant's behaviour in relation to the outdoor air temperature, the results were reasonable for the usage of the AC-unit both for heating and cooling.

2) Among the influence of other physically measurable factors such as humidity, maximum and minimum air temperatures, and also the average values of air temperature of the preceding nights on the decision to sleep with the AC-unit switched on or off, the current temperature in combination with those prevailing in the preceding nights had the highest influence, which is consistent with some results presented in Chapter 4. On the other hand, humidity was found to have a negligible influence on the decision to sleep with an AC-unit switched on or off.

3) As a trial for coming up with a more sophisticated model, which can be used to predict the AC-unit usage during night-time, individual factors were combined with the outdoor air temperature. It was found that the factors originating from experience, attitude and origin of the individual are affecting the AC-unit usage behaviour in summer in the same magnitude than external factors. In winter the individual factors affect the AC-unit usage much more than the external factors.

4) Even though the statistical model described here is based solely on an intensive measurement of one building, and the results can hardly be generalized, the results support further assumptions of the theoretical model presented in Chapter 2 and may be consistent with such complex phenomena within the brain. Nevertheless, it is of course too early to state a concrete conclusion. Further investigations are necessary to improve and verify the theoretical model, which is to explain the empirical model in relation to human behaviour controlling the built environment.

5) The fact that the temperature values of the foregoing nights affect the usage of AC units according to the present statistical analysis looked consistent with the theoretical model proposed. Some assumptions of this theoretical model were further supported by findings of studies related to the occupant behaviour and thermal comfort.

6) Due to the particular conditions of this measurement and also the fact that the measurement was performed in only one building, the model might not be transferable to other circumstances without adjustments, but it is still interesting to
have been able to see the results that the influence of various individual factors sounds fairly logical. Therefore, further investigations on the real reasons behind the occupant behaviour are to be pursued more deeply.

The logging of the mean radiant temperature, air speed, clothing insulation and metabolic rate is not easy to measure without disturbing the occupants in their normal behaviour. As already mentioned, it is known that these factors affect on the thermal sensation (CEN, 2007; Fanger, 1970). It is therefore suggested that these factors should also be taken into consideration in the further research on occupant behaviour to be done in the future.
7 Comparison of Imagined and Real Behaviours

7.1 Introduction

Recently post-occupancy evaluation gets more common to compare simulated and real performances of so-called energy saving building components and building systems (e.g. Donn, 1999; Bulteau et al., 2007). In reality, the occupants have several choices how to achieve comfortable conditions, e.g. by switching on an air-conditioning unit (AC-unit) or opening a window. The decision and the resulting behaviour have a significant influence on the exergy balance of the building systems.

Measuring the occupants’ behaviour is cost- and time-consuming, due to the necessary instrument set-up, which may cause a difference from daily occupancy. In order to minimize cost and time, it would be favorable to use a method of survey alone to be able to evaluate the occupants’ behaviour. This would lead to building a broader database and knowledge about the occupants’ decision processes and hence helping to improve the above-mentioned choice and thereby to save a significant amount of exergy supplied and consumed for creating comfortable condition.

This chapter therefore discusses the reliability of the conclusions based on the answers found through surveys, which will be called the “imagined behaviour”, and a method to improve the outcome in order to have a higher consistence with the “real behaviour”.

7.2 Grouping Procedures

For this analysis the data from the survey and measurement in the dormitory building during summer 2007 as described in Chapter 5.2 were used. In order to compare the imagined behaviour stated in the questionnaire and the real behaviour, the students were divided into four groups labelled with “N”, “E”, “L”, and “A”.

Group “N” consists of those never using the AC-unit; when the conditions get unbearable, they prefer to stand the heat or change the place to stay; Group “E” are those using AC-unit only when the conditions get unbearable for them and other measures such as the use of a fan have failed; Group “L” are those trying not to use AC-unit, but are likely to use it before trying other strategies; and group “A” are those using AC-unit all the time, even when it should not be necessary.

This time the two grouping processes were done twice: first, based on the answers given in the questionnaire, resulting in a group of the “imagined behaviour”; and second, based on the data from the measurement, resulting in the other group of the “real behaviour”.
a) AC-unit usage: The use of the AC-unit was not necessary due to the fact that the average values of daily highest and lowest temperature were 24.1°C and 15.8°C respectively and the average value of relative humidity was 53% in the period of the questionnaire survey.

<table>
<thead>
<tr>
<th>Answer</th>
<th>Assigned Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Never</td>
<td>1</td>
</tr>
<tr>
<td>1 – 4 times</td>
<td>2</td>
</tr>
<tr>
<td>5 – 7 times</td>
<td>4</td>
</tr>
<tr>
<td>More than 7 times</td>
<td>4</td>
</tr>
</tbody>
</table>

b) Strategies to keep room cool during daytime: The number and type of stated strategies were judged. The more passive strategies were raised, the lower is the expected usage of AC-unit and therefore the smaller the assigned value.

<table>
<thead>
<tr>
<th>Answer</th>
<th>Assigned Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passive</td>
<td>1</td>
</tr>
<tr>
<td>Nearly passive</td>
<td>2</td>
</tr>
<tr>
<td>Passive or AC-unit</td>
<td>3</td>
</tr>
<tr>
<td>Only AC-unit</td>
<td>4</td>
</tr>
</tbody>
</table>

c) Strategies to keep room cool during nighttime: The number and type of checked strategies were judged as for question b).

<table>
<thead>
<tr>
<th>Answer</th>
<th>Assigned Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passive</td>
<td>1</td>
</tr>
<tr>
<td>Nearly passive</td>
<td>2</td>
</tr>
<tr>
<td>Passive or AC-unit</td>
<td>3</td>
</tr>
<tr>
<td>Only AC-unit</td>
<td>4</td>
</tr>
</tbody>
</table>

Fig. 43. Answers in the questionnaire and assigned values for the evaluation of “imagined behaviour” group.
7.2.1 Grouping of Imagined Behaviour

The grouping process resulting in the “imagined behaviour” group was based on the ways of answers given within the following three questions: those with regard to a) the frequency of AC-unit usage during the week before the survey, b) their strategies to keep their room cool during daytime in summer stated in an open-answer-type question and c) the strategies while sleeping checked in a multiple-choice-question. Figure 43 shows the percentage of the answers to these three questions.

Four integers were assigned as values from 1 to 4 as indicated in the middle of Figure 43 to respective answers in the three questions and then the non-weighted rounded up average of the three assigned values was calculated. Those students with the average of assigned values to be 1 are grouped in “N”, 2 in “E”, 3 in “L”, and 4 in “A”. In the process of determining the assigned values and possible weighting factors for the calculation of the average, it was assumed that “imagined” and “real behaviour” are congruent. Therefore, the combination of assigned values and calculation method as described above, which led to the highest consistency with the “real behaviour” group to be explained in the following section, was chosen.

7.2.2 Grouping of Real Behaviour

The grouping of the “real behaviour” was done in the same way as described in Chapter 5.3, so that each student was assigned to one of the four groups.

7.2.3 A Comparison of Imagined and Real Behaviours

Figure 44 shows the distribution of imagined and real behaviour groups after the above mentioned grouping processes. The difference is 15% at maximum and the average is 12%. Figure 45 shows the difference in the AC-unit usage between “imagined” and “real”. Only 42% behave the same in reality as imagined and most of the rest use their AC-units more often. One can say that “imagined” and “real” behaviours are not always congruent.

7.3 Optimisation of Grouping Procedure

In order to have a better understanding what Figures 44 and 45 imply and to find a higher congruence between “real” and “imagined behaviour” group, the grouping procedure of “imagined behaviour” group was modified with additional individual factors using a series of macros.

For this procedure, the previous calculated value of the “imagined behaviour” group was taken as step 1 (s1), because it combined the three most direct questions about the behaviour.
Fig. 44. Comparison of imagined and real behaviour groups after first grouping process (N=38).

Fig. 45. Difference in the AC-unit usage between “imagined” and “real” after first grouping process. In reality the air-conditioning unit is used more often than imagined (N=38).

Fig. 46. Comparison of imagined and real behaviour group after the six steps described (N=38).
to the highest consistency possible taking no further factor into account. Additional questions were analysed and categorized to individual factors and then each factor was considered as one step. All of these factors were examined by adding or removing and by changing their relative positions within the macro until no higher percentage of congruence between imagined and real behaviour groups was achieved. This optimisation procedure was done by hand, this means the algorithm of the macro was changed manually and not by using another program.

The above-mentioned procedure allowed testing different hypotheses about the effect of a certain factor. Though multiple factors result in numerous possibilities of combination, not all possible combinations have been tested. Therefore there is a small chance that the current result is not the best result achievable. Multiple regression analysis commonly used could not be used with the existing data due to the variety of factors and relatively small number of subjects.

Figure 46 shows the comparison of “imagined” and “real behaviour” group after the last grouping process. The difference turned out to be 3% at maximum and the average 2%. The congruence between “imagined” and “real behaviours” group is 82% as shown in Figure 47. What follows describes the additional individual factors in the step-order they appear in the macro, which resulted in this so far highest achievable congruence. The influence of each step on the congruence is shown in Figure 48.

The first factor added after the above described grouping process is the preference of AC-unit use during nighttime and is the single factor having the highest influence as can be seen in Figure 48 between s1 to s2. A person claiming to like the AC-unit usage at night time seems to use it more often than imagined and therefore is grouped into the next higher group if he or she belonged to group “N” or “E” (s2). No knowledge of passive strategies would not
allow a person to cope with the summer conditions in Japan without the use of the AC-unit. Therefore a person belonging to group “N” with no knowledge of passive strategies was placed in the next higher group (s3).

The “imagined effectiveness” on the personal comfort of a strategy is taken into consideration in two ways. A person believing that switching on an AC-unit makes it more comfortable is unlikely to be in group “N” and is therefore placed in group “E” (s4a). On the other hand, a person believing that switching on the AC-unit makes it less comfortable, but opening windows results in more comfort, will react this way more likely and was therefore placed in one group lower than just one step before (s4b).

The next factor is the AC-unit usage at home during childhood, which must have been mainly done by the parents. The influence of this factor is diverse. Someone who always slept with the AC-unit switched on is supposed to be used to it and therefore they were placed in group “L”, if they were in group “N” or “E” just one step before, or they stayed in group “A”. On the other hand, someone belonging to group “L” who slept sometimes during childhood with the AC-unit switched on, must still be able to judge whether it is necessary to use the AC-unit and therefore placed in group “E” (s5a). In the case the AC-unit was sometimes used at school and at home during childhood, the person again must have been exposed to the indoor environment controlled by the AC-unit more likely and was therefore placed in group “L”, if he or she was in group “E” one step before (s5b). Someone claiming that the AC-unit was not used at school or at home at all was placed in group “E”, if he or she was group “N”

![Development of consistency between imagined and real behaviour groups](image.png)

**Fig. 48.** Development of consistency between imagined and real behaviour groups. After each step the percentage of congruence increases, the average difference decreases.
(s5c). Finally, someone claiming that the AC-unit was always used at school and at home must regard the usage of an AC-unit as normal and therefore it was assumed that they use it automatically without consciousness. He or she was therefore placed in group “A” (s5d).

The combination of knowledge of passive strategies and climate in the home country is the next factor. A person having no or little knowledge of alternatives and originating from a cool climate according to the categorization of Koeppen (Kottek, 2006) will not be able to cope with the summer conditions in Japan so that he or she is placed in the next higher group (s6).

Finally a correction is done based on the frequency of usage and the strategies to cool the room during daytime. To balance prior placement, those who used the AC-unit in the week before the survey more than seven times and at the same time stated only to use the AC-unit to cool the room during daytime were placed one group higher than that in the step before (s7).

7.4 Conclusions

This chapter discussed a comparison of “imagined” and “real” behaviour of students living in an international student dormitory in Tokyo. A written survey and physical measurement was done and the behaviour stated within the questionnaire, which is called the “imagined behaviour”, and that performed in their rooms, which is called the “real behaviour” were analysed. According to the grouping process made first for imagined and real behaviours simply assuming that they are independent from each other, there were only 42% of the students who’s “imagined” and “real” behaviours agreed. Five individual factors: preference; imagined effectiveness of passive strategies; knowledge of passive strategies; AC-unit usage during childhood; and climate in their home country were then included in the grouping process and thereby the above percentage was raised up to over 80%. This implies that what they answer in the questions given in the questionnaire influence very much on the judgement of the real behaviour.

This result shows that imagined and real behaviour may differ quite far from each other. In order to have a good prediction of the “real” behaviour on the basis of a written survey only, it is useful to add individual factors. Furthermore, comparing the results presented in this chapter with those of Chapter 6, it can be seen that the same factors, such as preference for an air-conditioned space, have a significant influence on the behaviour. With two different ways of analyses leading to similar conclusions, the confidence in the obtained results must be elevated and the influence of individual factors on the behaviour got confirmed.
PART III
Influenceability of the Occupant Behaviour and its Reference Levels by Long- and Short-Term Experiences

第3部
長期経験と短期経験による行動変化の閾値の影響性

“Be very, very careful what you put into that head, because you will never, ever get it out.”

Thomas Cardinal Wolsey (1471-1530)
8 Cross-Cultural Comparison of the Factors Influencing on the Occupants Choice of Sleeping Conditions – the Effect of Long Term Experiences on the Reference Levels –

8.1 Introduction

The analyses presented in the foregoing chapters were based on the measurement and survey conducted in a dormitory building, i.e. one special type of building. The effects of thermal and behavioural background were shown, but the influences of the current thermal environment could not be analysed due to this limitation.

As mentioned above, the decision whether to sleep with an open or closed window and whether to keep the heating/cooling device on or off affects not only the health of the individual, but also the exergy consumed within the built environment.

Therefore this chapter focuses on differences in the sleeping behaviour resulting out of differences in the surrounding thermal built environment partly determined by the culture of the respective place as described below for the comparison between the concept of providing thermal comfort in Japan and Germany.

![Graph showing development of insulation level in Japan and Germany](image-url)

**Fig. 49.** Development of insulation level in Japan and Germany. Data for Germany (solid lines) for single-family buildings (IWU, 2003); data for Japan (dashed lines) for single-family buildings in region IV (e.g. Yokohama) (Iwamura et al., 2005).
For this analysis, first, a general comparison was made between participants from various countries or cultures with the hypothesis that there are some differences. In order to see if those differences are due to the variations in the climatic conditions or other factors, the behaviour of Japanese and Germans were compared. This comparison is interesting due to the above-mentioned differences in the concept of achieving thermally neutral conditions.

In Japan, the insulation level is low compared to German buildings as can be seen in Figure 49 for the example of typical single-family houses. The biggest difference is in the quality of the windows and the insulation level of the floor.

Regarding the way of providing heat in winter, there is traditionally a favour for rather small devices in Japan such as the “Kotatsu”, a combination of table and blanket with additional means for heating providing a comfortable neutral conditions for a limited space. At the same time, the room itself and other rooms of the building are minimally heated. Despite the fact that such devices are sold and used until these days, the distribution of air-conditioning (AC)-units, which can be used for cooling and heating, partly continues this concept by providing one room with coolness or warmth. According to a survey conducted by Tokyo Gas in the year 2005, 75% of the participants are using the AC-unit for heating. However, 90% of them are using other devices such as an electrically heated carpet, or the “Kotatsu” mentioned above in addition to the AC-unit, i.e. more than one heating device is used to provide local comfort (Tokyo Gas, 2009). Additionally, Fujii and Lutzenhiser (1992)

<table>
<thead>
<tr>
<th>Childhood residence</th>
<th>Current residence</th>
<th>N (winter)</th>
<th>N (summer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ni_ni</td>
<td>Japan</td>
<td>Japan</td>
<td>181</td>
</tr>
<tr>
<td>de_ni</td>
<td>Germany</td>
<td>Japan</td>
<td>41</td>
</tr>
<tr>
<td>de_de</td>
<td>Germany</td>
<td>Germany</td>
<td>224</td>
</tr>
<tr>
<td>ot_ni</td>
<td>Other 1)</td>
<td>Japan</td>
<td>75</td>
</tr>
<tr>
<td>ot_de</td>
<td>Other 1)</td>
<td>Germany</td>
<td>12</td>
</tr>
<tr>
<td>ot_ot</td>
<td>Other 1)</td>
<td>Other 1)</td>
<td>147</td>
</tr>
<tr>
<td>un</td>
<td>Unknown</td>
<td>Unknown</td>
<td>165</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>845</td>
</tr>
</tbody>
</table>

1) Other countries than Japan and Germany. Overall, these participants originated from 50 different countries and are living now in 35 countries, despite Japan and Germany. The largest groups originated from Portugal (17), USA (15), Spain (11), Malaysia (9) and are currently living in Spain (17), Portugal (14) and Switzerland (9).
found that even though 50% of the AC-units in Japan are equipped with the heating function, only 30% of those who have this function are using it. The other 70% reported to use other heating devices, such as portable heaters.

On the other hand, the heating concept of the average German house is based on a central unit, which is providing hot water to be circulated by pumps through so-called radiators in each room. These radiators distribute the heat partly by convection and partly by radiation. The portion of radiation is thereby depending on the type and form of the device between 30% and 70%.

Taking the differences in the insulation level and the type of heating together, the radiative thermal environment is very different between the two countries and it must be interesting to see if this affects the sleeping behaviour.

Additionally, this chapter looks at the influenceability of the occupant behaviour and its reference level by analysing how far and fast a change in the thermal environment affects the decisions made regarding the preferred sleeping conditions.

8.2 Methodology

For this analysis, the data obtained from the Internet-based survey, described in detail in Chapter 3.3, was taken. For the first overview, the participants were sorted out into seven groups. Table 19 shows how the database was divided into groups, depending on the country where the participant is living at the moment and the country the participant spend most of their time during childhood and the total number of participants belonging to each group. Table 20 shows the geographical distribution of those living neither in Germany nor Japan according to the country of residence.

For a more detailed analysis, only the data from the first three groups, namely ni_ni, de_ni and de_de were taken. The geographical distribution of the current residence within both countries of the participants is shown in Table 21. In addition to the answers received from the participants, the date of participation was recorded and real-time hourly weather data for the 14 days before the participation were gathered from publicly available data provided by the meteorological institutes of Japan (Japan Meteorological Agency, 2009) and Germany (Deutscher Wetterdienst, 2009).

These sets of data were then used for a multivariate logistic regression analysis of the behaviour and thereby a statistical model for each type of behaviour in relation to the outdoor air temperature, the country of residence and origin, the type of heating device and season was derived by stepwise elimination on the basis of Nagelkerkes $R^2$-index and Akaike's information criterion as described in Chapter 6.2.
### Table 20. Continent of residence of participants in the Internet-based survey not living in Germany or Japan.

<table>
<thead>
<tr>
<th>Continent</th>
<th>Winter</th>
<th></th>
<th></th>
<th>Summer</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of participants</td>
<td>Number of countries</td>
<td>Number of participants</td>
<td>Number of countries</td>
<td></td>
</tr>
<tr>
<td>Africa</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Asia</td>
<td>11</td>
<td>5</td>
<td>15</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Europe</td>
<td>84</td>
<td>17</td>
<td>59</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>North America</td>
<td>6</td>
<td>2</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Oceania</td>
<td>15</td>
<td>2</td>
<td>16</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>South America</td>
<td>31</td>
<td>8</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
</tbody>
</table>

### Table 21. Regional distribution of participants within Germany and Japan.

<table>
<thead>
<tr>
<th>Germany</th>
<th>Winter</th>
<th>Summer</th>
<th>Japan</th>
<th>Winter</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Saxony</td>
<td>7</td>
<td>2</td>
<td>Hokkaidō</td>
<td>20</td>
<td>11</td>
</tr>
<tr>
<td>Hamburg</td>
<td>13</td>
<td>8</td>
<td>Tōhoku</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Bremen</td>
<td>1</td>
<td>–</td>
<td>Kantō</td>
<td>221</td>
<td>108</td>
</tr>
<tr>
<td>Brandenburg</td>
<td>1</td>
<td>–</td>
<td>Chūbu</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>Berlin</td>
<td>8</td>
<td>3</td>
<td>Kansai</td>
<td>11</td>
<td>7</td>
</tr>
<tr>
<td>Saxony Anhalt</td>
<td>2</td>
<td>–</td>
<td>Chūgoku</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>North-Rhine Westphalia</td>
<td>69</td>
<td>36</td>
<td>Shikoku</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Saxony</td>
<td>4</td>
<td>2</td>
<td>Kyūshū</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Thuringia</td>
<td>1</td>
<td>–</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hesse</td>
<td>42</td>
<td>19</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rhineland-Palatinate</td>
<td>13</td>
<td>8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saarland</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baden-Württemberg</td>
<td>24</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bavaria</td>
<td>50</td>
<td>16</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
8.3 General Comparison of Stated Sleeping Behaviour

Figure 50 shows the distribution of heating and cooling devices, which differs quite large between the groups. In Japan most persons have AC-units for heating at home, while on the other hand, in other regions the dominant way to heat seems to be central heating without knowing if participants referred to a central heating with convective heat distribution or one with partly radiative heat distribution. In summer, less than 10% of the participants are using a cooling device in Germany, while more than 60% do so in Japan, which can easily be understood looking at the climate of each area. In average, one quarter stated to use an AC-unit for cooling and another 20% stated that they are using some type of fan. Comparing this percentage for Japan with the distribution rate of AC-units being around 80% in the year 2000 as given by (ESRI, 2007), it looks rather small here. This can be explained with (1) participants who chose more than one option due to using AC-unit and fan as described in the

a) Winter

![Winter Bar Chart]

b) Summer

![Summer Bar Chart]

Fig. 50. Distribution of heating and cooling device at home.
Fig. 51. Distribution of sleeping conditions chosen in winter.
introduction for the case of heating; (2) participants who possess an AC-unit, but use it only in case of extreme hot conditions; and (3) a high percentage of participants being interested in alternative strategies due to the way the survey was announced and its combination with information as described in the following Chapter 9.

Regarding the sleeping behaviour, participants were asked to choose the state of window, heating/cooling device, type of blanket, and level of clothes in a series of closed-ended questions permitting only the choice between two options. The analysis of the distribution of possible combinations of sleeping behaviour showed that the combination performed by nearly half of the participants is a closed window with stopped heating device, a thick blanket and long sleeping clothes in winter and an open window with stopped cooling device, a thin blanket and short sleeping clothes in summer. Further, the percentage of persons choosing conditions leading to an unnecessary high exergy consumption, i.e. an open window with running heating or cooling device, is fortunately below 5%.

Figures 51 and 52 show the distribution of sleeping conditions of each group for winter and summer, respectively. In winter, as shown in Figure 51, the differences between the seven groups are most obvious for the state of the window and the type of clothes. As can be seen in Figure 51a) more than 25% of the de_de-group, the Germans living in Germany, stated to sleep with an open window in winter, while this percentage is much lower in all other groups with the lowest percentage shown for the ni_ni group, the Japanese living in Japan, and the ot_de, others living in Germany. At the same time, more than 30% of the de_de group are sleeping with short clothes even during winter, but less than 10% have a thin blanket. In contrast, more than 30% of the ot_de group stated to sleep with a thin blanket, so that the low percentage of persons sleeping with an opened window might be explained. Taking these two observations together, this implies that, on the one hand, a good thermal environment, as provided by many buildings in Germany, permits such behaviour, like sleeping with an open window, but on the other hand, the choice of a thick blanket permits the clothes to be shorter and the window to be opened more often due to its higher level of thermal insulation.

The differences between the seven groups are in general much smaller in summer than those described for winter, as shown in Figure 52. However, it can be seen that the choice of the window state is the only one in summer and winter where both options, open and closed, are chosen by more than 30% in all groups. This implies that this decision depends on factors deriving out of differences in the built environment or individual being, which have to be analysed by further investigations.

Figure 53 presents the same analysis concerning the sleeping conditions chosen during nighttime for each country of the ot_ot group, of which more than 10 persons participated.
Fig. 52. Distribution of sleeping conditions chosen in summer.
Besides the numbers of participants being rather small and therefore no general conclusions to be drawn, it is shown also here that there are huge differences either due to the climate or the culture of the respective country. However, comparing for example the percentage of heating devices switched on between Portugal and Spain, huge differences are observed even though the climate must be similar.

Fig. 53. Distribution of sleeping conditions chosen in winter (The numbers in brackets behind the country names are the total number of participants from the respective country).
Fig. 54. Result of logistic regression analysis for each action and group.
8.4 Result of Logistic Regression Analysis

The previous analysis does not consider the differences in the outdoor temperature prevailing during night-time. In order to clarify, if the differences between the groups and countries are solely due to this factor, a regression analysis was done comparing the first three groups. Table 22 shows the number of observations for each choice. For the interpretation of the corresponding models, it should be kept in mind that the number of cooling devices running was very low.

Figure 54 shows the relationship between mean outdoor air temperature and the probability that a state is chosen based on the results of the logistic regression analysis for each action and group. While the usage of heating device and cooling device are similar for all three groups, there are huge differences in the chosen condition of the window and length of clothes. It can be seen that the Germans living in Germany are opening the window much more often and at lower mean outdoor air temperatures than the other two groups. It can also be seen that the Germans living in Japan have a similar behaviour as Japanese people in Japan. The same applies with a different degree for the thickness of the blanket and the length of the clothes.

This means that there is still a difference in the behaviour after excluding temperature as reason for this difference. Let us therefore have a look at the result of the univariate regression analysis in order to see, which factor describes this difference best. As shown in Table 23, the best single predictor is the type of device for heating, the outdoor air temperature for cooling, and the season for all other actions, if the preference is excluded. In case of heating it can be seen that none of the models has a high $R^2$-value. Therefore the preference was tested as additional factor following the results presented in the previous chapters and turned out to be much more significant than the other factors. The fact that the season as a factor predicts the state chosen for window, blanket and clothes signifies that there is a period between summer and winter when, e.g. the type of blanket is changed, but that there is not much change within one season. Further, it can be seen that the factors related to the type of building are not able to predict the chosen option alone.

<table>
<thead>
<tr>
<th>Table 22. Number of observations for each choice.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>244 stopped</td>
</tr>
<tr>
<td>57 running</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>
Table 23. Values of AIC-index and Nagelkerke’s $R^2$-index for the logistic regression model of each action and factor.

<table>
<thead>
<tr>
<th>Action</th>
<th>Heating</th>
<th>Cooling</th>
<th>Window</th>
<th>Blanket</th>
<th>Clothes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AIC</td>
<td>$R^2$</td>
<td>AIC</td>
<td>$R^2$</td>
<td>AIC</td>
</tr>
<tr>
<td>Temperature</td>
<td>293.02</td>
<td>0.02</td>
<td>38.035</td>
<td>0.21</td>
<td>475.02</td>
</tr>
<tr>
<td>Residence$^{1)}$</td>
<td>292.02</td>
<td>0.02</td>
<td>48.013</td>
<td>0.09</td>
<td>518.01</td>
</tr>
<tr>
<td>Origin$^{2)}$</td>
<td>294.01</td>
<td>0.01</td>
<td>52.001</td>
<td>0.06</td>
<td>527.01</td>
</tr>
<tr>
<td>Device type$^{3)}$</td>
<td>290.09</td>
<td>0.32</td>
<td>49.018</td>
<td>0.18</td>
<td>461.03</td>
</tr>
<tr>
<td>Season$^{4)}$</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>440.03</td>
</tr>
<tr>
<td>Preference</td>
<td>249.21</td>
<td>0.53</td>
<td>0.01</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Surrounding$^{5)}$</td>
<td>294.01</td>
<td>0.01</td>
<td>50.008</td>
<td>0.01</td>
<td>574.01</td>
</tr>
<tr>
<td>Building type$^{6)}$</td>
<td>294.03</td>
<td>0.13</td>
<td>54.013</td>
<td>0.02</td>
<td>577.01</td>
</tr>
<tr>
<td>Year of construction$^{7)}$</td>
<td>285.08</td>
<td>0.18</td>
<td>52.018</td>
<td>0.07</td>
<td>576.00</td>
</tr>
<tr>
<td>Size of dwelling$^{8)}$</td>
<td>293.03</td>
<td>0.15</td>
<td>54.015</td>
<td>0.02</td>
<td>573.01</td>
</tr>
<tr>
<td>Smoking$^{9)}$</td>
<td>290.03</td>
<td>0.06</td>
<td>53.006</td>
<td>0.03</td>
<td>569.02</td>
</tr>
<tr>
<td>Ownership$^{10)}$</td>
<td>292.03</td>
<td>0.15</td>
<td>54.015</td>
<td>0.02</td>
<td>574.01</td>
</tr>
<tr>
<td>Nr. of persons$^{10)}$</td>
<td>290.05</td>
<td>0.16</td>
<td>53.016</td>
<td>0.04</td>
<td>574.01</td>
</tr>
</tbody>
</table>

$^{1)}$ Japan = 1 & Germany = 0  
$^{2)}$ Six dummy variables (central system, air-conditioning, small devices, surface heating/cooling, no heating, other)  
$^{3)}$ Winter = 0 & Summer = 1  
$^{4)}$ City centre = 1 & Countryside = 0  
$^{5)}$ Three dummy variables (single family house, apartment building, dormitory)  
$^{6)}$ Three dummy variables (before 1985, between 1986 and 2000, after 2000)  
$^{7)}$ $<79m^2 = 0$ & $>80m^2 = 1$  
$^{8)}$ Someone smoking inside dwelling = 1  
$^{9)}$ Two dummy variables (owning the dwelling, living for rent)  
$^{10)}$ Three dummy variables (single person, 2 persons, more than 2 persons)
The coefficients of the final models are presented in Table 24. They were derived by searching for the combination of factors leading to the multivariate regression model with the lowest AIC-value. Except for heating, all other models have an $R^2$-value in the range between middle and high. This implies that there are other factors more influential for heating in winter as was shown already in Chapter 6.

For the interpretation of the factors included into the models, the importance factor (IF) introduced in Chapter 6.2 can be used. For the models shown in Table 24, the range of the temperature variable for the cooling model is 10 and for all other models 30, while on the other hand, that of the other variables is 1, because they can be either 0 or 1. Therefore, the IF of those variables is equal to the absolute value of the coefficient.

The model with regard to the heating device does not contain the temperature and the highest IF is related to the preference towards the usage of the AC-unit, which again supports the results presented in Chapter 6. Following preference, the year of construction has a strong influence, with old buildings leading to a higher usage of the heating device and modern buildings leading to a lower usage. The reason must be the differences in the quality of the building. According to the coefficients related to the heating device type, those having a central heating system or a surface heating system are using the heating device more often than others. This is probably due to the impression that those systems might need longer to restart, so that keeping it on seems to be more practical than stopping it for the night. One point not asked directly, but mentioned by several participants within the comment box included on every page of the survey, is the automation of the system, e.g. in Germany, many central heating systems have an automatically reduced heat output during nighttime. In such a way, the heating system is still running, but in a silent mode not using much energy.

The IF for the temperature variable in the cooling model is equal to 28 (2.8*10) and shows that temperature is the prevailing factor. It can also be seen that the usage of small devices such as a fan can reduce the usage of the AC-unit very much as well as the condition that someone is living in the city centre. The value of the coefficient for origin shows that those originating from Germany use less cooling devices compared to the Japanese. However, as mentioned before, this model is based on very few observations of a running cooling device, so that the characteristics of the few persons using it must have influenced the derivation of the model very much.

The model for the window opening behaviour shows that season (IF = 2.4) and temperature (IF= 2.1 = 0.07 * 30) are the main factors. We can see that the characteristics of the dwelling/building as well as the origin of the occupant have also a significant influence on the chosen state. This means that, on the one hand, the behaviour learned in the country of origin is still influencing on the behaviour after moving, but on the other hand, the current
Table 24. Parameters for the final models for each action together with their AIC- and Nagelkerke’s R²-values.

<table>
<thead>
<tr>
<th></th>
<th>Heating on</th>
<th>Cooling on</th>
<th>Window open</th>
<th>Blanket thin</th>
<th>Clothes short</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIC</td>
<td>Nag.-R²</td>
<td>219</td>
<td>0.39</td>
<td>25</td>
<td>0.77</td>
</tr>
<tr>
<td>Intercept</td>
<td>-0.07 (*)</td>
<td>3.85*10⁻³⁸ (0.14)</td>
<td>12.18 (*)</td>
<td>22.4 (*)</td>
<td>1.49 (0.12)</td>
</tr>
<tr>
<td>Temperature</td>
<td>-</td>
<td>2.8 (0.15)</td>
<td>0.07 (0.08)</td>
<td>0.11 (0.02)</td>
<td>0.06 (0.14)</td>
</tr>
<tr>
<td>Residence²</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-1.19 (0.01)</td>
</tr>
<tr>
<td>Origin²</td>
<td>-</td>
<td>8.06 (0.18)</td>
<td>-1.46 (*)</td>
<td>-1.09 (0.005)</td>
<td>-1.15 (0.006)</td>
</tr>
<tr>
<td>Type of device³</td>
<td>A</td>
<td>10.6 (0.11)</td>
<td>-1.25 (0.002)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>0.85 (0.03)</td>
<td>1.53 (0.001)</td>
<td>1.07 (0.04)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>W</td>
<td>1.3 (0.03)</td>
<td>-</td>
<td>-14.73 (0.9)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>S</td>
<td>-26.2 (0.99)</td>
<td>1.01 (0.01)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>O</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.29 (0.06)</td>
</tr>
<tr>
<td>Season²</td>
<td>-</td>
<td>-</td>
<td>2.4 (0.002)</td>
<td>3.06 (*)</td>
<td>2.43 (*)</td>
</tr>
<tr>
<td>Preference²</td>
<td>2.24 (*)</td>
<td>-</td>
<td>(not tested)</td>
<td>(not tested)</td>
<td>(not tested)</td>
</tr>
<tr>
<td>Surrounding²</td>
<td>-</td>
<td>-21.9 (0.99)</td>
<td>-</td>
<td>-</td>
<td>0.76 (0.02)</td>
</tr>
<tr>
<td>Building type⁴</td>
<td>A</td>
<td>-</td>
<td>-</td>
<td>1.52 (*)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>-</td>
<td>-</td>
<td>1.82 (0.08)</td>
<td>-</td>
</tr>
<tr>
<td>Year of construction⁵</td>
<td>O</td>
<td>0.72 (0.13)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>-</td>
<td>-</td>
<td>-1.2 (0.006)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>N</td>
<td>-1.81 (0.11)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Size of dwelling²</td>
<td>-</td>
<td>-</td>
<td>-0.88 (0.03)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Smoking³</td>
<td>-1.04 (0.02)</td>
<td>-</td>
<td>-0.76 (0.05)</td>
<td>-</td>
<td>-1.26 (*)</td>
</tr>
<tr>
<td>Ownership⁶</td>
<td>O</td>
<td>-</td>
<td>-</td>
<td>1.4 (0.003)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>-</td>
<td>-</td>
<td>0.69 (0.06)</td>
<td>-</td>
</tr>
<tr>
<td>Nr. of persons⁷</td>
<td>S</td>
<td>-</td>
<td>-</td>
<td>-1.43 (0.004)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>-1.2 (0.07)</td>
<td>-</td>
<td>-1.24 (0.006)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>F</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.72 (0.03)</td>
</tr>
</tbody>
</table>

1) Numbers in brackets are the respective p-values. (*) signifies that the p-value is below 0.001 (see also comment to Table 16).

2) See the footnotes of Table 23 for further explanations.

3) A = AC-unit, C = central heating/cooling equipment, W = surface heating/cooling, S = small heating/cooling devices such as stove or fan, O = others such as natural ventilation

4) A = apartment building, D = dormitory

5) O = before 1985, M = between 1986 and 2000, N = after 2000

6) O = owning the dwelling, R = living for rent

7) S = single person, C = 2 persons, F = more than 2 persons
surrounding also has some influence and that the surrounding built environment can influence the reference levels of the respective behaviours.

Similar conclusions can be drawn from the other two models for the type of blanket and clothes as well. Overall, this analysis clarified the importance of the built environment and type of heating system. The surrounding of the building, i.e. whether it is placed in the centre of a city or on the countryside has according to the present analysis only a minor influence on the type of clothes chosen, but a negligible one for all other decisions. One reason for the former might be a possible longer distance between bed and toilet, and therefore a longer exposure to the low temperature during night, or a more traditional lifestyle performed in the countryside.

In order to evaluate, whether and to what degree the behaviour is influenceable by the surrounding, the data of the Germans living in Japan was divided according to the period of time they were staying in Japan before participating in the questionnaire. Figure 55 shows the result for the state of window and type of clothes in winter. The change of behaviour varies between the types of behaviour in its speed; while the adaptation to the current conditions is completed within a short period in case of window opening behaviour, it takes longer in case of clothes. A possible explanation is the correlation between cause and sensation; the sensation of discomfort due to coolness might be first attributed to the opened window, so that closing must be a first countermeasure. Only when this change failed for overcoming the feeling of discomfort, further countermeasures are taken. Another explanation might be the easiness of the action. While the window can be closed easily, there is a high probability, that long sleeping clothes were not brought from the home country, so that it is necessary to buy such clothes, before this countermeasure can be applied. Unfortunately, the number of participants not living in the country they originated from is too small to perform a more detailed analysis so that this finding has to be evaluated further with future research.

![Fig. 55. Speed of change in behavioural pattern.](image)
8.5 Conclusions

In this chapter, a cross-cultural comparison of the sleeping behaviour was shown, which led to the following results:

1) While the usage of heating and cooling devices is in general low and rather independent from the culture, especially the window opening behaviour varies strongly between countries.

2) Focussing on those originating from Japan and Germany and living in either of these countries, it revealed that the differences in the behaviour with respect to the decisions before going to sleep are not solely due to different climatic conditions and such factors as the types of heating/cooling devices, but also due to the country of origin, and the characteristics of the building.

3) A higher quality of the radiative environment may lead to a higher percentage of windows open and a lower percentage of heating devices used.

4) The behaviour and therefore the reference levels are influenceable by the current thermal built environment. The speed of change depends on the type of action.

Therefore, a careful design of a high-quality radiative environment by the implementation of a sufficient level of insulation material and solar shading is recommended in order to create a sleeping environment, which permits well-being with low exergy consumption.
9 Evaluating the Influence of Various Methods of Knowledge Transfer on Occupant Behaviour – the Effect of Short Term Experiences on the Reference Levels –

9.1 Introduction

First attempts to influence on the occupants behaviour towards less energy usage originate from the mid seventies (Hayes, 1977; Seligman, 1977; Becker, 1978; Becker and Seligman, 1978). This is probably due to the first oil crisis and the sudden awareness of limited resources. In the following years many papers appeared in the field of environmental psychology dealing with studies about environmental behaviour (Midden et al, 1983; Costanzo et al., 1986; Dennis et al., 1990; deYoung, 1993). These studies focus on the general energy usage within households, but few on the energy used for thermal comfort.

In the recent past, searching for a way to combat global warming towards a sustainable future, the role of the occupant is claimed more and more both by scientific papers (Andersen et al., 2007; Lucy and Meisgeier, 2008) and common articles in the news press (Gill-Austern, 2008; Williams, 2008) especially in relation to the way thermal comfort is provided. Nevertheless, recent studies about the intention to change the occupants' behaviour are very scarce (Gyberg and Palm, 2009; McMakin et al., 2002; Bae et al., 2007). Out of these studies, Gyberg and Palm (2009) give a general overview about the type of consumer information available in Sweden. McMakin et al. (2002) observed the changed energy usage within the setting of residential buildings of the American military before and after the distribution of information. They showed that it is possible to reduce the energy usage within the building by up to 10%, but did not observe the thermal conditions before and after the distribution of information. Bae et al. (2007) analysed in detail the thermal conditions in South Korean apartment buildings during winter before and after the distribution of information. They showed that the information has a positive effect on the occupants behaviour, but do not try to quantify this change.

The first part of this chapter describes the theoretical background underlying the information procedures and gives a brief overview about the impact of information on the decision process according to studies within the field of brain science. In the second part, several information processes are described together with their effect on the occupants' behaviour as well as constraints reported by the occupants to change their behaviour. In addition, a method is shown which enables researchers to implement the effect of
information into building simulation programs in order to judge the potential of such a measure. The results can be used to improve the information procedure of environmental information projects in order to have better benefit-cost relationships.

9.2 Knowledge, Memory and the Effect of Learning on Human Behaviour

In neurology, knowledge is defined as a function of existing connections among neurons (Cziko, 1995). These connections are weak in the new born, have their highest density in the child aged 6 years and will slowly die afterwards if they are not used (Carter, 1998; p. 21). The first development after the birth thereby depends on the genetic inheritance together with the environmental experiences. The genetic inheritance, which is based on the information present in the genome, lays down the general structure, which is then adjusted by the information coming from the environment through the nervous system. This adjustment is achieved by the elimination of big parts of the original structure and not by the addition of new things (Cziko, 1995). This is supported, e.g. by a work done by Danchin and Wagner (2008), which found that many human actions are influenced by the social environment of that individual early in his or her life.

However, even in the adult age, the number of connections can be increased through learning or the acquisition of new skills (Carter, 1998; p. 21). Learning is usually “defined as an adaptive change in behaviour through the effect of acquired information, which provides experience” (Danchin and Wagner, 2008; p. 701). This can be seen in the animal world, where e.g. individuals who failed in one breeding season show a higher probability to change their breeding site the next breeding season, which is most probably a sign of learning (Boulinier et al., 2008; p. 303). Following Carter (1998), our memory is continually changed by new learning due to the modification of the connections between the nerve cells in the brain. She thereby distinguishes between several different types of memory, which can be categorized as (1) long term memory, (2) procedural memory (to perform actions like riding a bike), (3) unconscious traumatic memories, and (4) instincts or genetically encoded memories. Furthermore, she mentions that the state of excitement during an experience has an influence on the period a memory about this experience is kept. In case the experience is meant to be for the long term memory, it is held in the storage of the hippocampus for 2 to 3 years and replayed mainly during sleep until neural connections are established in the cortex so that the hippocampus is no longer needed. However, a memory will not be stored in case it is not part of someone’s personal belief about him or herself (Carter, 1998; p. 170). This is related to the word ‘contingency’, which is described by (Damasio, 2005; p. 182) as “your own thing, related to your own experience, relative to events that vary with the individual”. Considering the fact
that only a tiny amount of all the experiences one has throughout life stays in the memory (Evans, 2001; p. 79), one can explain above statements in a way that not only the attention paid towards one object is highly selective between individuals, but also the memory.

Damasio (2005) states that the behaviour reacts to the images and experiences of the now together with the images and experiences the memory is generating internally, relative to the current ones. Those memories, e.g. about a feeling of discomfort due to the presence of an air-conditioning unit, consist of (1) representations of the status of biochemical regulation in brain stem and hypothalamus; (2) representations of the body including muscular mass and the skin; and (3) representations of the musculoskeletal frame and its potential movement. In relation to these findings from neurology, Takahashi et al. (2000) compared the temperature that the subjects answered within a survey with those felt comfortable by those subjects during a physical measurement. They found that those subjects who are used to air-conditioned spaces in daily life imagined a much lower temperature to be comfortable as they really perceived as comfortable during the experiments. They conclude that this lack of knowledge might lead to a misuse of the AC-unit, followed by a waste of electricity and that it could be helpful for those persons to understand which temperature they really sense as comfortable.

A further point to mention is that without a name or a symbol for an object, one has nothing with which to recover the memories of it from the memory. This can be seen, e.g. on the fact that billions of personal and meaningful memories can be held in a healthy brain, while dry facts learnt at school may fade away (Carter, 1998; p. 138). Together with the findings stated above, this shows that a successful intervention needs to be based on the daily experience of the occupant.

According to deYoung (1993), interventions aiming at changing the behaviour can be grouped into three categories: (1) information techniques, (2) positive motivational techniques, and (3) coercive techniques. The first describe interventions that should help the people to understand, the second aspect are for example social or monetary rewards and the last one would mean punishment for a “wrong” behaviour, and is not recommended by many psychologists. McMakin et al. (2002) found that a change in the behaviour is likely to be observed, if (1) the new behaviour is easy, (2) skills and resources to apply the behaviour exist, (3) neighbours and friends also change their behaviour accordingly, and (4) people made commitments to change. Furthermore they say that occupants are more likely to adapt so-called energy-efficient behaviours when (1) the relation between energy efficiency is realized as being equal to benefits in comfort and health, (2) the energy use before and savings afterwards are made visible, and (3) when the information is vivid, salient, personal and including demonstrations of specific actions.
Table 25. Overview of the presented strategies during the knowledge transfer measures in summer and in winter.

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Presented in summer</th>
<th>Presented in winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adaptation</td>
<td>Doing sports or similar outside to increase adaptation to prevailing conditions</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Uchimizu</td>
<td>Sprinkling (used) water outside, which evaporates and cools surface and passing air</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Nocturnal ventilation</td>
<td>Opening windows and doors so that cool outside air can enter the room during night, or alternatively use a fan to force air movement</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>External shading</td>
<td>Applying a shading device outside the window</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Electric fan</td>
<td>Using an electric fan in order to increase air current</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Changing clothes</td>
<td>Adapting level of clothes to prevailing outside conditions</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Green curtain</td>
<td>Growing plants outside the window, which form a green outside shading which also cools the air by evaporative cooling</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Wall insulation</td>
<td>Applying insulation material to the walls in order to decrease heat loss through it</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Do-it-yourself (DIY) wall insulation</td>
<td>Applying sheets of aluminum to the walls in order to decrease radiation through them</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Window insulation</td>
<td>Applying double or triple glazing</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>DIY window insulation</td>
<td>Attaching a transparent plastic sheet to window so that a layer of air is formed</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Closing curtains</td>
<td>Closing curtains at night to decrease heat loss through windows</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Ventilation</td>
<td>Open the window fully for few minutes in order to increase the indoor air quality</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Hot/ cold drink</td>
<td>Drinking something hot/ cold to increase comfort</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Electric carpet</td>
<td>Getting an electric carpet, which increases the quality of the radiative environment but uses less electricity than an AC-unit</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Reduce space</td>
<td>Dividing the room with curtains so that the volume of heated space gets reduced</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Sun gains</td>
<td>Installing reflective material on the balcony in order to increase solar gains</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>High-temperature cooling/ low temperature heating</td>
<td>Install a wall heating/ cooling system using water running through pipes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Cziko (1995) states that those actions, which are followed by satisfaction, will be more likely recur next time and at the same time it can be observed that actions, which are accompanied or followed by discomfort, will be less likely to occur again.

Therefore, the emphasis was put on the information techniques, which can consist of a) techniques, which increase the awareness, help an individual to gain knowledge, and/or alter the attitude and belief so that they take appropriate action, b) self discovery including all known problems how to lead and control it and c) direct experience. In doing so, the assumption was made that an individual who gained certain knowledge about alternative behaviour and its effect will take appropriate actions (deYoung, 1993).

9.3 Methodology

9.3.1 Outline of the Investigations

The findings of this chapter are based on the physical measurement as described in Chapter 5.2 and the Internet-based survey as described in Chapter 3.3.

9.3.2 The Knowledge Transfer Measures

At present several definitions of the term “Environmental Education” are found, e.g., “Environmental Education is an active process that increases awareness, knowledge and skills that result in understanding, commitment, informed decisions and constructive action to ensure stewardship of all interdependent parts of the earth’s environment” (dyBay, 1995; p. 10). In contrast, the term “Built Environmental Education” is used by different authors (e.g. Iwamatsu, 2005), but actually was not defined by any of them. Therefore, Built Environmental Education will be defined here as being all education related to the built environment, which itself is defined as “all buildings, monuments, roadways, landscapes” (Heimlich et al., 1999; p. 3). Even though the interventions conducted in the frame of this research could be called “Built Environmental Education”, they will be called knowledge transfer methods throughout this treatise, because they consist of one-time knowledge transfer actions from the researcher to the occupant and are no pedagogically sound education programs.

For this study, an approach situated in the category of the information techniques was chosen. This means that all of the interventions presented here are methods to increase the knowledge of the occupant by information distribution. Additionally, the workshops also include the effect of personal experience.
b) Screenshot of one of the information pages

Fig. 56. Screenshots of the online information pages.
The knowledge transfer methods of both investigations, the measurement and the Internet-based survey, presented the same information. In the first part of this information, an overview was given over the conditions leading to comfort together with a small explanation of low exergy thinking (Annex 49, 2009). In the second part, several strategies, which are supposed to lead to a lower exergy consumption while providing a higher level of comfort, were presented; those strategies were called “lexhic”-strategies as conjunction from low-exergy high-comfort. The information given to the participants is still accessible (Schweiker, 2009).

An overview of the strategies presented in all the knowledge transfer processes in summer and winter is given in Table 25. According to McMakin et al. (2002), information is more likely to be leading to a change in the behaviour, if it is localized to the conditions of the receivers of that information. Therefore, the information was customized to the local conditions, climatic as well as specifically to the building features, of the dormitory building. At the same time, the information given to the participants of the Internet-based survey is partly not suitable to all of them.

In the case of the investigation done in the dormitory building, the information was distributed in two ways: a free workshop and a 30-page information brochure. Furthermore, the type of workshop varied between summer and winter. In summer, a lecture, which was accompanied by small experiments about the effect of external shading and insulation, was given. In winter, one of the dormitory rooms of a student not participating in the measurement was modified so that it included an electric carpet, self-made wall and window insulation as well as measures to reduce the heated space. Students were then invited to experience this room themselves for 30 minutes during which a presentation was given about the implemented and non-implemented strategies. Some of the students not attending the workshops were given the information brochure while others received no information at all and served as control group.

In case of the Internet-based survey, participants were free to access the information area on their own schedule. The information area was designed so that participants viewed a three-dimensional view of a single room with a desk, window, door and heating/cooling device as shown in Figure 56a). By clicking e.g. on the window, an information page appeared containing several explanations about the strategies related to the window as shown in Figure 56b). The reading of such information pages was interrupted from time to time by few questions asking the participants to evaluate the last part they just finished reading. Additionally, every action done by a participant such as clicking on some information or going to the next page was automatically logged to a database via a php-protocol (PHP, 2009) after logging in with an access code. This allows the analysis of period, time of watching and type of information viewed for each participant. Those not accessing the information area were taken as control group.
9.3.3 Analysis Methods

Changes in the behaviour after a certain intervention are commonly analysed according to the reliability, speed of change, particularism, generality and durability (deYoung, 1993). This is relatively easy for single behaviours such as shopping decisions, but a rather complex task when dealing with behaviour aiming at thermal comfort. In order to analyse the effect of the knowledge transfer measures conducted in the frame of this research on the occupant behaviour, a general analysis of the strategies the participants tried compared to those they wanted to try immediately after the knowledge transfer was performed as the first step. This analysis was based on the data obtained by a couple of surveys and interviews. The students were divided into four groups. Into the WS-group were sorted those who participated in the workshop, into the PA-group those who got the information paper and answered the attached questionnaire sheet, into the PR-group those who got the information paper but did not answer the questionnaire and into the CO-group those of the control group who did not get any information material. The intensity of the knowledge transfer methods is highest for the WS group and then decreases in the order stated above towards zero for the CO group. The participants of the Internet-based survey were grouped into those who viewed the information pages and those who did not view the information pages.

In addition to the answers obtained from those surveys and interviews, the only physical data available to analyse a possible change in the occupant behaviour due to the knowledge transfer were the data from the dormitory building. For the analysis of this data, first the AC-unit usage was analysed for each student participating in the measurement for the night time period, for which occupancy is known (see Chapter 5 or Schweiker and Shukuya (2009a) for a further discussion).

For each group, a logistic regression analysis was done for the whole period of measurement as well as a separate analysis for the period before and after the knowledge transfer process. For the analysis of the period before the intervention the data from the beginning of the measurement up to the day of the workshop was taken and the data from one week after the workshop till the end of the measurement was taken for the analysis of the period after the intervention.

For this analysis the relation between the percentage of persons using their AC-unit, $p_{AC}$, and the mean outdoor air temperature, $t_{oav}$, was examined according to

$$p_{AC} = \frac{1}{1 + e^{-(\alpha + \beta t_{oav})}},$$

(19)
with $\alpha$ and $\beta$ being constants, which have to be determined by a generalized logistic regression analysis. A characteristic of eq. (19) is that the value of $-\alpha/\beta$ is the mean outdoor air temperature at which 50% of persons are using the AC-unit. This value is called $T_{30}$.

A first analysis resulted in the models expressed by eq. (19) with different slopes (meaning a different value of $\beta$), which made it difficult to compare the groups and their behaviour before and after the knowledge transfer process. Due to this result, the logistic regression analysis was done for each model again, but this time by normalizing $\beta$ to 0.375 for summer and -0.030 for winter, which are rounded values of the models containing all data from all groups.

In order to compare the behaviour of the groups before and after the knowledge transfer process, two values were examined. The first one is the difference in the value of $T_{30}$ for each group before and after the knowledge transfer process, which will be called $\Delta T_{30}$. The second one is the difference in the percentage of persons using their AC-unit at a certain value of the mean outdoor air temperature between the behaviour before and after the knowledge transfer process, which gives a more tangible value for those not familiar with logistic regression analysis. This value will be called $\Delta p_{25}$ for summer and $\Delta p_{3}$ for winter. The number in the respective suffix indicates the mean outdoor air temperature 25°C for summer and 5°C for winter.

The models obtained by this logistic regression analysis can be easily implemented into recent developed algorithms for building performance simulation, like the Humphreys algorithm (Rijal et al., 2007).

In the case of the data obtained from the Internet-based survey, one can analyse the effect of the knowledge transfer methods by comparing the answers given by the group of participants, who viewed the information pages with those given by the participants, who did not view the information pages. Beside a comparison of a non-standardized effect size, meaning e.g. the difference in the percentage of persons using their heating device between those groups, one can also calculate the significance of such difference by calculating the $z$-value

$$z = \frac{p_x - p_y}{\sqrt{p_{xy} (1 - p_{xy}) \left( \frac{1}{n_x} + \frac{1}{n_y} \right)}} \quad \text{(20)}$$

with $p_x$ and $p_y$ being e.g. the probability of heating devices switched on in each group, $p_{xy}$ the probability of heating devices switched on in both groups, and $n_x$ and $n_y$ being the number of participants in each group. One requirement for applying this formula is that $n_x$ and $n_y$ are both greater than 5. In this case the only concern was if the probability in the group who
Table 26. Key points of the two investigations.

<table>
<thead>
<tr>
<th></th>
<th>Dormitory building</th>
<th>Internet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of data acquisition</td>
<td>- Physical measurement</td>
<td>- Two surveys</td>
</tr>
<tr>
<td></td>
<td>- One survey</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Two interviews</td>
<td></td>
</tr>
<tr>
<td>Medium of survey</td>
<td>Paper</td>
<td>Internet</td>
</tr>
<tr>
<td>Subjects and place of data acquisition</td>
<td>International students living in Tokyo, Japan</td>
<td>Various participants from 55 different countries</td>
</tr>
<tr>
<td>Type of knowledge transfer</td>
<td>- Workshop</td>
<td>- Information pages (on-line)</td>
</tr>
<tr>
<td></td>
<td>- Information brochure (paper)</td>
<td></td>
</tr>
<tr>
<td>Period</td>
<td>a) Summer 2007</td>
<td>a) Northern hemisphere winter 2008/09</td>
</tr>
<tr>
<td></td>
<td>b) Winter 2007/08</td>
<td>b) Northern hemisphere summer 2009</td>
</tr>
<tr>
<td></td>
<td></td>
<td>c) Southern hemisphere winter 2009</td>
</tr>
<tr>
<td>Number of participants</td>
<td>a) 39</td>
<td>a) + c) 854</td>
</tr>
<tr>
<td></td>
<td>b) 34</td>
<td>b) 435</td>
</tr>
</tbody>
</table>

Table 27. Overview of the number of persons participating in the different knowledge transfer methods during the investigation in the student dormitory.

<table>
<thead>
<tr>
<th>Group</th>
<th>Summer</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>WS (participated in the workshop)</td>
<td>11 (31%)</td>
<td>7 (23%)</td>
</tr>
<tr>
<td>PA (received information and answered the attached questionnaire sheet)</td>
<td>6 (17%)</td>
<td>6 (20%)</td>
</tr>
<tr>
<td>PR (received information but did not answer the attached questionnaire sheet)</td>
<td>11 (31%)</td>
<td>10 (33%)</td>
</tr>
<tr>
<td>CO (control group)</td>
<td>8 (22%)</td>
<td>7 (23%)</td>
</tr>
<tr>
<td>All</td>
<td>36</td>
<td>30</td>
</tr>
</tbody>
</table>
viewed the information pages is higher than in the other one, so that a one-tailed test of hypothesis could be used. This means that the significance levels of 0.1, 0.05, 0.01, and 0.002 correspond to $z$-scores of 1.28, 1.645, 2.33, and 2.88 respectively.

The participants were asked to judge their level of comfort during both surveys according to the 7-point Bedford-scale and their votes were analysed according to the feeling of comfort, for which the three middle categories of the 7-point scale were combined, as well as the feeling of cold or too cold and that of warm or too warm.

9.4 Results

In order to facilitate the reader the distinction between the results from both investigations, Table 26 summarizes their key points. Furthermore, in the following it will be referred to students and the information brochure for the case of the investigation in the student dormitory. The counterparts for the Internet-based survey are the terms participants and information pages.

9.4.1 Participation in the Knowledge Transfer Methods

Table 27 shows the number of students participating in the workshop, receiving the information brochure and those who did not receive any information in order to compare the other groups to them as control group in case of the physical measurement in the dormitory building. While in summer, nearly one third of the participating students attended the workshop, in winter less than one quarter did the same.

Table 28 shows the number of persons participating in each step during the Internet-based survey and Table 29 shows the result of the analysis of the log data. Even though the number of actions logged in winter, 3005, is similar to the one in summer, 3256, and also the time spend by each person is similar, the number of pages viewed per person is showing a huge difference as can be seen in the 3rd row of Table 29. This is due to an improvement made to the way the different information pages are linked together. In the summer version it was possible to click through the information pages continually, while in the winter version every information page stands alone and can only be activated by clicking on the respective item.

As mentioned above, all participants finishing the introductory Internet-based survey and giving their mail addresses were invited to take part in a second survey six to eight weeks after the first one. After the summer period 135 participants answered during this survey that they had a look at the information pages once or more, while in winter this number is 164 persons. Comparing these numbers to the analysis of the log data, the numbers of persons stating that
Table 28. Participation in the Internet-based survey.

<table>
<thead>
<tr>
<th></th>
<th>Winter</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Participants starting 1st survey</td>
<td>854 (100%)</td>
<td>435 (100%)</td>
</tr>
<tr>
<td>Participants completing 1st survey</td>
<td>686 (80%)</td>
<td>390 (90%)</td>
</tr>
<tr>
<td>Participants giving mail-address</td>
<td>548 (64%)</td>
<td>361 (83%)</td>
</tr>
<tr>
<td>Participants logging into information area</td>
<td>219 (26%)</td>
<td>108 (25%)</td>
</tr>
<tr>
<td>Participants viewing information pages</td>
<td>154 (18%)</td>
<td>91 (21%)</td>
</tr>
<tr>
<td>Participants correctly stating that they viewed the information pages</td>
<td>88 (10%)</td>
<td>54 (12%)</td>
</tr>
<tr>
<td>Participants correctly stating that they did not view the information pages</td>
<td>120 (14%)</td>
<td>62 (14%)</td>
</tr>
<tr>
<td>Participants starting 2nd survey</td>
<td>333 (39%)</td>
<td>209 (48%)</td>
</tr>
<tr>
<td>Participants completing 2nd survey</td>
<td>307 (36%)</td>
<td>201 (46%)</td>
</tr>
</tbody>
</table>

Table 29. Comparison of log data from winter and summer information area.

<table>
<thead>
<tr>
<th></th>
<th>Winter</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of actions logged</td>
<td>3005</td>
<td>3256</td>
</tr>
<tr>
<td>Number of login per person</td>
<td>1.19</td>
<td>1.18</td>
</tr>
<tr>
<td>Number of pages viewed per person</td>
<td>10.49</td>
<td>24.84</td>
</tr>
<tr>
<td>Average time spend per person</td>
<td>8:40 min</td>
<td>7:02 min</td>
</tr>
<tr>
<td>Maximum time spend per person</td>
<td>1hr 15:46 min</td>
<td>1hr 39:15 min</td>
</tr>
<tr>
<td>Minimum time spend per person</td>
<td>0 min</td>
<td>0 min</td>
</tr>
</tbody>
</table>
they viewed the information pages are in both seasons higher than the real numbers of persons entering the information area. A comparison of survey data and log data for summer revealed that 62 of those answering that they did not view the information pages did not view it in reality and 54 persons who answered they viewed the information pages really viewed it. The numbers for the winter case are 120 and 88, respectively. Only the data from those persons whose logged data and survey answer are congruent were used for the analysis.

Figure 57 shows the main reason for not viewing the on-line information area, which was in both seasons the lack of time as well as the fact that participants did not know that such information existed. Additionally, in summer nearly 50% of the participants stated that they perceived no need to view any information.

Fig. 57. Reason for not viewing the information page stated by the participants who did not access the information area. (N = 62 (summer) / 120 (winter).
Fig. 58. Percentage of the students who answered to try out a strategy in general and in their own room after the workshop or the information paper a) in summer and b) in winter.

Fig. 59. Percentage of the students who tried a strategy in reality between knowledge transfer and the end of the measurement period a) in summer and b) in winter.
9.4.2 The Influence of Knowledge Transfer on the Occupant Behaviour

In the questionnaire right after the information process, the students living in the dormitory were asked which strategies they plan to try in general and in their own room. While the first question asked about their general intention, the second question was intended to ask about their concrete plans in their current situation. The result of the analysis is shown in Figure 58. All strategies show higher percentages when asked about the intention in general than asked about the intention to try them in their own room except for “changing clothes”. Especially insulation and high temperature cooling, which are impossible to apply in the student rooms, show a significant difference. Those attending the workshop were slightly more motivated to try several strategies compared to those only reading the information brochure. This difference is in general around 10%, but it is close to 40% in the case of DIY wall insulation in winter. As mentioned above, this was one of the strategies applied visible in the workshop room and its effectiveness was shown and could be personally experienced during the workshop.

Figure 59 shows the results of the final interviews. One third tried “Uchimizu” and ventilation, the easiest methods to apply in summer, while another third of the students answered during the final interview that they did not try anything. In winter, closing the curtains during nighttime as insulation and improving the ventilation behaviour being the main strategies tried, while the percentage of students not doing anything is around 40%. In the comparison between those who participated in the workshop, those who received the paper and answered the questionnaire, and those who received the paper and did not answer the questionnaire, the workshop group tried most strategies, while the paper non-answered group tried the fewest. This implies that in the comparison between the information procedures, the participation in a workshop seems to be more effective than the reading of an information paper.

Looking at the results from the Internet-based survey, Figure 60 shows the percentage of persons answering the question “Are you going to try/use the introduced strategy?” right after looking at one part of the information page in the Internet with “definitely yes” or “probably yes”.

Figure 61 shows the percentage of participants who tried out a strategy after looking at the information pages. Focussing on the number of participants answering the question concerning a strategy e.g. between ventilation and solar gains, huge difference are observed. This is due to the circumstance that only those persons who claimed not to have used the strategy before in an earlier question were asked. The answers clearly show that the easiest strategies are already used by many participants before looking at the information pages, and
Fig. 60. Percentage of participants in the Internet-based survey who answered that they will definitely or probably try/use an introduced strategy (Those numbers in the brackets show the number of those who said definitely yes or probably yes regarding the respective strategy).

Fig. 61. Percentage of the participants of the Internet-based survey who tried a strategy after the knowledge transfer a) in summer and b) in winter (The numbers in brackets show the number of those who said they tried the respective strategy).
are applied by those who had not used them before. It can be also seen that many people do try a strategy sometimes only once or twice, but do not continue using them for reasons not asked, and that the percentage of persons answering that they are still using a strategy is in most cases much smaller. Again one third answered that they did not try anything. Comparing the answers given by the students with those given by the participants of the Internet-based survey, it is observed that in both investigations, those strategies, which are the easiest to be done, rank the highest while those demanding any physical or financial effort rank lowest. Additionally, it is clear that beside a majority of people being motivated to try a certain strategy right after the knowledge transfer process, an implementation in reality occurs very seldom. This gap and its reasons as well as the reasons for trying but not continuing to use a strategy need to be researched further with well designed studies.

9.4.3 Quantification of the Influence on the Heating and Cooling Behaviour

While above results show that the knowledge transfer methods led to an implementation of various passive strategies by the participation in either of the investigations, those strategies cannot be monitored so that their effect on the energy usage within the built environment can hardly be quantified. Whether the applied knowledge transfer methods affect on the energy use may be given by comparing the usage of the cooling and heating devices before and after the knowledge transfer.

Figure 62 shows the result of the logistic regression analysis described before for the summer case, which was done for the data obtained by the physical measurement in the dormitory building. Table 30 shows the intercept values of those logistic regression models together with those for winter for each group before and after the knowledge transfer process.

![Fig. 62. Comparison of the AC-unit usage behaviour before and after the information process for each group in summer.](image-url)
Table 30. Intercepts, the values for $T_{50}$ and $p_{25}$/$p_{5}$ of the models resulting out of the logistic regression analysis with normalized $\beta$ ($\beta = 0.375$ for summer and -0.030 for winter).

<table>
<thead>
<tr>
<th>Model</th>
<th>Intercept summer</th>
<th>$T_{50}$</th>
<th>$p_{25}$</th>
<th>Intercept winter</th>
<th>$T_{50}$</th>
<th>$p_{5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>WS – Before info</td>
<td>-9.247</td>
<td>24.7</td>
<td>0.53</td>
<td>-0.131</td>
<td>-4.4</td>
<td>0.43</td>
</tr>
<tr>
<td>WS – After info</td>
<td>-9.915</td>
<td>26.4</td>
<td>0.37</td>
<td>-0.192</td>
<td>-6.4</td>
<td>0.42</td>
</tr>
<tr>
<td>$\Delta T_{50}$ / $\Delta p_{25}$ or $\Delta p_{5}$</td>
<td>1.8 / -0.16</td>
<td>-2.0 / -0.01</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PA – Before info</td>
<td>-9.448</td>
<td>25.2</td>
<td>0.48</td>
<td>0.043</td>
<td>1.4</td>
<td>0.47</td>
</tr>
<tr>
<td>PA – After info</td>
<td>-9.334</td>
<td>24.9</td>
<td>0.51</td>
<td>0.109</td>
<td>3.6</td>
<td>0.49</td>
</tr>
<tr>
<td>$\Delta T_{50}$ / $\Delta p_{25}$ or $\Delta p_{5}$</td>
<td>-0.3 / 0.03</td>
<td>2.2 / -0.02</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PR – Before info</td>
<td>-9.042</td>
<td>24.1</td>
<td>0.58</td>
<td>0.161</td>
<td>5.4</td>
<td>0.50</td>
</tr>
<tr>
<td>PR – After info</td>
<td>-8.857</td>
<td>23.6</td>
<td>0.63</td>
<td>-0.158</td>
<td>-5.3</td>
<td>0.42</td>
</tr>
<tr>
<td>$\Delta T_{50}$ / $\Delta p_{25}$ or $\Delta p_{5}$</td>
<td>-0.5 / 0.04</td>
<td>-10.6 / -0.08</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO – Before info</td>
<td>-9.361</td>
<td>25.0</td>
<td>0.50</td>
<td>0.446</td>
<td>14.9</td>
<td>0.57</td>
</tr>
<tr>
<td>CO – After info</td>
<td>-9.108</td>
<td>24.3</td>
<td>0.57</td>
<td>0.734</td>
<td>24.5</td>
<td>0.64</td>
</tr>
<tr>
<td>$\Delta T_{50}$ / $\Delta p_{25}$ or $\Delta p_{5}$</td>
<td>-0.7 / 0.06</td>
<td>9.6 / 0.07</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 63. Comparison of the exergy consumption pattern of 100 persons of the WS and CO group before and after the knowledge transfer process.
together with the respective values of $\Delta T_{50}$ and $\Delta P_{25}$ or $\Delta P_5$. In summer, the knowledge transfer led to nearly 2°C increase in $T_{50}$ and a 16% decrease of the percentage of persons using the AC-unit for the workshop group, while all other groups tend to use the AC-unit as they used it before or a little more often after the knowledge transfer. In winter, the knowledge transfer led to a decrease of $T_{50}$ for the WS and PR-group and an increase for the other groups. However, the $\Delta P_5$ values are below 10% for all groups.

Using the coefficients obtained by this analysis, one can compute the exergy consumption within the built environment as described in Chapter 10 and by Schweiker and Shukuya (2009b). Figure 63 shows the effect of the knowledge transfer process in the case of summer comparing 100 persons of the WS and the CO group and assuming an outdoor air temperature of 28°C and a desired indoor air temperature of 26°C. The WS group consumes 20% less exergy after the knowledge transfer, while on the other hand, the CO group's behaviour leads to a consumption of 6% more compared to the period before the knowledge transfer.

In the case of the Internet-based survey, the answers given cannot be compared to and proved by physical data. However, the change in the heating behaviour was assessed both by asking the participants during the second questionnaire directly whether they are using the cooling or heating device more often or less often than before the first questionnaire and by comparing the answers given to the question about the current state of the cooling or heating device given in both questionnaires.

![Diagram](image)

Fig. 64. Percentage of persons stating that the heating/cooling devices were used more often or less often than before the first survey.
Figure 64 shows the percentage of answers given during the second questionnaire of each season of the Internet-based survey, asking directly if the participant believes to have used the cooling/heating device more often or less often compared to the period before the first questionnaire. There is a visible difference in summer and in winter between those who answered that they believe to use the cooling/heating device more often.

In summer, a higher percentage of those who viewed the information pages stated to use the cooling device as often, less often or much less often compared to those who did not view the information pages. At the same time the percentage of the former is lower for the answers more often and much more often.

**Fig. 65. Comparison of the answers in terms of heating- and cooling-device usage between the first and second surveys.**
In winter, 7% of those viewing the information pages answered that they used the device more often, while the same answer, i.e. that they used it more often, was given by 17% of those who did not view the information pages. This means that the non-standardized effect size is 10%. For the significance tests, those answering that they are using the heating/cooling device more often and much more often were taken together because otherwise the condition that the number of successes in each group has to be greater than 5 was not fulfilled. The significance tests show a significant difference on the 0.05 significance level between those who viewed the information and those who did not for the answers stating to use the heating device more often or much more often. Namely, there is a positive influence of the knowledge transfer process with a high probability. None of the other tested differences showed a significance lower than 0.1.

![Fig. 66. Comparison of comfort votes stated while answering the first and second surveys.](image-url)
Fig. 67. Reasons (constraints) for not applying a strategy raised by the participants during the final interview after a) the summer measurement and b) the winter measurement.
Figure 65 shows the comparison of the frequency of heating- and cooling-devices usage during the last 14 days before answering one of the questions during the first and second questionnaire. It can be seen that the cooling-device usage of those who viewed the information pages did not increase as much as that of those who did not view the pages in summer and that the daily usage of the heating device was even reduced in the former group, while the latter stayed the same.

Figure 66 clarifies that such observed change in the behavioural pattern does not necessarily have to lead to less comfort. For both groups, there are no major visible differences between the level of comfort stated during the first and second survey. This suggests that those who viewed the information pages probably reduced their usage of the cooling and heating device by using alternative passive strategies as proposed within the information material and not by reducing their level of comfort.

9.4.4 Constraints to Change Behaviour

The students living in the dormitory can be regarded as very mobile due to the fact that they have to leave the dormitory after a maximum period of two years. This fact must have influenced very much on the reason why they did not apply one or more passive strategies as shown in Figure 67. Next are the reasons concerning a perceived a difficulty and a lack of time to apply the mentioned strategies besides their own study. Following are two reasons that either the students already did some of the strategies before or that they found that the trees surrounding the dormitory provide enough shadow, so that there is no need for external shading. In summary, the fact that the students are living only temporarily in their rooms and do not have a lot of time besides their own study seem to be the highest constraints to apply the gained knowledge to their daily behaviour.

The answers given to the Internet-based survey with regard to the reason for not trying a specific strategy were either of no time, doubting effect, tedious, or no need. As shown in Figure 68, most participants agreed with time limitations and the perception that it is tedious to do as reasons for not implementing the strategy both in summer and in winter. In summer, many participants also answered that there is no need, because they feel already comfortable. These reasons are similar to those stated for not viewing the information and those named by the students.
9.5 Discussion

The knowledge transfer method used in above mentioned sets of investigation was designed to be completely in the first type, the information technique, for two reasons. First, according to the literature, positive motivational techniques, like material incentives, as well as coercive techniques, like social pressure or material disincentives, have a fast effect on the change, but at the same time bring about problems such as the weakness of the change and undesirable side effects. Second, the circumstances of the investigation did not allow any of those techniques, because as mentioned above, the electricity bill does not represent the individual

![Diagram]

Fig. 68. Reasons for not trying or implementing one of the strategies presented within the information pages as stated by the participants of the Internet-based surveys (The numbers in the brackets are the total number of answers obtained).
consumption, the social pressure is small because the students seldom meet others in their rooms, and finally it was of course not possible to implement any monetary punishment for any behaviour.

Additionally, the decision was made to conduct the knowledge transfer process only once for each set of investigation. Even though Bae et al. (2007) argues that the information given by the knowledge transfer has an effect, but should be repeated, because the effect gets smaller after some period of time, most knowledge transfer projects conducted in reality do not have the monetary resources to repeat the process. The results presented in this chapter therefore do give an idea, what one can expect with a one-time information process, even though it is agreed that a repetition would be useful. Unfortunately, the long-term effect of the knowledge transfer process in the dormitory cannot be accessed due to the limited period the students are allowed to live in the dormitory. However, due to an ongoing personal contact with some of the students, it is observed that many of them still use some of the introduced strategies and that the consciousness towards the topic of comfort and energy usage for most of them is still increasing.

Within the conditions of these investigations, the acquisition of information was free, i.e. the students could choose if they want to participate in the workshop or not. Therefore there was no control who attended the knowledge transfer processes and an even distribution of individuals could not be assured. It was found that the attendance strongly depended on personal attitudes and that the workshop group was already using the AC-unit less often than the other groups before the distribution of information. While this difference is rather small for the summer case, there was a huge difference in the usage patterns for the winter case as was shown in Table 30. According to the previous analyses, the AC-unit usage behaviour in winter is more sensible to individual factors than to the prevailing outdoor air temperature (see Chapter 6 or Schweiker and Shukuya (2009a)). This might be a reason why there is no effect of the knowledge distribution observable in the winter case.

In general, the participants of both investigations must have been interested in the research and therefore the magnitude of the observed change due to the knowledge transfer processes might be a bit overestimated, but the tendencies are expected to be found also in other studies dealing with a higher percentage of less interested persons.

Furthermore, the strategies presented for summer were easier to be accomplished by changes of behaviour alone, while those in winter most often required changes of the physical environment. This might be another reason for the differences between the observed effects of summer and winter investigation and supports the findings of McMakin et al. (2002) that there is a bigger chance of a certain behaviour to be implemented in case it is easy to be done and does not need further monetary or physical investments.
9.6 Conclusions

This chapter has discussed the effectiveness of knowledge transfer based on two sets of investigations, both of which included a one-time knowledge transfer process. One of them took place in a dormitory building and was accompanied by a physical measurement. The other one was conducted solely through the use of the Internet.

1) The participation in the offered information materials was low in general, for time limitations being one of the main reasons.
2) It could be observed that those persons participating in and receiving the information about passive strategies are more likely to apply such methods, if provided that they attended a workshop.
3) There is a huge discrepancy between the motivation to apply new behaviours right after the knowledge transfer methods and the action to be applied in reality.
4) For the cooling season, the workshop attendance resulted in a reduction of the percentage of persons using their AC-unit of up to 16%. This change in the behaviour pattern was presented in such a way, using logistic regression analysis that it can be easily implemented in simulation programs.
5) Most people claimed time limitations and a perceived tediousness as main factors for not applying one or more strategies.

It is further proposed to conduct more research in this field in order to have a better quantification of the effect of any information transfer method in order to judge their cost-wise efficiency.
PART IV
Effect of Variations in the Reference Levels on the Exergy Consumption for Cooling and Heating

第4部
住まい手行動変化の閾値の違いが暖冷房エクセルギー消費パターンに及ぼす影響評価

“In economics the depletion of deposits is regarded as creation of value, when in physics or ecology it is the opposite.”

(Wall and Gong, 2001; p. 141)
10 Effect of Occupant Behaviour on the Exergy Consumption of a Community of People

10.1 Introduction

In order to show the importance of the previous findings with respect to energy use in buildings, this chapter looks at the effect such individual differences of the occupants’ behaviour have on the exergy consumption pattern in comparison to the improvements of building envelope systems.

Several papers are addressing the role of exergy in energy policymaking, sustainability and efficiencies (Dincer, 2002; Gong and Wall, 2001; Kondo, 2009; Rosen, 2002a; Rosen et al., 2008; Ulu and Hepbasli, 2006; Wall and Gong, 2001). However, according to a comprehensive review over the existing work on the exergy consumption analysis of climatisation systems within the built environment as given in Torio et al. (2009), the common approach is the assumption of a standard behaviour pattern, simply by a fixed set-point room air temperature as done by Angelotti and Caputo (2007). This is due to the fact that those papers are mostly focussing on the improvement of the building systems. In reality one can expect the human occupant to choose a different set-point room air temperature according to their desired level of comfort and the surrounding conditions.

It must be important to see the effect of occupant behaviour in addition to that of building systems. Therefore, this chapter first describes a simplified steady-state calculation method for the exergy consumption within the built environment including one specific type of heat-pump system in the form of an AC-unit, which is typical for Japanese residential buildings, consisting of an outdoor unit and a room unit, and can be used both for cooling and heating. This is followed by the description of how the occupants choice of set-point temperature and frequency of AC-unit usage were set up based upon the results of the analysis on occupant behaviour presented above and then the result of the exergy consumption calculation for four different combinations of building envelope improvements and occupant behavioural changes are presented.

The objective is thereby to show the quantitative effect and theoretical potential of changing the occupants’ behaviour compared to the improvements of building envelope system in order to increase the awareness that it is meaningful to have a more detailed look not only at the calculation method of the building envelope system, but also the interaction of the human occupant. Further addressed are adjustments of the commonly used calculation methods, which had to be done due to the inclusion of individual difference of the occupant behaviour into the exergy analysis of the built environment.
10.2 The Concept of Exergy with Respect to the Built Environment

Taking into account qualitative aspects of energy leads to the introduction of the exergy concept in the comparison of systems. Energy, which is entirely convertible into other types of energy, is exactly exergy, i.e. the highest valued energy such as electricity. Energy, which has a very limited convertibility potential, such as thermal energy close to room air temperature, is low valued energy. Due to such a characteristic, the exergy analysis is useful to have a clearer look at sustainability, because it enables us to supply high quality, where high quality is really needed and low quality wherever possible. In such a way, its application assures an optimal usage of the existing resources.

The advantages of the consideration of the thermodynamic concept of exergy can be summarized as follows: (1) it is easy to show the quality of the energy involved in any process, (2) one can show the process of exergy consumption in every system and its subsystems, and (3) it is possible to compare different qualities of energy, e.g. electricity and heat.

In the year 2000, a group of scientists from all over the world started its work on the IEA Annex 37 (Ala-Juusela, 2003), which is already completed, and they are now about to finish the work on the IEA Annex 49 (Annex 49, 2009). Their work is focused on the importance of all kinds of so-called “energy saving measures”, and the necessity for an increased efficiency in all forms of energy utilization. Both of these matters are affected by the energy efficiency of the built environment and the quality of the energy carrier in relation to the required quality of the energy. One of those investigations revealed that the major exergy loss for space heating is caused by the boiler. But this happens on the basis of the heat loss of the building, the quality of the building envelope. A good thermal insulation and a reduction of internal loads for the case of cooling are mandatory for a good low exergy design of buildings (Shukuya, 2001; p. 2).

“Exergy is the concept that explicitly indicates ‘what is consumed’. All systems, not only engineering systems but also biological systems including the human body, work feeding on exergy, consuming its portion and thereby generating the corresponding entropy and disposing of the generated entropy into their environment. Entropy is a function of temperature and pressure, therefore it only changes when the temperature or the pressure changes. In order to keep any process running, entropy has to be discarded into the environment to allow the feeding of exergy. The whole process is called ‘exergy-entropy process” (Shukuya and Hammache, 2002; p.3).

The concept of entropy is best visualized by the Boltzmann Demon, a small creature always replacing one atom of an object (Atkins, 1984; pp. 67ff). Starting with a total organized structure, the demon cannot change anything without us being able to recognize that something was changed. In this case the entropy is zero. But after a while of rearranging atoms, we will not be able to realize if there was a change or not. The entropy got high.
In addition to the application for power plants and the built environment, one could apply these exergy principles to everyday life by e.g., consequently using low quality paper and ink for test printing and high quality for the presentation. Another example would be the choice when buying clothes between cheap and more expensive ones. Buying cheap clothes, which normally have a low quality, might first be good, but in the long-term view it is bad, because higher quality clothes last longer and one will eventually save money at last.

“It often seems that members of the public actually mean exergy when they say energy” (Rosen, 2002b; p. 211). This is obvious, when the public is talking about energy crisis, energy efficiency, energy conservation and energy security, which should be called exergy crisis, exergy efficiency, exergy conservation and exergy security with regard to the First and Second Law of Thermodynamics (Rosen, 2002b).

10.3 Outline of the Exergy Calculation and Basic Assumptions

A steady-state calculation was chosen for the present comparative study, because the understanding of the implications due to the implementation of occupant behaviour to exergy analysis was considered as being necessary, before proceeding to a dynamic exergy simulation.

Figure 69 shows the four sub-systems considered for the exergy calculation together with the human occupant behavioural model. The latter is described more in detail in Chapter 10.4. The four sub-systems are (1) the building-envelope sub-system, (2) the room-air sub-system, (3) the heat-pump sub-system, and (4) the power-supply sub-system. Following

Fig. 69. Scheme of the four sub-systems: (1) building envelope; (2) room air; (3) heat-pump; and (4) power supply, as well as (5) the occupant assumed for exergy calculation.
Shukuya (2004), the energy and entropy balance equations of each sub-system are for a steady-state case always in the form of

\[ Q_{in} = Q_{out} , \]  

(21)

with \( Q_{in} \) being the rate at which energy is supplied to a sub-system (W/m\(^2\)) and \( Q_{out} \) the rate at which energy leaves it (W/m\(^2\)), and

\[ \frac{Q_{in}}{T_{in}} + S_g = \frac{Q_{out}}{T_{out}} , \]  

(22)

with \( S_g \) being the rate of entropy generation (W/m\(^2\)K), \( T_{in} \) the temperature associated with the energy supplied, \( Q_{in} \), and \( T_{out} \) the temperature associated with the energy left, \( Q_{out} \). Both temperatures have to be in the unit of Kelvin. Having set up these balances and assuming a common environmental temperature for all of the sub-systems, \( T_0 \) also with the unit of Kelvin, the exergy balance equation turns out to be the difference between eq. (21) and the product of eq. (22) with the environmental temperature. Namely,

\[ Q_{in} (1 - \frac{T_0}{T_{in}}) - S_g * T_0 = Q_{out} * (1 - \frac{T_0}{T_{out}}) . \]  

(23)

Considering the first part of eq. (23) as the rate of exergy entering the sub-system, \( E_{in} \), the second part as the rate of exergy consumed, \( E_{cons} \), and the third part as the rate of exergy leaving the sub-system, \( E_{out} \), eq. (23) can be rewritten into

\[ E_{cons} = E_{in} - E_{out} . \]  

(24)

The value of exergy-consumption rate, \( E_{cons} \), is calculated from eq. (24) for each respective sub-system. For the building envelope system, the environmental temperature, \( T_0 \), is equal to \( T_{out} \) so that eq. (23) can be transformed into

\[ Q_{in} (1 - \frac{T_0}{T_{in}}) - S_g * T_0 = 0 \]  

(25)

or
\[ E_{in} = E_{cons} = Q_{in} \left( 1 - \frac{T_0}{T_{in}} \right) . \]  

(26)

For the building-envelope sub-system \( Q_{in} \) can be calculated by

\[ Q_{in} = Q_{win} + Q_{wal} + Q_{air} - Q_{int} , \]  

(27)

with \( Q_{win} \) and \( Q_{wal} \) being the thermal energy transferred by conduction through window and wall, \( Q_{air} \) the heat-losses through ventilation and \( Q_{int} \) the internal heat gains from persons and electric appliances.

Such a procedure as mentioned above is described in detail for the heat-pump sub-system in Chapter 10.5.

For the room-air sub-system, the net exergy rate, \( \Delta E_{air} \), supplied to the room space turns out to be the difference between the exergy contained by an amount of air leaving the AC-unit and that contained by an amount of room air entering the AC-unit,

\[ \Delta E_{air} = c_{air} * m_{air} * \left[ (T_{r-out} - T_r) - T_0 * \ln \frac{T_{r-out}}{T_r} \right] , \]  

(28)

with \( c_{air} \) being the specific heat of air, \( m_{air} \) the airflow rate blown into the room by the AC-unit, \( T_{r-out} \) the outlet air temperature of the AC-unit and \( T_r \) the room air temperature.

For the power-supply sub-system, being assumed as liquefied natural gas fired, the primary exergy supply rate, \( E_{gas} \), is given by

\[ E_{gas} = \tau_{gas} * \frac{E_{elect}}{\eta_{pg}} , \]  

(29)

with \( \tau_{gas} \) being the ratio of chemical exergy to the higher heating value of natural gas, \( E_{elect} \) the electricity to be supplied to the heat pump system, and \( \eta_{pg} \) the energy efficiency of the whole power supply system.

Figure 70 shows the room dimensions assumed for the present exergy calculation, which are similar to those of the dormitory room observed for collecting the data of occupant behaviour to be described in the following sub-chapter, namely a small room having one external wall of a poor thermal insulation level and a single-glazing window. For the exergy calculation, two cases for the building envelope system were assumed, a standard and an advanced case. The thermal performances used for the former case were also chosen to be as
similar as possible to that in the dormitory building: U-value of 3.85 W/m²K for the external wall and 5.2 W/m²K for the window. For the advanced case, the physical parameters of the outside wall and window were changed assuming an additional 200 mm of thermal insulation for the wall and a replacement of the single-glazing window by a double-glazing one, which is similar to measures conducted during renovations of existing buildings as e.g. described by Bell and Lowe (2000). However, for a Japanese building situated in Tokyo, the addition of 100mm would be sufficient, because there is not much improvement between 100mm and 200mm in the prevailing climatic conditions. The standard case therefore represents a poorly insulated building and the advanced case will be a building with an improved level of insulation. Furthermore, the heat distributed by one person together with the one distributed due to a low level of electric-appliance usage were assumed as internal heat gains of in total 125 W.

Two types of occupants were assumed: one tends to switch frequently on the AC-unit and the other uses it only occasionally. Table 31 shows the summary of four cases to be compared. As can be seen, the four cases are the combination of either a standard and or thermally well insulated building envelope system and either of two types of occupant groups.

The calculation of these four cases was done first for an individual person and second for a group of 100 persons, which will be called community in the rest of this chapter. The calculation for an individual person will clarify the differences due to a variety of desired room-air temperatures alone. On the other hand, the calculation for a community includes

![Fig. 70. Dimensions of the room assumed for exergy calculation. The wall having a window is exposed to outdoors. The other walls, the ceiling, and the floor face the room spaces next to this room.](image)
not only such difference in the desired room air temperature, but also the difference in individual behaviours with respect to the use of AC-units, which is expressed in the percentage of persons switching on their AC-units. This permits the implementation of different behavioural patterns without the need to rely on computer generated random numbers as done by recent algorithms presented by Rijal et al. (2007) as well as Haldi and Robinson (2008). Therefore, it is important to study not only the relationship between occupant behaviour and air temperature but to study the actual human behaviour also in relation to human nature and societal characteristics.

All cases were calculated for nighttime in winter in order to limit the number of cases and due to the reason that the database used to analyse the occupant’s behaviour has the highest accuracy concerning the occupancies rate during this period (see Chapter 5 or Schweiker and Shukuya (2009a) for further explanations).

In order to assume realistic values for the outdoor air temperature for exergy analysis, the mean outdoor air temperature during each night of February was calculated for the fifteen-year period from 1980 to 1995, which is used as basis of the general reference year. For this calculation the data for Tokyo given by Akasaka et al. (1999) was used. The mean together with the minimum value, which are shown in Table 32, were then taken for the calculation.

There is no solar radiation, because the calculation is done for nighttime.

### Table 31. The four cases analysed.

<table>
<thead>
<tr>
<th></th>
<th>AC-unit usage</th>
<th>Building envelope system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>Frequently</td>
<td>Standard(^1)</td>
</tr>
<tr>
<td>Case 2</td>
<td>Occasionally</td>
<td>Standard</td>
</tr>
<tr>
<td>Case 3</td>
<td>Frequently</td>
<td>Advanced(^2)</td>
</tr>
<tr>
<td>Case 4</td>
<td>Occasionally</td>
<td>Advanced</td>
</tr>
</tbody>
</table>

\(^1\) Standard building envelope system assumes the U-value of 3.85 W/m\(^2\)K for the external wall and 5.2 W/m\(^2\)K for the window.

\(^2\) Advanced building envelope system assumes a well insulated building with the U-value of 0.19 W/m\(^2\)K for the external wall and 1.3 W/m\(^2\)K for the window.

### Table 32. Assumed outdoor air temperature during nighttime.

<table>
<thead>
<tr>
<th></th>
<th>Mean outdoor air temperature during night</th>
<th>3.5°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2</td>
<td>Minimum mean outdoor air temperature during night</td>
<td>-2.5°C</td>
</tr>
</tbody>
</table>
Table 33. The values of the coefficients for the logit model usable to predict the percentage of persons using their AC-unit during night-time in winter, and also for the linear model usable to predict the indoor air temperature chosen.

<table>
<thead>
<tr>
<th></th>
<th>Coefficients for percentage of persons</th>
<th>Coefficients for indoor-air temperature</th>
<th>Frequent / occasional usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>α</td>
<td>0.02(^1)</td>
<td>a</td>
<td>29.91(^2)</td>
</tr>
<tr>
<td>Running mean of outdoor air temperature</td>
<td>β(_1) (-0.12)</td>
<td>b(_1) -1.19*10(^{-4})</td>
<td>–</td>
</tr>
<tr>
<td>Prefer working with AC-unit on</td>
<td>β(_2) 1.86</td>
<td>b(_2) 0.82</td>
<td>x(_2) 1 / 0</td>
</tr>
<tr>
<td>Prefer sleeping with AC-unit on</td>
<td>β(_3) 0.12</td>
<td>b(_3) 4.78</td>
<td>x(_3) 1 / 0</td>
</tr>
<tr>
<td>Switching on the AC-unit leads to more comfort</td>
<td>β(_4) 2.91</td>
<td>b(_4) -1.61</td>
<td>x(_4) 1 / 1</td>
</tr>
<tr>
<td>Opening window leads to more comfort</td>
<td>β(_5) 2.6</td>
<td>b(_5) -0.53</td>
<td>x(_5) 1 / 1</td>
</tr>
<tr>
<td>School was always heated during childhood</td>
<td>β(_6) 1.73</td>
<td>b(_6) 0.31</td>
<td>x(_6) 1 / 0</td>
</tr>
<tr>
<td>Male</td>
<td>β(_7) 1.92</td>
<td>b(_7) -9.63*10(^{-4})</td>
<td>x(_7) 1 / 1</td>
</tr>
<tr>
<td>Originating from a moderate climate</td>
<td>β(_8) -2.9</td>
<td>b(_8) -2.11</td>
<td>x(_8) 1 / 1</td>
</tr>
<tr>
<td>Originating from East-Asian country</td>
<td>β(_9) -3.47</td>
<td>b(_9) -1.75</td>
<td>x(_9) 1 / 1</td>
</tr>
<tr>
<td>Studying natural not social science</td>
<td>β(_{10}) -4.44</td>
<td>b(_{10}) -0.14</td>
<td>x(_{10}) 1 / 1</td>
</tr>
<tr>
<td>South orientated window</td>
<td>β(_{11}) -0.92</td>
<td>b(_{11}) -2.82</td>
<td>x(_{11}) 1 / 1</td>
</tr>
</tbody>
</table>

1) The p-values of the coefficients are given in Table 18 (page 98).
2) The p-values of the coefficients are below 0.001 except for the following: β\(_1\): 1; β\(_2\): 0.01; β\(_4\): 0.01; β\(_5\): 0.25; β\(_6\): 0.51; β\(_7\): 1; β\(_{10}\): 0.82 (see also comment to Table 16).
3) The suffix numbers from 1 to 11 in this table correspond to the numbers 1, 5, 6, 8, 10, 19, 23, 14, 21, 24, 27, respectively, given in Chapter 6 and Schweiker and Shukuya (2009a).
10.4 Data Set and Assumptions Concerning the Occupant Behaviour

In order to use realistic assumptions for the occupant’s behavioural choices, the results from a field measurement were analysed to see the differences in (1) the percentage of persons using their AC-units, and (2) the indoor air temperature chosen by the occupants according to the change in prevailing outdoor conditions and individual characteristics.

A short summary of the measurement and the resultant empirical formula for occupant’s behaviour is given below (Schweiker and Shukuya, 2009). For the field measurement, which was made in 2007 and 2008, the air temperature and humidity inside each of the 39 student rooms of an international student dormitory in Tokyo and outside the building were measured with a wireless temperature and humidity sensor and data logger along with a detailed written questionnaire survey about psychological and individual factors, including preference. Preference in this context meant whether a person answered that he or she likes or dislikes working/sleeping in an air-conditioned space. All rooms of about 12m² are equipped with one AC-unit each and occupied by a single person. While the outdoor air temperature ranged between -2.4°C and 12.1°C during the winter measurement, the indoor air temperatures of the rooms where the students did not use the AC-unit varied between 7.7°C and 24.4°C and of those where the AC-unit was used between 7.5°C and 31.8°C.

In order to be able to have a realistic assumption of the percentage of persons using their AC-unit, the data was analysed using the multivariate logistic regression method and the final number of variables contained within the models were derived based on the lowest Akaikes Information Criterion (Akaike, 1973). The result of this analysis is a formula, describing the percentage of persons using their AC-units in relation to the running mean of the outdoor air temperature during night, \( \theta_{\text{mean}} \) and ten individual factors \( (x_2-x_{11}) \)

\[
P_{\text{AC-Unit On}} = \frac{1}{1 + e^{-\left(\beta_1 \theta_{\text{mean}} + \beta_2 x_2 + \beta_3 x_3 + \cdots + \beta_{11} x_{11}\right)}}. \tag{30}
\]

The first two columns of Table 33 show the values of the constants \( \alpha, \beta_1, \beta_2, \ldots, \beta_{11} \), in eq. (30) as derived from the measured data using the statistical software R (R Development Core Team, 2005). The individual factors, \( x_2, x_3, \ldots, x_{11} \), are binomial, namely 0 or 1 and depend on the occupant’s characteristics.

Analysing the data from the field measurement it was also found that there is a rather huge difference between individuals in the indoor air temperature preferred and chosen. To analyse these differences and use a realistic assumption for the desired room air temperature in exergy analysis, a linear multiple regression analysis was done for the same factors that
Table 34. The values of the coefficients for the logit model usable to predict the percentage of persons using their AC-unit during night-time in summer, and also for the linear model usable to predict the indoor air temperature chosen.

<table>
<thead>
<tr>
<th>Coefficients for percentage of persons</th>
<th>Coefficients for indoor-air temperature</th>
<th>Frequent / occasional usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>α 7.361x10^7 1)</td>
<td>a 17.442)</td>
<td></td>
</tr>
<tr>
<td>Running mean of outdoor air temperature</td>
<td>β₁ 0.58 b₁ 0.43 x₁ 1 / 0</td>
<td></td>
</tr>
<tr>
<td>Prefer sleeping with AC-unit on</td>
<td>β₂ 1.85 b₂ -2.26 x₂ 1 / 0</td>
<td></td>
</tr>
<tr>
<td>Switching on the AC-unit leads to more comfort</td>
<td>β₃ 2.32 b₃ 1.21 x₃ 1 / 1</td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>β₄ 1.89 b₄ 0.24 x₄ 1 / 1</td>
<td></td>
</tr>
<tr>
<td>Studying natural not social science</td>
<td>β₅ 0.43 b₅ -2.37 x₅ 1 / 1</td>
<td></td>
</tr>
<tr>
<td>South orientated window</td>
<td>β₆ 1.03 b₆ -2.73 x₆ 1 / 1</td>
<td></td>
</tr>
<tr>
<td>Originating from a moderate climate</td>
<td>β₇ -1.39 b₇ 1.54 x₇ 1 / 1</td>
<td></td>
</tr>
<tr>
<td>Originating from East-Asian country</td>
<td>β₈ -0.28 b₈ 1.92 x₈ 1 / 1</td>
<td></td>
</tr>
<tr>
<td>Living between 2nd and 4th floor</td>
<td>β₉ -1.57 b₉ -1.56*10⁻³ x₉ 1 / 1</td>
<td></td>
</tr>
</tbody>
</table>

1) The p-values of the coefficients are given in Table 17 (page 96).
2) The p-values of the coefficients are below 0.001 except for the following: β₃: 0.09; β₄: 0.43; β₉: 1 (see also comment to Table 16).
3) The suffix numbers from 1 to 9 in this table correspond to the numbers 1, 6, 8, 23, 24, 27, 14, 21, 26, respectively, given in Chapter 6 and Schweiker and Shukuya (2009a).
appeared in eq. (30). One would normally define the desired room air temperature to be the
temperature chosen by the occupant and displayed on the remote control (also called the set-
point temperature). However, the set-point temperature was neither observed by our
measurement nor asked in the surveys. Even though the indoor air temperature is especially
in the first minutes after switching on the AC-unit different from the set-point temperature, it
is reasonable to assume the room-air temperature being similar to the set-point temperature
for the steady-state case, which assumes that there was no change in the status of the AC-unit.
Additionally, one can say that the indoor air temperature, not the set-point temperature, must
be the temperature judged by the occupants as being comfortable, because otherwise they
would have changed the status of the AC-unit with the remote control. Therefore, the
decision was made to use the indoor air temperature instead and to analyse the data from the
student rooms according to the average of the maximum air temperatures during one period
of the AC-unit usage. This led to the determination of the constants for the linear formula of
the indoor air temperature as a function of the same factors as present in eq. (30):

\[
\theta_{\text{ind}} = a + b_1 \theta_{\text{r,mean}} + b_2 x_2 + b_3 x_3 + \ldots + b_{11} x_{11} ,
\]  

(31)

The two columns in the middle of Table 33 give the constants a, b_1, b_2, ... b_{11}, of eq. (31).
The occupant behaviour in summer is very different from that in winter. Table 34 presents
the values of the coefficients for the occupant behavioural models for summer time on the
basis of the data from the summer measurement.

10.5 Field Measurement of the Heat-Pump System and Resulting Assumptions for
the COP

Referring to Figure 71, it is possible to set up the energy and entropy balance equation for the
heat-pump sub-system in winter to be

\[
Q_{\text{cold}} + E = Q_{\text{hot}} ,
\]  

(32)

where \( Q_{\text{cold}} \) is the rate of thermal energy taken from the environment (W), \( E \) is the electric
power input (W) and \( Q_{\text{hot}} \) is the output rate of thermal energy into the room air (W), and

\[
\frac{Q_{\text{cold}}}{T_{\text{cold}}} + S_g = \frac{Q_{\text{hot}}}{T_{\text{hot}}} ,
\]  

(33)
where \( T_{cold} \) is the temperature of the working fluid in the evaporating unit (K) and \( T_{hot} \) that in the condensing unit (K). The COP of a heat pump in winter season, \( \text{COP}_{H} \), is given by

\[
\text{COP}_{H} = \frac{Q_{hot}}{E},
\]  

(34)

which can be transformed into

\[
E = \frac{Q_{hot}}{\text{COP}_{H}}
\]  

(35)

being the exergy supplied to the heat-pump sub-system (Moran and Shapiro, 1999). Due to the First Law of Thermodynamics, \( Q_{hot} \) is equal to \( Q_{in} \), the thermal energy transferred into the building-envelope subsystem, so that we have to find a reasonable assumption for \( \text{COP}_{H} \), in order to estimate the value of \( E \).

A general approach to calculate the coefficient of performance (COP) of an air-source heat-pump system for the heating case is to make the COP as a linear function of the outdoor temperature. This kind of approach can be seen, for example in Angelotti and Caputo (2007), who are referring to a sub-program library to be used together with TRNSYS, one of the dynamic simulation programs used by quite a few engineers and researchers. They calculated the COP to be a function of outdoor air temperature as

![Fig. 71. The heat pump system assumed.](image-url)
\[ \text{COP}_{\text{TRNSYS}} = l_1 + l_2 \cdot \theta_{\text{out}}, \]  

(36)

where \( l_1 \) and \( l_2 \) are constants related to the heat-pump system chosen and \( \theta_{\text{out}} \) is outdoor air temperature (°C).

This is a rational assumption when considering a case that indoor temperature is kept constant at a certain value, e.g. 20°C for heating, as done by the same authors (Angelotti and Caputo, 2007). However, according to the analysis of the occupant’s behaviour as shown in Table 35, the chosen indoor-air temperature values are not necessarily the same as a nominal set-point temperature value to be found in textbooks. Therefore, the decision was made to give the COP-value for the heat pump of the AC-units as a function of both indoor and outdoor air temperatures for the present exergy analysis.

Eq. (34) can be transformed by substituting eq. (32) and considering that the value of \( \text{COP}_{\text{H}} \) is inevitably smaller than the COP of an imaginary reversible Carnot-type of heat pump, which can be derived from eq. (33) having \( S_g \) equal to null. This leads to

\[ \text{COP}_{\text{H}} = \frac{Q_{\text{hot}}}{Q_{\text{hot}} - Q_{\text{cold}}} < \frac{T_{\text{hot}}}{T_{\text{hot}} - T_{\text{cold}}} . \]  

(37)

The inequality sign denotes that in reality no system can perform as the reversible Carnot-type of heat pump could do in a thought experiment.

For the further analyses, an empirical equation was derived which can be expressed as

\[ \text{COP}_{\text{H}} = k_1 + k_2 \cdot \left( \frac{T_{\text{r-out}}}{T_{\text{r-out}} - T_{\text{o-out}}} \right) . \]  

(38)

In eq. (37), the temperatures taken were those of condenser and evaporator as \( T_{\text{hot}} \) and \( T_{\text{cold}} \) respectively, but these values are not easily accessible, so that it was decided to replace \( T_{\text{hot}} \) and \( T_{\text{cold}} \) with the indoor unit outlet temperature \( T_{\text{r-out}} \) and outdoor unit outlet temperature \( T_{\text{o-out}} \) respectively, as can be seen in Figure 71 and eq. (38).

A small field measurement for a heat-pump system similar to those present in the dormitory rooms was conducted to analyse the relationship between the outlet air temperature of the indoor-unit the outlet air temperature of the outdoor-unit as well as the set-point room-air temperature. For this measurement, the heating behaviour of the system was measured and analysed over a period of four days with a variety of set-point temperature values from 21°C to 31°C. The values of temperature and relative humidity were measured at a one minute interval.
Fig. 72. Relationship between the outlet temperature of the indoor-unit of the AC-unit, $\theta_{r-out}$ and the inlet temperature of the indoor-unit, $\theta_{r-in}$, which is equal to the room air temperature, as well as the set-point temperature, $\theta_{set-point}$.

\[
\begin{align*}
\theta_{r-out} &= 1.3\theta_{r-in} + 10.9 \\
R^2 &= 0.54 \\
\theta_{r-out} &= 1.4\theta_{set-point} + 7.6 \\
R^2 &= 0.88
\end{align*}
\]

Fig. 73. Relationship between the outlet temperature, $\theta_{o-out}$, and the inlet temperature, $\theta_{o-in}$, of the outdoor-unit.

\[
\begin{align*}
\theta_{o-out} &= 0.75\theta_{o-in} + 0.1 \\
R^2 &= 0.95
\end{align*}
\]
for the outdoor air, room air, as well as the inlet/outlet air of outdoor- and indoor-unit. During
the period of measurement, the outdoor air temperature varied from 5°C to 17°C and the
relative humidity from 24% to 99%. For the analysis, only the data when the AC-unit was in full
operation except those in the periods of warming up were used.

Figures 72 and 73 present the results of this measurement. Figure 72 shows the
relationship between inlet and outlet air temperatures of the indoor-unit and Figure 73 that
between inlet and outlet air temperatures of the outdoor-unit. It can be seen that, (1) the
outlet air temperature of the indoor-unit depends strongly on the chosen set-point
temperature, \( \theta_{\text{set-point}} \), while it is rather constant for a range of the inlet air temperature, \( \theta_{\text{v,air}} \)
and (2) the outdoor-unit outlet air temperature depends strongly on the outdoor-unit inlet air
temperature, \( \theta_{\text{o,air}} \). The same type of graph as Figure 73 drawn for the set-point temperature
and the outdoor-unit outlet-temperature showed no correlation.

Even though the relationship between set-point temperature and indoor-unit outlet air
temperature is better than that between indoor air temperature and the latter with respect to
the \( R^2 \)-value, both analyses led to a similar relationship and it was assumed that the
temperature in the student rooms was more or less very close to the set point temperature.
The indoor-unit outlet temperature was therefore assumed to be a linear function of the room
air temperature in the unit of Kelvin as

\[
T_{\text{r, out}} = 1.4 \times T_{\text{room}} - 101.7 , \tag{39}
\]

and the outdoor unit outlet temperature to be that of the outdoor air temperature in the unit
of Kelvin as

\[
T_{\text{o, out}} = 0.75 \times T_{\text{out}} + 68.4 . \tag{40}
\]

Substituting eqs. (39) and (40) into eq. (38), the relation turns out to be

\[
\text{COP}_{\text{H}} = k_1 + k_2 \times \left( \frac{1.4 \times T_{\text{room}} - 101.7}{1.4 \times T_{\text{room}} - 0.75 \times T_{\text{out}} - 170.1} \right) . \tag{41}
\]

Since the real performance of the measured heat-pump system, \( \text{COP}_{\text{H}} \), could not be
measured, it was decided to calibrate its performance to be similar to the one in the sub-
program library of TRNSYS referred to by Angelotti and Caputo (2007). The COP of this
system, calculated with eq. (36), is valid for the case of heating the indoor air temperature to
20°C. Setting \( T_{\text{room}} \) in eq. (41) to 20°C and fitting \( k_1 \) and \( k_2 \) so that the minimum sum of squared
residuals between the values calculated by eq. (36) and (41) is obtained for a range of outdoor air temperatures between -5°C and 20°C led to $k_1$ equal to 1 and $k_2$ equal to 0.16, respectively.

Figure 74 shows a comparison of the COP-values when calculated with eq. (36) and eq. (41) for the case of heating to 20°C as well as those calculated with eq. (41) for other cases, in which the indoor air temperature is different from 20°C. As can be seen, we now have different values for the COP for different values of the indoor temperature. The COP-values tend to be smaller as the difference in temperature between indoors and outdoors is larger; this tendency looks consistent with a general and qualitative knowledge about heat-pump systems.

A few modifications to the models presented above were necessary in the calculation made for the summer season, since the heat-pump system is going to be used for cooling. For a summer case, $Q_{hot}$ becomes the rate of thermal energy given off into the outdoor environment, and $Q_{cold}$ the output rate of thermal energy into the room air. In other words, the outdoor environment in Figure 71 should be regarded as indoor space and the indoor space as the outdoor environment. While all other equations to calculate the exergy consumption within each sub-system can remain unchanged, eq. (35) has to be changed into

$$E = \frac{Q_{cold}}{\text{COP}_C}. \quad (42)$$

![Fig. 74. COP\textsubscript{TRNSYS} calculated from eq. (36) and COP\textsubscript{H} from eq. (41).](image-url)
$Q_{cold}$ is thereby the sum of the heat gains through the building envelope system, ventilation and the internal gains. $\text{COP}_{c}$ is different from $\text{COP}_{H}$ and was derived in the same way as shown above for the winter case to be

$$\text{COP}_{c} = k_1 + k_2 \left( \frac{0.79 \cdot T_{\text{room}} + 49.7}{1.1 \cdot T_{\text{room}} - 0.79 \cdot T_{\text{out}} - 75.1} \right),$$

(43)

with $k_1$ estimated as being equal to 1.4 and $k_2$ as being equal to 0.1. For hot and humid summer regions such as Yokohama in Japan, it is desirable to include the effect of dehumidification, but this was neglected since the discussion here in this chapter is based on a series of rather simplified calculations and the neglect of dehumidification would not cause the first order of magnitude for the present discussion.

10.6 Results and Discussion

The statistical analysis of the observed occupant behaviour resulted in the values of the coefficients for the models to predict the percentage of persons using their AC-unit and to choose a certain indoor air temperature for heating and cooling as shown in Table 33 and 34 (p. 166f). The values of the coefficients can be interpreted as follows. In the case of the values for the coefficients for percentage of persons, a positive value means that this factor leads to a higher percentage of persons using the AC-unit, while a negative value means the opposite.

In the case of the coefficients for indoor-air temperature, a positive value means that this factor leads to a higher indoor-air temperature chosen by that person. For the winter case (Table 33), looking for example at the factor “Prefer working with AC-unit on”, this means that out of a group of persons who prefer working with the AC-unit on, $x_3$ is 1, a higher percentage uses the AC-unit compared to another group of persons who do not prefer working with the AC-unit on, $x_3$ is 0. In this manner, the difference between the percentage values of each group varies with the outdoor air temperature due to the logistic equation as given in eq. (30).

At the same time the former group will choose a temperature being 0.82°C higher than that chosen by the latter group. Similar conclusions can be made for the other factors included in the models. In general, the models show that the behaviour and therefore also the attitude towards the use of the AC-unit depends on the outside air temperature as well as individual factors and it shall be highlighted here that these differences are derived out of the measured room air temperatures and thereby represents the observed behaviour of the occupants.
Table 35. The indoor air temperature chosen by the two types of persons and the percentage of persons using the AC-units for them.

<table>
<thead>
<tr>
<th>Assumed outdoor air temperature (°C)</th>
<th>AC-unit usage</th>
<th>Indoor air temperature (°C)</th>
<th>Percentage of persons using the AC-unit (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5</td>
<td>Frequently</td>
<td>26.9</td>
<td>96</td>
</tr>
<tr>
<td></td>
<td>Occasionally</td>
<td>21</td>
<td>38</td>
</tr>
<tr>
<td>-2.5</td>
<td>Frequently</td>
<td>26.9</td>
<td>98</td>
</tr>
<tr>
<td></td>
<td>Occasionally</td>
<td>21</td>
<td>55</td>
</tr>
</tbody>
</table>

Table 36. COP values assumed for two types of persons.

<table>
<thead>
<tr>
<th>Assumed outdoor air temperature (°C)</th>
<th>AC-unit usage</th>
<th>COP (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5</td>
<td>Frequently</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>Occasionally</td>
<td>2.5</td>
</tr>
<tr>
<td>-2.5</td>
<td>Frequently</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>Occasionally</td>
<td>2.3</td>
</tr>
</tbody>
</table>

Fig. 75. Result of the exergy and energy calculation for case 1.
Table 35 shows the values of the desired indoor air temperature and the percentage of persons using their AC-unit for the two types of occupants for respective assumed outdoor-air temperatures. These values were calculated using the values from Table 32 and the coefficients from Table 33 in equations (30) and (31). The results from the statistical analysis of the observed occupant behaviour reveal that there are huge differences between individual occupants in the frequency of using the AC-unit as well as the chosen indoor air temperature provided. As can be seen from the values in Table 35 there is a difference of 0.2°C between the minimum and mean outdoor temperatures for each group, but a 6°C difference between the two groups under the same conditions. This shows the huge influence of individual differences on the chosen set-point temperature so far neglected in energy simulations. Regarding the percentage of persons using their AC-unit, there is a difference of 50% between both groups in case of the mean outdoor air temperature and 30% in case of the minimum outdoor air temperature, which repeats the findings presented earlier.

Table 36 shows the COP values resulting out of the different outdoor air temperatures and chosen indoor air temperatures for the two types of occupants shown in Table 35. As was the objective for the modification of the calculation method for the COP-value, it is not only dependent on the outdoor air temperature, but also the indoor air temperature, which must be a realistic performance of such an air-source heat-pump system. The higher the COP-value the higher is the energy efficiency of the AC-unit system, which means that more heat is produced with the same amount of electricity. But this also shows that, due to the differences in the COP-values of 0.2 to 0.3 between the two types of occupants, the one using the AC-unit occasionally is not only using it less often and with a lower temperature compared to the frequent user, but also using it in a mode, which is more energy efficient.

Figure 75 shows exergy flow and consumption patterns for each of the four sub-systems in case 1 together with the energy flow. It can be seen that every sub-system consumes some amount of exergy, while on the other hand, a relatively large amount of energy looks produced by the heat pump system. The heat-pump system takes in some amount of thermal energy from the environment by feeding on the electricity supplied to the system. If we disregard the qualitative aspect of thermal energy taken in and energy supplied by electricity, it may look that a heat pump produces energy, but it is clear that the heat pump system also consumes exergy and it never produces more exergy than supplied. A comparison of the primary input with respect to exergy and energy alone does not lead to a very different conclusion from ordinary energy calculations as can be seen in the values of exergy and energy supply to the power plant. But the merit of exergy calculation is that it is possible to take a look at the whole system including the consequence of energy use, namely exergy consumption. Therefore, in what follows the results of the exergy consumption calculation shall be discussed.
Figure 76 shows the results of the exergy calculation for the four cases, in which an individual person is assumed. The upper graph, a), is the case of the minimum mean outdoor air temperature and the lower graph, b), the mean outdoor air temperature. Figure 77 shows the results for the four cases, in which a community of one hundred people is assumed.

Looking at part a) of Figure 76, the difference between the two types of occupants, case 1 and case 2, is rather small compared to the reduction of exergy consumption achieved by the
improvement of the building envelope system, case 1 and case 3. However, the occupant who uses the AC-unit occasionally (case 2) consumes less exergy by 25% to 30% than the frequent-using occupant (case 1). This is due to the effect of a lower indoor air temperature chosen by the occupant who uses the AC-unit occasionally. Combining the improvement of the building envelope system with a change in such behavioural pattern (case 4) leads to a reduction of the exergy consumption of more than 80%.

Fig. 77. Results of the exergy calculations of the four cases for a community of people. The upper graph, a), is for the minimum mean outdoor air temperature and the lower graph, b), is for the mean outdoor air temperature.
The results shown in part b) of Figure 76 are more or less the same as those in a), but the exergy inputs are smaller in b) than in a) due to the higher value of outdoor air temperature.

The results of the calculation for the community shown in Figure 77 turned out to be different from those in Figure 76. The combined effect of a different indoor air temperature and a different percentage of persons using their AC-unit has a comparable effect as the building envelope improvements. This can be seen both in a) and in b). In the case of a) minimum mean outdoor air temperature, the reduction of the exergy consumption of around 50% due to the change of occupant behaviour from case 1 to case 2 is still a bit less than that due to the building envelope improvements, which is more than 60% from case 1 to case 3. This relation is changed for the case of b) the mean outdoor air temperature.

This finding motivated us to have a closer look at the effect of both measures with varying outdoor air temperatures. Therefore, the calculation was done again for the community of people in terms of all four cases changing the outdoor air temperature from -5°C to 15°C. The exergy consumption of all cases was then normalized to the value of case 1 being 100%. Figure 78 shows the relative reduction of the exergy consumption due to either a change in the occupant behaviour or an improvement of the building envelope system as well as the combination of both. This figure clarifies that the reduction due to the improved building envelope system is much less affected by the outdoor conditions compared to the one due to the change in the occupant behaviour.

![Figure 78](image)

Fig. 78. Relationship between the reduction in the exergy input for heating due to the change in the occupant's behaviour versus the reduction due to the building envelope improvements at different outdoor air temperatures.
The combination of both changes leads to a reduction of almost 80% for the case of the lower outdoor air temperature up to even 95% for the case of the higher outdoor air temperature.

Figure 79 shows the result for summertime, which is parallel to the winter case shown in Figure 78. It can be seen that the same conclusions can be drawn as in the winter case beside that the overall reduction is smaller. The higher the difference between indoor and outdoor air temperature, the more effective gets the improvement of the building envelope system, but when the indoor air temperature is close to the outdoor air temperature, the change due to the occupant behaviour is the highest.

Some may claim that it is therefore necessary to inform the people to use their AC-units less often, but such a strategy without the improvement of the building envelope system would not be justified, since this would cause the people living indoors with less well-being. It is important either to show the occupants how to adapt to the current building envelope systems by means of passive strategies such as putting on more clothes or to improve the building envelope system thermally. Both strategies may lead to a less frequent usage of the AC-unit due not to living with discomfort, but with well-being.

In order to understand the last statement, one has to consider the six basic factors influencing on thermal comfort, which are the room air temperature, the mean surface temperature of walls and windows, the relative humidity, the air current inside the room, the insulation level of the clothes and the level of activity (Fanger, 1970). Therefore, in the case of the improvements of the building envelope the higher level of comfort is due to a higher mean radiant temperature, which usually provides thermal comfort in winter with less exergy-consumption rate of the human body (Shukuya, 2009). In the case of a change in the occupant behaviour, one would have to observe more than just the room air temperature and analyse the combination of the indoor air temperature chosen and the clothing level to be able to draw further conclusions. This would lead to a great disturbance of privacy and possibly also a manipulation of the behaviour and was not intended by us. Within the previous mentioned surveys, the occupants were not asked about the reason for choosing a certain temperature, but one participant stated voluntarily in a discussion that even in winter he does not like to wear long shirts or pullovers inside his room. It must be clear after reading above analyses and explanations how this personal preference of clothing level easily influences the percentage of times the AC-unit is switched on, the temperature chosen and therefore also the exergy consumption of this individual. The question, how such preference of an individual evolved throughout his or her time of life so far, is an interesting question to deal with in future studies.

The findings described above are based upon the assumptions derived from a field measurement of occupant behaviour within one building alone. The room characteristics taken for the calculation are similar to the ones in which the measurement took place,
however, this room has only one outside wall and one window. Although the impact of other room dimensions was not addressed in this chapter, a higher percentage of outside facing walls and windows will most probably lead to a higher reduction of the exergy consumption due to building envelope improvements than shown here. Nevertheless, the type of room assumed for the present exergy analysis can be found with only slight variations in an uncountable number of apartment buildings all over the world.

The concept of exergy is used to calculate the results presented in this chapter, because exergy is the concept that is able to explain what is consumed and where it is consumed (Shukuya and Hammache, 2002). The results obtained by the exergy calculation are not very different from those, which would have been obtained by an energy calculation alone, if the comparison is made only on the primary exergy and energy inputs. However, beside the reasons stated in the introduction to this chapter, the application of the exergy concept is useful to understand the underlying processes especially for the adjustments made on the calculations of the system’s COP. Even though these adjustments were not the main objective of this study, they were necessary for the inclusion of individual differences in the chosen set-point temperature.

Second arguable factors are the assumptions for the occupants’ behaviour for the cases of an improved building envelope system. The calculations performed here do not consider any change in the behaviour even though one might expect adaptations of the occupant due to the

![Graph](image_url)

**Fig. 79.** Relationship between the reduction in the exergy input for cooling due to the change in the occupant's behaviour versus the reduction due to the building envelope improvements at different outdoor air temperatures.
improved radiative environment. Considering this factor would demand many more field measurements and much more complicated calculations considering not only the occupant's behaviour in relation to the outdoor air temperature but also including more complex factors such as the resulting level of comfort represented for example by the predicted mean vote (PMV), whose calculation includes above mentioned six factors related to thermal comfort and leads to a number between −3, meaning cold, and 3, meaning hot, that is representing the mean vote of a large population of people being exposed to a certain thermal environment and was introduced by Fanger (1970) especially for a room space with an air-conditioning system. While this will be done in a future study, it must lead to a further advantage for the improvement of the building envelope system. The results shown here definitely show that further studies of the occupant behaviour are meaningful in order to find solutions towards a built environment causing less impact on the external environment.

Finally, within this chapter the phrase “change of the occupant’s behavioural pattern” is used several times. This chapter is showing the differences between different types of occupants observed in field measurements. However, the problem if and how far it is possible to change the behaviour of one type of occupant towards another type is not addressed here, but in the previous Chapter 9, where the effect of information on the occupant behaviour was analysed.

10.7 Conclusions

This chapter presents a comparison of the impacts that a change of occupant behaviour and an improvement of the building envelope system have on the exergy consumption for one specific type of heat-pump system. Data from field measurements were used in order to make rational assumptions for the calculations. What was found by a steady-state estimation of the exergy consumption for heating and cooling can be summarized as follows:

1) The choice towards a lower indoor room air temperature in winter by the occupant leads to a reduction of the exergy consumption by 25% to 30%.

2) The combined effect of indoor air temperature choice and percentage of persons using their AC-unit leads to a reduction of 40% to over 90% and strongly depends on the outdoor air temperature. The reduction is in winter larger with higher outdoor temperature and in summer with lower outdoor temperature.

3) The improvement of the building envelope system causes a reduction of 55% to 65% and is less affected by the outdoor air temperature. It gets in winter larger with lower outdoor temperature and in summer with higher outdoor temperature.
4) In regions having moderate outdoor temperature it may look more important to improve the occupant behaviour than to invest in building envelope systems, but the improvement of the building envelope system would probably trigger a change of behaviour as well.

5) The combination of occupant behavioural changes and building system improvements result in a reduction of 75% to 95% and should be the final goal.

It is further proposed that the effect of the changed radiative environment due to the building envelope systems improvements on the occupant behaviour should be considered in future studies to clarify any correlation between them. Furthermore, the problem of changing the occupant behaviour should also be considered in future studies.

Even though the chosen approach of using the steady-state exergy calculation is lacking the accuracy of many dynamic energy simulation algorithms, the whole picture of the importance of looking both at building envelope system and at the occupant behaviour in the built environment would not be different. The understanding of factors and their magnitude of change are therefore very important for setting up the building energy policy measures in the future to come. Further detailed analyses are expected to be done in a future study.
Concluding Chapters

結論の部

“It is essential to rule out alternative explanations before raising our confidence that a given interpretation is true.”

(Danchin et al., 2008b; p. 32)
11 General Discussion

11.1 Comparison of Theoretical and Statistical Models

The statistical models developed in the preceding chapters have some parameters with a certain value of their corresponding constants. It is worthwhile to compare them with the theoretical and rather qualitative model introduced in Chapter 2 to have a better understanding of human behaviour in a given built environment.

The models presented in Chapter 6 include the running mean of the outdoor air temperature at nighttime as one factor, which signifies that the previous nights have an influence on the decision whether to sleep with the AC-unit running. This seems to retain logic, because no one knows how the night will be beforehand and therefore they must make the decision partly based on the experience during the previous night(s). The model may look illogical if one is of the view that people are not able to recall exactly their thermal experience during the night before. But it is not necessarily illogical since there is considerable subconscious function according to neurological studies. Even though it may not be possible for a person to articulate their sensations during the foregoing night(s) because of sleeping for most of the time the brain is still receiving information from the sensory portals and upon this information controlling our thermo-regulatory system without our conscious knowledge. Both subconscious sensations and the resulting subconscious reactions are then stored in the brain and probably modify the reference levels, even though one is not able to recall them consciously (Damasio, 2000).

As was raised in the description of the theoretical model in Chapter 2 and the following analysis with regard to the purpose of behaviour in Chapter 3, human occupant behaviour is affected by several factors. The statistical models presented for summer and winter include up to 17 different factors, each of which probably influences on the AC-unit usage behaviour. Even though the statistical analysis was based on the outdoor air temperature as reference value, this might signify that those 17 factors also influence the reference levels. Since the database used for these analyses does not allow a further discussion about the nature of the real reference level as stated in Chapter 3, it should be reserved for more intense studies in the future.

Following the theoretical model, external factors so far taken for the statistical model to predict the behaviour might only be intermediate representatives, but as there are no studies on other more-complex factors like core-/skin-temperature or the exergy consumption rate in relation to behaviour, one cannot elaborate the modelling further. The pilot study presented in
Chapter 4 and in Schweiker and Shukuya (2007) showed a positive relationship between HBx-rate and behaviour, but more intense studies are necessary. For the second and third part of this dissertation, the outdoor air temperature was taken as the starting point for the statistical model, because it is the easiest accessible factor. Indoor temperature was not included into the analysis, because of the already mentioned ongoing discussion as to whether to use outdoor temperature, indoor temperature or both for the prediction and the strong dependence of the indoor temperature on the state of the AC-unit. Additionally, the scope of this work is to determine, which position external factors such as the outdoor air temperature have on the occupant behaviour. A further investigation, whether the implementation of the indoor temperature is favourable or not, would be interesting in a future study.

The influence of preference on the occupant behaviour and its reference level was highlighted at several points throughout this work (see e.g. Chapter 5, p. 72). A factor such as preference is not easy to grasp and in the frame of this research, it was simply accessed by asking whether a person likes to sleep in a space heated or cooled by an AC-unit, by other means or not at all. However, preference itself must be the sum of multiple experiences over the whole life-span of the individual as already stated in Chapter 2.4.3. Therefore, it seems to be reasonable to place preference into the group of long-term experiences together with the cultural influences, the thermal background as well as the behavioural background. This, together with the findings presented in Chapters 8 and 9, proofs again that the reference levels cannot be fixed, but that they are constantly adapted through time and experience. This type of adaptation is itself much more dynamic than e.g. the adaptive model introduced by Humphreys and Nicol (1998), because it does not only consider seasonal changes, but also the continuous flow of experiences each of us has every day.

Although the factors influencing on the occupant behaviour vary possibly with other settings, their magnitudes look consistent with the initial assumption of the theoretical model. How far these factors represent initial values given by the genes or adaptations to life experiences is beyond the remit of this investigation.

The statistical models presented in Chapter 8 are focussing on the influence of differences in the built environment rather than individual differences on the behaviour. The importance of a high-quality radiative environment provided by a sufficiently insulated building envelope is highlighted in this context. With regard to individual factors, the preference towards the AC-unit had a major influence on the usage of the heating device. Furthermore, it was shown that the behaviour changes with modified characteristics of the built environment. In case of the Germans living in Japan, it could not be clarified, if this is due to a change in their expectations. However, also the expectations must be part of the reference level as shown in Chapter 3.4.2 with regard to the purpose of behaviour.
Above discussion can be summarized in such a way that the results obtained so far are supporting each other, but in order to be more confident, further research would be greatly appreciated to rule out alternative explanations.

### 11.2 The Reference Level

Throughout this work, graphs showing the distribution of the logistic probability are shown, based on different variations of eq. (7) (p. 83), in order to visualize the relationship between the probability of a certain occupant behavioural action and outdoor air temperature. This graph was analysed by the value of $T_{50}$, the temperature when 50% of persons are switching on their AC-units. In this case, the outdoor air temperature can be regarded as the stimulus triggering a certain percentage of successes, e.g. AC-units switched on. In this part of the discussion another interpretation shall be given to relate the stimulus to the reference level.

Referring to the short description about the human brain and the functioning of neurons made in section 2.4.1, each neuron has a specific threshold level and in case the intensity of the input stimulus is above this level, the neuron “fires”. However, the firing of one neuron does not lead to an action – millions of neurons have to fire at the same time. Observing an action, which was performed by an occupant then signifies that for this person the threshold level of many neurons was exceeded by a specific level of one stimulus or a combination of many. If we define this level of stimulus as the reference level for one specific action, we can assume that every person has – without knowing it – a precise value of reference level for each action and stimulus. However, as seen above this reference level is not fixed at a certain moment in time, which can be explained by the permanently changing combination of connections between the neurons of our brain.

![Graph showing the distribution of the logistic probability](image)

$$p_{\text{action}} = \frac{1}{1 + e^{-(a + b \times x)}}$$

$$p'_{\text{action}} = \frac{b \times e^{-(a + b \times x)}}{(1 + e^{-(a + b \times x)})^2}$$

Fig. 80. Example for a logistic regression curve (left) and its derivation (right).
With this theoretical explanation in mind, we can define the curve obtained by logistic regression analysis as cumulative relative frequency of the existing reference levels for the observed occupants in the moment or period of observation. As shown in the left part of Figure 80, the difference in the probability, \( dy \), related to a difference in the stimulus, \( dx \), would then be the percentage of persons whose reference level is between \( x_1 \) and \( x_2 \).

The above stated assumption would follow that the derivation of the logistic probability function, shown in the right part of Figure 80, signifies the distribution of the relative frequency of the reference levels for the concrete action. This permits further visualizations of the type of results included within the logistic regression models obtained throughout this work. The maximum of the derivative function is equal to \( T_{50} \) and presenting the temperature, which most

\[
p_{\text{action}} = \frac{1}{1 + e^{-(a + b \times x)}}
\]

\[
p'_{\text{action}} = \frac{b \times e^{-(a + b \times x)}}{(1 + e^{-(a + b \times x)})^2}
\]

Fig. 81. Comparison of two logistic regression models.

\[
p_{\text{action}} = \frac{1}{1 + e^{-(a + b \times x + c_1 \times y_1)}}
\]

\[
p'_{\text{action}} = \frac{b \times e^{-(a + b \times x + c_1 \times y_1)}}{(1 + e^{-(a + b \times x + c_1 \times y_1)})^2}
\]

Fig. 82. Shift of reference levels due to an additional binary factor. a) \( c_1 = 0 \); b) \( c_1 = 1 \).
people have as reference level. Furthermore, it would be easy to estimate, e.g. a temperature range around this value at which 80% or 95% of the persons reference levels are placed.

Comparing two different models obtained e.g. by the comparison of two distinctive groups, as shown in Figure 81, one can see that in case a) there are few differences between individual human beings, while in case b) the reference level is distributed rather wide, so that there are more differences between individual human beings. In this way, the effect of knowledge transfer measures could be analysed without the normalization as done in Chapter 9. A result could be that those measures lead to a scattering of behavioural patterns due to some individuals following the suggested behavioural changes given within the information, but others who do not follow them. On the other hand, those measures could lead to a homogenisation of behavioural pattern due to a newly formed common knowledge base. This kind of analysis was unfortunately not possible with the data gathered, but it would be interesting to be pursued in the future.

Furthermore, regarding multivariate analysis, the effect of another binary variable can be easily interpreted as a positive or negative shift of the whole distribution as shown in Figure 82. This means that the specific factor influences the reference levels of all persons in only one direction. This has to be seen critically, because in this way it is not possible to include variables, which are affecting some people positively, but others negatively. One example could be the behavioural background. While growing up in an air-conditioned space might lead to a high usage later as shown for the majority of persons in Chapter 6, but it cannot be excluded that for others the same background might lead to less usage due to e.g. a series of bad experiences. Therefore it should be noted that – beside being much more individualized than previous models – the models obtained are still giving an estimation how each factor influences the majority of persons. Further researches as well as analyses have to be done to see if and how individuals react to each factor, i.e. what percentage is affected positively and what negatively.

An additional discussion concerning the reference level is the definition of comfort level taken for this dissertation. The research is not dealing with the comfort level directly, but through the observation of occupant behaviour. The comfort level is therefore defined as the thermal conditions prevailing in the moment of observation, with the assumption that an occupant would change the conditions in case they are not comfortable; even though this will not be always the case as shown in Chapter 3. Following the results obtained, one can also conclude that (1) not only the behaviour is influenced by individual factors, but also the comfort level, (2) there cannot be one comfort level for all humans, and (3) it is important to think about the way people grow up. However this cannot be investigated further with the available data.
12 Conclusive Summary

With the decline of fossil energy resources, the necessity to change our way of energy usage in order to keep the actual living standard is apparent. One solution commonly heard of is the reduction of demand through greater efficiency of the building system. This is at issue even in the residential building sector even though its demand depends strongly on the occupant behaviour as shown in previous studies. The research of occupant behaviour focuses on the analysis of general behaviour patterns not on the factors leading to individual differences in the behaviour, however it can be said that such differences are the reason for many variations in the energy used for heating and cooling.

The objectives of this research are (1) the identification of those factors having a major influence on the occupant behaviour and its reference levels, (2) the analysis of the reference-level’s influenceability towards a change of occupant behaviour and (3) the evaluation of the exergy consumption for cooling and heating in relation to the differences in occupant behaviour.

The investigations are standing on three pillars: (1) a comprehensive literature review not only including publications within the field of built environmental research, but also in the fields of neurology, psychology, control theory and behavioural ecology; (2) a field measurement conducted in an international student dormitory gathering quantitative physical data of 39 students in summer and 36 students in winter together with their answers given to an introductory survey and two interviews; and (3) an Internet-based survey conducted also during summer and winter season leading to a qualitative database of comfort votes, recent behaviour and personal background of 434 participants for summer and 845 for winter.

The work is divided into one introductory chapter, nine main chapters, which are grouped into four parts, and two concluding chapters. In the following the results shall be summarized for each part.

12.1 Defining the Reference Level

In part I (Chapters 2-4), the development of a theoretical occupant-behaviour model is described in Chapter 2 based on the comprehensive literature review. This model is consisting of four main elements, which are the sensory sub-system, the control sub-system, the adjustment sub-system, and a novel component called reference level. The reference level is introduced as the entity to which all input values deriving from the body’s sensual systems are compared. Therefore, it has a special place in the model, because the decision whether to perform or not to perform a certain type of behaviour is based on the outcome of this comparison.
In Chapter 3 the nature of the reference level was analysed by looking at the success, purpose and the ranking of occupant behaviour based on the data from the Internet-based survey. It was found that there must be a separate reference level for different input values such as thermal comfort and noise, which are independent from each other. Additionally, distinctive reference levels for different actions, such as opening the window and switching on the cooling device, can be expected, whose order and value is very different from person to person.

A first trial analysis about the human body exergy consumption (HBx) rate as reference level is shown in Chapter 4. The decision to sleep with an open or closed window could be partly explained with the current HBx rate in comparison to the HBx rate range during childhood, showing that the thermal background leads to differences in the individual behaviour and its reference level. Furthermore, the decision of closing a window is set in relation to the current HBx rate and it was found that this action leads not only to a reduced HBx rate, but that it can be explained by comparing the current HBx rate to the HBx rate during childhood.

12.2 Influences on the Reference Level

In part II (Chapters 5-7), the factors influencing the reference levels for thermal comfort were elaborated and a method to quantify the relative importance of those factors was established.

In Chapter 5 the data from the student dormitory was divided into four groups according to the frequency of air-conditioning (AC)-unit usage. It could be shown that factors like preference for air-conditioned spaces and the thermal background of a person show significant differences between the groups. This lead to the assumption that those factors also influence on the reference level.

In the following Chapter 6 the influence of external factors such as temperature and humidity were evaluated according to their significance for describing the observed behaviour. This lead to advanced models of occupant behaviour prediction showing that the exponentially weighted running mean of the outdoor air temperature at night influences on the behaviour respectively the reference level, while humidity was found to have a negligible influence on the decision to sleep with an AC-unit switched on or off.

The advanced models were then extended by including individual factors such as the previous mentioned preference and thermal background. In total 17 factors were found to be improving the models without overfitting the data. Those factors were then judged by introducing an importance factor and it was found that, on the one hand, the running mean of the temperature has a similar impact to individual factors in summer, while, on the other hand, the latter have a much higher influence in winter.
In Chapter 7 the answers given by the students during the interviews, called the imagined behaviour, were compared to the behaviour observed during the measurement, called the real behaviour. It was shown that imagined and real behaviour do not agree in 60% of the cases. Using additional statements given during the interviews and surveys a method was shown to adjust the imagined behaviour so that the congruence with the real behaviour becomes higher than 80%.

12.3 Influenceability of the Reference Level

Part III (Chapter 8-9) analyses whether and to what degree long-term or short-term experiences can influence the set-up or a change of the reference levels.

Firstly, the effects of long-term experience such as cultural influences are analysed in Chapter 8 by comparing the stated behaviour with respect to the chosen sleeping conditions of those participating in the Internet-based survey. This revealed that there are differences in the behavioural patterns due to the current thermal environment. Even more, it was demonstrated at the example of Germans residing in Japan that the behaviour and its reference level is not fixed at one moment in life but adapting to changing conditions.

Secondly, as presented in Chapter 9, the influences of knowledge transfer methods on the reference levels, which can be regarded as short-term experiences, were evaluated. Workshops, information papers and an Internet-based information page were examined as knowledge transfer methods. They contained all nearly the same type and amount of information about passive strategies such as natural ventilation. It was shown that the knowledge transfer methods can motivate the recipients to try out strategies not practised before, but there is a huge discrepancy between the stated intention immediately after the knowledge transfer and the actions performed in reality.

With respect to the usage of the AC-unit, the effect of the knowledge transfer processes such as workshops or information papers could be quantified as follows. While the information paper did not lead to a significant difference between those receiving it and a control group, the workshop led to a noticeable reduction of the AC-unit usage by up to 16%. Furthermore it was shown that the short-term experience of a workshop can lead to an decreased exergy consumption compared to a control group.
12.4 Effect on the Exergy Consumption for Heating and Cooling

Part IV (Chapter 10) describes the effect of differences in the reference levels compared to building envelope improvements on the exergy consumption for heating and cooling. Based on a steady-state exergy calculation, the influence of the occupant behaviour was highly significant (more than 90% decrease of exergy consumption) when the difference between indoor and outdoor air temperature is small, which is the case for long periods in those regions with moderate temperatures during summer and/or winter. On the other hand, the building envelope improvements have a much higher influence wherever the difference in temperature between indoors and outdoors are larger. Nevertheless, both measures combined lead to a reduction of up to 95% and should be the final goal.

12.5 Discussion

In the discussion, Chapter 11, the theoretical occupant behavioural model presented in Chapter 2 was set in relation to the findings based on the conducted investigations. Many elements and assumptions stated in the frame of the theoretical model were supported by the statistical models. Additionally, the concept of reference levels was used for an alternative interpretation of the logistic curve. This led to a further understanding of the results obtained. Overall, it was shown that the occupant behaviour can only be presented by a complex and dynamic model, which includes the variations in time due to continuous experiences of the occupant. In considering such theoretical approach, the models presented within this work show, besides their roughness, a possible way towards such a dynamic model by combining theoretical knowledge with statistical analyses of observed behaviours.

12.6 Future Research Tasks

The research presented in this dissertation cannot be regarded as finished. The paradigms, analysis methods and results should rather be taken as starting points for future research aiming at a further understanding of the occupant behaviour and its reference levels towards a dynamic model of the occupant’s interaction with the built environment and a society of well-being but low exergy consumption.

Based on the results and their implications, the following researches seem to be promising and are highly recommended:

- The outcomes of this research showed that occupant behaviour and its reference level are not only influenced by various external and internal factors, but also varying in
time (and possibly in space – see remark about the effect of scenes in Chapter 3). Future research should address these changes together with the factors influencing such changes to analyse past behavioural changes and to be able to predict the effect of future environmental changes on the behaviour.

- The extension of the statistical models, which are so far related to the outdoor air temperature alone, towards models including more complex representations of thermal comfort such as the HBx-rate as shown in a trial analysis in Chapter 4 must be an interesting topic.

- Furthermore, the analyses presented so far were done for one single action, such as switching on the AC-unit. As mentioned previously, the occupant has to choose between several options to achieve thermally neutral conditions. In order to integrate this choice, the concept of utility used in discrete choice analysis or other statistical methods to be found will be interesting in order to come up with a more complete model of occupant behaviour.

- Leaving the thermal aspect of occupant behaviour, further analysis about other physical factors such as noise, IAQ, air current etc, must be fruitful in the future in order to have estimates for the related reference levels introduced in Chapter 3 and to find solutions to improve thermal comfort and well-being for the occupants.

- Following above step, the application of the methodology presented in this dissertation to behaviours related to other areas of the residential sector such as water usage as well as other sectors like the choice of transportation medium must be relatively easy and will most probably help finding solutions towards a sustainable society.


13 Concluding Remarks

This dissertation summarises the research done between 2006 and 2010 at the Tokyo City University supervised by Professor Shukuya. While I was trying to avoid any “I” or “we” throughout this work, I would like to conclude with some personal remarks about the already existing positive impact of this research on the environment, an outlook on possible future applications, benefits and further impacts I hope this dissertation can contribute to at least in parts.

I am very happy to be able to write here that the research I conducted so far already had a positive impact on the environment, even though it must be very small compared to the existing problems. The knowledge transfer processes, such as the workshops, led to a reduction of the electricity consumption due to a changed behaviour by some of the participating persons as described in Chapter 9. Beyond that, in case of the investigation in the student dormitory, the information was given to international students, which were selected by the Japanese embassies of their countries as promising future researchers and leaders. The increased awareness of this group towards the energy usage within the built environment will hopefully lead to a further reduction of our impact on the world’s climate. A promising start has been done by these knowledge-transfer processes, which can instantly be supported by three statements given to me by different persons during the final interviews:

• “I read it [the information brochure] once more and I send it with my sister back to Europe, where I have more space to store it.”
• “... we bought that Sudare [Japanese bamboo screen used for shading of the window and placed on the outer side of it], but I didn’t use it in my room here [in Japan], my mom is using it at our home in [country in Europe (I deleted the country name to secure anonymity)]”
• “I send it [the pdf of the information brochure] to friends [in an Asian home country], who I told about the seminar as much I could...”

The practical approach of this research allows a direct application for products and services in different areas concerning environment and energy. In the following, I shall describe the main applications and their benefits:

• The methodology described in this dissertation can be applied to other types of behaviours such as the (warm) water usage or the choice of transportation medium and thereby contribute to the understanding of such behaviours and a possible reduction of their impact on the environment.
• Companies conducting energy predictions for future buildings as well as for future scenarios of energy supply and demand structures can directly implement the final algorithms of this dissertation into their software and thereby decrease the gap between simulation and reality. Being able to have a more realistic model to simulate the energy demand of a future building will help reducing their costs and a possible unnecessary resource usage due to decisions based on a higher uncertainty. Additionally, the implementation of the advanced models into energy demand predictions will give energy suppliers the chance to optimise their supply structures based on a higher percentage of renewable energies in the future.

• Those dealing with services related to environmental information, will be able to improve their materials and processes as well as to conduct more sophisticated cost-benefit calculations of their information by applying the proposed methods and findings of this research. Additionally, the application of the found algorithms will lead to a higher cost-benefit ratio due to fewer uncertainties for future knowledge-transfer projects.

• Furthermore, the application can lead to an advantage in the marketing of buildings and energy services, when the algorithms are combined with information pamphlets. This will also improve the communication with the client and thereby lead to an improvement of the customer-client relationship and possible follow-up orders.

• The findings concerning the occupant behaviour can be used by architects, construction companies as well as investors in order to improve their building design as well as the building management system. One of such adjustments would concern an improved design of the radiant built environment by the usage of sufficient insulation material and external solar shading for areas with a hot summertime. As seen in Chapter 8, this would enable the occupants to sleep within healthier conditions. Additionally, the implementation of thoughts about the way occupants are using the building throughout a year into some sort of time design beyond the often conducted space design will probably lead to residential buildings allowing the occupants to fine-tune their thermoregulation system as mentioned in Chapter 2.3.1 in combination with Chapter 2.3.3 and thereby leading to a further understanding of the benefits of healthy living in harmony with nature.

Regarding the further desired impact, this research and the application of its findings will hopefully be one element on the way towards the vision of a sustainable and healthy society based on a high level of education. I believe that the design of buildings should, on
the one hand, embrace passive strategies so that thermal comfort is provided efficiently for most parts of the year, while – simultaneously – sufficient time to train the thermoregulation system is given, and on the other hand, permit the occupants to interact with their built environment and guide them towards doing this positively. Together with an increased knowledge of both, decision makers as well as laymen, and a sensitive addition of active technologies for the moments of extreme heat or cold, this is the proposal of this dissertation for reducing the energy usage, while maintaining or improving the thermal comfort and health of the individual occupant, you and me.
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This research project is based on the work, I have done staying at Shukuya Laboratory of the Tokyo City University (former: Musashi Institute of Technology). As it is always the case with such a work, I would not have been able to finish it without the help and support of numerous colleagues and friends.

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  • Schweiker, M. and Shukuya, M. (in review), Investigation on the effectiveness of
    various methods of knowledge transfer aiming at a change of occupant behaviour
    related to thermal comfort and exergy consumption, Energy Policy.
Papers Published in Conference Proceedings

• Schweiker, M. and Shukuya, M. (2010), Cross-cultural Comparison of the Factors Influencing on the Occupants Choice of Sleeping Conditions Based on a Multi-language Internet Survey; CLIMA 2010, Antalya, Turkey (abstract accepted).


Papers/Posters Presented at Conferences


Papers/Posters Presented at Conferences (continued)


Others

Additional Material

The following supplementary materials can be requested by sending a mail to info@lexhic.com. This mail should include a statement concerning the purpose of utilization and how the material will be used:

a) Materials used during the investigation in the student dormitory building
   (available in English only):
   – Introductory Survey Summer
   – Information Brochure Summer including questionnaire
   – Introductory Survey Winter
   – Information Brochure Winter including questionnaire

b) Screenshots of materials used during the Internet-based investigation
   (available in English, German, Japanese, and/or Spanish)
   – First Survey Winter
   – Second Survey Winter
   – Information Pages Winter
   – First Survey Summer
   – Second Survey Summer
   – Information Pages Summer