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Johan Halvarsson

Occupancy Pattern in Office Buildings

Consequences for HVAC system design and operation

NTNU
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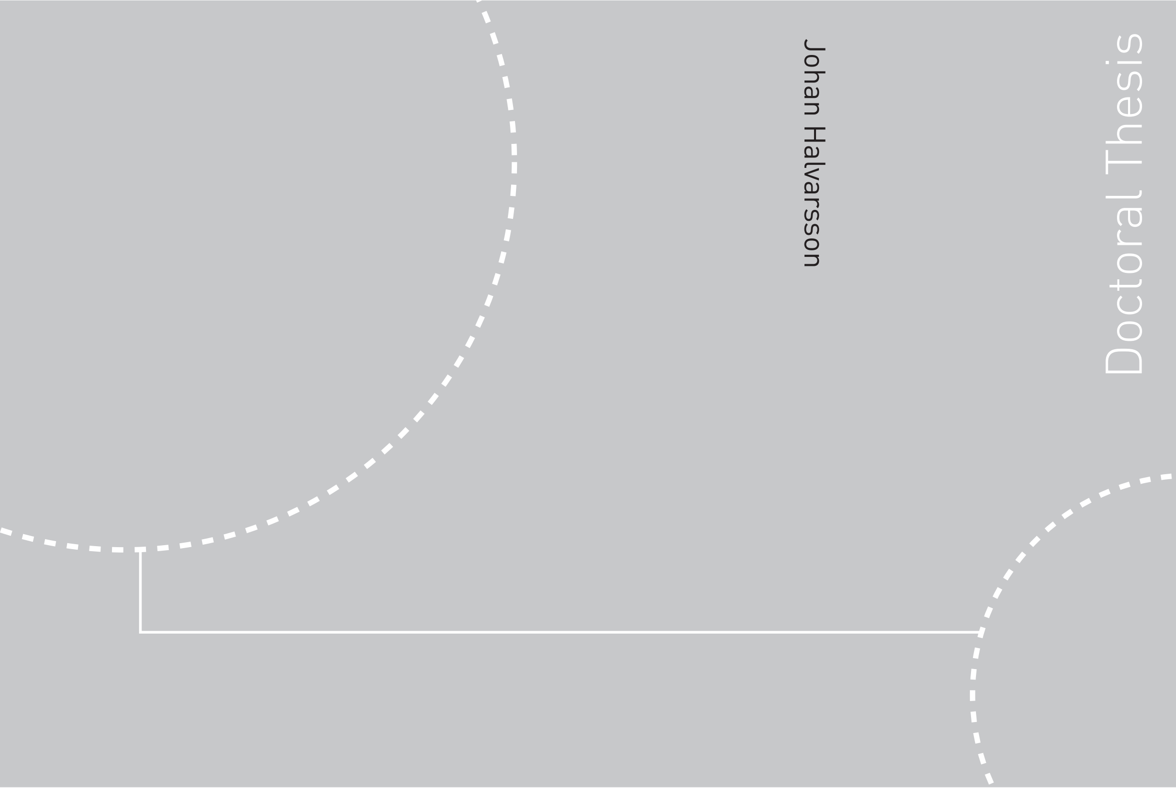

Doctoral Thesis

Johan Halvarsson

ISBN 978-82-471-3338-5 (printed ver.)
ISBN 978-82-471-3339-2 (electronic ver.)
ISSN 1503-8181

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Science and Technology
Thesis for the degree of
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Trondheim, January 2012

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Printed by Tapir Uttrykk

Preface

The work for this thesis has been carried out at the Department of Energy and Process Engineering at the Norwegian University of Science and Technology (NTNU).

First of all, I would like to thank my supervisor Professor Sten Olaf Hanssen and my co-supervisor Professor Hans Martin Mathisen, both at Department of Energy and Process Engineering at NTNU. To both of you; thank you for your kindness, support and many valuable advices. You have been both good colleagues and good friends during these years.

I would also like to thank all my colleagues both at NTNU and SINTEF.

To my family and friends; warm thanks for supporting and encourage me. Finally and most importantly; thank you Maria, Elias and Emelie. I could not have done it without you!

Trondheim, 2011
Johan Halvarsson

Abstract

The main objectives with the work presented in this thesis have been: (a) to contribute to an increased understanding of the consequences that the occupancy pattern can have on the indoor climate and for Heating, Ventilation and Air Conditioning (HVAC) system design and operation; and (b) to investigate how typical occupancy patterns can look like in office buildings.

The occupancy pattern in an office is a function of the floor layout of the building, and the user organisation(s) occupying it and their way of working. The combination of these two, will decide how the users occupy the building, which in turn is an important design prerequisite/constraint for the HVAC system design process. There are many assessments related to indoor climate and HVAC that involve considerations of the occupancy pattern, reaching from estimates of internal heat and pollution loads to deciding on an appropriate control strategy of HVAC systems, or estimating the energy saving potential with demand controlled ventilation.

A few numerical measures have been used to describe different aspects of the occupancy pattern. The zone based occupancy factor (*OFz*) expresses the ratio between the number of occupied sub-zones/rooms in a zone and the total number of sub-zones/rooms in the zone. *OFz* does not take the number of people into account, only whether a sub-zone/room is occupied or unoccupied. *OFz* can be used both to express instantaneous occupancy levels and averages over time. Superscript is used to specify the time, or time period, that the measure refers to. For instance, $\overline{OFz}^{06-18,wd}$ means the average *OFz* between 6 a.m. and 6 p.m. on working days, while the 95th percentile of $OFz^{6-18,wd}$, means the 95th percentile of all instantaneous values (one or five minute averages in the case studies) of *OFz* that have occurred during the same time period. The utilisation rate (*UR*) expresses the fraction of time that a room is occupied, within a specific time period.

It is important to distinguish between the actual occupancy state of a room (occupied or unoccupied) and the detected occupancy state, which is the one monitored in case buildings presented in this thesis. The detected occupancy state can differ from the actual occupancy state, because of false-detection and time-delay of the detector. The OFF-delay (*TD-OFF*) is the time from the last detected motion occurred until the detector changes the output signal, and the zone is recorded as unoccupied in connection with logging. It is however possible to make some corrections regarding *TD-OFF* to estimate the actual occupancy levels.

Based on a literature study, it can be concluded that there is a need for more empirical basic data on occupancy in offices, with measurements from a wide spectre of organisations. In particular, detailed data describing variations between zones/rooms in one and the same building and short- and long-term fluctuations are very limited. In addition, there is a lack of data on peak, or close to peak, occupancy rates, relevant for HVAC system design.

Occupancy has been monitored in room samples from eleven organisations in five Norwegian office buildings. The data set contained 247 office cells and 16 meeting rooms. The case studies indicated that $\overline{OFz}^{06-18,wd}$ with 20 minutes *TD-OFF* and actual occupancy during working hours ($\overline{OFz}^{8-17,wd}$) for one-person cellular offices is on average around 0.4, and somewhere between 0.2 and 0.6 for most Norwegian organisations. There is a large variation in utilisation rates for meeting rooms, with $UR^{6-18,wd}$ ranging from 0.1 to 0.7. Furthermore, the case studies indicate that in a zone with more than 10 office cells, we can expect roughly the following close to peak levels of $OFz^{6-18,wd}$, with 20 minutes *TD-OFF*: between 0.5 and 1.0 for the 98th percentile and between 0.45 and 0.95 for the 95th percentile.

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1 Introduction

1.1 Background

Design, and management, of HVAC systems requires that both the physical properties of the building and the needs and attributes of the users of the building are taken into account. The building and the users can sometimes be considered as separate entities, while it in other situations is a need for predicting the results of combining the properties of these two. The occupancy pattern in an office building is an example of the latter case; a combination of the spatial configuration of the building and the activities of the user organisation.

While a lot of effort is put into estimating proprieties of the building elements and adjusting the systems to the building related prerequisites and constraints, less effort is spent on considerations regarding the users and their activities. The occupants will interact with the building and the HVAC systems and try to control the indoor climate by adjusting windows, blinds, opening doors, adjusting set-points etc. The possibility for the users' to control their own indoor climate will be important for their satisfaction; but it also requires that the building services can handle instantaneous changes in loads, demands and conditions and still be able to function as intended. The occupancy pattern and the behaviour of the users are difficult to predict. Nevertheless, this should not hinder the design team from estimating occupancy patterns roughly and since the behaviour of the occupants is an uncertainty factor, it is even more important to take it into account. So, when common practice today can be characterised to be building adapted; what is actually needed is building and user adapted HVAC systems.

Demand controlled ventilation (DCV) is an approach that aims at adapting the supply to the dynamic demand caused by variations in occupancy and other loads. With increasing focus on energy performance in buildings and a growing awareness of the importance of a satisfying indoor climate, not only for our health and comfort, but also for work related performance, the use of DCV can be expected to increase. Prediction of occupancy is of vital importance to forecast the performance of a DCV system; and to design and size it so that it is well adapted to the loads that actually occur when the system is taken into use.

1.2 Objective and research approach

The main objectives with the work presented in this thesis have been to:

- contribute to an increased understanding of the consequences the occupancy pattern can have on the indoor climate and for HVAC system design and operation; and
- investigate how typical occupancy patterns can look like in office buildings.

The research work has been performed in accordance to a five-step approach illustrated in Figure 1.1. Most focus have been on the first four steps, while the use of the collected occupancy data have had less priority and is planned to be used to a larger extent in future research efforts. The methods used for collecting, processing and analysing the occupancy data is presented in Chapter 4.

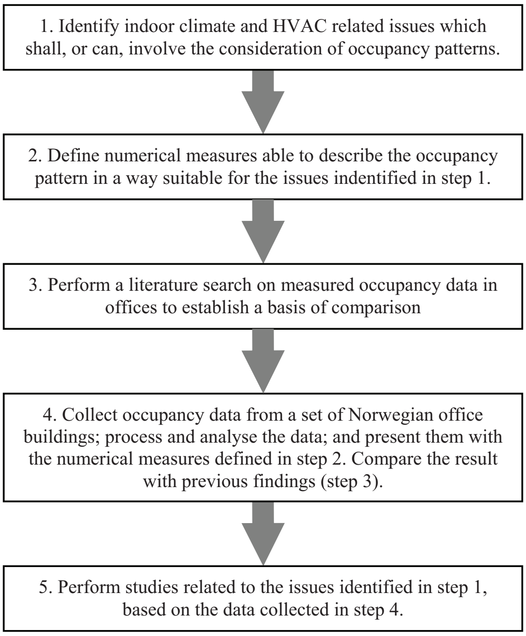

Figure 1.1 The five-step research approach used during the work.

The research has been concentrated on office buildings, and mainly on Nordic conditions. It has however been of interest to compare occupancy in Nordic offices against other parts of the world. There is a number of indoor climate and HVAC related issues in which the occupancy pattern is believed to be of great importance. Knowing if there are significant differences between geographical regions, makes it easier to judge how relevant non-Nordic research and experiences related to such topics is for Nordic buildings.

1.3 Thesis outline

The thesis contains three main parts. The content in these parts follows the steps in the research approach presented in Figure 1.1: Part I (Theoretical framework) corresponds to step 1, 2 and 3; Part II (Case studies) corresponds to step 4; and Part III (Example of applications and conclusions) corresponds to step 5.

Part I: Chapter 2 first discusses the building and the user organisations and the relation between those two and then indentifies issues related to indoor climate and HVAC system design which shall, or at least can, involve considerations of the occupancy pattern. Chapter 3 discusses advantages and drawbacks of different methods for measuring occupancy and presents an overview of measured occupancy data found in the literature.

Part II: Chapter 4 describes the data acquisition and data analysis procedure used for collection of occupancy data in a set of case studies. Chapter 5 presents data from one of the case building in detail, while Chapter 6 presents all cases together and compares them with previous findings.

Part III: Chapter 7 addresses different topics related to sizing and selection of components in ventilation systems, with special emphasis on DCV[1] systems, and uses the occupancy data from the case building presented in Chapter 5 to illustrate some potential sectors of application of empirical occupancy data. Finally, Chapter 8 presents the main conclusions that can be drawn from the work and provides some suggestions for further research work.

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[1] DCV is in this thesis synonymous with variable air volume (VAV) and vice versa, meaning that all systems where the ventilation flow rate is controlled and altered to meet varying demands are considered to be DCV systems, independent on whether the measured indicator is temperature, occupancy, humidity, CO_2 or any other air pollution. DCV can also be a constant air volume (CAV) system, e.g. if the amount of outdoor air is varied according to the demands, but the supply flow rate is kept constant. However in Norwegian and Nordic office buildings, this is not a common solution. Therefore, when writing CAV-systems in this thesis, it is not considered as a DCV-system.

The thesis includes three papers, included in the Appendix; one dealing with occupancy patterns in offices. The two other papers address other topics, but the content in them is connected to occupancy patterns. Paper I discusses the rationale for IAQ requirements and recommendations stated by authorities in Scandinavia, with special emphasis on ventilation flow rates. Since the occupants are a significant pollution source themselves, making judgments on the occupancy pattern should be an important part of the process of determining design air flow rates. Paper II makes comparisons of central and decentralised air handling units, which is closely related to considerations regarding the zoning of a building. This, in turn, must take the expected load variations (pollution and heat generation) into consideration, including the occupancy and occupancy related loads.

PART I:

THEORETICAL FRAMEWORK

Part I consists of two chapters:

Chapter 2 introduces some occupancy related numerical measures and discusses the two entities behind the occupancy pattern in offices; the building and the user organisation. Furthermore, the chapter gives an overview of issues related to indoor climate and HVAC systems, involving the consideration of the occupancy pattern.

Chapter 3 first describes and discusses possible methods for measuring occupancy in buildings, and then provides an overview of measurements of occupancy in offices found in the literature.

2 The occupancy pattern in relation to HVAC system design

The first part of this chapter provides some occupancy related definitions and appurtenant numerical measures, frequently used in the rest of this chapter and subsequent chapters. The next two subchapters deal with the spatial configuration of office buildings and the activities in offices, respectively. Thereafter, the relation between the building, the user organisation(s) and the HVAC systems, with emphasis on the occupancy pattern, is discussed from a HVAC system point of view. While this discussion is on a more general level, the next subchapter identifies examples of specific issues related to indoor climate and HVAC systems involving the consideration of the occupancy pattern. The way occupancy and occupancy related loads are managed in standards and in building energy and indoor climate simulation tools are the topic of the next subchapter. This is followed by a discussion of possible sectors of applications of empirical occupancy data, and the uncertainty involved in occupancy pattern predictions.

2.1 Some occupancy related definitions

The occupancy pattern of a building is an important parameter that should be taken into account in the process of designing a HVAC system. In this thesis, occupancy pattern means the number of people in different parts of the building as a function of time.

It is important when comparing occupancy patterns between buildings or discussing the consequences of occupancy patterns for HVAC system design, to clearly specify what the occupancy levels are representing, in order to avoid misunderstandings. When expressing some aspect of the occupancy pattern numerically, three variables have to be considered: the number of people, the location of people and time. Hence, both which zone of the building and at which time, or during which time period, the level refers to, must be specified. To exemplify, we can think of an office premise with cellular offices along the facades, with a common area in the interior space for team work, coffee breaks etc. The office premise is occupied by one user organisation and is said to have an occupancy level of 50 % on working days. This statement is however quite inaccurate and could be interpreted in several ways. For example, does this mean that 50 % of the cellular offices are occupied or that 50 % of the people working at the office are inside the office premise, independent on where in the premise each individual is located? If for instance the existing ventilation system in this premise is considered to be replaced with a new demand controlled ventilation (DCV) system in which the amount of supply air is dependent on the number of people, this is a relevant question for a cost-benefit analysis of the system. Moreover, which time period is 50 % referring to? Is it the time period on an average working day where the occupancy is highest (e.g., 9 a.m. to 11 a.m. and 1 p.m. to 3 p.m.) or is it an average of the whole working day (e.g., 8 a.m. to 4 p.m.), or maybe an average for the operation hours of the ventilation system (e.g., 6 a.m. to 6 p.m.)?

Chapter 3 presents a review of studies that have measured occupancy in offices. Occupancy can be measured in several ways, both regarding what is measured and regarding measuring methods. What is measured varies somewhat dependent on the purpose of the studies; for instance, some focus on the quantity of people simultaneously occupying a space and some on the time individuals spend in different places of the office premise. Although some studies have measured the same, they use different terms for describing the results. The occupancy related numerical measures listed below have been defined to match the specific topics of this thesis; design of HVAC systems. They are not necessary convenient to use for other purposes, such as lighting plant design or office interior design. To be consistent and avoid misinterpretations it has been aimed at using the definitions below throughout the thesis, also when referring to other studies which have used other terms. This means that the data found in the literature review have been converted to fit the definition presented below, as long as it has been possible.

Definitions

A building can be divided into zones. A zone can be one part of a room, a whole room or several rooms. Each zone can be further divided into several smaller sub-zones. When design of HVAC systems are considered, a suitable division into sub-zones may be to first let each room be one sub-zone; and then, further divide rooms that consist of more than one individually controlled area, with respect to ventilation flow rates, room temperature etc., into several sub-zones. For instance, if the zone of interest is an office landscape, and the ventilation flow rate is controlled by one CO_2-sensor, no further division into sub-zones is required. If the zone instead have roof-mounted motion detectors, each covering a zone of a few workstations, it may be convenient to let the detection area of each detector be a separate sub-zone.

The occupancy factor (*OF*) is a ratio that compares the actual occupancy of a zone with a reference value. In relation to HVAC systems it can be convenient to distinguish between two different occupancy factors. The first occupancy factor is an expression for the quantity of people in a zone and is denoted *OFp.* The reference value for *OFp* is the design occupancy load, i.e. the total number of people that the zone is designed for, for office cells or office landscapes typically equal to the number of workstations. The second occupancy factor is an expression for the number of sub-zones occupied in a zone, and is denoted *OFz*. That is, *OFz* does not take into account the number of people in each sub-zone, only whether it is occupied or not. The reference value for *OFz* is the number of sub-zones in the zone.

Definition 3.1: Let n be the number of sub-zones in zone I, p_x the number of people in sub-zone i_x and p_x^d the number of people sub-zone i_x is designed for. Then, *OFp* for zone I can be expressed mathematically:

$$OFp_I = \frac{\sum_{x=1}^{n} p_x}{\sum_{x=1}^{n} p_x^d} \qquad (2.1)$$

with limits

$$OFp_I \geq 0$$

Definition 3.2: Let n be the number of sub-zones in zone I and occ_x the occupancy status of sub-zone i_x. If sub-zone i_x is occupied, then occ_x equals 1. If sub-zone i_x is unoccupied, then occ_x equals 0. Then, *OFz* for zone I can be expressed mathematically:

$$OFz_I = \frac{1}{n}\sum_{x=1}^{n} occ_x \qquad (2.2)$$

with limits

$$0 \leq OFz_I \leq 1$$

OFz is a measure primarily intended to express the simultaneous occupancy state of more than one sub-zone; however, it is valid also for one single sub-zone and will then have an instantaneous value of either 0 or 1. If *OFz* of one single sub-zone is expressed as an average over a certain time period, it is equal to what can be defined as the utilisation rate (*UR*) of that sub-zone. In situations where the occupancy state on a sub-zone level is of interest, it will in the following be referred to the *UR* instead of *OFz*. *UR* is simple the portion of time that a sub-zone is occupied and is expressed either as a factor between 0 and 1 (or %) or as the number of time units within a specific time period, such as minutes per hour or hours per day.

The occupancy pattern can be presented graphically as one or several occupancy profiles, showing, for example, how *OFp* for an office landscape or *OFz* for a group of cellular offices elapses through a typical working day. It is convenient when working with data sets of measured occupancy to represent the occupancy pattern with one or a few numerical quantities (e.g., average and standard deviation) instead of, or as a complement to, high-resolution data series. This has two obvious advantages. First, it will be easier to compare different buildings or organisations. Second, it will simplify the use of occupancy data in a design process. As mentioned above, it is of vital importance that both the zone and time that the occupancy level refers to are precisely specified. In subsequent chapters, a superscript is used to specify the time, or time period, and a subscript to specify the zone. When a time-averaged occupancy factor is used to describe the data, it will be denoted $\overline{OF}$, and the superscript will specify for which time period the average has been calculated. *UR* is always expressing an average over time and the overbar is therefore left out; the superscript and subscript are, on the other hand, used in the same way as for *OF*.

Example 2.1

Occupancy is measured in an office premise, shown in Figure 2.1, at a Norwegian University. For two weeks, the employees are asked to report the point of time for each time they are entering or leaving their office cell, by filling out a schema. In addition, the number of people in the meeting room is measured by letting the users of the room fill out a schema regarding the number of people and point of time for entering and leaving the room (including short breaks).

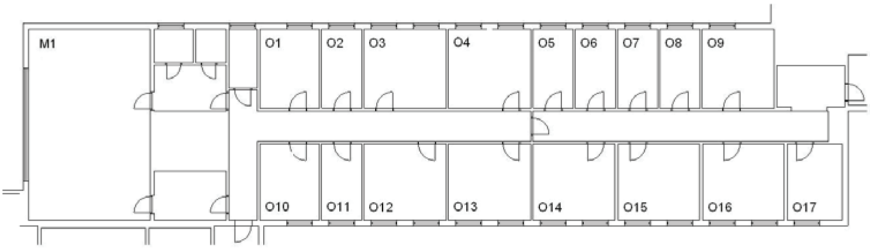

Figure 2.1 Floor plan of an office premise at a Norwegian university with seventeen cellular offices and one meeting room.

Let the meeting room be denoted *Zone A* and the cellular offices *Zone B*:

$$Zone\ A = \{i_1 = \mathrm{M1}\}$$

$$Zone\ B = \{i_1 = \mathrm{O1},\ i_2 = \mathrm{O2},\ i_3 = \mathrm{O3},\ \ldots,\ i_{17} = \mathrm{O17}\}$$

The number of sub-zones are $n_A = 1$ and $n_B = 17$. The design airflow rates are based on 30 people for the meeting room, two persons for the larger offices and one person for the smaller offices.

Table 2.1 Recorded occupancy Wednesday at 10 a.m.

Sub-zone	occ_x	p_x	p_x^d	Sub-zone	occ_x	p_x	p_x^d
M1	1	12	30	O9	0	0	1
O1	1	1	1	O10	1	2	1
O2	0	0	1	O11	0	0	1
O3	0	0	2	O12	0	0	2
O4	1	1	2	O13	0	0	2
O5	0	0	1	O14	0	0	2
O6	1	1	1	O15	1	2	2
O7	1	1	1	O16	1	1	2
O8	0	0	1	O17	1	1	1

If we assume the reported occupancy at Wednesday at 10 a.m. to be equal to the numbers presented in Table 2.1, then *OFp* and *OFz* can be calculated for the two zones:

$$OFp_A^{10.00,Wed} = \frac{12}{30} = 0.40 \qquad OFz_A^{10.00,Wed} = \frac{1}{1}\cdot(1) = 1.0$$

$$OFp_B^{10.00,Wed} = \frac{6\cdot1+2\cdot2+9\cdot0}{10\cdot1+7\cdot2} = 0.42 \qquad OFz_B^{10.00,Wed} = \frac{1}{17}\cdot(8\cdot1+9\cdot0) = 0.47$$

Such instantaneous values can be calculated (e.g., with a time resolution of five minutes), for the whole measuring period and based on that, the average values of interest can be found. For instance, it can be convenient to differ between working days (*wd*) and weekends (*wknd*) and to calculate separate values for the operation hours of the ventilation system. In Norway, it is common to operate the ventilation system in office buildings between 6 a.m. and 6 p.m. on working days and no operation during weekends. Computing *OFp* or *OFz*, selecting a suitable division of zones and sub-zones, and selecting a relevant time period to calculate averages for, are of course dependent on the purpose of the investigation. For instance, for a rough estimate of the energy saving potential with a DCV system compared to a CAV system in this premise, useful factors to compute may be: $\overline{OFp}_A^{06-18,wd}$, if a CO_2-sensor, for example, in the meeting room is considered; $\overline{OFz}_B^{06-18,wd}$, if motion detectors in the office cells are considered.

Finally, it is worth naming that there is an alternative way of calculating $\overline{OFz}$ values for a zone with more than one sub-zone. Instead of calculating the instantaneous value of *OFz* at each time step and then taking the average of all time steps, the utilisation rates of all sub-zones can be averaged. For instance, taking the average of $UR_{i_1}^{6-18,wd}$, $UR_{i_2}^{6-18,wd}$,..., $UR_{i_{17}}^{6-18,wd}$ equals $\overline{OFz}_B^{06-18,wd}$.

2.2 Office building categorisation

An overview of ways to categorise office buildings based on the shape and the dimensions of the building shell, either qualitatively or quantitatively, and based on the office layout concepts of the interior of the building, is provided by Wigenstad (2000). With this categorisation, Wigenstad shows how different building shapes and floor layouts give different prerequisites for the technical installations (including the HVAC systems), especially regarding the layout of the pathways, zoning and module division. This is closely related to the topic in Paper II (see Appendix A.4); comparison of central and decentralized air handling units (AHUs). In this paper, two different fictitious buildings with the same total floor area but with different shapes, one high-rise (17 floors) and one medium-rise (4 floors) were used as case buildings. Calculations showed that the difference in life cycle costs (LCC) between an alternative with several decentralized AHUs and an alternative with fewer centralized AHUs was clearly affected by the shape of the buildings. The occupancy pattern can have an influence on what is the most suitable number of AHUs and on the zoning of a building. The effect of the occupancy pattern is, however, very case sensitive and it can be somewhat difficult to quantify in economical terms and was not included in the LCC calculations in Paper II.

The floor layout, i.e. factors as open versus enclosed individual workspace, number of available rooms for collaborative work etc., will have greater impact on the occupancy pattern than the shape and dimensions of the body shell. The building shape and exterior dimensions can however, at least to a certain degree, influence the choice of office layout concepts and thereby indirectly have an influence on the occupancy pattern. In addition, the shape will affect the distances that the workers have from their individual workstations to different functions in the building and thereby influence the time spent on internal movement.

2.2.1 Office layout concepts

Office layout concepts can be categorised as by Wigenstad (2000), for instance, into four categories: the cellular office; the open plan office; the combi-office, combining office cells with more open multifunctional zones; and finally, a category of newer “alternative office concepts”, that started to be developed in the mid 1990th, which to some extent use elements from the traditional concepts in combination with new elements aiming at more flexible solutions. The last category can, for example, involve the use of: movable workstations and spaces with possibility to ad hoc establishment of a setting for collaborative work; activity settings, where the workers can chose, and move around, between a variety of spaces designed to support different needs; fewer workstations than employees, occupied based on the principle of sharing on scheduled bases, booking (“hotelling”) or simply letting the worker chose among unoccupied workstation upon arrival (Wigenstad, 2000; Blakstad et al., 2009; Harrison et al., 2004).

According to Blakstad et al. (2009), it can be favourable to work with a further division of the open plan office concept, to describe the different layouts of open plan solutions that exist. They suggest using the terms used by Becker and Sims (2001) to describe possible arrangements in the open plan office: high-paneled cubicle (can not see over the panel when seated), low-paneled cubicle (can see over the panel when seated); team-oriented workstation/pod, a cluster of low-paneled workstations separated from other pods with higher partitions; team-oriented bullpen, a group of desks in an entirely open space; and shared enclosed office[2].

Relevance for occupancy patterns and predictions

The floor layout and physical arrangements (furnishing) constitutes the framework for and forms the occupancy pattern. First of all it decides which types and number of zones/rooms are available for occupancy. For instance, if a HVAC system designer wants to predict the average fraction of the working day that the workstations in an open office space are occupied; then, it is necessary, or at least favourable, to know if there are other spaces available for individual work, such as private rooms for activities that requires silence and/or privacy, and if the office is designed for one workstation per employee, or if a concept based on less than one workstation per employee has been used. Secondly, it decides which type of numerical measures that are relevant for describing the occupancy pattern in the building and the division of the office premises into zones and sub-zones required when calculating these numerical measures.

The choice of numerical measures, zones and sub-zones must also, as mentioned in the previous subchapter, be based on other factors than only the physical boundaries in the floor layout: (1) which type of assessment the measure is input to (e.g., estimating internal heat gains or estimating the air flow rates in a DCV system); (2) if there are significant differences in pollution or heat load in parts of a building, including the occupancy itself, it can the be convenient to predict occupancy separately for those zones; (3) if the further analysis involves using any computerised tool, the possibility for zone division in this tool; and (4) the zoning of the space related to the control of the HVAC systems, which is a choice that, among other factors, is influenced by the floor layout. The reason for taking the control zones into account during occupancy prediction is simply that different control strategies may require different types of occupancy data to be estimated (*OFp*, *OFz* or *UR* and levels of detail).

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[2] The literature is not consistent regarding the number of persons an enclosed office shall be designed for to be called an open plan office. In Harrison et al. (2004, p. 24), an enclosed space designed for 1-3 workstations is called a cellular office, for 4-12 workstations is called a group office and for 13 workstations or more is called an open plan office.

An occupancy related aspect that can be of importance for the choice of zones related to HVAC system control, is the users' felling of ownership to a space. According to Boardass and Leaman (1997), a room or zone for individual work or group work, can be characterised either as:

- *owned*, a space assigned to and solely occupied by one or a few workers, such as cellular offices for one or two persons;
- *shared*, a space shared by several workers and where the occupants regard part of the space as their own, such as open plan offices; and
- *temporarily owned*, a space either for individual or group work that is usually occupied for a shorter period at a time, such as meeting rooms or a workstation not assigned to any specific employee.

The users felling of ownership to a space will affect the expectations that they have on the quality of the indoor climate and on their own possibilities to control it; something that should be taken into account when taking decisions about the control of the HVAC systems in different spaces (Laing et al., 1998). Consequently, it can be favourable to consider areas characterised to have different "space ownership" as separate control zones and deal with them separately when predicting occupancy.

The fact that the base building elements a building consists of have different life-cycles has, or at least should have, a strong influence on the design of HVAC systems in offices. Laing et al. (1998) present a model of generic office buildings, where the building is divided into four basic life-cycle elements: (1) the shell (structure and cladding) with a typical life cycle of 50-75 years; (2) the building services (HVAC systems, light, power supply etc.), with 15 years[3] as typical life cycle; (3) the scenery (fixed interior elements as ceiling, partition walls, IT equipment etc.), with 5 years as typical life cycle; and (4) the settings, i.e. the physical arrangement, where the rearrangements of the furnishing is on a day-to-day basis.

The settings, and resulting occupancy and movement pattern in a space, will have an impact on the resulting indoor climate conditions and the occupants' perception of it. The

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[3] Components of HVAC systems can have a life cycle that differs considerably from 15 years. Most components have a life cycle in the range 10 to 30 years, according to standard NS-EN 15459 (2007) that lists data of typical lifespan for HVAC components.

partitions, desks and other obstacles will influence the air flow pattern, the occupants' position in relation to the windows, and potential obstacles between them and the window, may influence their thermal comfort etc. Hence, for two different settings (e.g., high panelled cubicles versus team-oriented bullpens in an open plan office) the optimal HVAC system solution, regarding control strategies, placement of sensors and supply air units etc., will most probably not coincide. Then, knowing that especially the settings can change frequently, but also that the scenery can be rearranged one or a few times (e.g., from office cells to open plan office) during the expected life-cycle of the HVAC-system, this implies that:

- It is of vital importance to think in terms of adaptability when designing the HVAC system in offices, in order to get a sustainable solution that not only performs well the day it is taken into use, but also has the potential, with the right management, to perform well throughout its expected life-cycle.
- Thinking in terms of adaptability is essential when predicting occupancy, because it, as described here, is part of the HVAC system design.

In practice, this implies that it may not be meaningful in open areas of offices to do a detailed division of the space when predicting occupancy, not even in cases when it is expected to be significant variations in occupancy density or occupancy pattern as a consequence of the settings that is planned for at the design stage. Moreover, it may be convenient in some situation to make somewhat conservative estimates of occupancy; for instance, when the occupancy is a determining factor for the size/capacity of components. This topic is further discussed in Chapter 2.6.

The importance of adaptability is confirmed by the results of a survey of 750 Nordic enterprises, carried out in a project called DEKAR (Bakke, 2007). More than 40 % of the responding managers claimed that their company had made rearrangements in the use of the workspace during the last two years. Moreover, almost one third of the managers reported that their company was planning to rearrange, rebuild or make changes in their office buildings in the next coming two years. When asked for relevance of possible changes in the future, improvement of lighting, heating and ventilation was rated as the second most relevant, next after increased use of IT.

The content in previous sections and its implications for occupancy prediction in practice can be summarised as follows: The occupancy pattern is decided by the floor layout and settings, of course in combination with the organisation(s) occupying the building. Hence, it is favourable if the HVAC system designers understand the intentions behind the office layout concept when making occupancy predictions. A good communication with architects and space planners involved in the project are therefore important. An example of a relevant question to ask is to what extent sharing of workstations is planned for, i.e. number of workstations in relation to the number of employees. Other issues that can be discussed are: what the most probable settings (physical arrangements) of the space are, in order to roughly estimate the range of occupancy densities that can occur (when *OFp*/*OFz* equals 1.0); how likely it is that the scenery of the present floor layout will be changed and in which way (e.g., from cellular offices to open plan office). These are questions that will be difficult to give an exact answer on, but it can still be useful to at least have an idea of what the most likely scenarios are.

2.2.2 Characteristics of Nordic office design

Some characteristics and trends of Nordic office design, in comparison to other parts of the world, and consequences for occupancy patterns and occupancy predictions are listed below:

- Wigenstad (2000) presented some characteristics of what was called the new North-European or Nordic office design. The buildings typically have four to five floors with a floor height of approximately 3.2 meter. The shape of the building shell can differ somewhat, but is often what can be called climate adaptive with a high outer wall surface to volume ratio. This means that a large part of the building has a close interaction with the outdoor climate and with great possibilities to utilise the daylight and consequently less use of artificial lighting. The building often consists of a main wing and several side wings. The depth of the floors and the distance from workspace to windows are less than in many other design concepts, such as many North American buildings with open plan offices and a shape of the building that is more compact and more climate rejecting. A high degree of sectioning is often utilised, where the building is divided into smaller zones, of typically 200 m^2 (Wigenstad, 2000, p. 94-95); supplied with HVAC from their own core area/vertical shaft. This means that the HVAC is more decentralised and often with a higher number of AHUs than in many other design concepts. It also means that it may be a need for a more extensive zone division during occupancy predictions compared to other office designs. Finally, the most common floor layout concepts are either the cellular office or the combi-office, often with relatively large common areas for internal movement and communication. It is however, according to Wigenstad, a trend towards less use of cellular offices and an increasing degree of frequent rearrangements of the settings. Most new Norwegian open plan offices are team-oriented pods or bullpens (Blakstad et al., 2009).

- The survey carried out in the DEKAR project (Bakke, 2007), revealed that individual (cellular) offices, small open plan offices (less than 10 individuals) and large open plan offices are all common in Nordic office building. The survey showed that open plan offices are more common than individual office in Denmark, while it in Iceland is a more even distribution between open plan and individual offices. In Norway, Sweden and Finland, the individual office is by far the most common office type; in Norway around 75 % of the workplaces have individual offices, while around 40 % has small or large open plan offices (some workplaces have both individual and open plan offices). In USA, the situation is the opposite; most office workers, estimated to approximately 70 % around year 2000 (Olson, 2002), are working in open areas. In the DEKAR survey (Bakke, 2007), it was, as mentioned earlier, asked for the relevance of possible future changes. When it comes to office layout, more than 40 % answered that more small open plan offices with individual reservation are either highly relevant or relevant; and almost 40 % that more large open plan offices with individual reservation are highly relevant or relevant, while more individual offices was classified as highly relevant or relevant by almost 30 %. This is in accordance with many other forecasts in the last years, see for instance Barber et al. (2005); it is expected that office layout moves towards more open workspaces and less use of individual cellular offices. However, the individual (cellular) office is still the most common environment for individual work in many countries, such as Norway. Consequently, when collecting occupancy data in a relatively limited extent as in the case studies presented in Part II, with the objective to improve our knowledge about occupancy patterns in offices, with emphasis on Norway and other Nordic countries; then, monitoring the occupancy in single person cellular offices, is the room type with highest relevance for most offices, when space for individual work is considered.

- In a survey carried out in 2003, including both North American and European organisations, on average 2 % of the staff in the surveyed organisations did not have their own assigned workstation (Barber et al., 2005). However, the respondents in the survey expected that over the next five years, this portion will increase to over 10 %. The portion of employees using workspace on an as-needed basis (hotelling/free address) was in this survey higher in Europe than in North America. For the occupancy levels, desk sharing results in a higher *OFz* or *OFp* in spaces for individual work, compared to if every employee have their own assigned workstation. Strongly related to the concept of using less workstations than employees, is the incidence of teleworking. The survey by Barber et al. indicated that teleworking is more common in Europe than North America.

2.3 Activity patterns in office buildings

J. Farbstein defined and discussed, as he called it, “the fundamental dimensions of human activity in the built environment” (Farbstein, 1974, p. 18), which according to him are:

- the nature of the activity;
- the actors, i.e. the individual or group of individuals performing the activity; and
- the time pattern that the activities follow.

The first two, the nature of the activity and the actors, are discussed below. Considerations regarding the last dimension, time, such as suitable time resolution, and instantaneous or average values, in connection with measurements or predictions of occupancy patterns are to some extent discussed in Chapter 2.5 and also later on in subsequent chapters.

In studies of activity patterns in buildings it is often necessary with some degree of aggregation to classify activities and populations into categories. As mentioned by Farbstein (1974), in the process of aggregation each step can improve the comparability and generality of a study; however, at the same time it also results in some loss of information. Hence, the categories should be selected carefully. The categories are not universally valid, and are often chosen for the purpose of one specific study.

The nature of the activity

A general definition proposed by Farbstein (1974, p. 19) is that: “activities are the observable actions of individuals, alone or in group”, and as Farbstein stated, it can be described by verbs of action or position. People thinking, feeling or perceiving are not according to this definition considered as activities, because it is not possible by only observing a person to decide if and what he/she is thinking, feeling or perceiving. Consequently, to feel warm or perceive the air as stuffy is not an activity, but it can be the reason behind an action that can be observed and considered to be an activity, such as opening a window.

Steen et al. (2005) divide office activities into eight categories: concentrated work at the workstation, practical work at the workstation, telephone conversation at the workstation, interacting (face-to-face conversation) at a workstation, participating in a (scheduled) meeting in a meeting room, staying in break/coffee areas, staying at common functions (printers, files etc.), and in space for movement. In addition to the action itself, Steen et al. use the location as an attribute to categorise the activities, which is consistent with the statement by Farbstein (1974). Hence, the activity pattern can be said to be consisting of:

- the pattern of actions, and
- the pattern of occupancy.

When studying the activity pattern in buildings we can chose to observe or measure and describe it by: one, focusing only on the actions without specifying where they take place; two, specifying both the actions and the locations; three, focusing only on the location of the occupants, i.e. the occupancy pattern, without studying and specifying what is being done; or finally, specifying the actions for some locations and only the location for other parts of the building (e.g., like Steen et al. (2005) have done in their studies of office buildings). There exist studies with relevance for HVAC system design and management within all these alternatives.

The relevance of studying the occupancy pattern alone without focusing on the actions taking place, as done in this thesis, is the topic of chapter 2.5. Studying the pattern of different actions in offices is also very important, to better our understanding and accuracy in predictions of: (a) how frequent different activities that we know affect the indoor climate occur (e.g., use of office equipment that is regarded as a significant pollution source); and (b) how we interact with the building services in order to affect and control our indoor climate conditions. With the latter is meant, a better understanding of the probability that an occupant, during different indoor or outdoor climate conditions: opens or closes a window; manually adjusts the position of venetian blinds; switches on or off artificial lighting; change room temperature set point; adjust the ventilation flow rate in a mechanical ventilation system; or by other means tries to affect their indoor climate. There has in recent years been an increased focus on including, to a higher extent than before, the human behaviour related to perception and control of the indoor climate, in building simulation tools. However, a vital necessity for these actions to take place is that the occupant is present. Hence, studies of occupancy pattern is of relevance also here, because more advanced behaviour models need a good and detailed enough occupancy model.

The actors

In studies of the activity pattern of more than one individual we can observe, measure and describe the activities either on a level equal to the individual actors or on group level. The latter case means using either one group including all studied individuals or dividing the population into several sub-groups. This corresponds to expressing the occupancy state either on individual room/zone level or aggregately for a group of rooms/sub-zones when studying, or predicting, the occupancy pattern and expressing it by *UR* or *OFz*, as defined in Chapter 2.1. It is seldom meaningful to predict the occupancy pattern in one specific cellular office, or the use of one specific workstation or small group of workstations, in a design phase; simply because we do not know who is going to occupy it/them, at least over time, and because the occupancy pattern will differ, sometimes considerably, between individuals within one and the same organisation (which is shown in the case studies presented in Part II). This however, does not mean that it is of no relevance to study the occupancy pattern in cellular offices or other small zones, one by one. For instance, it can be of interest to know how a typical distribution of *UR* for cellular offices looks like in different organisations. Moreover, during development and/or testing of HVAC system solutions and control strategies where the occupancy pattern is thought to be of importance, it is important to use relevant occupancy scenarios, preferably based on empirical data.

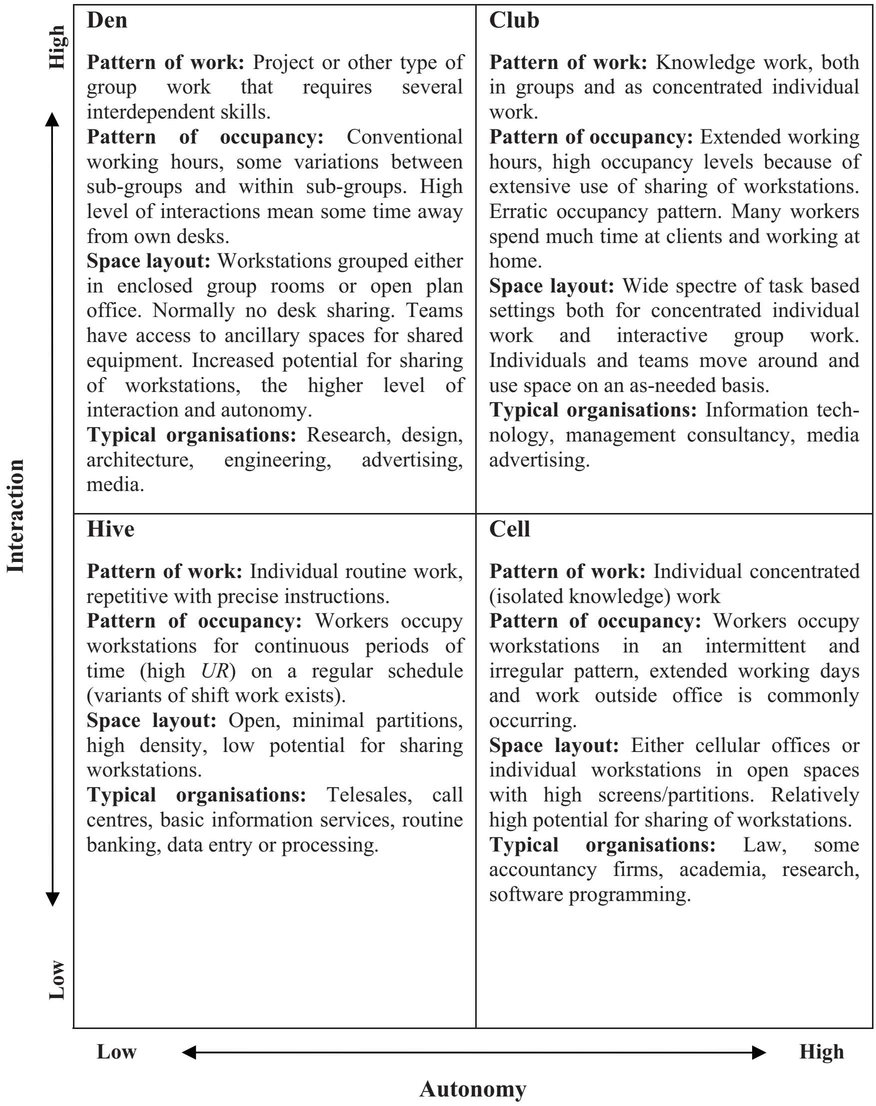
Some studies of activity patterns use socio-economic indicators (gender, age, income, education etc.) to search for an explanation for the observed differences between individuals. In studies of organisations, the individuals can be classified according to their role in the organisation (manager, teaching assistant etc.). Then, by knowing the composition of a group of individuals, it could be possible to predict the activity pattern of the group. However, according to Farbstein (1974), these indicators are not powerful enough in explaining the activities of people. Instead, Farbstein suggested another possible approach; to group individuals, proven empirically to have similar activity pattern, and then search for explanations for the similarities. The occupancy pattern in an offices building is a result of the office layout and of parameters related to the working tasks and work style of the organisation(s) occupying the building. Hence, when searching for explanations for observed similarities and differences in occupancy patterns among offices, we shall search there.

Laing et al. (1998) present a model that uses two variables, interaction and autonomy, to characterise the work processes and patterns of work of an organisation, or group within an organisation. By interaction they mean the extent of face-to-face interactions occurring both in the individual’s own working group and externally. By autonomy they mean the level of control, responsibility and discretion the individuals have over their work content, methods and tools, and over the locations where the work is takes place. Laing et al. use the level of interaction and the level of autonomy to define four main categories of patterns of work, each category with its own requirement for space layout and associated occupancy pattern. The model with the four work patterns and spatial requirements, which are called the hive, cell, den and club, respectively, is illustrated in Figure 2.2.

The levels of interaction and autonomy are associated with the occupancy pattern in the following way, as explained by Laing et al. (1998):

- Individuals whose work can be characterised as having a high level of interaction will leave their workstations frequently to visit a colleagues’ workstation or participate in a meeting, either within, or outside their own office premise.
- Individuals whose work can be characterised as having a high level of autonomy are more likely to work in other locations than at their own workstations, both within and outside their own office premise (e.g., at clients or at home).

In sum this mean that a higher level of interaction and a higher level of autonomy, normally results in a more intermittent occupancy pattern of the workstations.



Den **Pattern of work:** Project or other type of group work that requires several interdependent skills. **Pattern of occupancy:** Conventional working hours, some variations between sub-groups and within sub-groups. High level of interactions mean some time away from own desks. **Space layout:** Workstations grouped either in enclosed group rooms or open plan office. Normally no desk sharing. Teams have access to ancillary spaces for shared equipment. Increased potential for sharing of workstations, the higher level of interaction and autonomy. **Typical organisations:** Research, design, architecture, engineering, advertising, media.	**Club** **Pattern of work:** Knowledge work, both in groups and as concentrated individual work. **Pattern of occupancy:** Extended working hours, high occupancy levels because of extensive use of sharing of workstations. Erratic occupancy pattern. Many workers spend much time at clients and working at home. **Space layout:** Wide spectre of task based settings both for concentrated individual work and interactive group work. Individuals and teams move around and use space on an as-needed basis. **Typical organisations:** Information technology, management consultancy, media advertising.
Hive **Pattern of work:** Individual routine work, repetitive with precise instructions. **Pattern of occupancy:** Workers occupy workstations for continuous periods of time (high *UR*) on a regular schedule (variants of shift work exists). **Space layout:** Open, minimal partitions, high density, low potential for sharing workstations. **Typical organisations:** Telesales, call centres, basic information services, routine banking, data entry or processing.	**Cell** **Pattern of work:** Individual concentrated (isolated knowledge) work **Pattern of occupancy:** Workers occupy workstations in an intermittent and irregular pattern, extended working days and work outside office is commonly occurring. **Space layout:** Either cellular offices or individual workstations in open spaces with high screens/partitions. Relatively high potential for sharing of workstations. **Typical organisations:** Law, some accountancy firms, academia, research, software programming.

Figure 2.2 Four main types of work patterns (adopted from Laing et al., 1998).

Using the model of Figure 2.2 can be a helpful tool in connection with occupancy predictions. There is however, as stressed by Laing et al. (1998), some limitations with this way of categorising organisations, which should be kept in mind. First, for many sectors of work and professions, the diversity in work style is large enough to find organisations that belong to different work pattern categories in the model. Therefore, one shall not automatically assume that an organisation belongs to any specific work pattern category, based solely on its sector of work or profession, without doing further analysis of the organisation's work style and routines. On the other hand, Laing et al. claim that there exist evident affinities between certain sectors of work and a certain work pattern category. Second, most organisations will be a combination of two or more of the four defined work pattern categories, meaning that it in some cases may be necessary to divide the organisation into sub-groups when using the model in practice. Third, the correlation between the work pattern and the occupancy pattern will vary significantly. Hence, although the model can be useful in connection with occupancy predictions, it should only be considered as a tool to support the prediction, in combination with other resources, such as empirical occupancy data.

2.4 Building – User – HVAC system relationship

The relation between the building and the user organisation(s) occupying it, which is dynamic and changes continuously, is the main topic in a thesis by Blakstad (2001), *A Strategic Approach to Adaptability in Office Buildings*. Blakstad describes the relationship, which she labels the building-user relationship (BUR), as a demand and supply relationship, where the building (the supply side) is designed and managed to match the needs of the users (the demand side). The user organisation(s) and their demands changes more or less continuously. The building is more static, but will undergo a slow decline in quality. Hence, there will almost permanently be a gap between the demands and what the building can offer, resulting in the user organisation to adapt to the building and a need to more or less regularly carry out smaller adaptations of the building. When the gap, or as Blakstad labels it, the mismatch, between demand and supply becomes larger and finally exceeds what is considered to be an acceptable level, the alternatives are to upgrade the building by means of major adaptations, demolition, or for the organisation(s) to move and find new office premises.

Blakstad (2001) provides an overview of models, from Laing et al. (1998) and McGregor and Then (1999), for instance, all describing BUR as a supply and demand relationship. Figure 2.3 is partially based on some of those models. Because the focus in this chapter is on BUR from a HVAC system point of view, the HVAC systems are considered as a separate entity in this model, although it actually is an integrated part of the building.

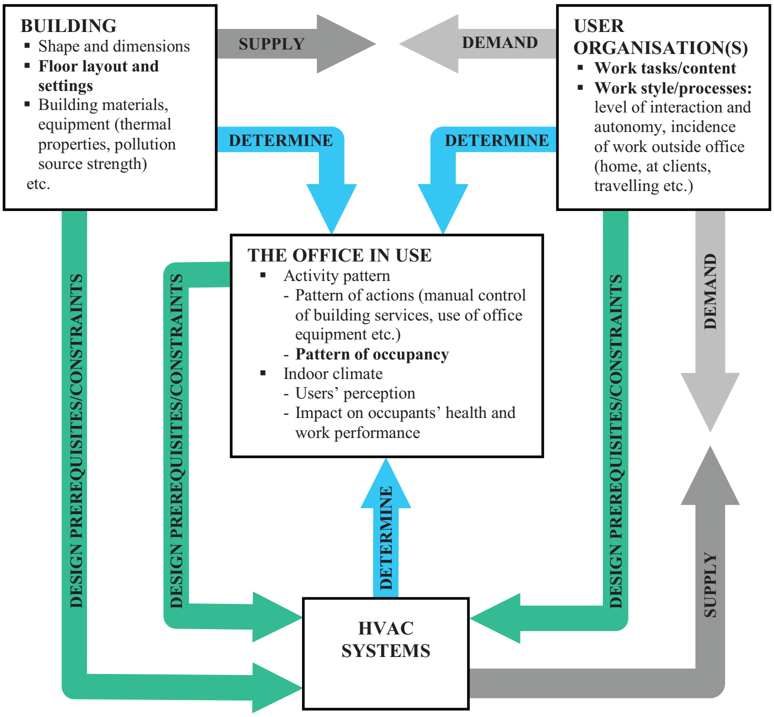


Figure 2.3 Building-user-HVAC system relationship, from a HVAC system design point of view, with focus on the occupancy pattern.

Not all connections between the three elements and not all properties of the building and user organisation(s) that are involved in a design process are shown in Figure 2.3, because the figure is not intended to summarise the whole design process; the focus is on the occupancy pattern in connection with HVAC system design.

In the same way as for the relation between the users and the building as a whole, the relation between the HVAC systems, when thinking of them as a separate entity, and the users, can be regarded as a demand and supply relationship. The demand side of this relationship is an expression for the needs of the users, which during design are formulated as quantitative and measurable requirements. In the model in Figure 2.3, the demand includes the primary requirements; the ones that have to be fulfilled in order for the users to be able to practice their intended work in a satisfactory manner, such as indoor climate related requirements (Persson, 2001). Of course, also other (secondary) requirements must be taken into account during design; for example, those related to energy performance.

To be able to design and construct HVAC systems that fulfil the requirements of the users, and other stakeholders (e.g., building owner and authorities) as well, a set of design prerequisites and constraints must be analysed. Those can be divided into three categories:

- prerequisites and constraints related to the building;
- prerequisites and constraints related to the user organisation(s) and their type of work, which can be specified without having to predict how the activities vary with time when the users occupy the building; and
- prerequisites and constraints related to the expected pattern of actions and occupancy when the building is taken into use.

The last category can be challenging to involve in the design phase, simply because the behaviour and occupancy of the users, which are dynamic, can be difficult to predict. The next subchapter presents some examples of assessments that should, or at least could, involve considerations of the occupancy pattern. The uncertainty involved in predictions of occupancy might be relatively high. Nevertheless, this should not hinder the design team from estimating it roughly, or only assume one or a few scenarios, to see if actual occupancy levels that deviate from the design occupancy density given by the floor plan, change the prerequisites for the design. The essential here is to be aware of the connections in Figure 2.3; when looking at the office as a result of combining properties from the building and the user organisation(s), new design prerequisites and constraints are added to the ones that the building and users give alone, which may give new useful insight in the search for more optimal solutions.

2.5 Potential assessments involving the consideration of the occupancy pattern

Table 2.2 lists some examples of assessments related to indoor environmental quality (IEQ) in general and ventilation design in particular, where some aspects of the occupancy pattern have to, or may, be taken into account. Some of these assessments are relevant for both CAV- and VAV-systems and some only for VAV-systems, which is specified in the third column of the table.

Different kind of assessments requires knowledge about different aspects of the occupancy pattern and with different levels of detail. With the levels of detail means the time-resolution of the predicted, or measured, occupancy. The second column of Table 2.2 specifies possible types of measures of the occupancy pattern that can be relevant for the assessment in question, where *OFp*/*OFz*/*UR* means that *OFp*, *OFz* and *UR*, or a combination of them, all can be of interest. The choice of measure(s) is in those cases dependent on the space layout and how the system controlling the indoor climate is built-up. Dependent on the purpose of the assessment, different aspects of *OFp*, *OFz*, *UR* or another occupancy related measure can be of interest:

- sometimes the average load (expressed with, e.g., the mean or median);
- sometimes the peak, or close to peak load (expressed with, e.g., the maximum or 95 percentile); and
- in some situations, the distribution of the load (either summarised in a histogram or a profile varying with time showing the dynamic behaviour).

Moreover, in Table 2.2 it has been differed between low, medium and high time-resolution. Low time-resolution means one averaged value per day, either for all 24 hours or a segment of the day. With medium means a time resolution of one hour. With high means sub-hourly time resolution, which if it is a prediction a not direct use of measured occupancy data, usually means using some stochastic model.

Some loads are more or less dependent on the occupancy, such as the use of lighting and office equipment, which means that estimating these loads, can involve estimating the occupancy first. The lighting load will be more closely correlated to the occupancy load if occupancy-sensing control is used than it will be for other control strategies. How closely correlated the office equipment load is to the occupancy load, will depend on the settings of stand-by functions. These loads can be expressed as diversity factors, expressing the fraction of the total installed load that is utilised.

Table 2.2 Examples of assessments related to HVAC-system design involving predictions of the occupancy pattern

Type of assessment	Relevant aspects of the occupancy pattern	CAV/ VAV
1. Estimation of internal heat gains (people themselves and loads which depend on occupancy, e.g., office equipment and lighting) as input to computation of for example: a. Indoor thermal climate conditions b. Maximum cooling demand c. Annual energy demand/use. If facilities which limit the heat load involve manual control by the occupants, like window opening or adjustment of venetian blinds, estimates of the occupancy is important for computation of the heat and air flow balance, presumed the computation model can take such effects into account.	*OFp*/*OFz*/*UR*, expressed as: a. Peak level, average or a distribution b. Peak level or a distribution c. Average or a distribution Resolution: low-high	CAV and VAV
2. Estimation of the pollution source strength of one or a number of pollutants, in cases where the occupants themselves and/or their activities are a non-negligible source to the pollutant(s) in question, which in turn can be used as input to for example: a. Evaluations/comparisons of different measures (source control, local exhaust, general ventilation) to limit the concentration of pollutants in the indoor air. b. Predictions of the resulting IAQ level (pollution concentrations, level of perceived air quality (PAQ)) with a certain ventilation flow rate, or calculation of necessary ventilation flow rate to achieve IAQ target levels.	*OFp*/*OFz*/*UR*, expressed as peak level, average or a distribution. Resolution: low-high	CAV and VAV
3. Estimation of the time the occupants are exposed to different levels of an indoor climate parameter, for assessments such as: a. Judging, from a comfort point of view, if the predicted indoor climate conditions are acceptable. If one or several parameters (pollutant concentration, temperature, noise level etc.) exceeds/falls below the target levels, it is of interest to know if this occurs when the zone in question is unoccupied or when occupants are present. Moreover, if it occurs during occupancy, it is of interest to know to what extent, (e.g., expressed as hours per year), and possibly also the variation among the occupants. b. Cost-benefit analysis involving productivity gains/losses.	Time occupants spend in different part of a building (workstations, meeting rooms etc), which can be computed from *OFp*/*OFz*/*UR*, expressed as average or a distribution. Resolution: low-medium	CAV and VAV

Table 2.2 continued

Type of assessment	Relevant aspects of the occupancy pattern	CAV/ VAV
4. For VAV-systems, development/testing of different flow rate control strategies in the air distribution system. Simulations of relevant scenarios regarding the air flow variations throughout a system, partly for checking the ability to handle different loads and partly to investigate the effect of introducing a deviation between what is planned and what is installed (e.g., the location of pressure sensor being changed or introducing additional pressure lossess).	*OFp*/*OFz*/*UR*, expressed as a distribution. Resolution: high	VAV
5. Estimation of the expected peak, or close to peak, occupancy load in larger spaces like office landscapes. In office cells designed for one or a few persons, the probability for all workers being present simultaneously, i.e. *OFp* reaches 1.0, is high enough to expect that it will occur from time to time. In spaces such as office landscapes on the other hand, *OFp* or *OFz* may never, or seldom, reach 1.0. Hence, in some larger spaces the following ventilation flow rates may potentially be based on a lower peak occupancy load than the design load: a. Design ventilation flow rate when using a CAV-system. The design air flow rate is often chosen proportional to the number of people, from an IAQ point of view, or to control the room temperature to a certain level, which among others factors is dependent on the occupancy (see row 1.). b. The expected maximum demanded ventilation flow rate when using a VAV-system, which is either directly (motion/occupancy detectors, CO_2) or indirectly (temperature) dependent on the peak occupancy load, and important for proper selection of, for example, the supply terminal units and size of ducts close to the ventilated zone(s). c. The base ventilation rate when using a temperature controlled VAV-systems where the ventilation runs on a base rate and is increased during periods when the temperature rises over a certain level. The base ventilation rate is needed to maintain an acceptable IAQ level also when no cooling is demanded, corresponding to the design ventilation flow rate of a CAV-system.	Peak-levels of: a. *OFp* b. *OFp*/*OFz* c. *OFp* Resolution: medium-high	CAV and VAV

Table 2.2 continued

Type of assessment	Relevant aspects of the occupancy pattern	CAV/ VAV
6. Estimation of the expected maximum air flow rate at different positions throughout a VAV-system. While the estimation in row 4 considers the simultaneous presence of several occupants in one individually controlled area, these estimates are based on considerations regarding the simultaneous ventilation demand of several individually controlled areas. By taking into account that the expected peak of the simultaneous occupancy of many rooms/sub-zones aggregated is lower than the sum of the peak occupancy of each separate room/sub-zone, there is an opportunity to limit the size of some components compared to traditional sizing procedure. This must of course be weighted up against potential disadvantages of smaller dimensions (e.g., higher pressure losses in the case of ductworks). If considering OFp_I or OFz_I for different point in the ductwork, where I is the zone equal to the total area that the air in a point is going to be supplied to or is extracted from, then OFp_I or OFz_I will decrease throughout the ductwork, when starting from the room side and travelling to the outdoor air side. Consequently, this approach is foremost applicable for sizing of components such as main ducts (including duct components like silencers and flow control units), AHUs and outdoor air intake sections.	OFp/OFz, expressed as a peak level. Resolution: medium-high	VAV
7. Assessing the performance of one or several VAV-system solutions, where the performance can be evaluated by judging, for example, the energy performance and/or the ability to control indoor climate parameters such as room temperature, CO2 or PAQ (actually a combination of row 1, 2 and 3). Examples when this can be of interest are when: a. Selecting among components with efficiency dependent on the air flow rate (e.g., fan system, rotary heat exchanger) and estimating annual energy demand/use for heating, cooling and fan-operation, based on an expected ventilation flow rate distribution. b. Selecting one or several appropriate indoor climate parameters to base the control of the ventilation flow rate on and finding suitable values of control parameters (set-points etc). For a cellular office with motion detector and temperature sensor, parameters to be evaluated can be, for example, time-delay(s) of the motion detector, proper base ventilation rate when the office is unoccupied, potential change of deadband between the heating and cooling set-point when the office is detected as unoccupied.	a. OFz/OFp, expressed as a distribution b. OFp/OFz, expressed as a distribution, dynamic behaviour of occupancy and vacancy periods in single person office cells Resolution: medium-high	VAV

2.6 Occupancy in standards and simulation tools

Many of the considerations mentioned in Chapter 2.5 involve making energy and/or indoor climate calculations, reaching from simplified manual calculations to more detailed dynamic calculations with a computerised simulation tool. Many of these calculations can be made with guidance from, or completely in accordance with, one or several standards. The following subchapter discusses a few Norwegian and European standards that in some way address occupancy loads. The next subchapter gives a brief description of how occupancy loads are managed in building simulation tools.

2.6.1 Norwegian and European standards

The European standards (EN standards) referred to below are all adopted as Norwegian standards (labelled NS-EN).

NS-EN 13779

Standard NS-EN 13779 (2007) (*Ventilation for non-residential buildings – Performance requirements for ventilation and room-conditioning systems*) specifies what kind of information is necessary during a design process. Chapter 5.6.2 in the standard deal with human occupancy and states that the activity, the clothing and the number of people the room is designed for shall be defined. Furthermore, it states that “The occupancy level shall be given as schedule, for example by specifying hourly values on typical days” (NS-EN 13779, 2007, p. 11). This means that in a design process performed in accordance with EN 13779, schedules shall be defined, showing how *OFz*, *OFp* or *UR* (depending on room types) varies throughout typical days, for example, from hour-to-hour on working days and weekends, respectively.

NS 3031

New requirements for energy use in building were introduced 2007 in the Norwegian building code, and later revised 2010 (Byggteknisk forskrift – TEK 10, 2010), and are intended to fulfil the European Energy Performance of Building Directive (Directive 2002/91/EC, 2003). In addition to a set of minimum requirements that have to be met, a building has to fulfil either a set of energy measure requirements or not exceed a limit value for the total net energy demand. The net energy demand and the heat transmission coefficient (part of the energy measure requirements) shall be calculated in accordance with the Norwegian standard NS 3031.

Standard NS 3031 (2007) is to a large extent based on EN ISO 13790, and includes methods to compute the energy performance of buildings. The standard contains a set of standardised data that shall be used as input when calculating the net energy demand, for control against the requirements in the building code, and the need for delivered energy, when performing energy certification[4] of a building. The standardised data includes values for operation hours, set-point temperatures, internal heat loads, thermal bridges of building elements, outdoor climate parameters and power and energy demand for lighting, equipment and hot tap water. This means that the requirements for the net energy demand in the building code is a theoretical energy demand during standardised usage, operation and outdoor climate conditions.

The standardised input data for internal heat loads are all specified as average values for the operation hours (12 hours/working day for offices), expressed in W/m^2 or kWh/m^2, without differentiating between different hours of the day. These values shall also be used as input when using a dynamic method with hourly time-steps, which is recommended for office buildings. The values for internal heat gains for offices are: 4 W/m^2 from people; 11 W/m^2 from equipment; 8 W/m^2 from lighting.

There are two places in the standard where diversity factors related to occupancy are specified:

- If the building has a control system based on daylight availability or occupancy detection, then the energy use for and heat generation from lighting can be reduced with 20 %; or any other level if it is documented in accordance with NS-EN 15193, or any corresponding method.

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[4] In 2009, regulations for energy certification of buildings and inspection of HVAC systems (Energimerkeforskriften, 2009) were introduced, with effective date 1st of January 2010; also they intended to fulfil EPBD. An owner of a building (residential and non-residential) that are sold, rented out or constructed, or a non-residential building with a floor area of at least 1 000 m^2, is according to these regulations obligated to ensure that the building has an energy certificate. The certificate includes, among other things, an energy label with two grades: an energy grade and a heating grade. The energy grade is based on calculated theoretical amount of delivered energy, and shall be calculated in accordance with the methods described in Norwegian standard NS 3031.

- If the building has a VAV system, either CO_2-controlled or with occupancy-sensing control and no detailed calculations/simulations are made, then the average air flow rate within the operation hours can be reduced with 20 % compared to the design air flow rate. With design air flow rate is here meant the air flow rate that a CAV system would have had in the building in question.

A reduction of 20 % does not mean that the occupancy level in the building, expressed with *UR*, or average *OFz* or *OFp*, during operation hours equals 0.8, which it easily can be interpreted as. It corresponds to a lower occupancy level than that. The exact level is not only dependent on the occupancy level, but also on the way the lighting or ventilation are controlled.

NS-EN ISO 13790

According to standard NS-EN ISO 13 790 (2008) (*Energy performance of buildings – calculation of energy use for space heating and cooling*), weekly and hourly schedules with values for metabolic heat generation from occupants and heat emitted from appliances (e.g., office equipment) shall be decided on a national basis. Nevertheless, the standard provides default values for occupancy related data that can be used if national values do not exist, which represents typical levels in different building categories. These values are, as in NS 3031, expressed as W/m^2 conditioned floor area. For office buildings, the heat emitted from occupants and appliances are added together into one single value. Four levels are specified: one for the office space and one for other rooms, corridors, lobbies etc; and for each of these two space categories, one value for weekdays between 7 a.m. and 5 p.m. and one level for the rest of the week. The default value for weekdays between 7 a.m. and 5 p.m. is 15 W/m^2 (occupants plus appliances), when recalculated to an average of both space categories. This is the same value as specified by NS 3031 (4 + 11 W/m^2). For heat dissipation from lighting, the standard refers to EN 15193.

The standard also specifies default values for the presence of people, as a monthly average. The default for office buildings is 6 hours per day; however, it is not specified whether this accounts for the office building as a whole or only the presence at the workstations.

NS-EN 15193

Standard NS-EN 15193 (2007) (*Energy performance of buildings – Energy requirements for lighting*) is as mentioned above referred to in NS 3031 and EN 13790. The standard provides two methods for calculation of annual energy used for lighting; one called the quick method and one called the comprehensive method. Independent of which method that is used, the equations for estimating the lighting energy includes a factor called the occupancy dependence factor F_O. This factor is multiplied with the total installed lighting power in the room or zone in question; a correction that takes into account the impact that the occupancy level and type of control system have on the energy use.

In the quick method, default values for F_O are provided that can be used if national levels are not available. For offices, the default is 0.9 if 60 % or more of the connected load has some sort of automatic control, and 1.0 for manual control.

If the comprehensive method is selected, F_O is calculated with a set of equations that include two other factors: F_A, which is the fraction of time a room or zone is unoccupied; and F_{oc}, which is dependent on the type of control. F_A is equal to 1-UR. The default values for F_A, recalculated to UR are:

- 0.6, for one-person cellular offices;
- 0.7, for cellular offices for two to six persons;
- 0.8-1.0, for an open plan office with more than six persons;
- 0.5, for conference rooms; and
- 0.8, if the entire building is considered as one zone.

The default value for annual operating hours for the lighting is 2500 hours for offices, corresponding to 10 hours/day. Consequently, the default UR in a one-person cellular office, for example, corresponds to 6 hours of occupancy during the operating hours. The default values, which according to the standard are based on empirical data, can be compared to the monitored data in some Norwegian office buildings, presented in Chapter 6.

NS-EN 15232

Standard NS-EN 15232 (2007) (*Energy performance of buildings – Impact of Building Automation, Controls and Building Management*) specifies methods for estimating the influence that building automation control systems (BACS) and technical building management (TBM) have on energy use in buildings. The standard includes a series of different BAC and TBM functions, where DCV is one of them. Two different calculation procedures are provided; one detailed method and one called the BAC Factor method.

In the detailed procedure, the standard refers to other EN standards regarding evaluations of the impact DCV has on energy use. In those standards, methods for computing the savings are provided, first in amount of air supply, and then to recalculate this into energy savings. No default values for occupancy levels, or factors that express the saving in amount of air supply with occupancy-sensing control, in the same way as for lighting in EN 15913 is however provided.

The BAC Factor method is a simplified approach, where a set of BAC efficiency factors are provided. The factors express the relative change in annual energy use when going from one BAC efficiency class to another, where each class includes a defined set of BAC and TBM functions. The BAC efficiency factors are based on a series of energy simulations of a standardised room (dimensions and U-values) and occupancy profile, for different building categories. The standardised occupancy profile for offices, specified as hourly averages of the occupancy factor (corresponding to *OFp*), varies between 0.33 and 1.0 between 7 a.m. and 6 p.m., with an average of approximately 0.7, and is zero outside these hours. Use of DCV in offices, in this case based on occupancy detection, corresponds to going from BAC efficiency class B (advanced) to class A (high energy performance). The relative reduction when going from class A to B is 12.5 % for thermal energy and 6.5 % for electric energy. The transition from class B to A includes however also other energy efficiency improvements; hence, the reduction in annual energy use is not a result of going from CAV to DCV alone.

Summary and discussion of standards

Both Norwegian standard NS 3031 (2007) and standard NS-EN ISO 13790 (2008) (and also other European standards not referred to here) specify values for internal heat loads in W/m^2 instead of diversity factors. However, if these values are assumed to be fairly representative for what is typical in actual buildings, a diversity factor is already included. NS 3031 specifies 4 W/m^2 for heat (sensible) emitted by occupants. This value shall be used in all parts of the building, representing an average of different zones, and during all 12 operation hours. The default design value for floor space per person in the Norwegian building code is 15 m^2/person (Statens bygningstekniske etat, 2011). If we think of an office building with one-person cellular offices of 10 m^2 and with 15 m^2/person, when including both office cells and other supporting space; then, with 80 W sensible heat per person (specified in NS-EN ISO 13790), 4 W/m^2 corresponds to an average *OFp* of 0.75 for the whole office premise and an average *OFz* of 0.5 for the cellular offices. This mean that on average during the operation hours of the building services, 75 % of the occupants are present somewhere in the office premises and that every second office cell is occupied. With 12 hours of operation, this corresponds to an average *UR* of 6 hours per day for the office cells; the same as is in NS-EN 15193 (2007).

One consequence of the chosen approach in NS 3031 (2007), is that, for instance, a small one-person office cell that actually has higher internal heat loads per m^2 than a larger office cell, in the calculations/simulations will have the same specific internal heat load in W/m^2. It is however important to stress that the standardised input data in NS 3031 shall be used for control against the requirements in the building code, and are not meant as design values. Although, the limits (net energy demand) in the energy frame in the building code are based on the same values as in the standard, it can have some practical consequences. For instance, if a building with a VAV system where the air flow rates are controlled by the room temperature is considered, the level of internal heat gains specified in the standard affect the calculated benefit of using a VAV instead of CAV system. An alternative approach would be to specify diversity factors for different types of office space, for example, differentiate between spaces for individual work, meeting/conference rooms and other types of space. For occupancy, this means specifying *UR* /*OFz* in spaces for individual work (or *OFp* if the effect of visits shall be included) and *OFp* in other spaces. The factor/rate is then multiplied by a default value for heat generation per occupant (dependent on activity level) and the number of people the room is designed for. This approach requires, however, just like for specific heat loads in W/m^2, that reliable data are available. A combination of the two approaches could be another alternative (e.g., diversity factors for spaces for individual work and meeting/conference rooms and specific heat load in W/m^2 in remaining parts of the office).

While NS-EN 15193 (2007) specifies *UR* for different types of office space, only NS-EN 15232 (2007) provides a schedule with hourly occupancy factor levels. This schedule is, however, used only as input to estimates of the potential with different energy saving measures, and is not specified as default values for design. No simplified method with default input values for estimating the energy saving potential for DCV with occupancy-sensing control (versus CAV), as the one for lighting in NS-EN 15193, seems to exist.

2.6.2 Building simulation tools

A common approach for modelling heat emitted from occupants and occupancy related lodes, such as office equipment and lighting fixtures, is to use diversity factors. The user of the simulation program specifies a schedule with diversity factors between 0 and 1.0. Some programs provide predefined diversity profiles for different types of building categories and type of loads. The diversity factor for occupancy corresponds to *OFp*, as defined in Chapter 2.1. The factors are then multiplied by a maximum load (e.g., in Watt or in Watt-hours over a defined time period), which is specified by the user (Bourgeois, 2005). The same approach can be used for contaminants, such as CO_2 generated by occupants.

Usually, at least for the more comprehensive whole-building energy simulation programs, the diversity profiles are specified as schedules with a time resolution of one hour. The number of day types, i.e. the possible number of days with different schedules that can be specified in one simulation, is often relatively limited. Typically two or three day types are specified, for example, to differentiate between weekdays and weekends, and possibly between Saturdays and Sundays. This means that no day-to-day variations between working days, and no week-to-week variations are introduced in the simulations. The occupancy and occupancy related loads will consequently become more concentrated around one level than in most real offices. This does not necessarily result in an incorrect annual energy demand; however, it might lead to misleading results regarding the distribution of the cooling, heating ventilation, lighting and office equipment demand over the year. The distributions of the cooling, heating and ventilation demand are important inputs to the sizing and selection of HVAC system components. Another situation where this approach can be doubtful is, as emphasised by Keith (1997), when estimating annual operation costs for buildings where electric demand charges, based on monthly peak demands, are a significant part of the overall energy costs. In such cases, using one repetitive average profile will give incorrect results for the monthly peak demands, especially in buildings with occupancy-sensing control of lighting and/or ventilation.

There exist programs with possibility to specify detailed occupancy and occupancy related load variations. The whole-building energy simulation tool ESP-r (ESRU, 2005), offers the opportunity to specify time series of data for casual gains with a length of up to one year and with a time resolution between one minute and one hour.

Sub-hourly stochastic occupancy and advanced behavioural models

It has been, and still is, common practice in simulations of energy and indoor climate in buildings to model the occupancy pattern and the occupants' interaction with the building in a simplified manner; not taking into account the behaviour of the occupants (Mahdavi and Pröglhöf, 2009). As stated by Newsham, occupants are considered as "fixed metabolic heat generators passively experiencing the indoor environment" (Newsham, 1994, cited in Bourgeois et al., 2006, p. 816). Instead, occupants and their activities not only affect the indoor climate by heat and contaminant generation, they perceive it through their senses, and if they are not satisfied they try to control it by manually adjusting solar shading devices or set-point temperatures, opening/closing windows, switching on/off lighting fixtures etc.

A relatively large number of studies of occupants' control actions in buildings have been conducted during the last three decades (see e.g., Mahdavi and Pröglhöf (2009), Bourgeois (2005) or Page (2007) for an overview). The studies have typically investigated the relation between one or a few measurable outdoor or indoor climate parameters and control actions undertaken by the occupants. Studies have also investigated how aspects of the occupancy pattern can influence control actions. For instance, Pigg et al. (1996) found a relationship between the probability of switching of the lights when leaving the office and the length of the vacancy period. Some of the findings of these studies have been implemented in simulation tools.

To fully take advantage of behavioural models in simulation tools, more detailed occupancy models than the commonly used 24-hour profiles of occupancy factors are needed. This has actuated the development of sub-hourly stochastic occupancy models. Newsham et al. (1995) presented in the mid-1990s such a model, taking the probability of arrival, departure and temporally absence as a function of time of the day as input to prediction of the occupancy pattern in small zones occupied by one person. Since then, new models have been developed and suggested (see e.g., Page (2007) for an overview).

Behavioural models and detailed occupancy prediction models have been coupled to, or embedded in, simulation programs; usually tools related to one single indoor climate and energy domain, such as lighting conditions and electric energy demand for lighting purposes. One example is the simulation algorithm Lightswitch-2002 (Reinhart, 2004), which has been integrated in simulation tools and predicts the energy performance of lighting systems in one- or two-person office cells. The model includes both manually and automatically controlled lighting and blind systems, and use probabilities established from field studies to predict the on/off switching pattern of light fixtures and adjustments of blinds undertaken by the occupant(s). The Lightswitch-2002 algorithm uses an adapted version of the model developed by Newsham et al., referred to earlier, for sub-hourly occupancy prediction. The algorithm does not include the thermal energy, meaning that the indoor temperature is not simulated, although a high temperature can trigger the occupant to change the position of blinds.

Sub-hourly occupancy models and advanced behavioural models have also been included or coupled to whole-building energy simulation tools, able to simulate more than one indoor climate and energy domain. Bourgeois (2005) developed a sub-hourly occupancy-based control model (SHOCC), making it possible to integrate advanced behavioural models within a whole-building energy simulation tool called ESP-r. SHOCC was used to couple the Lightswitch-2002 algorithm to ESP-r, making it possible to analyse the effect of different control strategies and occupant behaviour related to lighting and window blinds and at the same time analyse the influence these have on the thermal climate and on cooling and heating demands. Bourgeois also included a behavioural model for predictions of occupants' manual operation of windows in relation to thermal comfort, but stated that more research is needed to fully understand the behaviour, for instance, regarding the likelihood of opening windows immediately after arriving to the office and the likelihood of changing the window status when leaving for the day. Nevertheless, the SHOCC together with ESP-r were used to demonstrate the possibility for combining behavioural models related both to lighting and thermal comfort conditions into one single simulation, by performing simulation of different lighting and room temperature control strategies. Later on, an algorithm for predicting occupants' opening and closing of windows was embedded in ESP-r (Rijal et al., 2007). Page (2007) also developed a model for window opening, but in contrast to others, also added the perceived air quality as a parameter that can trigger the occupant to open a window.

It is important to underline that in many cases the use of sub-hourly occupancy and occupancy related loads, instead of hourly input, will have marginal outcome on simulated annual energy use, because of the thermal lag of building constructions and mechanical systems (Bourgeois et al., 2004). If the lighting control is based solely on occupancy-sensing or the ventilation flow rates are based on occupancy-sensing, solely or in combination with other automatic control, it will most likely have no, or at least only small, impact on annual energy demand, as long as the hourly averages are representative for the short term load variations. For instance, if we have a 24-hour profile of the occupancy load with hourly values representing the average over the year (e.g., *UR* in a one-person cellular office), it should be possible to estimate the corresponding load profile for lighting if it is solely based on occupancy-sensing (time-delay of detector has to be taken into account). It is when the occupants have the possibility to manually control building services and devices (blinds, windows etc.) that sub-hourly occupancy input, in combination with behavioural models, can make a difference, not only on the simulated artificial lighting demand but also on annual energy demand for heating and cooling. The use of sub-hourly occupancy prediction is not limited only to situations with manual control involved. It can be advantageous to use a model capable of producing a realistic occupancy pattern, which often is highly intermittent and stochastic, if we are interested in studying the short-term variations of indoor climate parameters (e.g., contaminant concentration or PAQ in an office cell with occupancy-sensing controlled ventilation).

Discussion of sub-hourly stochastic occupancy prediction

There are some limitations with sub-hourly stochastic occupancy prediction models as part of whole-building energy simulation. First of all, the usefulness is of course dependent on the accuracy of the model and the availability of reliable input data. Bourgeois et al. (2006, p. 822), states that the extensive use of advanced behavioural models is a bit thwarted by the dependency on detailed occupancy pattern data. Furthermore, Bourgeois et al. discusses the limitations and future developments of the sub-hourly stochastic occupancy prediction model used in the Lightswitch-2002 algorithm (referred to earlier). They claim that the occupancy model is suitable for modelling occupancy in an office where the worker has the traditional 9-to-5, 5 days a week work style; but they also address the limitation of the model, because of the increasing diversity in work styles. A model that can handle all types of work styles may be too complex (e.g., both the Hive and Club work pattern, referred to in Chapter 2.3). Page et al. (2008) developed a detailed stochastic occupancy prediction model, which in contrast to, for example, the Lightswitch algorithm, includes randomly occurring periods of long absence (more than a day), to represent days where occupants work from home, travels, being sick etc. Page et al. (2008, p. 98) claims that their future effort will be focusing on making the model user friendly by providing guidance in the choice of input parameters. This will probably be a key to broaden the use of detailed occupancy prediction and behavioural models, both within and outside the research sector.

Another possible limitation with the sub-hourly occupancy prediction models, such as the one in the Lightswitch algorithm and the one presented by Page et al. (2008), is the capability of predicting the simultaneous occupancy of more than one person in larger zones (e.g., a group of office cells or an open plan office). Page et al. assume that the occupancy pattern of individual occupants can be considered as independent of each other. As a consequence, the occupancy pattern of several individuals can be found by simulating the pattern of occupancy for each occupant separately, and then adding them together. In offices, it is however logical to expect at least a small degree of dependence, because of co-ordinated activities, such as scheduled meetings.

2.7 Sector of application for empirical occupancy data and uncertainty in occupancy predictions

Assessments regarding the occupancy pattern in offices, like the ones in Table 2.2, can be made in different contexts, with different objectives, and with some involving a higher degree of uncertainty than others. Three different sectors of applications for empirical occupancy data are discussed below.

2.7.1 Estimating the effect of some intervention for a larger population of buildings

One example of an intervention that can be relevant to consider for a larger group of buildings is to upgrade buildings with CAV to DCV, or chose DCV instead of CAV in all new projects. A key issue in that consideration will be to estimate the energy performance of DCV compared to CAV. Presumed that the occupancy level is one of the most important parameter for the energy use of DCV systems, which is natural to assume, more published data on occupancy levels in offices will increase the quality of such estimate.

Making estimates of occupancy for a larger population of buildings can range from a group of buildings with identical owner and/or property manager to estimates on national level, i.e. for the entire office building population of a country. In that context, it is favourable with data from a broad spectre of different type of office organisations. First of all, it is of interest to see if there are any significant differences between organisations. If that is the case, then it is advantageous with enough data to establish, at least roughly, how the distribution of *OFz*/*OFp* among organisations looks like, for example, if it can be represented by a normal distribution. This will increase the possibility for more precise estimates of the effects of interventions, like the one mentioned above. For instance, if the consequences for energy use related to HVAC of changing from CAV to DCV with occupancy-sensing control in cellular offices shall be evaluated; then, only using the mean *OFz* will give an inaccurate estimate if the difference in energy use between the two alternatives is not directly proportional to *OFz*. For the same reasons, it will be useful to know if there are significant differences in occupancy levels among organisations within the same sector of work or profession. Considerations like the ones mentioned here, can be relevant for a university, a municipal or governmental property owner/manager or others with responsibility for a large amount of office building, all with occupants belonging to the same sector/profession. However, published data on occupancy levels in offices are limited (see Chapter 3); hence, all new measurements will be a useful contribution.

2.7.2 Estimating occupancy in one specific building

Ideally, the occupancy pattern throughout the first 20 to 30 years of a building's life could be predicted with a great level of precision. Unfortunately, this is far from the real situation. In existing buildings with a planned rehabilitation, we know who the users are. At the design phase of a new building, the designers in some cases know who are going to move into the building, while the user organisation(s), or even the type of organisation(s), are unknown in other cases. Furthermore, as mentioned in Chapter 2.2-2.4, the occupancy pattern can rapidly change, due to changes in work style, organisations moving in and out, rearrangement of the areas etc. If we know who the users are and that they most likely will stay in the building for many years, then this is a better starting point for a good estimate of the occupancy. In that case, it may also be a possibility to perform some type of measurement in the organisation(s) (e.g., on site-observations), in order to further diminish the uncertainty of the estimates. This is, however, not possible in many cases, because of time and cost limits.

One additional aspect related to the uncertainty, is the number of organisations or organisational units within the zone that the occupancy estimate refers to. To illustrate this, we can think of a simple example. We first select one organisation randomly from a large population and compute the average *OFz* on working days. We then pick ten organisations randomly from the same population and compute the same numerical measure for these ten organisations aggregated together. Then, it is more likely that the computed *OFz* for the first selection, i.e. when selecting one organisation, has a value that is far from the average of the whole population, than for the ten organisations aggregated together. The central limit theorem (Løvås, 2004) states that:

> The average $\overline{X}$ of n independent variables X_1, X_2, …, X_n that comes from the same probability distribution with mean value μ and standard deviation σ, will be approximately normally distributed with mean value μ and standard deviation $(\sigma / \sqrt{n})$. This is valid, independently of the distribution of the variables (X_1 to X_n), as long as n is high enough; a rule of thumb is $n \geq 20$. However, if the distribution of X is approximately symmetric, then n can be less than 20 and $\overline{X}$ will still be approximately normally distributed.

If this shall have any practical consequences, it requires that enough empirical occupancy data becomes available to establish average levels of different occupancy measures expected to be fairly representative for a large population of organisations working in offices. Then, if using these averages as estimates in situations where nothing or very little is known about the organisation(s) in a specific building, the uncertainty of the estimates will be lower for a larger zone (expected to house, e.g., five or ten organisations), than for a smaller zone (expected to house, e.g., only one organisation). If a numerical measure, such as *OFz*, in addition prove to be symmetrically distributed, then the central limit theorem can be used to quantify the uncertainty in situation where the average of several organisations are of interest (usually a office building, at least in Scandinavia, houses less than 20 organisations).

In summary, this means that the prerequisites for making an estimate of occupancy that prove to be close to the actual situation in a building, can diverge considerably from case to case. More empirical occupancy data to support the predictions will increase the chances considerably.

How to deal with the uncertainty in estimates of occupancy will depend on which type of assessments the estimates are input to, i.e. which element of the design process the estimate is a part of. A simplified and theoretical example is given below to illustrate this. It is important to stress that this is not intended to be any answer of how to manage the uncertainty, only examples how it could be handled, first and foremost to illustrate that different situation may require different approaches.

Example 2.2

A new office building is planned. The space for individual work is almost exclusively cellular offices designed for one worker. The building will be rented out, and the future user organisations are unknown at the time for the design of the HVAC systems. The building has five zones that are almost similar regarding layout, each with approximately the same number of office cells. The need for occupancy predictions refers to the cellular offices.

Imagine that occupancy have been monitored in a total of 30 organisations in Norwegian office buildings. Two numerical measures have been calculated for each of the monitored cases: yearly average of $\overline{OFz}^{06-18,wd}$ and the 98th percentile of daily $\overline{OFz}^{06-18,wd}$ on yearly basis. Furthermore, assume that it is proven that the distribution of the 30 cases is approximately normally distributed for both measures, with mean value μ_1 and standard deviation σ_1 for the first measure (yearly average), and with mean value μ_2 and standard deviation σ_2 for the second measure (the 98th percentile of the daily averages). Moreover, the data revealed that the distribution of *UR* also is approximately normally distributed with mean μ_3 $(= \mu_1)$ and standard deviation σ_3.

When the designers predict occupancy, they base their estimates on the data from the 30 monitored organisations. So, when estimating yearly average of $\overline{OFz}^{06-18,wd}$ they think of the five office cell zones as a random sample from the same normal distribution that has been fitted to the monitored data, meaning that they as a simplification assume that each of the five zones will house one organisation. They use the same approach for the 98th percentile of daily $\overline{OFz}^{06-18,wd}$. Furthermore, they make use of the follow two statistical facts (Løvås, 2004):

- For a normally distributed variable *X*, there is a 95 % probability that *X* gets a value in the interval $\mu \pm 1.96 \cdot \sigma$ and lower than $\mu + 1.65 \cdot \sigma$.

- The average $\overline{X}$ of n independent normally distributed variables $X_1, X_2, \ldots, X_n$ with mean value μ and standard deviation σ, will be normally distributed with mean value μ and standard deviation $(\sigma / \sqrt{n})$.

The design team uses a simulation tool, to perform dynamic simulations of the building. The occupancy load is modelled with a 24 hour profile with possibility to specify one value per hour (corresponding to *OFz* when simulating a zone containing more than one office cell and *UR* when simulating one single office cell). It is possible to specify one profile for working days and one profile for weekends; in this example only the working days are considered. Based on the monitored buildings, a standard profile have been created, which can be multiplied with a factor to change the daily average, but still keep the shape of the profile. In the simulations, the estimated occupancy load is used both for computing the heat generation from the occupants themselves, but also the heat generation from equipment and lighting (which has occupancy-sensing control), and to control the air flow rate if a DCV system is evaluated.

The following types of simulations are made in the schematic design and design development phase, each with different ways of thinking when specifying occupancy as input to the simulations:

A. Schematic design

First, simulations are made to estimate:

1. *The magnitude and the distribution of the heating and cooling demand over the year*: The occupancy profile is specified so that $\overline{OFz}^{06-18,wd}$ equals μ_1, representing the most likely average occupancy for the five organisations aggregated.

2. *The peak cooling demand* (and peak heating demand, not discussed here): Simulations of one or a few office cells, one-by-one, are made with outdoor climate considered to be design conditions from a cooling point of view. The number of cells that shall be simulated is dependent on the variation in solar gain between the cells, which is decided by the size of windows, solar shading and shape and orientation of the building. Here, it is convenient to assume that the worker is present in the office cell the whole working day (UR = 1.0 during normal working hours).

Based on that, and other prerequisites and constraints, a few system solutions are indentified, judged to be suitable alternatives able to meet the design requirements. These simulations can also reveal weak points in the building design, from an indoor climate and HVAC system point of view, which can be discussed with the architects and building owner. Then, simulations of the system alternatives and potential ways of controlling them are carried out, to analyse:

3. *The ability to maintain a satisfying indoor climate*: The type of simulations and the way occupancy is dealt with must reflect the design requirements (e.g., operative temperature 22-24 ^{o}C and maximum 50 hours per year above 26 ^{o}C) and is also dependent on which criteria the designers chose to base their judgement of the ability of the system and control strategy on (e.g., annual number of hours outside 22-24 ^{o}C during normal working hours). Like in the simulation of peek cooling demand (and peak heating demand), the design team simulates a few office cells (e.g., two with different orientation). If we here focus only on the thermal conditions (of course the design team has to assess the abilities related to IAQ too), the design team wants firstly to find the necessary supply air flow rate, or capacity of local cooling units, to meet the requirement for the upper allowed temperature limit. Like in bullet nr. 2, it can be convenient to use *UR* equal to 1.0. In addition, they run simulations to estimate the distribution of the operative temperature over the year. Here, they first run simulations with a yearly average *UR* equals μ_3, representing an average office worker, and then with a high and low (but no extremes) yearly average *UR*, equal to $\mu_3 + 2\cdot \sigma_3$ and $\mu_3 - 2\cdot \sigma_3$ respectively.

4. *The energy performance*: Here, the occupancy profile is kept from the first set of simulations, i.e. $\overline{OFz}^{06-18,wd}$ equals μ_1. If the design team is unsure of the uncertainty level of the results, and believe that the occupancy can be a factor having significant impact on the annual energy use, some complementary simulations can be made. Assumed that they have decided to use the same type of system in all zones for individual work, then the sensitivity for the occupancy level can be tested with an occupancy profile corresponding to $\overline{OFz}^{06-18,wd}$ equals $\mu_1 + 2\cdot (\sigma_1/\sqrt{5})$ and/or $\overline{OFz}^{06-18,wd}$ equals $\mu_1 - 2\cdot (\sigma_1/\sqrt{5})$.

These two sets of simulations will then be used as input to the system selection procedure, where the results are weighted against other advantages and weaknesses of the system alternatives in question.

B. Design development

Simulation of one of the five office cell zones, expected to house one organisation, are performed with outdoor climate considered to be design conditions for cooling demand calculations. Because it is not likely that all office cells reach their peak cooling demand simultaneously, the peak cooling demand for a larger zone will be lower than the sum of all the office cells' individual peak cooling demand. Assume that a DCV alternative is chosen, in which the control of the ventilation flow rates is based on detection of occupancy (motion) and room temperature. Then, the purpose of these simulations is to estimate the maximum air flow rate that will flow through the central part of the ventilation system(s). These estimates will be used as input to the selection and sizing of the ducts and components located near, or in, the AHUs.

The design team plans to divide the ventilation system into five separate systems; each supplying ventilation to one of the five office cell zones (and some additional room types). Based on the simulation, the ratio between the peak ventilation demand for the simulated zone and the sum of all the rooms' individual design ventilation flow rate is calculated. This ratio is then used for all five systems. Because they do not know in which zone the organisation with the highest peak occupancy load will be located, they estimate occupancy as it was one organisation. In addition, they use a conservative approach. The design team chooses to adjust the profile so that $\overline{OFz}^{06-18,wd}$ equals $\mu_2 + 1.7 \cdot \sigma_2$; based on an expectation that 95 % of the organisations have a 98th percentile of the daily $\overline{OFz}^{06-18,wd}$ that is equal to or lower than this level.

A few comments on the example:

- The number of different types of simulations in the example is most likely higher than in most real design process.

- Selection among alternative system solutions: The way occupancy is estimated will depend on the overall system selection process, i.e. how different parameters (quality of indoor climate, energy performance, costs, reliability, adaptability, space requirements etc) are weighted against each other. If the energy efficiency has low priority (weighting factor), then it might be considered enough to judge the energy efficiency solely based on experience, or making a less detailed estimate of the energy use, without putting a lot of effort in making dynamic simulations and detailed predictions of occupancy levels.
- In situations where a system solution is considered to be an alternative, only if it can be proved that it, with a high degree of certainty, is more energy efficient than the system it is compared to; then, a more conservative estimate of occupancy might be more appropriate than using the expected average level. If this, as an example, is evaluating the saving potential of upgrading a CAV system to a DCV system, based on occupancy-sensing control, in a building equal to the one in the example, it corresponds to use $\overline{OFz}^{06-18,wd}$ equals $\mu_1 + 2 \cdot (\sigma_1 / \sqrt{5})$ instead of μ_1. This is a scenario that probably is more common in connection with assessments of potential energy saving measures in existing buildings, than for design of new buildings.
- It is a logic approach to be more conservative in the occupancy predictions in connection with sizing of ductwork and components, than for choosing among system alternatives with the same maximum capacity. There is, however, a risk for being too conservative; adding safety margins both in the rooms and throughout the system and ending up with components that are not efficient during part-load operation. According to the *Advanced Variable Air Volume System Design Guide* (Hydeman et al., 2003) one of the keys to achieve a reliable and energy efficient system is to first estimate the variation in demands (heating, cooling and ventilation), preferably by simulation; and then selecting components that have a part-load efficiency characteristic that matches the demand characteristic well.

2.7.3 Research and development

Within research and development, empirical occupancy data can among other things have the following sectors of application:

- To develop and validate new, or validate the performance of existing stochastic occupancy predictions models, able to create realistic patterns of occupancy in offices. Models that can be used on small zones as office cells, like the sub-hourly prediction models mentioned in Chapter 2.6 are needed, but also models that can be used on larger zones occupied by several people (meeting rooms, open plan offices) or a cluster of smaller zones (e.g., predicting *OFz* for a group of office cells). These models will first and foremost be useful within the sector of research and development. However, simplified models that can be included or coupled to existing simulation programs, able to predict realistic hour to hour, or at least day to day, variations in occupancy, and occupancy related loads, could be useful to improve the ability to estimate realistic duration curves for heating, cooling and/or ventilation demand.
- To develop and validate new, or validate the performance of existing control strategies/schemes, equipment and software for indoor climate and HVAC system control. This can, for example, be:

    - Occupancy detectors with self-adaptive time delay (already exist, as discussed in Appendix A.2).
    - Optimise control parameters in control-on-demand systems involving occupancy-sensing (Bullet 7b in Table 2.2). Implement occupancy prediction in feed forward control, such as changing supply air temperature and ventilation flow rate before someone is expected to arrive to a room (Nilsson, 2003, p. 612).
    - Testing the reliability and durability of existing systems and components for air flow rate control in VAV systems, and find new improved solutions. (Bullet 4 in Table 2.2).

Here, relevant occupancy scenarios are needed, either in the shape of time series of occupancy data with high resolution or created by the use of a stochastic occupancy prediction model and reliable input data.

2.8 Summary

Two numerical measures (occupancy factors) related to the occupancy pattern in buildings are defined: *OFp*, the ratio between the number of present people in a space and the number of people that the space is designed for; and *OFz*, the ratio between the number of occupied sub-zones/rooms in a zone and the total number of sub-zones/rooms in the zone. *OFz* do not take the number of people into account, only whether a sub-zone/room is occupied or unoccupied. The utilisation rate (*UR*) expresses the fraction of time that a room is occupied, within a specific time period.

The occupancy pattern in offices is a function of the floor layout of the building, and the user organisation(s) occupying it and their way of working. The combination of these two, will decide how the users occupy the building, which in turn is an important design prerequisite/constraint for the HVAC system design process. There are many assessments related to indoor climate and HVAC that involve considerations of the occupancy pattern, reaching from estimates of internal heat and pollution loads to deciding on an appropriate control strategy of HVAC systems, or estimating the energy saving potential with demand controlled ventilation. Few default values of occupancy factors/utilisation rates are provided in standards to support those kinds of assessments. Many of the assessments can involve the need for performing simulations.

The sectors of application for empirical occupancy data includes: HVAC system design and building management, where more available data hopefully can contribute to more accurate occupancy predictions and thereby more optimised solutions; assessments of interventions in a larger population of building, for example, the energy saving potential if DCV is chosen to a higher extent than today in new buildings; research and development, where more detailed empirical data sets are needed, for instance, to understand the affinity between different types of occupancy patterns and HVAC control strategies.

3 Measuring occupancy in offices; methods and examples

It is well-known that at most times, even during the core working hours, a significant part of a regular office building is unoccupied, including both individual and group workspaces. Based on data from public and private sector organisations in USA, Europe and Japan during the early 1990s, Becker (1993, p. 48) stated that at any time during the working day about 70 % of the individual workspaces are unoccupied for workers in jobs like field sales, management consulting, project management and customer service, and that this is remarkably consistent across organisations and countries. DEGW, with expertise within planning and design of workplace environments, developed in the early 1990s a method they call Time Utilisation Survey (TUS), where on-site observations are used to map the use of individual workstations (Harrison et al., 2004), explained in more detail in the next subchapter. According to Duffy, founder of DEGW, and Powell (1997, p. 227), there are often significant differences in occupancy pattern between different types of staff. Observations in hundreds of cases have, however, shown that the occupancy level is highly consistent; individual workstations are seldom occupied for more than one-third of the core eight-hour working day, resulting in two-third of workstations being empty most times (Duffy, 2000, cited in Bjerrum and Bødker, 2003, p. 208). Later, Felix (2008, p. 53) confirms the statement by Duffy: “DEGW research consistently shows that individual workspace within a typical office building is only occupied 30 to 40 percent of the time between 8 a.m. and 5 p.m. during the week and up to 10 percent during weekends.”

Despite the claimed consistency of average occupancy levels among organisations in offices, it is natural to expect that at least some types of jobs result in the workers spending a higher portion of the working day at their workstations than 30 to 40 %. A typical graph from a time utilisation study of an organisation is presented by Harrison et al. (2004, p. 33), showing that while the utilisation rates of individual workspace during the core working day are approximately 35 % for sales staff and consultants, they are higher for other job types: around 55 % for system engineers; 60 % for clerical staff; 50 % for managers and senior managers. Provided that these utilisation rates are fairly representative for many organisations, it is despite the higher utilisation rates of some job types logical that the average utilisation rates in many cases is close to, or even below, 40 % when considering the whole organisation, because the number of managers and clerical staff are relatively small compared to the total number of employees in many cases.

Based on the statements above, it can be expected that the average *OFz* in most offices, when each cellular office or workstation in open spaces are considered as one sub-zone, will be as low as about 0.3 to 0.4 during most of the core working hours; while some organisations, with a relatively high portion of clerical staff, for instance, can have a higher *OFz*, in the range 0.5 to 0.6. A few statements in different Norwegian media, without referring to any particular data, indicate higher occupancy levels in Norway (*OFz* in the range 0.5 to 0.7). In the following, examples of reported measurements of occupancy found in the literature are presented, with the aim to: (a) see if published occupancy levels in case studies correspond well with what is indicated above; (b) see if Norway and other Nordic countries differ from other parts of the world; and (c) provide a basis for comparison for the measurements presented in Part II of this thesis. However, before that, different methods for performing such measurements are presented and discussed.

3.1 Methods for measuring occupancy in buildings

First of all, it is important to underline that this subchapter discusses methods for collecting data to increase the knowledge about the occupancy pattern in a building, and not for measuring occupancy as part of the continuous operation of a building. Some methods can however be used for both purposes, but then not necessarily with the same advantages and drawbacks in both cases. The methods that have been used for measuring occupancy in buildings can be divided into two main groups:

- on-site observations, logbooks or interviews/questionnaires, and
- using some type of devise to detect occupancy, usually motion detectors.

In addition, some indirect measures can potentially give an approximate estimate of the occupancy pattern.

3.1.1 Indirect measures of occupancy

Abushakra and Claridge (2008) suggested using monitored lighting and office equipment load profiles to estimate occupancy diversity profiles. They found a strong correlation between hourly monitored electric energy use from lighting and equipment and observed occupancy (a walk-through survey) in a university building comprising offices, laboratories and classrooms. Abushakra and Claridge proposed using a linear transformation of the hourly monitored energy use to compute an occupancy diversity profiles for different day types, which for the case building proved to provide occupancy profiles relatively close to those observed. However, as stressed by Abushakra and Claridge, and also pointed out by Bourgeois et al. (2006), this approach has its limitations. The occupancy profiles are derived without taking meteorological data into account, which may be reasonable for the core zones of a building, but is more doubtful for perimeter zones. For offices along the facades the lighting loads will not only be correlated to the occupancy, but also to the level of indoor illuminance due to daylight. As mentioned in Chapter 2.2, many typical Nordic office building have a shape that differs from North-American buildings, being less deep with a higher envelope-to-floor area ratio, and hence, greater influence of daylight on the lighting loads.

Continuously monitoring the concentration of carbon dioxide (CO_2) in the indoor air could also be an alternative, foremost in larger spaces where it can be difficult to detect the number of people present by other methods and on-site observations of some reason are not considered preferable; for example, if the occupants are not comfortable with people observing them. If the air change rate of the zone is reasonably constant, it will be possible to determine when people arrive and starts to leave and it will also give an indication of the occupancy level (Persily, 1997). The indoor CO_2-concentration of a zone is determined by: the number of people present and their average generation rate of CO_2; the air change rate, including infiltration; the air change effectiveness of the zone; the CO_2-consentration in the outdoor air; and the amount of recirculation of the air extracted from the zone. In addition, other sources than people, such as combustion processes, and potential removal mechanisms, such as plants, can have an impact on the CO_2 concentration, but will in most office premises be non-existing or negligible. An estimation of the occupancy level first of all requires an estimate of the CO_2 generation rate, based on the average size and activity level of the occupants. In addition, it requires that the other parameters affecting the indoor concentration are known or are determined through measurements and that the outdoor

CO_2-concentration is continuously monitored. Moreover, there can not be any significant air flow from other zones than outdoors, with different CO_2 concentrations. Otherwise this flow and its CO_2 concentration have to be monitored.

If the air change rate and air change effectiveness are fairly constant, the daily average *OFp* can be approximated based on the area between the curves of the monitored indoor and outdoor CO_2-concentration. If the indoor concentration seems to reach steady-state, the number of people present can be computed for that time of the day, if all other parameters affecting the indoor CO_2-concentration are assumed constant. This may occur in a conference room with stable occupancy level during a longer meeting and a high air change rate, for instance, but may seldom occur in an open plan office with continuous short-term variations in occupancy through the working day. If one or several parameters are varying considerably or if the purpose is to establish the daily occupancy profile so that the occupancy level at each subsequent time step has to be computed, then an equation expressing the rate of change of the indoor CO_2-consentration can be solved numerically[5], which however is much more complicated. To sum up, monitoring CO_2 to estimate the occupancy level can be demanding and result in uncertain estimates; partly due to the assumptions that have to be made; and partly because during field measurements it can be difficult both to measure and to have control of the influencing parameters over time, such as air flow rates into and out of the zone.

3.1.2 Observations, logbooks and self-estimated occupancy

Interviews or questionnaires, i.e. where the occupants estimates the average time spent in different locations, have been used in many studies, both to estimate the portion of the working hours spent in the office compared to other locations (working at home, travelling etc.) and to estimate how the time in the office is distributed between different locations and activities. However, such estimates must be considered to be quite uncertain. A research project which among other things involved interviews and on-site observations of office workers in several Norwegian organisations revealed significant deviations between how people believe they spend their working day and the actual situation, both regarding time spent on different activities and in which physical location the activities are taking place (Blakstad et al., 2009). The workers in the studied organisations thought they spend

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[5] This is demonstrated and validated in the field by Wang et al. (1999).

more time alone in front of the computer and less time cooperating and in dialogue with colleagues, than what was observed. Similar experiences are reported by others, Bjerrum and Aaløkke (2005), for instance.

An alternative to interviews or questionnaires is to ask the occupants to record in a logbook each time their location and/or type of activity changes throughout several working days. A drawback with this approach is that it requires some effort from the participants, and the accuracy is dependent on their motivation, which to some extent is dependent on the required levels of detail regarding the differentiation of location and activity. This disadvantage can be avoided by performing observations on-site instead. However, an obvious disadvantage with on-site observations is the possibility that the occupants feel uncomfortable with having people observing them. The on-site observations are usually performed by observing the occupancy state and activities at many spots along a predetermined route at consecutive time points to get a good estimate of the average activity pattern of an organisation, department or unit. It gives however a less precise picture of the work pattern of each individual.

The procedure for on-site observations used in published case-studies differs somewhat, both regarding the frequency of observations and the number of observed working days. In addition, they differ in how the activities and locations are aggregated or subdivided into categories, which is natural due to different purposes of the investigations. As mentioned in the introduction, DEGW has developed a technique they call Time Utilisation Surveys (or Time Utilisation Studies) to measure how effective time and space are being utilised. According to Duffy and Powel (1997, p. 227) observations by trained observers are usually performed approximately once per hour on every working day for two weeks, to get a reliable result. When observing workstations, it is usually recorded whether the workstation can be categorised as: (1) unoccupied; (2) temporally unoccupied, indicated by visual signs of recant occupancy; (3) occupied, and then also the type of activity performed by the occupant at the moment. The time when the desks or workstations are temporally unoccupied can be further analysed by studying the portion of time the occupants spend in other zones of the building.

A special case of on-site observations, relevant for the topic in next section, is when observing the occupancy state, i.e. only differing between occupied and unoccupied, to control the performance of some occupancy-sensing technology, such as motion detectors.

This was done for one of the case buildings presented in Part II of this thesis, and is presented in Appendix A.2.

3.1.3 Motion detectors and other occupancy detection technologies

When it comes to collecting occupancy data with some type of occupancy detection technology, devices normally used in buildings for occupancy-sensing control of lighting or HVAC systems, or for security purposes can be utilised. Guo et al. (2010) present an overview of such technologies: different types of motion detectors, light barriers, video cameras and biometric systems. Motion detectors are the most commonly used technology today for energy management purposes, while the other technologies primarily are used for security applications. Table 3.1 summarise some characteristics of these technologies.

Table 3.1 Comparison of some available technologies for occupancy detection in buildings. Adopted from Guo et al. (2010)

Technology	Number of occupants	Occupant identification	Occupant localisation	Price
Motion detectors[1]	No	No	No	Low
Light barriers	Yes	No	No	Low
Video	Yes	Yes	Yes	High
Access control (e.g., biometric)	Yes	Yes	No	High

[1] Passive infrared, ultrasonic, passive acoustic or microwave detectors.

According to Fraden (2004), there is a principal difference between motion and occupancy detectors (also called occupancy sensors and motion sensors). An occupancy detector detects the presence of people independent of if they are moving or not, in contrast to a motion detector that only responds to moving objects. This means that a motion detector may fail to detect occupancy if the movements are not large enough, which can be the case with for example sedentary office work. Some literature and also producers, however, call what according to this definition is a motion detector, an occupancy detector or an occupancy sensor.

A light barrier is a device that sends an infrared beam between a transmitter and a receiver and when an occupant, or other object, breaks the beam it is interpreted as occupancy. With two horizontally and parallelly separated beams installed at the entrance of a zone, it is possible to determine the direction of the passing occupants and consequently can the number of occupants present in the zone be counted. However, up to now, light barriers have rarely been used for building system control.

Video, where the images either are observed by building operation personnel or analysed by computer software, and access control systems both provide more information than necessary for lighting and HVAC control, which normally not require person identification. In addition, it has higher costs than motion detectors.

Finding a building with already installed and well functioning occupancy sensing devices and with possibility to log the detections makes the work easier when collecting occupancy data. In buildings with motion detectors installed, it means monitoring the occupancy state, i.e. occupied or unoccupied, on zone-level, where a zone can be a room or a smaller area like a workstations in an open office space. The main limitation with this approach is that it is only possible to detect whether there is someone present or not, but not the number of people[6] present. This is possible with video cameras and access control systems. They are however, because of the limited usage in lighting and HVAC control applications, usually installed at the main entrance, or entrance to a zone comprising many rooms, and consequently provide no information of the occupancy at one specific workstation or meeting room, for example. Another aspect is that it might be more difficult to get acceptance from the occupants to use video to monitor occupancy than other technologies, such as motion detectors.

If not an already existing detection system in the building is used, the alternative is to temporary install occupancy sensing devices. For instance, in studies of some Japanese office buildings (Shinkawa and Nobe, 2006; Nakagawa et al., 2007) light barriers were installed at the entrance to several zones to monitor the number of people present and temperature sensors were installed on the surface of the chairs to measure the occupancy rate of the individual workstations. In the case of motion detectors, there exist small

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[6] In a monitoring study of three meeting rooms, Vialle et al. (2001) found a correlation between the detection frequency (number of detections per time unit) of a set of four motion detectors and the number of present people. Although their might be such a correlation in some spaces, the equation of the correlation is most probably case specific and consequently unknown without performing measurements. Consequently, if this approach is planned to be used for collecting data of *OFp*, the correlation for the space and motion detector(s) in question must first be established, by measuring the actual occupancy (e.g. with camera or by observations) simultaneously with measurements of the detection rate of the motion detectors. Hence, this is a demanding alternative and probably only a relevant alternative if long-lasting monitoring of occupancy is planed and other potential techniques of some reason not are possible.

battery-driven data loggers with built-in motion detector, which record each detected change in occupancy state and stores a log of these events.

In most of the examples of measured occupancy in offices presented in the subsequent subchapter and in the case studies presented in Part II, motion detectors have been used for collecting the occupancy data, and is therefore described in more detail in the following sections.

Most common types of motion detectors

There are many ranges of application of occupancy and motion detectors and several types of detectors exist, which use different physical phenomena and technology for detection. In office buildings, security and control of light fittings and HVAC systems are common applications. For the energy saving purposes, the following two types of motion detectors are the most commonly used today:

- **Passive infrared (PIR) motion detector:** This type belongs to a group of detectors called optoelectronic motion detectors, which are based on detection of electromagnetic radiation with wavelengths in the range of about 0.4 to 20 μm. Common for the optoelectronic detectors are that they consist of a lens or mirror to focus the radiation, a light-detecting element and a threshold comparator. A PIR motion detector with the purpose to detect the presence of people has a detecting element that responds to infrared radiation with wavelengths between about 4 and 20 μm, because most of the radiation emitted by humans is concentrated within this spectral range. The detector is passive; it senses infrared radiation emitted by objects with a temperature that deviate from the surroundings. This means that no additional radiation source is needed, in contrast to an active motion detector where the detected radiation originates from a light source (e.g., daylight or electric lamp) and is then reflected by the moving object (Fraden, 2004). Because only PIR motion detectors are used in the case study buildings presented in Part II, a more comprehensive description of the manner of operation of this type of detector is presented in Appendix A.1.
- **Ultrasonic motion detector:** This is an active detector because it continuously transmits energy. It is based on the Doppler Effect. It transmits sound waves with frequencies between 25 and 40 kHz, inaudible for the human ear. The transmitted

waves are reflected by surfaces in the room. A moving object will change the frequency of the reflected waves, so by measuring this change with a receiver the ultrasonic detector is able to detect motion (National Lighting Product Information Program, 1998).

Time-delays and false detection

When a motion is detected, a relay in the detector is activated, which results in an alarm (output signal) being sent, for switching light fixtures on, for example. However, time delays before activating and/or deactivating the relay can be used to better the functioning. There are two relevant time delays (TD). The ON-delay, here called *TD-ON* is the time interval between the first detected motion and the activation of the relay. Not every motion detector has the possibility for adjustment of *TD-ON* and if they have, it is often not used (meaning *TD-ON* equals zero). The OFF-delay, here called *TD-OFF*, is the time interval between the last detected motion and the deactivation of the relay (the alarm signal switched off).

Related to the performance of the detectors is the risk for false detection, which can have one of the two following outcomes:

- **False-positive:** This is when the motion detector indicates occupancy, although there is no one present. Sources to false-positive detection reported by producers of PIR motion detectors are, among others: downdraft of cold air nearby windows; thermal buoyancy due to heating sources like radiators; other moving object than humans that either reflect infrared radiation or shield background radiation. Compared to PIR motion detectors, an ultrasonic motion detector is more sensitive to inanimate moving objects, such as papers from a printer, air turbulence from a ventilation system, waving curtains or waving leaves outside an open window (National Lighting Product Information Program, 1998; Guo et al., 2010).
- **False-negative:** This is when the motion detector fails to detect people present within the detection field. Increasing *TD-OFF* will decrease the rate of false-negatives and thus reduce the occurrence of lighting being switched off and/or the ventilation supply rate reduced, although someone is present. However, increasing *TD-OFF* will increase the operation time of the controlled equipment. Hence, selection of *TD-OFF* is a trade-off between energy use and operation costs on the

one hand and the comfort of the people using the space on the other. For PIR motion detectors, it is important that the detector has a clear sight-line to the occupant it is supposed to detect, because the infrared radiation from humans do not pass directly through objects such as partition walls and furnishings. On the contrary, an ultrasonic detector may sense an occupant behind an obstacle because the ultrasonic waves are reflected by the room surfaces.

In order to further improve the performance, some producers offer dual-technology detectors that use two technologies for detection. With a dual-technology detector with PIR and ultrasonic detection technology that controls a light fixture, the light is switched on when both the PIR and the ultrasonic detector detect motion, and is switched off when a time equal to *TD-OFF* has elapsed since the last detection for both detectors (National Lighting Product Information Program, 1998). Thereby, the risk for both false-positive and false-negative detection is reduced compared to a detector using only one type of detection technology.

3.1.4 Motion detectors in comparison with on-site observations or logbooks

In subchapter 2.5, some examples are given of indoor climate and HVAC system related issues that should, or might, involve considerations regarding the occupancy pattern. For some of these issues, occupancy data collected with motion detectors or by on-site observations or logbooks are of equal relevance. However, there are some disparities between the methods, some of them illustrated already, which make the field of application to differ somewhat:

- In contrast to on-site observations or logbooks, the number of present people in a zone can normally not be measured with a motion detector, only whether the zone is occupied or not. This means that from an indoor climate and HVAC system point of view, measurements with motion detectors have the broadest range of application in spaces designed for one person. In such cases, it is more difficult to find a good location for the detector in open spaces without walls or other partitions, because of the risk for false-positive detection caused by other occupants that are passing by the zone. In contrast to occupants just passing by a zone on their way to another space, it can be of interest to study how often a visit from a colleague, client or other occupant occur at the desk or workstation of an present worker, with respect to, for example, IAQ considerations. Obviously, this is not possible with motion detectors.

- Using motion detectors brings the opportunity for a longer monitoring period than for on-site observations or logbooks, still having a high time resolution of the occupancy data. If an estimate of the average level or daily profile of *UR*, *OFz* or *OFp* is searched for, then a few weeks with on-site observations or logbooks can be a good alternative. If long-term variations of *UR* or *OFz* are of interest instead, which can include finding an estimate of the peak, or close to peak, occupancy level, then using motion detectors is preferable.
- Detection with motion detectors usually involves some degree of false-detection, and a time-delay (*TD-OFF*) is necessary to limit the rate of false-negative detection. This means that the actual occupancy is not measured. The effect of *TD-OFF* can be only partly corrected. The deviation from the actual occupancy level is dependent on the detector performance, the value of *TD-OFF* and the distribution of the occupancy and vacancy periods of the occupants. If the purpose is to measure the actual occupancy, then the effect of this potential deviation has to be weighted against the accuracy requirements. The problem is that the magnitude of the deviation can be difficult to predict without performing on-site observations of the detector performance. This topic is further discussed in the next subchapter. The opposite situation occurs if the application of occupancy data from on-site observations or logbooks is considerations regarding occupancy-sensing control of HVAC systems. It can be difficult to predict the occupancy level as it would have been detected with motion detectors, including potential false-detection and time-delay(s).

3.1.5 Influence of motion detector performance and time-delay setting on measured occupancy levels

The time-delay *TD-OFF* and the frequency of false-detection will have the following influence on different aspects of the detected occupancy pattern:

- Increasing *TD-OFF* will increase the average *UR* and *OFz*; it can, but will not necessarily, increase the maximum instantaneous value of *OFz*; it will prolong the duration of occupancy periods and shorten the duration of vacancy periods; and finally, decrease the frequency of switches in occupancy state (occupied to unoccupied and vice versa).
- An increase in the frequency of false-negative detection will decrease the average *UR* and *OFz*; it can, but will not necessarily, decrease the maximum instantaneous value of *OFz*; and increase the frequency of switches in occupancy state (occupied to unoccupied and vice versa).
- An increase in the frequency of false-positive detection will increase the average *UR* and *OFz*; it can, but will not necessarily, increase the maximum instantaneous value of *OFz*; and increase the frequency of switches in occupancy state (occupied to unoccupied and vice versa).

One condition that can influence the occurrence of false-negative detection is whether the motion detectors control lighting or not. If the overhead light is switched off when the occupant is present, as a result of false-negative detection, she/he may react by making a movement to turn the lights on again and thereby end the false-negative detection period. Therefore, if false-negative detection periods occur, the duration of some of these will most probably be shorter, especially in periods with limited daylight, if the motion detectors control lighting compared to if they do not control the light.

A good understanding of the effects of *TD-OFF* and false-detection can be of importance in several contexts:

- When planning a monitoring study of occupancy with motion detectors.
- When choosing detectors and *TD-OFF* for control of lighting and/or HVAC systems.
- When comparing two or several measurements carried out with motion detectors (which is the topic of the next subchapter).
- If one wants to predict the occupancy as if it was detected by motion detectors with a certain *TD-OFF* and/or *TD-ON* based on the observed actual occupancy levels.

- If one wants to predict the actual occupancy in a case monitored with motion detectors (involving time-delay(s) and potentially a certain rate of false-detection). In that case, *TD-OFF* can be subtracted from each registered occupancy period, to approach the actual occupancy. However, vacancy periods lasting less than *TD-OFF* will not be registered in the log, meaning that despite this correction, it is not possible to compute the exact actual occupancy. Therefore, occupancy related measures computed with this correction is here said to have approximate zero *TD-OFF*, and the delay used for logging is written in brackets.

Example 3.1, presented below, illustrates the effect that *TD-OFF* and false-negative detection can have on the average *OFz* in one organisation. The example is taken from one of the cases presented in Part II, an organisation named *Organisation A*, and more details can be found there, and for other aspects of the occupancy pattern in Part III. In the majority of the studies presented in the next subchapter, *TD-OFF* ranges from 20 minutes down to less than 5 minutes, while no *TD-ON* is used. Therefore, the same range is used in the example (less than 5 minutes is however not possible due to the logging procedure in this case).

Example 3.1

The influence of *TD-OFF* and false-negative detection (no problem with false-positive detection was observed) on *OFz* for the 26 cellular offices in *Organisation A* are:

1. Changing *TD-OFF* from 5 minutes up to 10 or 20 minutes, result in an increase of $\overline{OFz}^{06-18,wd}$ with 21 % and 47 %, respectively.

2. Based on on-site observations (presented in Appendix A.2), it is estimated that if false-negative detections could have been avoided completely, then $\overline{OFz}^{06-18,wd}$ would on a yearly basis have been increased with 18 %, 12 % and 3 % for 5, 10 and 20 minutes *TD-OFF*, respectively.

3. The effect of correcting for *TD-OFF* to approach the actual occupancy can be illustrated by the estimates from the on-site observation. Again, if false-negative

> detection could have been avoided, it is estimated that without any correction for the time-delay, $\overline{OFz}^{06-18,wd}$ would have been 20 %, 38 % and 54 % above the estimated actual level, for 5, 10 and 20 minutes *TD-OFF*, respectively. If the correction is done, the deviation diminishes down to 7 %, 17 % and 19 % above the estimated actual level, with approximate zero *TD-OFF* (5, 10 and 20 minutes logging, respectively).

In the real situation, which includes false-negatives detection, the logged occupancy with 5 minutes *TD-OFF* is equal to the estimated actual level. This means that the time-delay, which prolongs each detected occupancy period and cause all vacancy periods lasting less than 5 minutes not to be recorded, compensates for the false-negative detection. Consequently, in the case of *Organisation A* where the occupancy was logged with 5 minutes *TD-OFF*, doing any correction for *TD-OFF* actually increase, instead of diminish, the deviation from the actual occupancy (provided that the estimates from the on-site observations are correct). With approximate zero *TD-OFF* (5 minutes logging), the occupancy is 26 % below the estimated actual level. If the data on the other hand would have been logged with 15 minutes *TD-OFF* and then corrected for, i.e. approximate zero *TD-OFF* (15 minutes logging), $\overline{OFz}^{06-18,wd}$ becomes equal to the estimated actual level. With approximate zero *TD-OFF* (10 minutes logging) and approximate zero *TD-OFF* (20 min logging), the deviation from the estimated actual level is -11 % and 9 % respectively.

It is difficult to predict how representative the example above is for other cases; the effect will depend on the frequency of actual vacancy periods and false-negative detections. The frequency of false-negative detection with 5 minutes *TD-OFF* and the frequency of actual vacancy periods in relation to the occupancy level are both high in *Organisation A*. Therefore, there are reasons to believe that the outcome expressed in percentage of changing *TD-OFF* or switching to a detector with better performance are higher than in many other cases.

3.2 Examples of measured occupancy in offices

In this section, studies where occupancy has been measured in office buildings are presented. The overview includes all studies that are known to the author. Some criteria have, however, been applied when choosing to include a study or not. First, self-estimated occupancy by means of interviews or questioners is not included, because it is considered to be relatively inaccurate. Second, it was required that enough information was provided about the monitored or observed zone(s) and the time period that the presented occupancy levels represent. Third, because one purpose is to provide a basis of comparison for the case studies presented in Part II, where cellular offices and meeting rooms have been monitored, only measurements from individual workspaces and meeting and conference rooms are presented.

The overview is divided geographically; differing between measurements from offices located in Nordic countries and other parts of the world, which in the latter case includes cases from Europe, North-America and Japan. This does not mean that any geographical limitation has been applied; these regions cover all the studies found and included based on the criteria mentioned above.

The most relevant studies where occupancy has been monitored with motion detectors, or other occupancy sensing technology, are in addition to being referred to in the two subsequent subchapters, also listed in Table 3.2 to Table 3.5 found at the end of this chapter, to provide more details of the measurements. These are the studies that had at least one week monitoring period and where days with low or no occupancy have not been excluded[7]. Other studies not fulfilling these criteria are however also mentioned in the subsequent subchapters, because they are still considered to give an indication of the typical occupancy level in the monitored/observed zone.

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[7] Rules of exclusion: In some studies, rooms with very low occupancy and/or days with no or very low occupancy are excluded. The scope of the study will be determinant for the chose of exclusion rule. For instance, if the scope is to estimate the energy saving potential with a VAV-system based on occupancy-sensing control compared to a CAV-system, working days and rooms with no or low occupancy are relevant to include because those are the days and rooms with highest saving potential. Moreover, if the monitoring period includes typical holiday periods, the average occupancy will be lower than if such periods are not part of the data. For instance, in *Organisation A* and *B* presented in Part II, was the average annual *OFz* for working days between 6 a.m. and 6 p.m. 11 and 13 % higher respectively, when typical holiday periods were excluded.

The overview in the following subchapters is primarily focused on average occupancy levels, simply because this is what is presented in most publications. Where possible, it was decided to use a nine hour average when presenting and comparing the studies. Based on the publications that provide graphs or hourly data of how the occupancy varies throughout the day, it was concluded that a nine hour period seems to cover the core occupancy hours in most cases. This means that on a graph showing the average occupancy at different times of the working day, a nine hour period can be selected for fulfilling the following criterion: beginning somewhere after the curve has started to increase/decrease, but before it has started to flatten out, in the morning and afternoon respectively. With a few exceptions, a period from 8 a.m. to 5 p.m. for the European and North-American cases, and 9 a.m. to 6 p.m. for the cases from Japan, meets this criterion. When possible, the fraction of the total occupancy hours on working days that occur in the nine hour period has been computed. In cases where a day-profile of *OFz* or *OFp* is provided without any nine hour average specified, the average has been graphically estimated from the profile and the estimate is rounded off to the nearest 0.05 (or 5 % when comparing 9-hour with 24-hour averages). In some of the cases without any nine hour average provided, no graph or data of how the occupancy varies throughout the day is presented. In other words, it was not possible to compute a nine hour average for all cases.

As mentioned in Chapter 2.1, the average *UR* of several rooms for a certain time period equals the average *OFz* for these rooms and the corresponding time period. In some studies the occupancy is not measured simultaneously for all rooms. However, assumed that the measured *UR* for most rooms is representative for the long-term situation, it can be expected that the measured average *UR* is close to the long-term average of *OFz*. Therefore, when the results of the measurement are summarised in the subsequent subchapters, the average occupancy level is expressed in terms of *OFz*, although the measurements have not occurred simultaneously in all zone in some of the studies.

3.2.1 Nordic countries

Three Nordic studies, where occupancy has been monitored with motion detectors, have shown average *OFz* levels in one-person cellular offices of between 0.28 and 0.56, over an eight or nine hour period per day. These three studies comprising four cases: a Norwegian public administration office, a Swedish university administration building, a Swedish university department and a Swedish municipality planning office. Except for the measurements at the university administration, relatively few rooms have been monitored. The average *OFz* of nine cellular offices during the eight hours between 8 a.m. to 4 p.m. on working days in the public administration office was 0.28 (Opdal and Brekke, 1995). The measured occupancy in the two university buildings was very close. The average *OFz* between 7 a.m. and 6 p.m. on working days was 0.33 for the 56 cellular offices in the university administration building (Maripuu, 2009) and 0.30 for the seven cellular offices at the university department (Johansson, 2005). For the nine hours between 8 a.m. and 5 p.m. on working days, *OFz* was 0.35 at the university department and about the same for the cellular offices in the university administration building (graphically estimated, see Table 3.2 for more details). The occupancy level in the eight cellular offices at the municipality planning office was significantly higher than the other cases; 0.56 between 8 a.m. and 5 p.m. on working days. The portion of the total numbers of occupancy hours on working days that occur in the time period between 8 a.m. and 5 p.m. was about 90 % and 85 % for the university department and the municipality planning office, respectively.

In the university administration building also other room types than cellular offices were monitored, and the average *OFz* between 7 a.m. and 6 p.m. on working days for five meeting rooms was as low as 0.16, ranging from just below 0.10 up to 0.28.

One of the publications provides information on the measured peak occupancy. In the university administration building the maximum *OFz* for the cellular office was 0.70 and the 90th percentile between 7 a.m. and 6 p.m. on working days was 0.53, with approximate zero *TD-OFF* (5/10[8] minutes logging). With 5/10 minutes *TD-OFF* included, the maximum increased up to 0.74 and the 90th percentile to 0.58, respectively.

Besides the four cases mentioned above, two other cases of measurements with motion detectors can be mentioned, which had a short measurement period and therefore less reliability. In addition to the two already mentioned cases, Johansson (2005) reported on a third case from Sweden; an industrial company where 32 randomly chosen cellular offices, in different buildings, were monitored for a period ranging between two days up to one week. The monitored rooms included both offices for development and administration personal and offices belonging to the factory. The average *UR* between 8 a.m. and 6 p.m. was 0.51. Furthermore, occupancy was monitored for two days in all of the 32 cellular

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[8] Different time delay during different parts of the monitoring period: 10 minutes during the majority of the time; 5 minutes during the rest of the time (9 % of the monitoring period).

offices included in the office part of a public library in Norway (Larsen and Ursin, 2005). The library personal only consisted of 27 people and at least five are always present in the book lending area, so *OFz* should theoretically never be close to 1.0. With 30 minutes *TD-OFF*, the average *OFz* for the two days was 0.45 between 8 a.m. and 4 p.m. and 0.28 for the time period from the first arrival in the morning until the last person left the office in the evening (13 hours the first and 16 hours the second day).

On-site observations were performed once every hour between 8.30 a.m. and 3.30 p.m. for five working days at the head office of a Norwegian bank (Andersen, 2009). Observations were made in different space types, including individual and group workspaces as well as office support spaces. About 370 workstations were observed, the majority located in open spaces and less than 5 % in cellular offices. The average *OFz* for the individual workspaces was approximately 0.45 (graphically estimated), when each individual workstation is considered as a sub-zone. The meeting rooms (number not specified) had an average *OFz* of around 0.35 and *OFp* of around 0.15 (graphically estimated). In Denmark, on-site observations of the presence at workstations, located in open office spaces, were carried out at an IT company and in editorial units of a media company (Bjerrum and Aaløkke, 2005). In the IT company, snapshot observations were made at different times of the working day during 14 days. A total of 10 snapshot observations were made in the media company. The observed average *OFz* for the workstations was 0.45 in the IT company and 0.32 in the media company. Finally, on-site observations of workstations in an open office space at the Danish Dairy Board, which were made regularly four times per day between 9 a.m. and 3 p.m. for 14 days, showed an average *OFz* of approximately 0.50 (Bjerrum and Brøndberg, 2007).

3.2.2 Non-Nordic countries

Europe

Monitored occupancy with motion detectors in European, but non-Nordic, office buildings have shown average *OFz* levels in individual workspaces between approximately 0.40 and 0.50, for a nine or ten hour period per working day. Occupancy was monitored in 27 individual offices in ten different French companies for a period of at least two weeks (Bernard et al., 2003). The average *OFz* for ten hours per working day was 0.42. In five office buildings in Austria, occupancy was monitored for 9 to 14 month, all together comprising a data set of more than 150 workstations (Mahdavi and Pröglhöf, 2008;

Mahdavi et al., 2008). The average *OFz* between 8 a.m. and 5 p.m. was approximately (graphically estimated): 0.50 for 29 workstation in a building housing the seat of international organisations; 0.40 for 17 workstations in a university building, including offices for teaching and research staff; 0.50 for 18 workstations belonging to occupants working with telecom services; 0.55 for 89 workstations in an insurance company. In the fifth case, a building housing municipal offices, the occupancy profile over the day differed considerably from the other cases; the occupants arrived earlier in the morning and left earlier in the afternoon. A more representative nine hour period is therefore between 7 a.m. to 4 p.m., in which the average *OFz* for ten workstations was 0.45 (graphically estimated).

On-site observations were performed at half-hourly intervals for a week in the building of a research laboratory in England (Harrison, 2004). The average *OFz* between 9.30 a.m. and 6.30 p.m. on working days for 47 workstations was around 0.50 (graphically estimated).

In addition to cellular offices, Bernard et al. (2003) also measured occupancy in 13 meeting rooms with logbooks, and web camera in some of the rooms. The average of *OFz* and *OFp*, for a ten hour period per working day, was equal to 0.16 (ranging from 0.06 to 0.28) and 0.08 (ranging from 0.02 to 0.14), respectively. Vialle et al. (2001) monitored the meeting rooms, used for meetings and training, at three different companies in France. The average *OFz* between 9 a.m. and 7 p.m. on working days was 0.20, 0.26 and 0.45 and the average *OFp* for the same time period was 0.11, 0.04 and 0.14.

North America

Studies involving monitoring of occupancy with motion detectors in North-American offices have shown average *OFz* levels between approximately 0.30 and 0.45 in private offices over a nine or ten hour period per day. The average *OFz* between 8 a.m. and 6 p.m. on working days was 0.46 in 56 monitored one-person cellular offices at a national research organisation in USA (Maniccia et al., 1999). Monitored rooms with low occupancy were excluded from further analysis, meaning that the average *OFz* in practice was lower than 0.46. The occupants were either administrative/clerical personnel or technical/scientific staff. In a university building in Wisconsin USA, 61 faculty, staff and teaching assistant offices were monitored for 11 month during 1995 (Pigg et al., 1996). All offices were individual offices for faculty and staff except for the five teaching assistant offices which had two occupants each. The probability of an office being occupied is higher for a two-person office than for a single person office. However, because the two-person offices comprised less than 10 % of the total number of monitored rooms it can be assumed that the deviation from a situation where all occupants had one-person offices is relatively small. The average *OFz* between 8 a.m. and 5 p.m. was approximately 0.30, which constituted approximately 90 % of the occupancy hours on working days (graphically estimated). In contrast to most of the other studies, the monitoring period here included typical holiday periods, which lower the average. Finally, occupancy was monitored in a total of 180 rooms from 60 organisations in USA (Von Neida et al., 2001; Maniccia et al., 2001) for two weeks each. The buildings were located in 24 different states and were selected to represent a cross section of the U.S. commercial building stock. After elimination of inconsistent or incomplete data records, the data set comprised among others 37 private offices and 33 conference rooms. The average *OFz* between 8 a.m. and 5 p.m. on working days was 0.45 and 0.30 (graphically estimated), for the private offices and conference rooms, respectively. In the private offices, approximately 80 % of the occupancy hours on working days occurred in the time span from 8 a.m. to 5 p.m. (graphically estimated).

Love (1998) found similar average levels as those of Pigg et al. (1996) measured in a university building, when monitoring occupancy in six one-person cellular offices in a University building in Canada, occupied by academic staff and doctoral candidates. The data set comprised between 13 and 20 days for the individual offices after excluding days with logging errors. Days completely without occupancy were excluded. The average *UR* for all 24 hours on working days was 3.7 hours/day, which can be compared to 3.4 hours/day in the building reported on by Pigg et al. No graph or average of *OFz* for a certain period of the day is provided. If all monitored occupancy hours, all days and rooms included, would have occurred within a nine hour period of the day, the average *OFz* would have been 0.41. Taken into account that this is unlikely, at least in the long run, a representative nine hour average on working days, also including days with no occupancy, is below 0.4 for the monitored rooms.

Occupancy was investigated at the headquarters of two large companies, including on-site observations of the accounting and benefits departments in one of the companies and the legal and financial departments in the other company (Erickson and Becker, 1999). The observations revealed that 50 % of the desks were occupied on average between 8 a.m. and 4 p.m., ranging from 43 % to 58 % for the individual departments. For small and large conference rooms the average *UR* was 0.20, ranging between 0.13 and 0.31, and typically occupied by half of their capacity when in use, indicating an average *OFp* of about 0.10.

Japan

A series of measurements have been carried out in Japan, where the utilisation of workstations has been measured by temperature sensors mounted under the seat cover of the workers' chairs. Measurements from seven offices, of altogether almost 550 workstations, have shown average *OFz* levels in the range 0.26 to 0.44 for nine hours per working day, when counting each workstation as a sub-zone.

The following average *OFz* levels between 9 a.m. and 6 p.m. on working days were measured in three of the buildings (Nakagawa et al., 2007): 0.26 for 31 workstations in a research organisation; 0.28 for 240 workstations at an energy supply company; 0.42 in an office where the type of work were either characterised as clerical or engineering. The low *OFz* level in the research organisation, which is an engineering laboratory, could be a result of the workers frequently movement between the office premises and the laboratory facilities where they perform experiments. In the energy supply company, workers characterised their work as either clerical-, technical- or business work. *OFz* was highest among the workers performing clerical work and lowest for those performing business work (Nobe et al., 2002). Furthermore, measurements were carried out in four different offices in Tokyo, in two to three departments at each office (Shinkawa and Nobe, 2006). A data set altogether comprising over 200 workstations. In three of the offices, the work was characterised mainly as clerical work, and the average *OFz* between 9 a.m. and 6 p.m. on working days was 0.35, 0.42 and 0.44. In the fourth case, where the work was characterised as either technical or business work, the average *OFz* was 0.32, i.e. somewhat lower than the other three cases. Again, organisations with a high fraction of workers performing clerical work seemed, not surprisingly, to spend more time at their workstations than many other workers doing other types of work, as also claimed in the introduction of this chapter.

In some of the cases from Japan, in contrast to the other studies referred to here, not only the utilisation of workstations has been monitored, but also the number of present people in the spaces where the workstations are located. This corresponds to *OFp*, as defined in Chapter 2.1. The investigated spaces are open office spaces where light barriers, described in Chapter 3.1.3, were mounted at the entrance of the rooms to count the number of people passing in and out of the zones. The average *OFp* between 9 a.m. and 6 p.m. on working days was, as an average for all monitored zones: 0.30 in the research organisation (Nakagawa et al., 2007); 0.42 in the office departments with workers performing technical and business work; and 0.65, 0.49 and 0.59 for the office departments with worker performing mainly clerical work (Shinkawa and Nobe, 2006). The office having highest *OFp*, had visits from the public. If this office is disregarded, the other four offices had average *OFp* levels that were between 15 % and 34 % above their *OFz* levels.

3.2.3 Overall summation of monitored occupancy

Figure 3.1 shows a frequency distribution of measured average *OFz* in spaces for individual work for 20 of the cases referred to in the previous two subchapters. These 20 cases include all cases listed in Table 3.2 to Table 3.5, i.e. all cases monitored with motion detectors or temperature sensors in the seat of the chairs with duration of at least one week, except for the two cases with measurements from several buildings. In other words, the cases in Figure 3.1 are all measurements from only one building, but can be measurements from several zones and from several organisational units. Two studies carried out as on-site observations are part of these 20 cases; both with short interval between observations and with data presented for one organisation separately (a Norwegian bank and a research laboratory in England). For three of the 20 cases, it was not possible to compute a nine hour average.

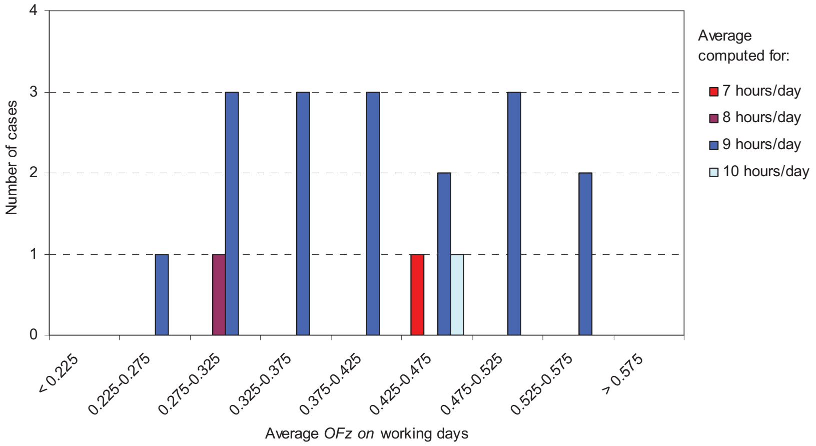

Figure 3.1 Frequency distribution summarising measured occupancy in individual workspaces in office buildings. One case corresponds to measurements in one or several zones from one and the same building, which can house workstations for one and the same or for different organisational units.

It is important to underline that there are some circumstances implying that many of the cases in Figure 3.1 have an actual average *OFz*, for typical occupancy periods, that deviates somewhat from the average used to construct the frequency distribution:

- In about one third of the cases, the average is graphically estimated, which involves some degree of uncertainty; meaning that the average actually can be located one bin down or up from the one in Figure 3.1.
- About one third of the cases include typical holiday periods with usually lower occupancy than normal. This means that if the average shall be representative for weeks with normal occupancy, it should in some of the cases potentially have been moved one bin up from the one in Figure 3.1.
- In 11 of the cases, motion detectors have been used to monitor the occupancy. As mentioned earlier, the use of a time-delay (*TD-OFF*) and potential false-detections contribute to a deviation between detected and actual *OFz*. With one exception (the study by Pigg et al, 1996), false-detection is not mentioned in the publications, which can be interpreted in either of three ways: (a) the occurrence of it is unknown and has not been investigated; (b) it is known that there were no or insignificant problems with false-detection; or (c) it has been considered as not relevant enough to mention. For 5 of the 11 cases, no information on *TD-OFF* is provided. In sum, this makes it difficult to judge how far the measured occupancy is from the actual. However, based on the experience from *Organisation A*, referred to in Example 3.1, it can be expected that the actual *OFz* for most of these 11 cases is within one bin up or one bin down from one in Figure 3.1. This is under assumption that: (a) the detector performance regarding false-negative detection is similar or better than in *Building 1* (occupied by *Organisation A*); (b) the time-delay used for logging in the five cases where no information about this was provided not deviated significantly from the other cases, i.e. that either a short *TD-OFF* (5 min or less) or approximate zero *TD-OFF* (with 20 minutes logging or less) was used.

As expected, the two studies with measurements from a mixture of many organisations (Bernard et al., 2003 and Von Neida et al., 2001; Maniccia et al., 2001) found average *OFz* levels that are close to the mean in the frequency distribution in Figure 3.1. The other studies not included in Figure 3.1, due to fewer observations or shorter monitoring period, have found *OFz* levels that match the frequency distribution well.

The published studies, referred to in the two subsequent subchapters include, too few cases to draw a conclusion valid for a large population of organisations. However, altogether they at least indicate that most individual workspace, occupied by workers from one and the same organisation, has an average *OFz* between 0.25 and 0.55, with a mean somewhere around 0.4, measured over a nine hour period per working day. It corresponds well with the statements referred to in the introduction of this chapter. Moreover, Figure 3.1 indicates that average *OFz* on working days for a large population of offices can be normally distributed; this requires, however, more published measurements to confirm. Furthermore, the measurements do not give any indication that the occupancy levels in Nordic offices differ from other regions of the world.

The fraction of the total occupancy hours on working days occurring within a nine hour period was between 75 % and 95 % (graphically estimated). There are too few cases where this fraction was possible to compute to get any indication of the existence of some geographical differences regarding the use of the offices outside the core occupancy hours.

The measurements have been carried out in a wide spectre of organisation, but the number of cases is too few to be able to conclude on what is typical in a certain type of organisation. In this context, university buildings are an exception, where the measurements provide a stronger indication than for other categories. Measurements from five different university buildings, two located in Sweden, one in Austria, one in USA and one in Canada, were consistent regarding *OFz*. According to these measurements, a guideline value for *OFz* for individual workspace in university buildings could be 0.35, as an average over a nine hour period per working day during periods of the year with normal occupancy.

Compared to individual workspace, the utilisation of meeting and conference rooms are more dependent on spatial parameters of the building, i.e. the number and size of available rooms for group work. Therefore, when predicting occupancy levels in meeting and/or conference rooms in a specific building, it is difficult to base the prediction on measurements from other buildings, as the ones referred to in subsequent subchapters. In order to make this possible, the occupancy data needs to be supplemented with information on the available space for group work in the monitored or observed office, such as total number of available seats in meeting and conference rooms in the investigated and adjacent zone(s) divided by number of occupants. Nevertheless, the measured occupancy levels are of interest; for example, they tell us something about the energy saving potential of occupancy-sensing control (*UR* and *OFz*) or CO_2-based control (*OFp*) of ventilation in spaces for group work in general. Measured *UR* for individual meeting and conference rooms ranges from 0.06 up to 0.45, as averages over seven to ten hours per working day, for the cases where data on individual room level are provided. As an average of all measured rooms, *UR* can be estimated to about 0.25 to 0.30 for a nine hour period per working day. According to measurements from French buildings (Bernard et al., 2003; Vialle et al., 2001), one American study (Erickson and Becker, 1999) and one Norwegian study (Andersen, 2009), *OFp* is between one-half to one-forth of *UR*. Altogether this indicates a large potential for demand controlled ventilation in meeting and conference rooms.

3.3 Discussion

To the knowledge of the author, very few case studies have been published where occupancy have been measured in offices either with on-site observations or logbooks. It seems that such measurements are limited almost exclusively to the internal use by the studied organisation; for instance, to investigate the possibility to increase space use efficiency or finding a new space layout that better supports their activity pattern. More studies have been found where occupancy has been measured with motion detectors or other occupancy detection technologies, but the total amount of these are nonetheless limited. The purpose of these studies is mostly related to the energy saving potential with occupancy-sensing control, control strategies or sizing of lighting or HVAC systems. In some of the studies where signals from motion detectors have been logged to estimate the energy saving potential of occupancy-sensing control of lighting, the savings are unfortunately reported without presenting any data on occupancy levels.

3.4 Summary

The most common methods, up to now, used for measurements of occupancy patterns in offices can be divide in two groups: (a) use of motion detectors; and (b) on-site observations, logbooks, interviews and questionnaires, where the last two ones, i.e. self-estimated occupancy, are considered to be the less accurate. The use of motion detectors compared to on-site observations or logbooks has both advantages and disadvantages, dependent on the purpose of the study. With motion detectors, it is possible to collect long-term data with high time resolution for many rooms/workstations. This is favourably when measuring peak, or close to peak, occupancy levels. A drawback with motion detectors is that it usually is possible only to differ between a zone being occupied or not, and not to decide the number of present people. Another obvious drawback is the risk for false-detection, which also is a reason for using a time-delay when logging occupancy. This means that the detected occupancy will deviate somewhat from the actual occupancy. On the other hand, it also means that based on observations or logbooks, it can be difficult to predict the occupancy level as it would have been detected with motion detectors, including potential false-detection and time-delay(s). This level, and not the actual occupancy level, is the relevant one in many considerations regarding occupancy-sensing control of HVAC and lighting systems in buildings.

Case studies where occupancy has been measured in offices were searched for in the literature. A limited number of studies from Europe, Japan and North-America were found, altogether comprising 20 offices with at least one week of monitoring/observations of individual workspace. In addition, two studies were found that provide averages of private offices from several different buildings, and a few studies with shorter monitoring period and/or less observations. These studies include too few cases to draw a conclusion valid for a large population of organisations. However, altogether they at least indicate that most spaces for individual work, occupied by workers from one and the same organisation, have an average zone-based occupancy factor (*OFz*) between 0.25 and 0.55, with a mean somewhere around 0.4, measured over a nine hour period per working day. Furthermore, the measurements do not give any indication that the occupancy levels in Nordic offices differ from other regions of the world. Most meeting and conference rooms seem to have low utilisation rates (*UR*); seldom more than 45 %, and on average about 25 to 30 % of the core occupancy hours on working days. Measurements from these room types, indicate that the person-based occupancy factor (*OFp*) usually is somewhere between one-half to one-fourth of *UR*.

It seems that there is a need for more empirical basic data on occupancy in offices, with measurements from a wide spectre of organisations. In particular, detailed data describing variations between zones/rooms in one and the same building and short- and long-term fluctuations are very limited, i.e. sub-hourly or hour-to-hour variations and variations between days. In addition, there is a lack of data on peak, or close to peak, occupancy rates, relevant for HVAC system design.

Table 3.2 *Examples of monitored occupancy with motion detectors in Nordic office buildings*

Reference	Type of organisation and/or type of work; location	Monitored zones: number (after exclusion) and type; occupancy based selection and/or exclusion rule	Monitoring period: duration; year	Detection technology: type; *TD-OFF*; controlled lighting	Time period working days: average *UR* of all monitored rooms
Opdal and Brekke, 1995	Public administration; Norway	9 one-person cellular offices; not specified	3 month; 1993	PIR motion detectors; approx zero (10 min logging); yes[1]	8-16: 0.28
Maripuu, 2009	University administration[2]; Sweden	56 cellular offices[3] and 5 meeting rooms; all rooms with installed motion detectors included	1 year[4]; 2007-2008	PIR motion detectors; approx zero (5/10[5] min logging); not specified	Offices: 7-18: 0.33 8-17: ca. 0.35 (gr. est.[6]) Meeting rooms: 7-18: 0.16
Johansson, 2005	1. University department 2. Municipality planning office ; Sweden	1. 7 one-person cellular offices 2. 8 one-person cellular offices ; randomly[7]	1. 6.5 weeks 2. 3.5 weeks ; 2003	PIR motion detectors; 5 min; not specified	1. 7-18: 0.30 8-17: 0.35 2. 7-18: 0.52 8-17: 0.56

[1] All rooms except from two had occupancy-sensing control of lighting, in addition to daylight control (either on/off or dimming).

[2] Some rooms rented out to administration staff within the field of research.

[3] All offices were one-person offices, except for a few, which housed two workstations.

[4] July, last week in December and public holidays were excluded.

[5] Different time delay during different parts of the monitoring period: 10 minutes during the majority of the time; 5 minutes during the rest of the time (9 % of the monitoring period).

[6] Graphically estimated. The graph showing the average occupancy for different times of the day includes all monitored room types, most of them being cellular offices. The 8-17 average is based on the 7-18 average, and the assumption that the offices follow approximately the same trend between 7 and 8 and 17 and 18 as the average of all rooms.

[7] Chosen randomly, but rooms where the occupant was on vacation or long-term sick leave, or rooms not utilised at all, were not included.

Table 3.3 *Examples of monitored occupancy with motion detectors in European, but non-Nordic, office buildings*

Reference	Type of organisation and/or type of work; location	Monitored zones: number (after exclusion) and type; occupancy based selection and/or exclusion rule	Monitoring period: duration; year	Detection technology: type; *TD-OFF*; controlled lighting	Time period working days: average *UR* of all monitored rooms
Bernard et al., 2003	Not specified; France	27 individual offices[1]; not specified	Minimum 2 weeks; not specified	PIR motion detectors; not specified; not specified	10 hours: 0.42
Mahdavi and Pröglhöf, 2008; Mahdavi et al., 2008	1. Seat of international organisations 2. University/teaching and research staff 3. Telecom services 4. Insurance 5. Municipal services ; Austria	1. 29 workstations 2. 17 workstations 3. 18 workstations 4. 89 workstations 5. 10 workstations ; not specified	1. 12 month; 2005 2. 12 month; 2005 3. 9 month; not specified 4. 14 month; not specified 5. 9 month; 2005-2006	Occupancy sensors (type not specified); not specified; no	1. 8-17: ca. 0.50 2. 8-17: ca. 0.40 3. 8-17: ca. 0.50 4. 8-17: ca. 0.55 5. 7-16: ca. 0.45 (all five gr. est.)
Vialle et al., 2001	Not specified; France	3 meeting rooms[1]; not specified	About 4 month; not specified	Web camera; not relevant; not relevant	10 hours: 0.30

[1] Located in different buildings.

Table 3.4 *Examples of monitored occupancy with motion detectors in office buildings in North-America (USA)*

Reference	Type of organisation and/or type of work	Monitored zones: number (after exclusion) and type; occupancy based selection and/or exclusion rule	Monitoring period: duration; year	Detection technology: type; *TD-OFF*; controlled lighting	Time period working days: average *UR* of all monitored rooms
Von Neida et al., 2001; Maniccia et al., 2001	Mixture[1]	37 private offices and 33 conference rooms; representative regarding floor plan, occupancy and lighting control	2 weeks; 1997	PIR motion detectors; < 5 min[2]; no	Offices: 8-17: ca. 0.45 (gr. est.) Conference rooms: 8-17: ca. 0.30 (gr. est.)
Pigg et al., 1996	University: faculty, staff and teaching assistants offices	61 private offices[3]; not specified	11 month; 1995	PIR; ultrasonic motion detectors; approx. zero (10 min logging)[4]; yes	8-17: ca. 0.30 (gr. est.)
Maniccia et al., 1999	Research: administrative/ clerical personnel and scientific/technical staff	58 one-person cellular offices; rooms with periodic low occupancy excluded[5]	7 weeks; 1996-1997	PIR motion detectors; approx zero (20 min logging); yes	8-18: 0.46

[1] 60 organisations located in 24 different states selected to represent a cross section of the U.S. commercial building stock.

[2] Not specified, but it can be understood from the results that it was below 5 minutes.

[3] All offices were individual offices for faculty and staff except for the five teaching assistant offices which had two occupants each.

[4] Ranged from 6 to 21 minutes, with an average of 10 minutes.

[5] The monitoring was divided into four two-week periods (with different lighting control settings), were the first week of the first period had to be excluded. Offices having less than 5 hours of occupancy per week (weekends excluded) in two or more of these two-week periods were excluded.

Table 3.5 *Examples of monitored occupancy with motion detectors in office buildings in Japan*

Reference	Type of organisation and/or type of work;	Monitored zones: number (after exclusion) and type; occupancy based selection and/or exclusion rule	Monitoring period: duration; year	Detection technology:	Time period working days: average *UR* of all monitored rooms
Nakagawa et al.,2007; Nobe et al., 2002	1. Energy supply company /clerical, technical and business work 2. Research 3. Clerical work, engineering	1. 240 workstations 2. 31 workstations 3. 43 workstations ; not specified	1-3 weeks per workstation; 1. 2001 2. 2005-2006 3. 2003	Temperature sensor under the seat cover of the chair	1. 9-18: 0.28 2. 9-18: 0.26 3. 9-18: 0.42
Shinkawa and Nobe, 2006	1. Public- and general affairs department/ clerical work 2. Accounting- and general affairs department/ clerical work (78 %) and other types 3. Technical- and sales department/ technical- and business work 4. Accounting-, general affairs and management department/ clerical work	1. 45 workstations 2. 36 workstations 3. 105 workstations 4. 43 workstations ; not specified	1-2 weeks per workstation; 2002-2004	Temperature sensor under the seat cover of the chair	1. 9-18: 0.35 2. 9-18: 0.42 3. 9-18: 0.32 4. 9-18: 0.44 Total: 9-18: 0.35

PART II:

CASE STUDIES

The importance of taking the occupancy pattern into account during the design process of a HVAC system and in other indoor climate and HVAC related issues is argued for in Chapter 2. The overview of measured occupancy in offices, presented in the last part of Chapter 3, showed that the extent of occupancy data that are relevant for indoor climate and HVAC system related assessments is rather limited.

In Part II, occupancy data from 11 organisations, monitored in five office buildings in Norway, are presented. First, a brief overview of the monitored buildings and the method used for logging and analysing the data are presented in Chapter 4. Then, results from *Building 1,* a case with one year of monitored occupancy data, are presented in detail in Chapter 5. Finally, all cases are presented together and compared, both with each other and with data found in other studies, in Chapter 6.

4 Data acquisition and analysis procedure

This chapter gives first a brief description of the five case buildings in which occupancy have been monitored. This is followed by a description of the logging, processing and analysis of data that have been carried out.

4.1 Brief case building description

Occupancy data were collected from six Norwegian office buildings. Unfortunately had one of the buildings problems with the occupancy detection, caused by incorrect detector location. This case is a good example underlining the importance of correct installation of components. This building was not visited in advance of the data collection, so the problem was not discovered until the analysis of the data had started. The data from this building were omitted in the further analysis. Consequently, the total set of occupancy data comprises five office buildings.

Four of the five buildings have motion detectors installed to control lighting and ventilation flow rates and to adjust room temperature set-points. These buildings have a computerized Building Automation and Control (BAC) system with the possibility to monitor and log the signal sent from the motion detectors. The number of existing office buildings with motion detectors installed is high; however, to find many buildings with the possibility to log the room occupancy state (occupied or unoccupied) with a BAC system proved to be difficult. In addition, it was necessary to purchase services from electro and automation companies. Thus, limitations regarding both economy and the range of potential case buildings contributed to the data set being restricted to five buildings. The criteria for selecting a building, in addition to having motion detectors and a BAC system able to log room occupancy state, was that it had motion detectors in cellular offices and acceptance from the building owner and the users to log occupancy data. The fifth building is a university building without motion detectors in the office cells. In this building, *Building 5*, a few office cells in one corridor were selected for temporary installation of motion detectors.

Some of the buildings include two or more organisations. Data were collected from a total of 12 different organisations. The analysis of the data from one of the organisations in *Building 4* showed that there had been problems with the logging for the floor that housed this organisation. No further analysis of these data was carried out, and the final data set therefore contained occupancy data from 11 organisations. Table 4.1 shows an overview of the 11 case organisations and which building they belong to. Each building and organisation will be presented in more detail in Chapter 5 and 6. Not all office cells in all buildings were monitored and none of the workstations in the open plan offices in *Building 4*. Hence, *Organisation A*, *B*, …, *N* means a sample of rooms from the organisation in question, and shall not be interpreted as the whole organisation.

Table 4.1 Overview of case buildings and organisations

Org.	Type of work or type of organisation	*Building*
A	Governmental network offering services within special need education	*1*
B	Public university college	*1*
C	Different governmental departments	*2*
D	Operator for gas transport systems	*3*
E	Public university and independent research organisation	*4*
F	Distributer of data and telecommunications services	*5*
G	Company offering audit, tax and advisory services	*5*
H	Radio station for maritime radio communication	*5*
I	Organisation with operational responsibility for search and rescuing operations	*5*
J	Organisation with responsibility for ambulance transport requiring airplane or helicopter	*5*
K	Real estate investing company	*5*

4.2 Data logging

It is very important to distinguish between the actual occupancy state of a room (occupied or unoccupied) and the detected occupancy state which is the one monitored in the five buildings referred to here. The detected occupancy state can differ from the actual occupancy state, because of false-detection and the time-delay of the detector. In the following, occupancy and occupancy related terms (e.g. occupancy factor) refer to the detected occupancy state. If the actual occupancy is meant, it will be clearly specified.

The monitoring in two of the buildings, *Building 3* and *5*, was carried out in cooperation with two master degree students[1]. The processing and analysis of the data is made completely separate from their work.

4.2.1 BAC systems

All buildings except for *Building 4* have a DCV system where the outdoor air supply rate in the cellular offices is dependent on detected occupancy state and room temperature. Some of the meeting rooms have a CO_2-sensor in addition. These four buildings all have a computerized BAC system. The system architecture differs somewhat between the buildings and will not be described in detail, but common for three of these four buildings (*Building 1, 3* and *4*) is that each office cell has a motion detector and a temperature sensor connected to a zone controller. The zone controllers can function in a standalone mode or as in the monitored buildings, connected to a communication network. In *Building 2,* there are no zone controllers, instead the motion detectors is connected directly onto the communication bus.

A BAC system can be divided into three levels: the management level, the automation level and the field level (Nilsson, 2003). The motion detectors and the zone controllers are located at the field level. The values of different variables that the zone controller uses for its operation can be sent to the automation and/or the management level through the network, either with fixed time steps or every time a value has changed. The motion detectors used in *Building 2* can in the same way send the detected occupancy state on the communication bus, either cyclic (fixed time steps) or whenever the state (occupied or unoccupied) changes. The values of the sent network variables can be logged as data trends and then transmitted to a computer at the central control station, where the values can be displayed. If required, the displayed data can be copied and saved in a format suitable for further analysis.

---

[1] *Building 3*: The log procedure was discussed and decided on together with the master degree student (Alsaker, 2007).

Building 4: Detectors were temporary installed in a few offices and one meeting room. The mounting of the detectors (including cabling) and the set up of power supply, logger and software was carried out by the master degree student, assisted by a laboratory head engineer (Olufsen, 2007).

Some programming work in the BAC systems had to be carried out in order to log the network variables in each of the four buildings. To execute this work, services were purchased from electro and automation companies.

4.2.2 Instrumentation of *Building 4*

In *Building 4,* 11 cellular offices and one meeting room were equipped with one, two or three motion detectors per room. The purpose of this study was partly to test the performance of the detectors and partly to investigate the occupancy pattern in a small part of this building. The data logging equipment, which were located in a store room in the same corridor as the monitored rooms, comprised National Instruments data acquisition hardware NI 9205 and NI cDAQ-9172 and a personal computer with the National Instruments data logging software LabVIEW (Olufsen, 2007).

4.2.3 Motion detectors

The motion detectors used for detecting occupancy in all five case buildings are passive infrared (PIR) motion detectors. As shown in Table 4.2 , three of the four buildings (*Building 1*, *3* and *5*) that have motion detectors installed for lighting, ventilation and temperature control, all have detectors from the same producer. This detector can either be mounted on walls (CALECTRO PIR-TF-25) or to the ceiling (CALECTRO PIR-TF-25-360) dependent on which cover that is used. In *Building 4*, this detector was temporary installed and tested together with a detector from another producer.

Table 4.2 Overview of motion detectors in the monitored buildings

Building	Detector	Position	*TD-OFF* (min)
1	CALECTRO PIR-TF-25	Wall	5
2	ABB Busch-Watchdog 180 Comfort Sensor[1]	Wall	about 15
3	CALECTRO PIR-TF-25-360	Ceiling	20
4	CALECTRO PIR-TF-25	Wall	10
	CALECTRO PIR TF-25-360	Ceiling	10
	Servodan 41-320	Ceiling	about 20
5	CALECTRO PIR-TF-25	Wall	20
	CALECTRO PIR-TF-25-360	Ceiling	20

[1] Manufactured by Busch-Jaeger for ABB.

Building 5 have wall-mounted detectors in most office cells, but some larger office cells and some office cells with glass partitions have ceiling-mounted detectors. In *Building 1* and *4*, the detector performance was investigated; more detailed information about that is given in Chapter 5 and 6.

The time delay *TD-OFF* of the different detectors is shown in Table 4.2. Some of the detectors also had possibility for adjustment of *TD-ON*; this was however equal to zero in all buildings (*TD-OFF* and *TD-ON* are described in Chapter 3.1.3).

In *Building 1*, a five minute *TD-OFF* was used for logging, while the control of the lighting and HVAC system used 20 minutes. The purpose of using a shorter *TD-OFF* for logging, was partly to reduce the deviation between the detected and the actual occupancy, and partly to be able to analyse the effect of changing *TD-OFF*. Logging with a five minute *TD-OFF* was also tried in *Building 3*; however, after a few days it had to be increased to 20 minutes. Explaining the reason for that requires a description of how the occupancy related variables are handled by the zone controllers. There are two occupancy variables. The zone controller receives a signal from the motion detector. This signal determines the value of the first occupancy variable that indicates the occupancy state of the zone as detected by the motion detector, included the *TD-OFF* of the detector. This variable can have two possible values: *Occupied* or *Unoccupied*. An additional time delay can be added in the zone controller. This means that when the first variable changes its value from *Occupied* to *Unoccupied* this additional time delay is added before the second occupancy variable makes the same change. This second variable is used in the computation of the signals sent to the actuators, for example, the damper operator in the ventilation supply. In *Building 3*, the *TD-OFF* of the detectors was short, resulting in the first occupancy variable to switch frequently between *Occupied* and *Unoccupied*. Because the network variable was sent cyclic (fixed time steps of five minutes) in this building, logging of this network variable would not have given a representative picture of the occupancy. Therefore, the second occupancy variable was the one logged. Because this is the variable used for controlling the lighting fixtures, a reduction of *TD-OFF* down to five minutes resulted in too many complains from the employees regarding the lighting being switched off during work, as the consequence of false-negative detection.

The time delays listed in Table 4.2 are the ones related to the logged network variable. If *TD-OFF* is set on the detector or the controller, or is a sum of these two, does not matter for the interpretation of the occupancy data. What is important is if the logged occupancy has the same *TD-OFF* as the one used for the control of the lighting fixtures. If the lighting is switched off when false-negative detection occurs, then the person using the space may move in order to be detected and switch the light on again. If the logged occupancy has shorter *TD-OFF* than the one used for control of the lighting, then the person will not notice the false-negative detection as quick as if they had equal *TD-OFF*. Only *Building 1* had different *TD-OFF* for logged occupancy and control of lighting. This means that the logged *OFz* in *Building 1* is somewhat lower than if also the lighting system had been controlled using a five minute *TD-OFF* (expressed in more detail in Appendix A.2).

The time delay on the CALECTRO detectors is adjusted by placing a jumper head on the pin corresponding to the intended time delay. Six alternatives between 0 and 30 minutes are available. On both the ABB and the Servodan detectors, the time delay is adjusted with a potentiometer. When the detectors were installed in *Building 2* it was aimed at adjusting *TD-OFF* to 15 minutes. The fabric setting for *TD-OFF* was kept on the Servodan detectors in *Building 4*, corresponding to approximately 20 minutes (Olufsen, 2007). The adjustment with the potentiometer is however not completely precise. The actual time delay for each individual detector deviated therefore somewhat from 15 minutes in *Building 2* and from 20 minutes for the Servodan detectors in *Building 5*. The chosen approach for handling this fact in the data processing is described in Chapter 4.3.

Some problems emerged during logging in a few rooms in *Building 4*, where detectors fell down. In one room this occurred several times, and the data from this room were omitted from further analysis. In two other rooms this problem occurred once, in both cases with the Servodan detectors. How this was dealt with in the data processing is described in Chapter 4.3.

4.2.4 Data logs

The logging procedure used for the five buildings differed somewhat, also between the four buildings with BAC systems because of different system architecture and possibilities for logging network variables. First, the procedure used for *Building 1* and *5*, which was almost identical, is described. Then, the differences for *Building 2*, *3* and *4* compared to *Building 1* and *5* are explained.

Building 1 and *5*

In *Building 1* and *5*, the value of the occupancy related network variable was sent from the zone controllers each time it was changed. The data logs comprised three columns for each monitored room, with the following information: date, time and occupancy state. For each time the occupancy state was changed for a room, a new date, time and occupancy state are added. That is, for each room there was one row with data for each time the room went from being unoccupied to occupied or vice versa. An extract from a log file from *Building 1* is shown in Figure 4.1.

```
03.04.2006          08:27:25          1.000000
03.04.2006          08:41:12          0.000000
03.04.2006          09:16:11          1.000000
03.04.2006          10:08:23          0.000000
03.04.2006          10:13:46          1.000000
03.04.2006          11:12:47          0.000000
03.04.2006          11:38:07          1.000000
03.04.2006          12:42:37          0.000000
03.04.2006          12:50:56          1.000000
03.04.2006          13:58:45          0.000000
03.04.2006          13:59:47          1.000000
03.04.2006          14:07:59          0.000000
03.04.2006          14:09:01          1.000000
03.04.2006          14:14:46          0.000000
```

Figure 4.1 Extract from a log file, showing one day of data for one room in Building 1.

The numbers in the third column represents a change in occupancy state where 1.000000 means a switch from unoccupied to occupied and 0.000000 and switch from occupied to unoccupied. Because of *TD-OFF*, it should always be at least five minutes between a registered 1.000000 (occupied) and 0.000000 (unoccupied) for *Building 1* and 20 minutes for *Building 5*. This means that if a person is absent from her/his office cell for less than five minutes in *Building 1* and for less than 20 minutes in *Building 5*, it will not be registered in the log file.

Building 2

As shown in Figure 4.1 each change in occupancy state was registered in the log file with a timestamp having the format *hour:minute:second* for *Building 1* and *5*. In *Building 2*, the value of the occupancy related variable was also sent from the detectors on the communication bus each time it was changed. However, the time for these events was rounded off in the logging process, so that the registered timestamp had the format *hour:minute*.

Building 3 and 4

The value of the occupancy related variable in the zone controllers of *Building 3* was polled (asked for) every five minutes. In *Building 4*, the signal from the detectors was also logged every five minutes. Hence, in contrast to the log files of Building *1, 2* and *5* the log files of both *Building 3* and *4* contained the same number of rows for all rooms, making the processing of the raw data easier.

4.3 Data processing

MATLAB (2007) was chosen as the tool for processing and analysing the data. The log files contained relatively large amounts of data. For instance, if each change between occupied and unoccupied, that is between 1 and 0 in the log files, counts as one event, then the log file of *Building 1* and *Organisation A* contained 91 198 events. MATLAB is an effective tool when it comes to handle large amount of data and for working with vectors and matrixes. Several MATLAB-scripts were written, both for the processing of the raw data, for the further analysis of the data and for the presentation of the results.

As explained above, the logging procedure used for *Building 1, 2* and *5* differs from the procedure used for *Building 3* and *4*. The disadvantage of the cyclic logging (fixed time steps) in *Building 3* and *4* is that it results in a significant larger amount of raw data. On the other hand, the processing of the data becomes significantly easier. To compute instantaneous values of *OFz*, information about the occupancy state in each sub-zone is needed at time steps that are synchronised between the individual sub-zones. This is already taken care of with the logging procedure for *Building 3* and *4*, but not for the other buildings.

The time resolution of the data from *Building 1* and *5* was one second. In order to reduce the need for data power and still keep the accuracy on an acceptable level, some approximations were made during the processing of the data from these two buildings. A few tests were carried out on the data from *Organisation A* in *Building 1*:

1. Different approaches for rounding off the time stamps were tested. The basis of comparison was *UR* in hours per year for a few randomly selected rooms with the original time resolution of one second. The approach with the smallest deviation between the logged *UR* with one second resolution and calculated *UR* with one minute resolution was selected [2].
2. A test was performed to compare the logging procedures used for *Building 3* and *4* (cyclic with fixed time steps) with the procedure used for *Building 1*, *2* and *5*. *OFz* was computed for *Organisation A* in *Building 1* for one year, but instead of the normal approach for this building, *OFz* was computed as if the occupancy data would have been logged cyclic with 5 minute time steps. It showed that the difference between the two logging procedures is negligible regarding yearly $\overline{OFz}$ (less than 0.04 %). In addition, this computation gave exactly the same yearly peak level of *OFz* as with the normal approach for *Building 1*. Hence, it does not matter which one of the two logging procedures that is chosen when *UR* and *OFz* are the measures of interest. However, if the distribution of the length of occupancy and vacancy periods is of interest, then the logging procedure used for *Building 3* and *4* will give less accurate results than the procedure used for *Building 1*, *2* and *5*.

Example 4.1 describes the approach for rounding off the time stamps for the data from *Building 1* and *5* and illustrates how *TD-OFF* is handled during the processing of the raw data.

Example 4.1

An employee in *Building 1* enters and leaves her office cell, between 08.00 and 08.30, in accordance with the events listed in the left column of Table 4.3. In *Building 1*, occupancy

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[2] The deviation in *UR* with the original time resolution of one second and the *UR* computed with a resolution of one minute and with the selected approach for rounding of time stamps is negligible; less than 0.03 % for all five randomly selected rooms.

is logged with *TD-OFF* equals five minutes, and the second column to the left shows how the data may have looked like in the log.

Table 4.3 An fictitious example of real versus detected occupancy, and approximations made in the data processing procedure for Building 1

Entering and leaving the office cell		Data log *TD-OFF* = 5 min		Approximation *TD-OFF* = 5 min		Approximation *TD-OFF* = 20 min	
Time	In/Out	Time	State[1]	Time	State[1]	Time	State[1]
08:00:35	In	08:00:35	1	08:01:00	1	08:01:00	1
08:04:25	Out	08:12:43	0	08:13:00	0		
08:06:28	In	08:18:51	1	08:19:00	1		
08:07:43	Out	08:28:12	0	08:28:00	0		
08:18:51	In	08:29:20	1	08:29:00	1		

[1] 1 = *Occupied*; 0 = *Unoccupied*.

The data log in this example contains one false-negative detection period. The employee enters the office cell at 08:18:51, after being out of her office cell for about eleven minutes. The detector detects motion until 08:23:12, when no more motion is detected, resulting in the alarm signal being switched off five minutes later (08:28:12). Not before 08:29:20 is a new motion detected. This means, that although the employee being present, the detector have failed to detect occupancy for about six minutes. This is not unusual for sedentary office work. If also the lighting fixture(s) had been controlled with a 5 minute *TD-OFF*, then the employee would probably had noticed this and made a movement a few seconds after 08:28:12, in order to switch the light on again.

Table 4.3 also shows how the logged data is processed in the MATLAB scripts, where the time stamps, both for a change from 1 to 0 and from 0 to 1, are rounded of to the nearest minute. This means that the computed duration of one single occupancy period or vacancy period can deviate maximally one minute from the actual duration, for *Building 1, 2* and *5*. However, this will, as already mentioned, have negligible effect on the computation of *UR* and *OFz* because the approximation can work both ways; either shorten or prolong the occupancy and vacancy periods, so that this effect will be evened out in the long-term.

It is possible to compute how the occupancy would have been detected if *TD-OFF* was increased. *TD-OFF* is in this example increased from 5 to 20 minutes. This is done in the MATLAB script by adding 15 minutes to the time stamp of each occupied-to-unoccupied event (the employee leaves the room or a false-detection period starts). It is important to understand that this is not possible the other way. For instance, if the occupancy is logged with *TD-OFF* equals 20 minutes, then it is not possible to compute the detected occupancy if a 5 minute *TD-OFF* had been used instead. This is illustrated in Figure 4.2. The green curve represents the computed occupancy, which is based on the detected occupancy registered in the log file, illustrated by the blue curve. As shown in the figure, neither of those curves will be able to register when the office is unoccupied for less than five minutes, between 08:04:25 and 08:06:28 (red curve). This mean that it is impossible to compute how the detected occupancy would have looked like if *TD-OFF* was less than five minutes. The topmost curve, which represents the computed occupancy with *TD-OFF* equals 20 minutes, fails to register when the employee leaves the room for about eleven minutes. Consequently, if the occupancy is logged with *TD-OFF* equals 20 minutes, as in *Building 3* and *5*, it is not possible to compute the detected occupancy with a shorter *TD-OFF* (e.g., 15 or 10 minutes).

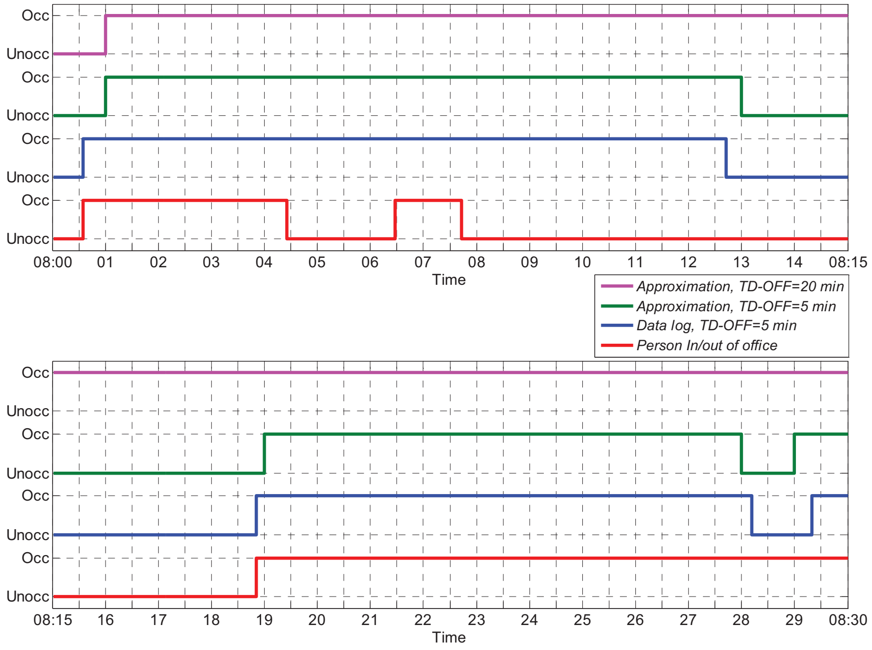

Figure 4.2 Illustration of actual versus detected occupancy and approximations made in the processing of the data for different values of TD-OFF.

Determination of *TD-OFF* in *Building 2* and *4*

In *Building 2*, the exact value of *TD-OFF* for the individual rooms was unknown. There will most probably always be some occurrences on every room where the employee enters the office cell and leaves it in less than half a minute. An investigation of the shortest registered periods of occupancy for each room in *Building 2* will therefore give a good estimate of *TD-OFF* on each individual detector. This approach showed that most of the office cells, most likely had a *TD-OFF* equal to just below 16 minutes, because the shortest registered occupancy in these offices was 16 minutes. An additional OFF-delay was added on each room individually to get the same *TD-OFF* for all rooms. This is not how the system is operated; it was done to compare *Building 2* with the other buildings.

All monitored rooms in *Building 4* were equipped with two or three motion detectors, except for the meeting room that had only one detector. All rooms had a detector from Servodan, while the other detector in the rooms with two detectors was either a wall-mounted or a ceiling-mounted detector from CALECTRO. The logged data from the Servodan detectors were used for computations of *OFz* and *UR* in order to minimise the difference in detector performance between the rooms (a few computations were however carried out for the CALECTRO detectors to study the effect of changing *TD-OFF*). It was easy to see if a Servodan detector had a *TD-OFF* that was shorter or longer than 20 minutes, simply by comparing it with the data from the CALECTRO detectors. The data was logged with fixed 5 minute time steps. Consequently, if the log file had three extra rows with 1.0 (*Occupied*) for the Servodan detector compared to the CALECTRO detector for many of the logged occupancy periods, it means that the detector had a time-delay of 20 to 25 minutes. Some of the Servodan detectors proved to have a delay between 20 and 25 minutes and some a delay between 15 and 20 minutes.

In the processing of the data, the logged data from the Servodan detectors were corrected so that each registered occupied-to-unoccupied event occurred 10 minutes later (two 5 minute time steps) than for the CALECTRO detector in the same room. This was only done if the data log had registrations of an occupied-to-unoccupied event for both detectors (but with the event registered one or three 5 minute time steps later for the Servodan detector). Only a few places in the data log indicated false-negative detection for the Servodan detectors (a vacancy period is registered in the data log for the Servodan detector at the same time as occupancy is registered in the data log for the CALECTRO detector). No corrections of the data were made (adding or subtracting 5 minutes of occupancy) for the few false-negative periods.

In the two rooms where the Servodan detectors fell down, the missing data were replaced by the data from the CALECTRO detectors and an extra 10 minutes time-delay was added.

4.4 Data analysis and result presentation

The main objective with the data collection was to present occupancy data that correspond well with the signals that control the ventilation air flow rates in the monitored buildings. The computed numerical occupancy measures that are presented in subsequent chapters (*UR* and *OFz*) are based on the detected occupancy, including *TD-OFF* and false-detection periods. Hence, the occupancy measures are not solely based on the actual occupancy, but will of course be strongly correlated to it. The measuring uncertainty related to the computed results must consequently include any potential inaccuracies in the logging procedure and approximations made in the data processing, but not include the false-detections by the motion detectors. The approximations made in the data processing are discussed in the previous subchapter and can be considered as negligible. The accuracy of the logging procedures have been controlled in Building *1* and *4* by comparing on-site observations of the occupancy state in the rooms with the log files. No deviations, when taking false-negative detection into account, were observed in these buildings. No such controls have been carried out in the other three buildings. There can potentially be some inaccuracies involved; for example, due to clock functions that are not completely synchronised. However, according to the companies that performed the programming job in the BAC systems, any potential inaccuracies are small, and the consequence of them is considered to be minimal for the utilisation rates and occupancy factors that are computed and presented in subsequent chapters.

4.4.1 Quality assurance of data

Before the final data analysis was made and the results were plotted, different types of plots were investigated. Two things were looked for: (a) any indication of problems with the logging system and (b) signs of high frequency of false-detection.

Outliers

Plots of *OFz* (a sample of rooms) and graphs showing how the occupancy state alters between unoccupied and occupied on one single room sometimes show a short time period that is inconsistent with the patterns of occupancy that appears for the major part of the time. On room level, this can, for example, be a detected occupancy period late in the evening in a room that normally is unoccupied outside normal working hours. However, it is very difficult to decide whether these periods are caused by an occupant or group of occupants that break with their normal routines, or by logging failure or false-detection (not considered as logging failure). Other persons than the ones working in the office cell can cause a distinct break in the short-term trend of *OFz*; for instance, cleaning of office cells located in the same corridor can cause a short-term peak in *OFz* because many office cells can be cleaned within a time period shorter than *TD-OFF*. Distinct and short-lasting peaks or drops have not been considered as logging failures.

Logging failures

No obvious logging failures were found by inspection of plots of the occupancy state on room level (e.g., constant occupancy for more than one day). There was, however, one exception; the plots from the rooms on one of the floors in *Building 5* showed that occupancy periods with duration shorter than *TD-OFF*, and often significantly shorter than *TD-OFF*, occurred frequently in the log files from that floor. As mentioned in Chapter 4.1, the data from that floor were excluded from further analysis.

Only one obvious logging failure was indentified when studying the plots of *OFz*. The plot showed that *OFz* was frozen on the same level for a couple of hours on a few days in the log files from *Building 1*. The cause proved to be maintenance work that had to be done in the BAC system in *Building 1*. During that work, the logging had to be stopped and the occupancy state of all monitored rooms remained the same until the system was started again. All days with this kind of logging failure was excluded from the data set.

False-detection

Because the actual occupancy pattern of the workers is not the primary focus in the case studies presented here, false-positive and false-negative detection by the motion detectors are not considered to be a logging failure, because these false-detections are part of the signals that controls the ventilation. The actual occupancy pattern is, however, of interest for many types of indoor climate and HVAC related assessments. Therefore, knowing how the frequency of false-detections affects, at least approximately, the deviation between the logged and actual occupancy is of interest when evaluating the data from the case buildings. The on-site observation carried out in *Building 1* (presented in Appendix A.2), gave an understanding of how false-negative detections affects different aspects of the detected occupancy pattern.

It was important that all the case building had motion detection with an acceptable performance, to make sure that any potential differences in utilisation rates and occupancy factors between the cases were caused mainly by the differences in the actual occupancy in the buildings and not by differences in detector performance. The performance of the detectors was discussed with people working with the operation and maintenance in the buildings (not *Building 4*). They all seemed to have approximately the same opinion; the detectors work as intended most of the times, but false-negative detection occurs now and then, especially when the occupants perform individual work.

The frequency of false-detections was investigated by on-site observations in *Building 1* and by manual registration of occupancy periods in one room in *Building 4*. Because each room in *Building 4* had two or three detectors, it was also possible to compare them and get additional information on the occurrence of false-detection. No on-site observations of the workers were made in *Building 2*, *3* and *4.* It is impossible to draw conclusions on the frequency of false-detection only by inspection of the logged data. However, producing some plots can at least give an indication of the occurrence of false-detections. The frequency distribution of the duration of detected vacancy periods was plotted for all rooms aggregated. This was done for each building separately (this is discussed in Appendix A.2.2.2). If the frequency of the shortest vacancy periods is much higher than the general shape of the distribution, then it can be an indication of a high frequency of false-negative detections. Graphs showing how the occupancy state alters between unoccupied and occupied for a sample of rooms from each building were also studied, both for normal working hours and outside normal working hours. Highly intermittent occupancy pattern with frequent short lasting vacancy intervals can be an indication of false-negative detection and many short lasting occupancy periods occurring on times when no occupancy is expected can be an indication of false-positive detection. No apparent differences between the buildings were found when studying the plots; hence, nothing indicated that there were significantly more false-detections in any of the buildings. Finally, one important outcome from the on-site observations in *Building 1* was some estimates made to assess the effect of reducing the false-negative detection frequency. These estimates showed that total elimination of false-negative detection in a building with false-negative detection frequency in the same magnitude as in *Building 1* (with *TD-OFF* equals 20 minutes) will only have a marginal effect on *OFz*. Hence, variation among the 11 case organisations regarding *OFz* is first and foremost a result of differences in occupancy, and most likely to a small extent a result of differences in detector performance.

4.4.2 Data presentation

Not all aspects of the occupancy pattern have been analysed to the same degree. It was decided to focus more on simultaneous occupancy of many office cells rather than the detailed occupancy pattern on room level. The result analysis is mainly based on descriptive statistics. Most of the results are presented graphically, sometimes supported by some measures of central tendency (average or median) and measures of variability (standard deviation or percentiles). Most results are computed with *TD-OFF* equals 20 minutes to facilitate a comparison of the organisations.

4.5 Summary

Occupancy data have been collected from six Norwegian office buildings. Unfortunately, one of the buildings had problems with the occupancy detection and was excluded from the further analysis. Four of the five remaining buildings have motion detectors installed to control lighting and ventilation flow rates and to adjust room temperature set-point. These buildings have a computerized Building Automation and Control (BAC) system with the possibility to monitor and log the signal sent from the motion detectors. In the fifth building, a few office cells in one corridor were selected for temporary installation of motion detectors. Room occupancy have been monitored in cellular offices and meeting rooms in 11 different organisations; however, not all office cells or workstations in these organisations have been monitored.

It is important to distinguish between the actual occupancy state of a room (*Occupied* or *Unoccupied*) and the detected occupancy state, which is the one monitored in the five buildings. The detected occupancy state can differ from the actual occupancy state, because of false-detection and the time-delay of the detector. The OFF-delay (*TD-OFF*) is the time from the last detected motion occur until the detector changes the output signal, and the zone is recorded as unoccupied in connection with logging.

5 *Building 1*

This chapter presents the results from one year of monitored occupancy in a Norwegian office building. First, a description of the building and the two organisations occupying it is provided. Then, the results are presented, first on organisational level and then on individual room level.

5.1 Description of building and organisations

Building: *A 3700 m^2 combined office and education building, distributed over two floors.*
Location: *Rural, in the middle part of Norway.*
User organisations: *Organisation A is part of a governmental network with the aim to support schools within special need education services for children, young people and grown-ups. Organisation B is a public university college.*

Building 1 consists of a central section with entrance hall and education premises and two side wings containing office premises. The building has also a basement with culvert for supply of ventilation air, storerooms, parking spaces and spaces for technical building systems. Figure 5.1 shows a plan view of the first floor of the building. The second floor of the office wings looks very much the same as the first floor.

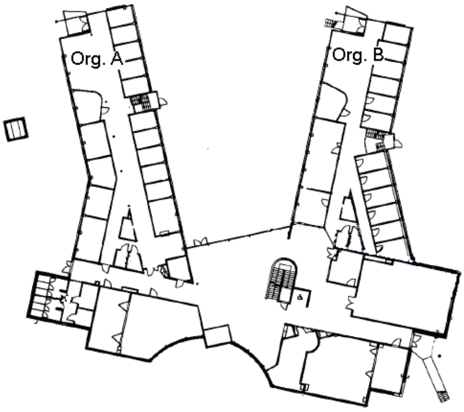

Figure 5.1 Plan view of the first floor of Building 1. Modified from (Statsbygg, 2002).

The side wings have cellular offices along the external walls with corridors and common areas in between. In addition, both side wings have one small meeting room, toilets, storerooms and rooms for printers and copy machines.

The office wing occupied by *Organisation A* contains 34 office cells. Two of these were no longer used as offices; one had become a storeroom and one contained a copy machine. Of the remaining office cells, 25 are smaller offices about 7.5 m^2 and 7 are larger office cells. Of these 32, only 26 offices have been monitored because six offices were forgotten when the logging was started up. The 30 office cells in the wing occupied by *Organisation B* are about 9 m^2. All office cells in this wing were monitored. In addition, this wing contains two larger computer rooms. These were not monitored. This means that 56 office cells were monitored in total. All office cells, in both office wings, were one-person offices. In addition, the two meeting rooms were also monitored.

The building was monitored for more than one year. A period of exactly one year, starting 1st of October 2005 and ending 30th of September 2006, was selected for further analysis. The logging had to be stopped for short periods due to maintenance work in the BAC system. All days with a stop in the logging, even if it was a short stop, were excluded. This resulted in a data set containing 243 working days and 111 weekends or holidays, as shown in Table 5.1.

Table 5.1 Overview of monitoring period

Start of monitoring period	01.10.2005
End of monitoring period	30.09.2006
Working days in monitoring period	252
Excluded working days	9
Remaining working days	**243**
Weekend days/public holidays in monitoring period	113
Weekend days/public holidays excluded	2
Remaining weekend days/public holidays	**111**

5.1.1 Detector performance

The detector performance was investigated by on-site observations of some of the workers in *Organisation A*. Figure 5.2 shows one of the offices in this office wing. The motion detectors are mounted on the wall, just beneath the ceiling, in approximately 2.4 m height, in the corner to the right of the door opening (seen from the corridor).

Figure 5.2 One of the office cells in the office wing occupied by Organisation A. The detector is located just above the door opening.

The shape of the office desk makes it possible for the worker to take different positions at the desk, in relation to the detection field of the motion detector. The two outer positions are: (a) the detector facing the back of the worker and (b) the detector facing the chest/right shoulder of the worker. Movements perpendicular to the detection field are easier for the PIR motion detector to detect than movements straight against or away from the detector. This means that the risk for false-negative detection is not only dependent on how much the worker is moving, but also where at the desk she/he is sitting. The position of personal computers can differ somewhat between the office cells. If it is placed at the window, as in the case of the office in Figure 5.2, the detector is facing the back of the worker and small horizontal arm movements or wrist motions when typing at the keyboard can be difficult to detect. Neither the position of the personal computers nor the exact positions of the workers inside each observed office cell were registered during the observations.

The results from the observations are presented in detail in Appendix A.2. Part of the conclusion is repeated below:

- The observations strongly indicate that the difficulty in detecting a present worker will vary significantly from time to time. The occurrence of false-negative detection is mainly dependent on the motion pattern inside the office cell, which is decided both by the type of work performed and the workers' position at the desk in relation to the detection field of the detector. Using a *TD-OFF* as low as 5 minutes would have resulted in occurrence of false-negative detection during most hours. With 20 minutes *TD-OFF*, false-negative detection is not completely avoided and during some types of work it can occur relatively frequent. Consequently, decreasing *TD-OFF* below 20 minutes is not considered to be a suitable solution in *Building 1*.
- Besides that, it is difficult to draw conclusions due to the limited total observation time. However, the observations indicated that there are no problems with false-positive detection.

5.2 Results on organisational level

Chapter 5.2 presents results only for office cells, i.e. meeting rooms are not included. The occupancy in the two monitored meeting rooms is briefly presented in Chapter 5.3. $\overline{OFz}$ has mostly been computed for working days between 6 a.m. and 6 p.m., because many Norwegian office buildings has intermittent operation of the ventilation system, and 12 hours per day, between 6 a.m. and 6 p.m., is a commonly occurring choice of operation hours. All presented results are based on 20 minutes *TD-OFF*, if nothing else is specified.

5.2.1 Long-term variations

Some weeks during the year have a significant lower occupancy factor than the rest of the year. Figure 5.3 shows the weekly levels of $\overline{OFz}^{06-18,wd}$. In addition to the summer, many Norwegian workers also take holiday during week 52 and the week before Easter. Week 52 had four working days in 2005, 27th to 30th of December, where the occupancy factor is strongly reduced for both *Organisation A* and *B*. The week before Easter, week 15, had three working days in 2006. The reduction in occupancy during that week was larger in *Organisation B* than in *Organisation A*. Other potential weeks with lower occupancy is when primary and lower secondary schools and upper secondary schools have holiday weeks during winter and autumn, because some parents are also taking holiday these weeks. However, for *Organisation A* and *B*, these weeks (40/2005 and 9/2006) had not a significant decrease in *OFz*. The summer holidays of the employees in *Organisation B* seem to be more spread over the summer compared to *Organisation A*, where most employees seem to have their holiday concentrated to July and first half of August.

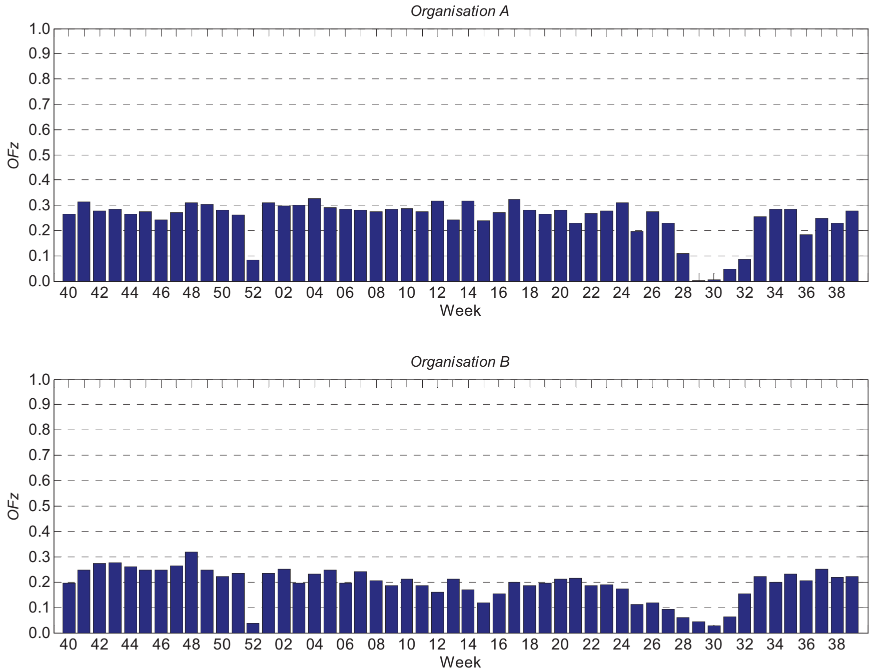

Figure 5.3 Weekly levels of $\overline{OFz_A}^{06-18,wd}$ *and* $\overline{OFz_B}^{06-18,wd}$*, illustrating the variations throughout the year.*

Figure 5.4 shows the monthly levels of $\overline{OFz}^{06-18,wd}$ and also the 90th percentile, the 95th percentile and maximum $OFz^{06-18,wd}$ for each month. The occupancy factor is not varying that much during the year in neither of the organisations, if holiday periods are disregarded. This indicates that monitoring the occupancy of these two organisations for a shorter period, such as one or two month, would have given a quite representative result regarding the average occupancy factor. On the other hand, increasing the size of the data set will normally increase the sample range (difference between maximum and minimum value) because the possibility for finding extremely high or low values increases (Løvås, 2004). Consequently, extending the monitoring period will increase the possibility for finding a higher maximum value. The maximum level is however seldom of interest, not even in connection with sizing of HVAC systems, because it is reached during short lasting peaks and make up a minimal part of the year (34 and 2 minutes during the monitoring period in *Organisation A* and *B* respectively).

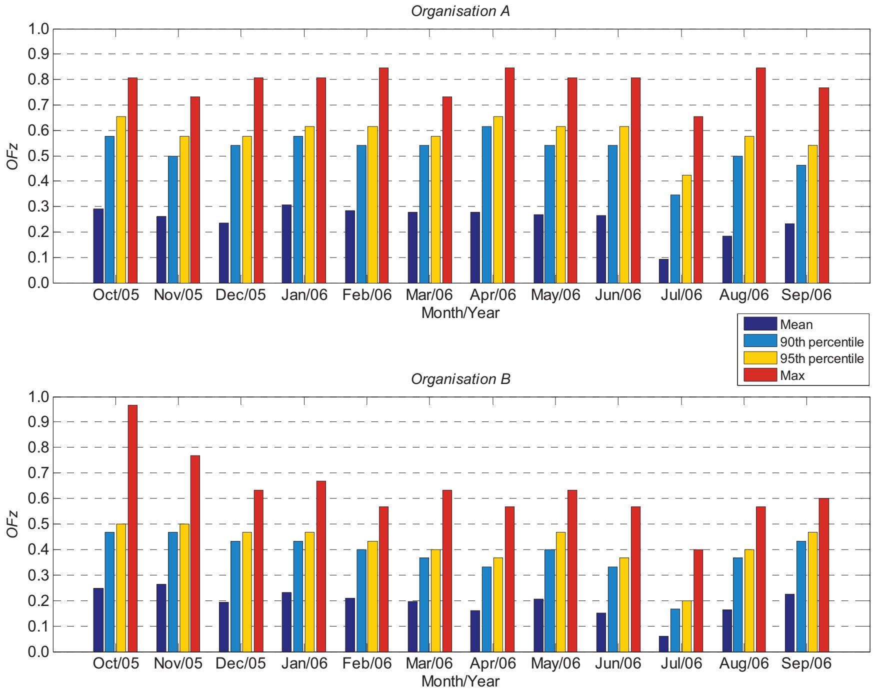

Figure 5.4 Monthly averages, 90th percentiles, 95th percentiles and maximum values of $OFz^{06-18,wd}$*, for Organisation A (upper) and B (lower).*

Table 5.2 shows some statistics of the numbers presented in Figure 5.4, both for all working days included and when periods defined as holiday periods are excluded. The holiday periods are defined as: week 52 and 15 for both organisations; week 28 to 32 for *Organisation A*; and week 25 to 31 for *Organisation B*. The variation among the months is lowest for the mean, somewhat higher for the 90th and 95th percentile and highest for the maximum *OFz*, except for *Organisation A* with holiday periods included. The variation among the months diminish when holidays period are excluded.

Table 5.2 Statistics of monthly $OFz^{06-18,wd}$ values for Organisation A and B

Variation among calendar months	Monthly $OFz_A^{06-18,wd}$				Monthly $OFz_B^{06-18,wd}$			
		Percentile				Percentile		
	Mean	90th	95th	Max	Mean	90th	95th	Max
	Oct/05-Sep/06:				*Oct/05-Sep/06:*			
Sample range	0.22	0.27	0.23	0.19	0.21	0.30	0.30	0.57
Standard dev.	0.06	0.07	0.07	0.06	0.05	0.08	0.08	0.14
	Week 52/05, 15/06, 28-32/06 excluded:				*Week 52/05, 15/06, 25-31/06 excluded:*			
Sample range	0.08	0.15	0.12	0.20	0.08	0.10	0.13	0.40
Standard dev.	0.02	0.04	0.04	0.06	0.03	0.04	0.05	0.12

Monitoring for only one calendar month, and avoiding holiday periods, would have given the following maximum deviations from the yearly values (organisation in parenthesis): 0.06 (*A*) and 0.07 (*B*) for $\overline{OFz}^{06-18,wd}$; 0.08 (*A*) and 0.07 (*B*) for the 90th percentile of $OFz^{06-18,wd}$; 0.08 (*A*) and 0.10 (*B*) for the 95th percentile of $OFz^{06-18,wd}$; 0.19 (*A*) and 0.40 (*B*) for maximum *OFz*.

Figure 5.5 shows a histogram of the computed daily levels of $\overline{OFz}^{06-18,wd}$ for *Organisation A,* with holiday periods excluded, together with fits generated by the probability distribution fitting tool in MATLAB. Although the holiday periods are excluded the distribution is somewhat skewed to the left, with a longer left than right tail. However, both a normal distribution and a t location-scale distribution seem to fit reasonably well with the monitored data. The mean value for the monitored data is 0.276 and the standard deviation equals 0.068. A corresponding plot for *Organisation B* can be found in Appendix A.3, but instead of probability density functions (PDFs), cumulative probability functions (CDFs) are plotted. How well a certain probability distribution seems to fit with the histogram of empirical data is dependent on the chosen bin width. This problem is avoided if the empirical CDF is plotted (Løvås, 2004). The empirical CDF can be found in Appendix A.3 also for *Organisation A* together with the same fitted distributions as in Figure 5.5. Both a normal and a t location-scale distribution seem to fit quite well also for *Organisation B*. Chi-square goodness of fit tests was performed of the null hypotheses that the daily average *OFz* levels, holiday periods excluded, are samples from normal distributions with estimated mean values (μ) equal to 0.276 and 0.219 and standard deviations (σ) equal to 0.068 and

0.048, for *Organisation A* and *B* respectively. With 5 % significance level, the null hypotheses could not be rejected[3] in neither of the two cases.

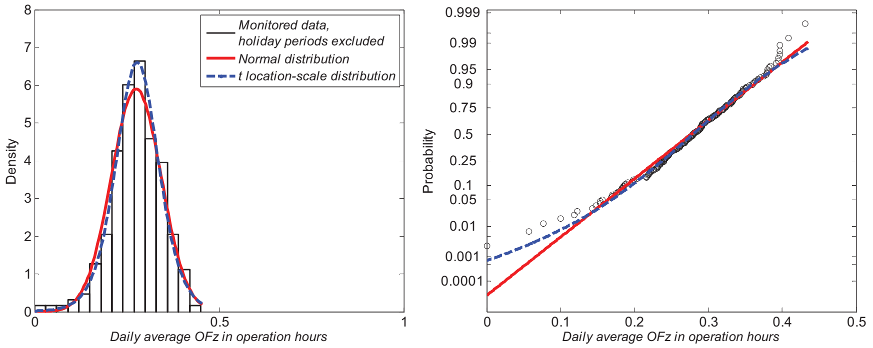

Figure 5.5 Left: Histogram of daily $\overline{OFz}^{06-18,wd}$ *for Organisation A, holiday periods excluded, together with fitted probability density functions. Right: Probability plot.*

5.2.2 Daily profiles

Figure 5.6 and Figure 5.7 show 24-hour profiles of *OFz* for working days in *Organisation A* and *B* respectively. These profiles represent the yearly average and dispersion, and not any specific day. For instance, the blue curve in the left side of Figure 5.6 shows the mean of all working days, holiday periods included. For example, this curve has an *OFz* value of 0.374 at 10:00, which are the mean value of 243 *OFz* values, one for each working day in the monitoring period at 10:00. This means that on a yearly basis, approximately four out of ten offices are on average detected as occupied at 10 a.m. on working days.

The profiles clearly show that many of the workers in *Organisation A* are taking their lunch break, and a coffee break around two o'clock, simultaneously. The average profiles are steep both when they are increasing in the morning and decreasing in the afternoon, which means that most workers are arriving and leaving the office within a narrow time span on most of the days. The fact that the workers seldom arrive earlier than normal in the morning or stay late at the office can be confirmed by examine the percentiles in the right side of

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[3] Performed with MATLAB (2007):

Org. A: Computed test-statistic $X^2 = 7.04 <$ Critical $\chi^2_{0.05} = 9.49$ (with 4 degrees of freedom), p = 0133.

Org. B: Computed test-statistic $X^2 = 6.74 <$ Critical $\chi^2_{0.05} = 9.49$ (with 4 degrees of freedom), p = 0.150.

Figure 5.6. The 90th percentile is zero until 07:30 and decreases down to 0.04 at 17:00. This means that on most days (at least nine out of ten), no one are present before half past seven in the morning and seldom more than 1 out of 26 offices are occupied after 5 p.m.

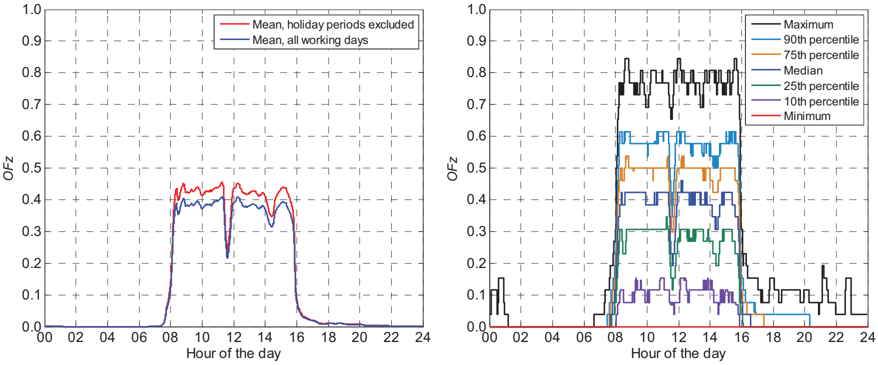


Figure 5.6 Left: Mean values of OFz on working days for Organisation A, both for all working days and when holiday periods are excluded. Right: Percentiles of OFz for Organisation A, all working days included.

Both the level and shape of the profiles for *Organisation B* differ somewhat from the profiles of *Organisation A*. The yearly average *OFz* is lower in *Organisation B*. The lunch break and any potential coffee breaks do not show as clearly as for *Organisation A*. The schedule of the lectures at the university college may affect the possibility for many workers to have lunch together with their colleagues. The workers in *Organisation B* seem to arrive and leave the office more gradually, because the gradient of the profile in the morning and afternoon is less steep than for *Organisation A*. The percentiles in Figure 5.7 show that similar to *Organisation A*, there are seldom many workers present outside normal working hours.

For both organisations, the distance between the curve of the median values and the curve of 25th percentiles are approximately equal to the distance between the curves of the median values and the curve of the 75th percentiles. The distance from the median values to the 90th percentiles is shorter than to the 10th percentile. This corresponds well with the probability distribution plots of daily levels of $\overline{OFz}^{06-18,wd}$. The distances are quite constant through large parts of the day, and plotting the distribution of *OFz* for one particular time of the day shows that it fits reasonably well with a normal distribution that is skewed somewhat to the left in the same way as in Figure 5.5.

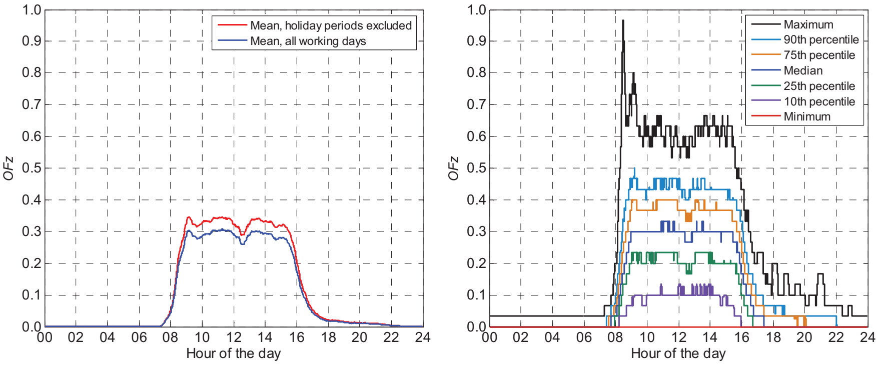


Figure 5.7 Left: Mean values of OFz for Organisation B, both for all working days and when holiday periods are excluded. Right: Percentiles of OFz for Organisation B, all working days included.

Yearly average occupancy factors for different time spans of the working day are summarised in Table 5.3. The yearly $\overline{OFz}^{06-18,wd}$ when holiday periods are excluded is 11 % and 13 % higher than when all working days are included, for *Organisation A* and *B* respectively.

Table 5.3 Yearly average occupancy factors for working days, both with holiday periods included and with holiday periods excluded

	Organisation A		*Organisation B*	
	All working days	Holiday periods excluded	All working days	Holiday periods excluded
$\overline{OFz}^{00-24,wd}$	0.125	0.139	0.098	0.112
$\overline{OFz}^{06-18,wd}$	0.248	0.276	0.193	0.219
$\overline{OFz}^{08-16,wd}$	0.363	0.404	0.271	0.307

What is here called the median working day is plotted in Figure 5.8 to show an example of a profile for one specific day, together with the 24-hour profile of the yearly average *OFz* levels. With the median working day means the working day (holiday periods included) which has the median value when they are sorted according to their $\overline{OFz}^{06-18}$, i.e. in this case the day with the 121 highest $\overline{OFz}^{06-18}$ out of 243 working days.

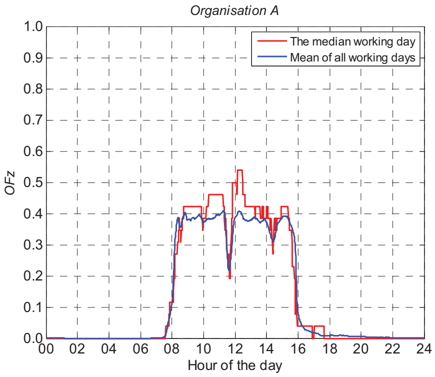


Figure 5.8 24-hour profile for the median working day and for the mean of all working days, in Organisation A (left) and Organisation B (right).

The average in the time span 06:00 to 18:00 is somewhat higher for the median working day than the profile representing the yearly average; 0.268 versus 0.248 for *Organisation A* and 0.207 versus 0.193 for *Organisation B*. This is because of weeks during holiday periods containing many days with very low occupancy, as already shown in Figure 5.3. The profiles representing the yearly average are smoother and less fluctuating than the profile for one specific day, as in this case the median day. This means that the curves in the left hand side of Figure 5.6 and Figure 5.7 are not representative for the short-term working condition of a DCV system based on occupancy-sensing or CO_2 control.

For both organisations, the profile of the median day coincides quite well with the mean profile. However, Figure 5.9, which shows the median working day together with four other working days, illustrates the fact that there are, as one could expect, differences between working days regarding the shape of their 24-hour profile. Peaks and drops in *OFz* are occurring at different times of the day. The four days, in addition to the median day, are the two days with $\overline{OFz}^{06-18}$ closet below (median -2 day and median -1 day) and the two days closest above (median +1 day and median +2 day) the median working day. Hence, this is five days with similar average occupancy levels. If the median day is the reference in the comparison, especially two days (the median -1 day and median +2 day) deviate, having a more fluctuating profile before lunch. However, all five days have one thing in common;

the occupancy starts to rise in the morning and drop in the afternoon at approximately the same time all days. The mean profile being so steep in the morning and afternoon indicates that this is the case also for most other working days.

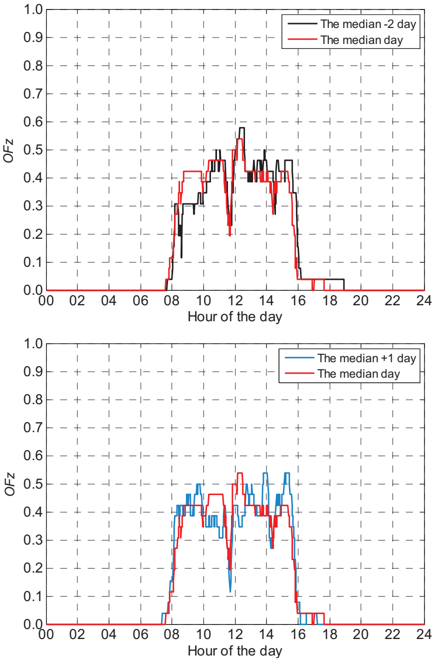


Figure 5.9 24-hour profiles for the median working day together with the two working days with $\overline{OFz}^{06-18}$ *closest below the median day (upper left and upper right), and the two working days with* $\overline{OFz}^{06-18}$ *closest above the median working day (lower left and lower right).*

5.2.3 Influence of *TD-OFF*

Figure 5.10 illustrates the effect of changing *TD-OFF*. Here, the 24-hour profile of *OFz* for the median working day of *Organisation A* is plotted for three different values of *TD-OFF*. Changing *TD-OFF* have two effects. First, when *OFz* drops, the decrease is starting later for higher values of *TD-OFF*. This is clearly shown in the right side of Figure 5.10 which shows an extract of the 24-hour profiles in the left side of the figure. The decrease in *OFz* at lunch-time starts 15 and 25 minutes later for the profiles with *TD-OFF* equals 20 and 30 minutes respectively, compared to the profile with 5 minutes *TD-OFF*. Second, the shorter *TD-OFF*, the more fluctuating is the *OFz* profile. This is because vacancy periods and false-negative detection with shorter duration than *TD-OFF* will not affect the *OFz* profile. The on-site observations in *Building 1* (presented in Appendix A.2) indicate that short vacancy periods are occurring frequently, especially in some office cells. As much as 66 % of the vacancy periods during the observations were shorter than five minutes. Such vacancy periods will not affect any of the profiles in Figure 5.10. Of the remaining vacancy periods (34 %), i.e. periods longer than five minutes, 44 % lasted more than 20 minutes. So, according to the observations, more than twice as many vacancy periods will affect the profile with 5 minutes *TD-OFF* than profiles with *TD-OFF* equals 20 minutes or more. Furthermore, decreasing *TD-OFF* from 20 to 5 minutes during the observations gave more than eight times more false-negatives. Hence, the reason for the profile with 5 minutes *TD-OFF* being more fluctuating is that there are a significant part of both the vacancy periods and false-negatives that are shorter than 20 minutes and not affecting the profile with 20 minutes *TD-OFF*. The difference is not that large if 20 and 30 minutes *TD-OFF* are compared, because there are relatively few vacancies and false-negatives with duration between 20 and 30 minutes.

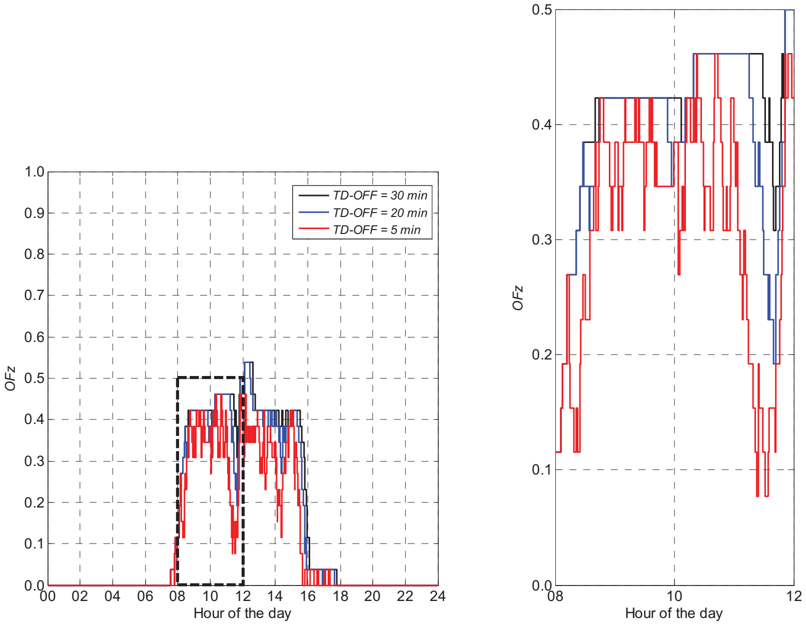


Figure 5.10 Left: OFz for the median working day with 5, 20 and 30 minutes TD-OFF. Right: Extract of the figure to the left, showing OFz for the median working day between 08:00 and 12:00.

The same 24-hour profiles as in Figure 5.6 and Figure 5.7 are plotted in Figure 5.11, representing the yearly mean values of *OFz*. However, in addition to profiles with 20 minutes *TD-OFF*, profiles with other values of *TD-OFF* are added to illustrate the effect of changing *TD-OFF* on a yearly basis. Periods of the day with much vacancy, such as lunch or coffee brakes, result in *OFz* to first drop and then rise again when people are returning to their offices. By increasing *TD-OFF* these vacancy periods become less distinctive on the *OFz* profile. The time when the profile starts to drop is moved forward, making the time gap between the starting point of the drop and the rise shorter. Moreover, the magnitude of the drop decreases. In addition to the lunch breaks in both organisations and the afternoon breaks in *Organisation A,* the left side of Figure 5.11 shows a drop in *OFz* around half past eight in the morning in *Organisation A*. This is not shown that clearly for the profile with 20 minutes *TD-OFF*, but becomes more and more distinctive when *TD-OFF* is decreasing. This indicates that many of the workers are leaving their respective office cells for a short while just after entering in the morning.

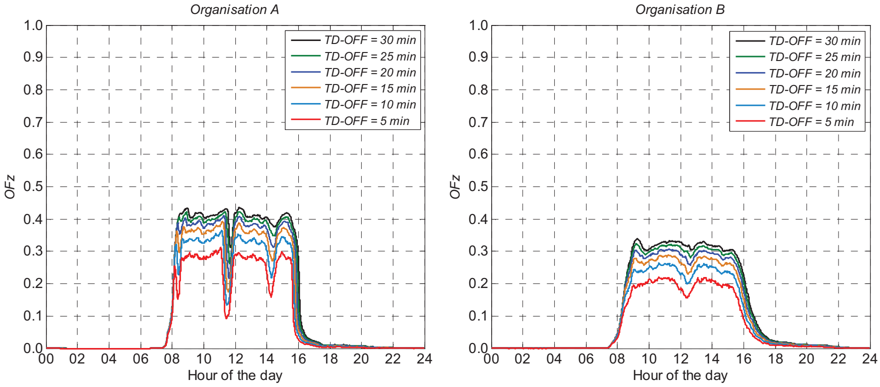


Figure 5.11 Yearly average OFz with different values of TD-OFF for Organisation A (left) and Organisation B (right).

In some cases, a drop in *OFz* can become less distinctive when *TD-OFF* is reduced, i.e. opposite to what is described above. One example of this can be seen when observing the profiles of *Organisation B* in the right hand side of Figure 5.11. One has to keep in mind that the graphs do not describe continuous series of events; they describe the average of many days. In the morning between half past eight and nine, occupants start to leave their office cells. The frequency of occupants arriving to their office cells is however higher, resulting in the curve to continue to rise. For the curves with 15 min *TD-OFF* or more, the outcome of the vacancy periods that started before nine begins to show at the same time as the arrival of occupants starts to flatten out immediately after nine. This occurs 15 minutes later for *TD-OFF* equals 30 minutes than for *TD-OFF* equals 15 minutes, when the arrival of occupants is even more reduced. This explains, way the drop in *OFz* is larger and occurs later for higher values of *TD-OFF*.

The relative deviation in the yearly average of $\overline{OFz}^{06-18,wd}$ when *TD-OFF* is changed is almost identical in both organisations, as shown in Table 5.4. This indicates that the frequency distribution of the sum of vacancy periods and false-negatives is similar in *Organisation A* and *Organisation B*.

Table 5.4 Yearly $\overline{OFz}^{06-18,wd}$ with different values of TD-OFF

TD-OFF	*Organisation A*		*Organisation B*	
	$\overline{OFz}_A^{06-18,wd}$	Deviation from *TD-OFF* =20 min (%)	$\overline{OFz}_B^{06-18,wd}$	Deviation from *TD-OFF* =20 min (%)
5	0.169	-31.9 %	0.130	-32.6 %
10	0.205	-17.3 %	0.159	-17.6 %
15	0.229	-7.7 %	0.178	-7.8 %
20	0.248	0.0 %	0.193	0.0 %
25	0.262	5.6 %	0.204	5.7 %
30	0.275	10.9 %	0.214	10.9 %

It should be mentioned that the computed *OFz* levels in Table 5.4 do not represent the actual situation regarding the control of the building services, with the exception of 20 minutes *TD-OFF*. When a false-detection occurs and the artificial lighting is switched off, then the occupant may make a movement to switch the light on again, resulting in the false-negative detection period to end. It is likely that the *OFz* values in Table 5.4 would have been somewhat higher for *TD-OFF* less than 20 minutes and somewhat lower for 25 and 30 minutes *TD-OFF*, if *TD-OFF* was changed also for the operation of the lighting and not only in the processing of the data. The effect is however small, especially for the longer time delays. Argumentation for that can be found in Appendix A.2.

The on-site observations in *Building 1*, presented in Appendix A.2, revealed a significant increase in occurrence of false-negative detection when *TD-OFF* is reduced below 15 minutes. In this context, it can be interesting to estimate *OFz* with fictitious ideal detectors, completely without false-negative detection, to illustrate the consequences of using detectors with better performance regarding false-negative detection. Table 5.5 shows estimates of the yearly $\overline{OFz}^{06-18,wd}$ if false-negative detection would have been avoided. The assumptions behind the estimates are explained in Appendix A.2.

Table 5.5 Estimates of yearly $\overline{OFz}^{06-18,wd}$ *in Organisation A for different values of TD-OFF, with fictitious ideal detectors completely without false-negative detection*

TD-OFF	$\overline{OFz}_A^{06-18,wd}$	Deviation from actual detectors (%)	Difference, ideal – actual detectors
5	0.199	17.7	0.030
10	0.229	11.5	0.024
15	0.244	6.4	0.015
20	0.256	3.3	0.008
25	0.266	1.5	0.004
30	0.277	0.7	0.002

Although there is some extent of uncertainty in the estimates, it indicates that if other detectors with better performance regarding false-negatives had been used in *Building 1*, it would have had minimal effect on *OFz* for *TD-OFF* equals 20 minutes. Using a detector with less false-negative detection implies a possibility to reduce *TD-OFF* without impairing the comfort of the occupants. For one and the same detector, a reduction in *TD-OFF* will result in a decrease in annual energy demand; however, this decrease will diminish the more the detector is approaching an ideal detector regarding false-negative detection. For instance, comparing two alternatives based on Table 5.4 and Table 5.5: (a) the detector used in *Building 1* with *TD-OFF* equals 15 minutes and (b) a detector close to the ideal detector with 10 minutes *TD-OFF* . The latter will probably reduce the occurrence of false-negatives, but in spite of shorter *TD-OFF* the reduction in *OFz*, and thereby energy demand, will be minimal.

Based on the estimates in Table 5.5 and observed frequency of vacancy periods lasting less than 5 minutes, the actual $\overline{OFz}_A^{06-18,wd}$ is estimated to 0.17, which is close to the detected occupancy level with 5 minutes *TD-OFF*.

5.2.4 Weekly profiles

Figure 5.12 shows the weekly profiles of *OFz* in *Organisation A* and *B*. As for the 24-hour profiles, these profiles represent the yearly average and dispersion, and not any specific week. For the yearly average, there are only small differences through the week from Monday to Friday. The occupancy is quite evenly distributed over the working days of the week in both organisations. However, in *Organisation A* the occupancy is somewhat higher at the start of the weeks. There seems not to be any permanent time of the week when either significantly more or significantly fewer workers are present than the rest of the week.

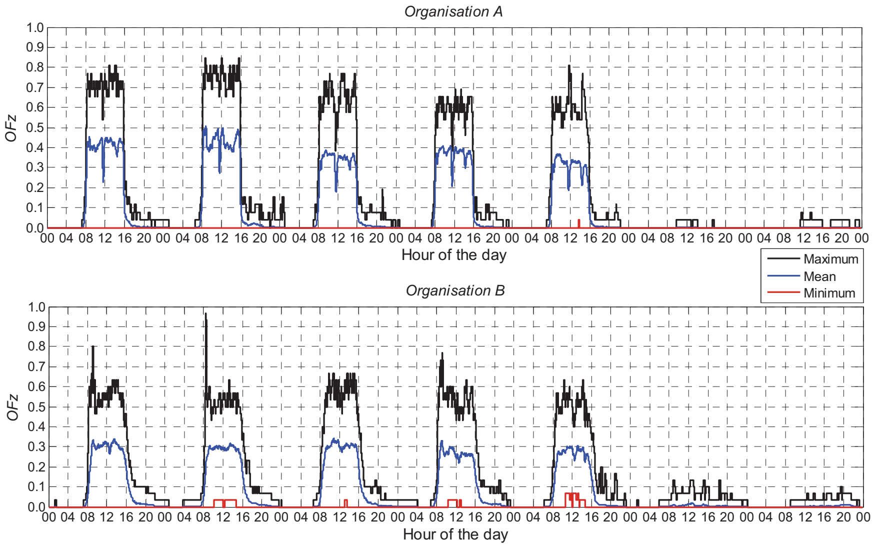


Figure 5.12 Weekly profiles, Monday to Sunday, of OFz for Organisation A (upper) and B (lower). The OFz values are the yearly average, maximum and minimum at each time of the week, i.e. the profiles are not representing any specific week.

As shown in Figure 5.12, there is seldom someone present at the office during weekends, in neither of the organisations. The maximum detected numbers of workers during weekends are two in *Organisation A* and four in *Organisation B*. Regarding the influence of occupancy levels on energy demand, the average *OFz* levels are so low in both organisations that the office can be considered as unoccupied during weekends.

5.2.5 Duration curves and peak loads

One way of illustrating how the occupancy is distributed is to plot *OFz* in a duration diagram, as in Figure 5.13. The percentages on the x-axis represent the fraction of the annual hours of operation for a ventilation system that is operating between 6 a.m. and 6 p.m. on working days only.

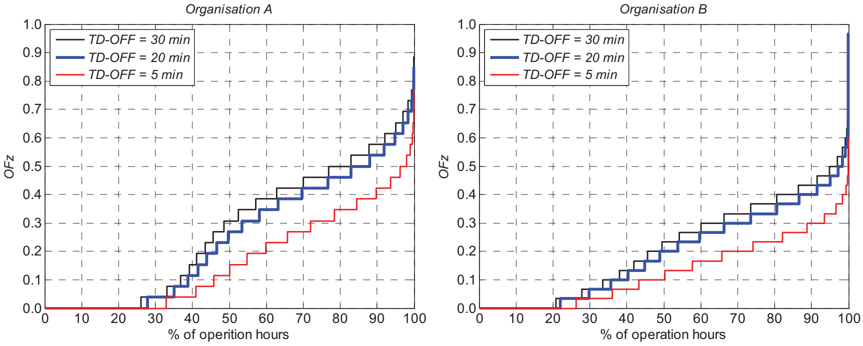


Figure 5.13 Duration curves for OFz for the operation hours (working days 6 a.m. to 6 p.m.) with different values of TD-OFF for Organisation A (left) and Organisation B (right).

The last part of the duration curve for *Organisation B* could easily be misinterpreted as a logging failure. The part exceeding 0.8 belongs to one single occupancy peak, where *OFz* increases gradually during 20 minutes up to 0.97, and after 2 minutes gradually decreases again during 20 minutes. It can, for instance, be a result of someone from the operating personnel quickly checking something in one office cell after the other. The part of the duration curve for *Organisation B* that exceeds 0.6 can be disregarded for most HVAC system related practical purposes. *OFz* exceeded 0.6 for only 5 hours and 20 minutes during the entire monitoring period.

5.3 Results on individual room level

As for the result on organisation level, the presented results are based on 20 minutes *TD-OFF*, if nothing else is specified.

5.3.1 Utilisation rates

Figure 5.14 shows utilisation rates (*URs*) in hours per day for the each of the individual office cells in *Organisation A* and *B* respectively. The office cells are sorted according to their respective average *URs* and it has no connection to their physical location whatsoever. The numbering is consistent for all figures in Chapter 5.3, i.e. office cell number 1 in subsequent figures is the same as office cell number 1 in Figure 5.14. The utilisation rates are based on working days only and 24 hours per day. The main part of the occupancy is however taking place within the time span 6 a.m. to 6 p.m. The fraction of the total occupancy hours on working days that occurs between 6 a.m. and 6 p.m. is between 91 % and 100 % for the office cells in *Organisation A* and between 92 % and 100 % for the office cells in *Organisation B*.

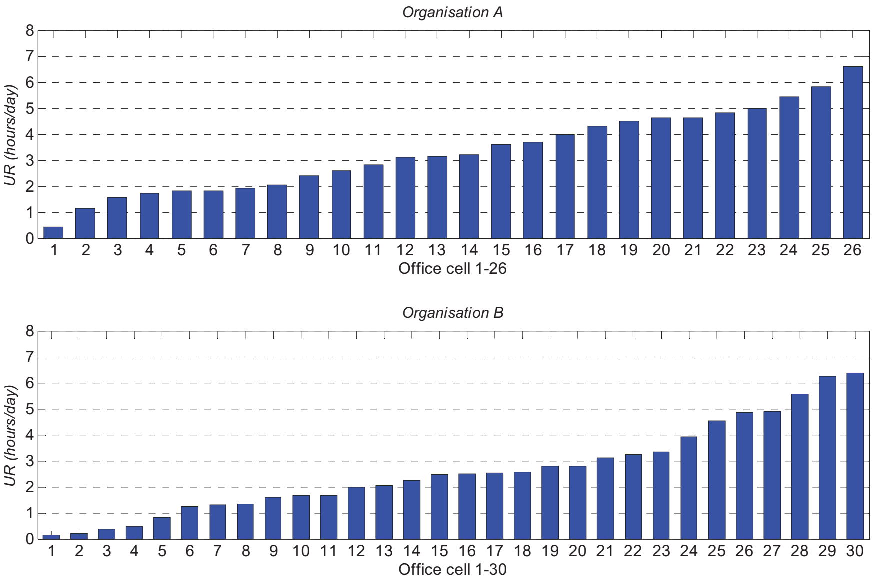
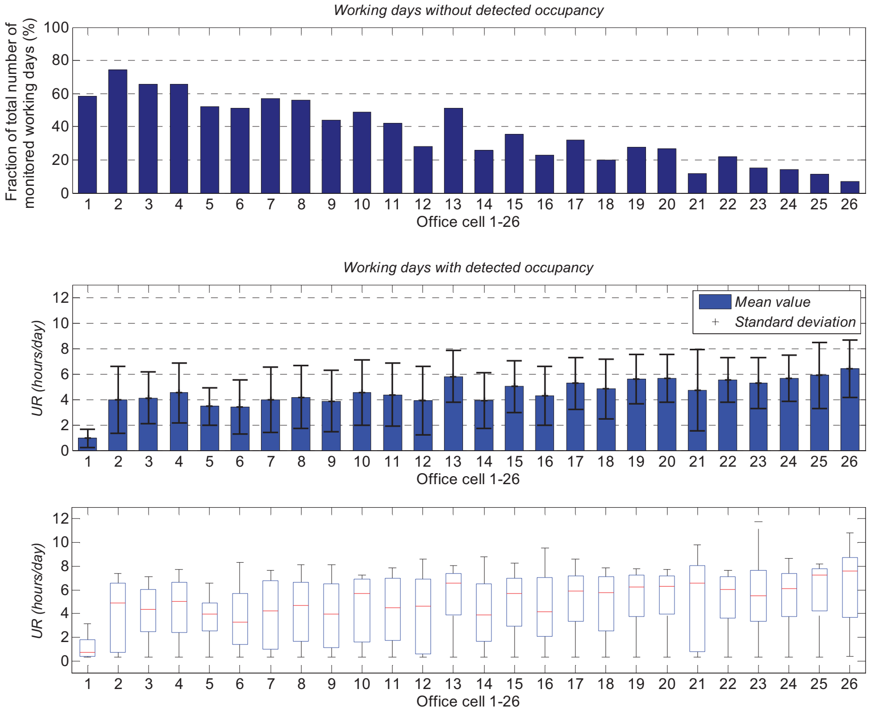


Figure 5.14 Utilisation rates for the individual office cells. The 25 days with lowest UR for each of the office cells are excluded to correct for holiday periods. Upper: Average URs in Organisation A. Lower: Average URs in Organisation B.

Utilisation rates based on the whole year are somewhat lower than what is representative for typical working days without holiday periods included. When computing the utilisation rates in Figure 5.14, the 25 days with lowest *UR* for each of the individual office cells were excluded, representing five weeks of vacation which is common practise in Norway. To get the annual average *UR*, including holiday periods, the utilisation rates in Figure 5.14 shall be multiplied with 0.9. One office cell in *Organisation A* and three in *Organisation B* had less than 25 days completely without detected occupancy. However, the excluded days with *UR* unequal to zero for those four offices were few and the *UR* those days were low. Consequently, multiplying with 0.9 also for those four offices will give an *UR* very close to the actual annual average.

On average, four out of ten office cells in *Organisation A* and three out of ten in *Organisation B* are detected as occupied between 8 a.m. and 4 p.m. on working days, holiday periods excluded. By many, this is probably considered as low *OFz* levels for an office organisation. However, as referred to in Chapter 3, measured occupancy in other offices confirms that this is far from unique in an international perspective. On the other hand, compared to most of the other office organisations presented in Chapter 6, this has to be considered as low. As Figure 5.14 shows, this is not a result of all workers spending a small portion of the working days at their office cell. On the contrary, the dispersion among the office cells regarding *UR* is relatively large in both organisations.

Many of the office cells that have low average *UR* are for many days of the year unoccupied the whole day. This applies for both organisations, but especially for *Organisation B*. Consequently, many of the workers in both organisations have working tasks that require, or gives the opportunity, to work outside the office building for many days throughout the year. The upper part of Figure 5.15 shows the number of working days with *UR* equals zero, as fraction of total number of monitored working days (holiday periods included), for each of the office cells in *Organisation A*. For instance, 9 office cells (35 %) have more than half of the working days completely without occupancy, and 18 office cells (69 %) have at least one fourth of the days with no occupancy at all. The middle part of Figure 5.15 shows average utilisation rates, and standard deviations, for the office cells in *Organisation A* when only working days having occupancy are included. The dispersion among the individual office cells is decreased compared to the utilisation rates in Figure 5.14, and most offices have an average *UR* between 4 and 6 hours per day. The standard deviation is for most offices around 2 to 3 hours per day.


Working days without detected occupancy

Working days with detected occupancy

Figure 5.15 Upper: Number of working days with UR equals zero as fraction of total number of monitored working days, in Organisation A. Middle: Mean and standard deviation of daily UR, when days with UR equals zero are excluded, in Organisation A. Lower: Box and whisker plot illustrating the distribution of daily UR when days with UR equals zero are excluded in Organisation A. The whiskers mark the maximum and minimum values and the boxes the upper quartile, median value (red line) and lower quartile.

The corresponding figure for *Organisation B* can be found in Appendix A.2. In *Organisation B*, 40 % of the office cells have more than half of the working days completely without occupancy, and 77 % of the office cells have at least one fourth of the days with no occupancy at all. Furthermore, roughly two third of the office cells have an average *UR* of around 4 to 6 hours per day and most office cells have also here a standard deviation of around 2 to 3 hours per day. The reason for a lower average *OFz* in *Organisation B* is partly because the number of days with no occupancy at all for the individual office cells is on average higher than in *Organisation A* (45 % versus 37 % of the working days), and partly because there is a relatively larger part of the office cells that have an average *UR* well below 4 hours per day.

The lower part of Figure 5.15 illustrates the distribution of the daily *UR* levels for each individual office cell in *Organisation A*, when days without occupancy are excluded. The box plot gives an indication of the skewness of the distributions. If the median is located approximately in the middle of the box, it indicates a symmetric distribution. Most office cells seem to have either a distribution that is approximately symmetric or a distribution that is skewed to the left (longer left than right tail). This applies also for *Organisation B*, except for some of the office cells with lowest average *UR*. Plotting the distributions in histograms reveals that almost every office cell has a distribution with two distinct peaks. One of these peaks is located nearby zero hours per day, because the frequency of days with a low *UR*, below approximately one hour per day, is high. The skewness of a sample can be computed to characterise the shape of the distribution. The absolute value of the sample skewness has the following interpretation (Løvås, 2004): below 0.5 suggests that the distribution is approximately symmetric; between 0.5 and 1 that it is weekly skewed; above 1 that it is strongly skewed. Computing the sample skewness for the distribution of daily *UR* levels give values that are spread between all these three categories for both organisations. Consequently, the daily *UR* levels, when days without occupancy are excluded, are distributed quite differently for the individual office cells. The distributions are in most cases bimodal; however, while some are approximately symmetric, some are to a greater or lesser degree skewed to the left.

Meeting rooms

In neither of the organisations, the meeting rooms are used frequently. The average utilisation rate, all working days included, is 1.9 hours/day for the meeting room used by *Organisation A* and 0.8 hours/day for the meeting room used by *Organisation B*.

5.3.2 Distribution of occupancy and vacancy periods

When processing the collected data from *Building 1* the time resolution was decreased from one second to one minute, to make the computation of *OFz* manageable. The chosen approach for rounding the time stamps in the data record entails that some of the vacancy periods lasting less than 30 seconds are left out. As mentioned in Chapter 4.3, this has negligible effect on the accuracy when computing *OFz* and *UR*. For the distribution of occupancy and vacancy intervals on the other hand, this approximation are not insignificant, since very short lasting vacancy periods are occurring frequently. In order to avoid excluding any vacancy periods, the computations of the duration of occupancy and vacancy intervals presented in this section were made without rounding off the time stamps. Because these computations can be made on each room individually without taking the simultaneous occupancy state in other rooms into account, it does not require matrixes as large as for computation of yearly *OFz* values. However, the duration of occupancy and vacancy periods was in the next step rounded off and is presented with one minute time resolution.

Once again, it is important to remember when studying the figures of this section that it is not the actual durations of the workers' occupancy and vacancy periods that are presented; it is computed durations based on what is detected by the PIR motion detectors, including 20 minutes *TD-OFF*. As explained in Chapter 3, this has the following consequences. First, an occupancy period, as presented here, can never be shorter than 20 minutes and the actual duration of the workers' occupancy periods are 20 minutes shorter than what is presented here. Consequently, the actual duration of each vacancy period is 20 minutes longer than what is presented here. Furthermore, actual vacancy periods lasting less than 20 minutes are not included. Second, a detected occupancy period may be caused by false-positive detection and a detected vacancy period by false-negative detection, i.e. all of the occupancy and vacancy periods presented here are not necessary a result of a worker being present in, or absent from, her/his office cell. The on-site observations indicated that false-positive detection is not a problem in *Building 1*, but it can not be guaranteed that it never occurs. False-negatives on the other hand, will occur at times. To summarise, occupancy periods shall be interpreted as periods where a higher ventilation flow rate is supplied and vacancy periods as periods where a lower ventilation flow rate, or no ventilation at all, is supplied. The distribution of these periods is first and foremost a result of the workers occupancy pattern, but the detector performance and chosen level of *TD-OFF* will certainly influence.

Relevance for indoor climate and HVAC systems

The frequency of occupancy periods, together with the duration of them and duration of the vacancy periods in between, is important for understanding the occupancy pattern on an individual room level. This in turn, is as emphasised in Chapter 2, of interest for considerations regarding control of the indoor climate, especially when occupancy-sensing control is involved and/or when the user can manually control the indoor climate to some extent. This is the background to the increased research efforts on including sub-hourly stochastic occupancy prediction models and advanced behavioural models in building simulation tools, as discussed in Chapter 2.6. Most published work on the use of such models have dealt with either the lighting systems or the thermal conditions, by simulating automatic and manual control of lighting and windows and the effect this have on lighting, cooling and heating demand. However, to better our understanding on how office workers occupy their office cells or workstations, is of equal importance for the possibilities to improve the control of the indoor air quality (IAQ). First of all, the occupants and their activities are significant pollution sources themselves, so the intermittent occupancy in the office cell will contribute to fluctuations in the concentration of some contaminants and in the perceived air quality (PAQ). Secondly, due to olfactory adaptation and recovery, the duration of occupancy and vacancy periods will influence how the workers perceive the air when entering their own office cells, and also colleagues' office cells, and during the first part of every occupancy period. The length of an occupancy period will influence the degree of olfactory adaption that is reached and the length of the absence, and which type of environment that is visited, will influence the degree of recovery from the olfactory fatigue that is reached. These two factors imply that the choice of design ventilation flow rates and potential strategies for varying the flow rates should take the occupancy pattern into account.

All rooms aggregated

Before studying the individual rooms, Figure 5.16 show the overall distribution of the duration of occupancy and vacancy periods for all monitored office cells in *Organisation A* aggregated. All 24 hours of the working days are included; however, 98-99 % of the occupancy and vacancy periods are occurring between 6 a.m. and 6 p.m. The periods that occur before the first and after the last occupancy period each working day, is not counted as a vacancy period here. The occupancy periods lasting between 20 and 30 minutes amount to 32 % of all occupancies and 37 % of all vacancy periods last less than 10 minutes.

The change in *OFz* when altering *TD-OFF* (Table 5.4) indicated that the distribution of the duration of vacancy periods is similar in the two organisations in *Building 1*. Plotting the frequency distribution also for *Organisation B* confirms this. Figure A.3.4 in Appendix A.3 shows the cumulative frequency distribution for occupancy and vacancy periods for both organisations, and illustrates the fact that also the distribution of the duration of occupancy periods is similar in *Organisation A* and *B*.

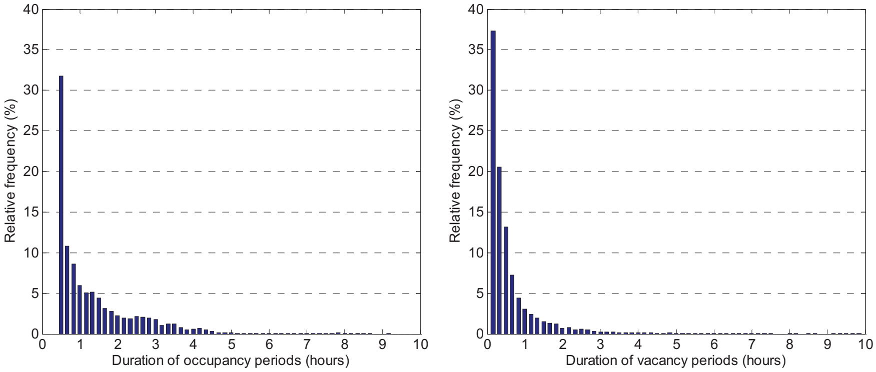


Figure 5.16 Frequency distribution of the duration of occupancy periods (left) and vacancy periods (right), for all monitored office cells in Organisation A aggregated.

A significant part of the shortest vacancy periods is caused by false-negative detection. An estimate of the fraction of vacancy periods that is a result of false-negatives, based on on-site observations, can be found in Appendix A.2. According to this estimate, approximately 40 % of the vacancy periods with duration up to 10 minutes in Figure 5.16 are caused by false-negative detection. Because of the high frequency of short lasting occupancy periods, it may seem advantageous to use an ON-delay for control of the ventilation, provided that it is possible to use different *TD-ON* for the lighting and ventilation. The occupancy periods lasting between 20 and 30 minutes are cases where the worker is present for less than 10 minutes and afterwards absent for more than 20 minutes; for example, arriving in the morning or returning after lunch to pick up some things and then leaving for a meeting. It can also be a result of others visiting the office (e.g., cleaning personal). It may be considered as unnecessary to increase the ventilation flow rate for such short occupancy periods. The disadvantage with an ON-delay is that the increase of ventilation is delayed not only during short occupancy periods, but every time the worker arrives at the office cell after being absent for more than 20 minutes. Moreover, some of the short lasting detected occupancy periods are probably a consequence of false-negative detection. If a worker is performing working tasks with few larger movements involved, such as reading, it may lead to false-negative detection that, in turn, result in the worker's presence being detected as one or several shorter occupancy periods instead of one longer. Using an ON-delay will prolong the time where the ventilation is at a lower level even though the worker is present, every time false-negative detection occurs.

Individual room level

The mean duration of occupancy periods and vacancy periods varies significantly among the individual office cells, as shown in Figure 5.17**.** Most office cells have a mean duration of occupancy periods between approximately one and two hours and between approximately 20 to 60 minutes for vacancy periods.

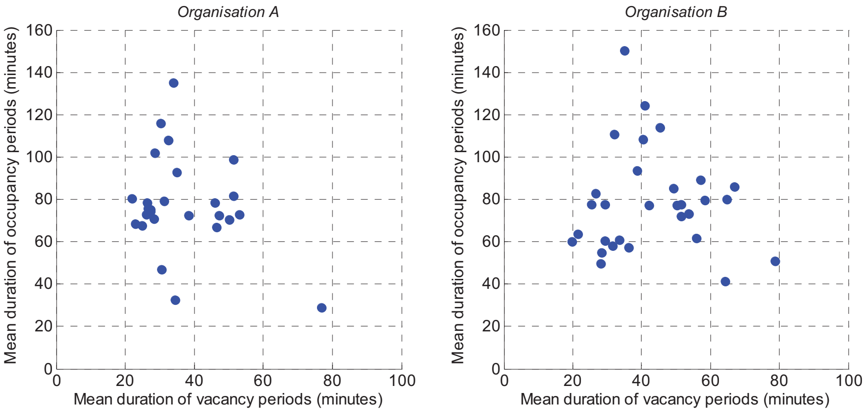


Figure 5.17 Mean duration of (detected) occupancy and vacancy periods for each monitored office cell in Organisation A (left) and B (right), with 20 minutes TD-OFF.

The averages of the individual office cells are (organisation in parenthesis): 78 minutes (*A*) and 79 minutes (*B*) for the mean duration of occupancy periods; and 37 minutes (*A*) and 43 minutes (*B*) for the mean duration of vacancy periods.

Wang et al. (2005) analysed data from one year of monitoring of 35 single person offices with PIR motion detectors in a federal office building in San Francisco. The motion detectors were used to control lighting and were operated with 15 minutes *TD-OFF*. The duration of occupancy periods was reduced by 15 minutes to get the actual duration. This could of course have been done also for the data presented here. However, because vacancy periods shorter than *TD-OFF* are not part of the recorded data and because the data include a certain amount of false-negative detection, the exact actual distribution of occupancy and vacancy intervals is still unknown. Therefore it was chosen to present the frequency and duration of occupancy and vacancy period with *TD-OFF* included, which are decisive for the amount of supplied ventilation. With four offices regarded as outliers, and therefore excluded, the average of the 31 remaining offices in San Francisco was 69 minutes for estimated mean duration of occupancy intervals and 46 minutes for estimated mean duration of vacancy intervals. To be comparable with the data presented by Wang et al., the duration of occupancy periods with *TD-OFF* equals approximate zero (15 minutes logging) was computed. Then, if the office with longest mean duration of vacancy intervals in *Organisation A* and longest mean duration of occupancy intervals in *Organisation B* are considered as outliers and disregarded, the average is 45 and 44 minutes for occupancy intervals and 46 and 53 minutes for vacancy intervals, in *Organisation A* and *B* respectively. Hence, while the averages of the office cells' mean duration of vacancy periods in *Organisation A* and *B* are in the same magnitude as presented by Wang et al., the averages of the mean duration of occupancy periods are considerably shorter. It is however not surprising that the medium duration of occupancy periods is lower for employees at a university college than in a federal office building. In addition, the frequency of false-detection in the two buildings is an element of uncertainty.

Figure 5.18 shows how the duration of the occupancy and vacancy periods for all monitored office cell in *Organisation A* are distributed in a box and whisker plot. The corresponding figure for *Organisation B* can be found in Appendix A.3.

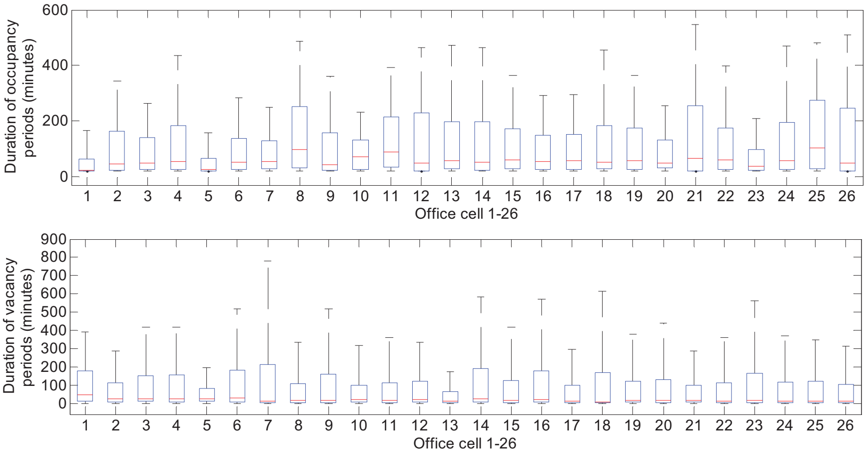


Figure 5.18 Distribution of the duration of occupancy periods (upper) and vacancy periods (lower) for the office cells in Organisation A. The box and whisker plot shows maximum and minimum (whiskers) together with upper quartile, median and lower quartile (boxes).

For distribution that are skewed and non-symmetric, like the distributions of the duration of occupancy and vacancy periods, the median and percentiles (e.g., quartiles) are more convenient measures of central tendency and dispersion than the mean and standard deviation. The median of the duration of occupancy periods ranges from 22 to 102 minutes for the 26 office cells in *Organisation A*, with an average of 56 minutes. In *Organisation B*, it ranges from 26 to 133 minutes, with an average of 53 minutes. The median of the vacancy periods ranges from 9 to 46 minutes for the office cells in *Organisation A*, with an average of 19 minutes; and from 9 to 51 minutes for the office cells in *Organisation B*, with an average of 23 minutes. Hence, the two organisations are very similar regarding both the sample range and the average of median durations of occupancy and vacancy periods on individual room level.

All office cells, except for a few which have very few occupancy and vacancy periods, have distributions that look much like the overall frequency distribution of the duration of occupancy and vacancy periods (Figure 5.16). That is, with a bin width of 10 minutes, they have mode values of 20-30 minutes for the occupancy periods and 0-10 minutes for the vacancy periods, and a clearly falling frequency the longer the occupancy and vacancy periods are. However, as shown by the box and whisker plots, the length and heaviness of the tail differ among the rooms. Hence, it is difficult to define what a typical occupancy pattern in the office cells looks like. What can be considered as a typical occupancy period and a typical vacancy period will deviate much between office cells. However, if the average of all office cells is used, then a typical occupancy period lasts approximately 55 minutes and a typical vacancy period lasts approximately 20 minutes, with 20 minutes *TD-OFF*. If two such periods occur in succession in an office cell with occupancy-sensing control of the ventilation, it mean that the occupant first is present for 35 minutes and then leaves the office cell; the ventilation system continuous to run on design air flow rate in another 20 minutes before it is reduced down to a base air flow rate; and finally, after an additional 20 minutes, the occupant returns and enters the office cell (40 minutes after she/he left) and the air flow rate is increased again.

According to Lindelöf and Morel (2006) some models of user behaviour in buildings assume that the time between events for some type of actions, for example, control of artificial lighting, window opening or closing, and arrival to and exit from a room, are exponentially distributed, provided constant environmental conditions. Wang et al. (2005), referred to above, found that the duration of vacancy periods in all 35 monitored office cells were exponentially distributed, while the duration of occupancy periods fitted less well with an exponential distribution (did not pass a goodness of fit test). For both vacancy and occupancy, the fitted exponential distributions underestimated the frequency of short-lasting periods. Page et al. (2008) found, in accordance with Wang et al., that the duration of monitored occupancy periods in four offices not were exponentially distributed. Dodier et al. (2006), who developed a network of PIR motion detectors (three in each office), monitored occupancy in two office cells for two days. They claimed that both the duration of monitored occupancy and vacancy periods were approximately exponentially distributed.

The box plots in Figure 5.18 provides a visual overview that shows roughly how the duration of occupancy and vacancy periods are distributed, and makes it easy to detect potential differences regarding central tendency and variability among the rooms. However, if one or a few existing theoretical probability distributions prove to correspond well with the monitored data, it would be a complement that gives a more complete view of the data and facilitates a comparison with other measurements or simulations of occupancy and vacancy intervals. Theoretical probability distributions are unambiguously defined and can be expressed by one or a few parameters, making it possible to describe the occupancy pattern in a compact manner.

It was tried to fit theoretical probability distributions to the duration of occupancy and vacancy periods in all 56 monitored office cells in *Building 1*. As a first attempt, an exponential distribution was tried and if the fit was poor, other distributions with similar shape were tried in order to improve the fit. The parameter estimations were carried out with MATLAB, using maximum likelihood estimation (MLE). The goodness of fits was evaluated graphically by inspection of the cumulative distribution function (CDF), quantile-quantile plots (Q-Q plots) and probability-probability plots (P-P plots), comparing the empirical and fitted distributions. No hypothesis tests were carried out.

The distributions that provided the best fit of the tested probability distributions were generalised Pareto distribution (GPD) for the duration of detected vacancy periods and either a Gamma distribution or a Nakagami distribution for the duration of the detected occupancy periods (with 20 minutes *TD-OFF*). An example of fitted GPD for two rooms can be found in Appendix A.3. An exponential distribution did not fit the duration of occupancy periods and not the duration of vacancy periods, except for a few rooms where it provided a reasonably good fit. As in the study by Wang et al. (2005), an exponential distribution underestimates the frequency of short lasting occupancy and vacancy periods. The logged vacancy periods consist of both actual absence from the office cells and false-negative detection, meaning that the distribution of vacancy periods for each room is a mixture of at least two distributions. Also the detected occupancy periods are a mixture of at least two distributions, actual occupancy periods and vacancy periods shorter than *TD-OFF*. The on-site observations in *Building 1* revealed that the duration of false-negative detection periods fits reasonably well with an exponential distribution for all observed rooms aggregated. However, it is not possible to separate the actual vacancy from the false-negatives on individual room level with the available data, and it is not possible to find the distribution of the duration of actual occupancy periods. Hence, if the hypothesis is that the duration of actual occupancy and/or vacancy periods in office cells are exponentially distributed, it can not be rejected based on the data from *Building 1*.

Figure 5.19 shows the average number of occupancy periods per day, and standard deviation, for each individual office cell in *Organisation A* and *B* respectively, when only days with occupancy are included.

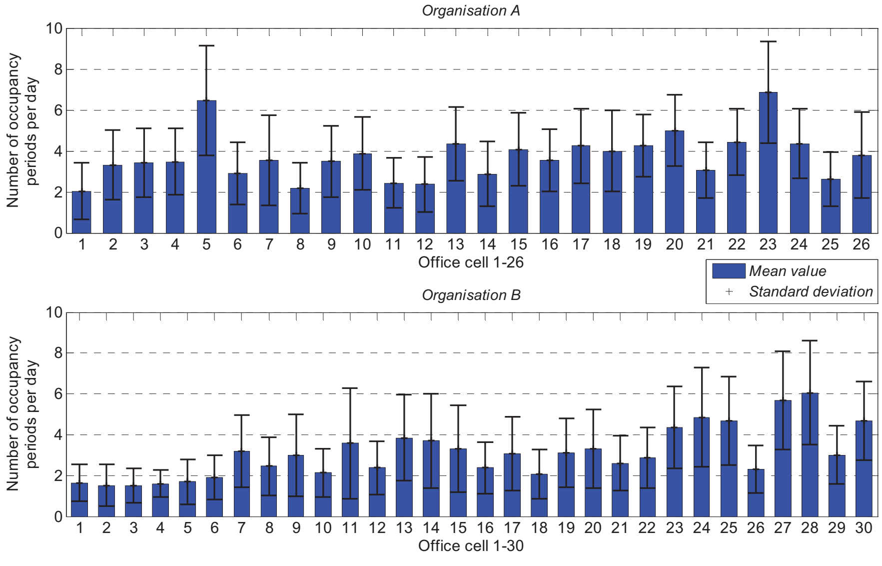


Figure 5.19 Average number of (detected) occupancy periods per day and standard deviation for the office cells in Organisation A (upper) and B (lower). Only days with occupancy are included.

Most offices have an average between approximately 2 and 4 occupancy periods per day. Again, it is important to keep in mind when studying the values in Figure 5.19 that a worker has to be absent from the office cell, or exposed for false-negative detection, for at least 20 minutes to split one occupancy period into two (i.e. the values are not equal to the actual number of times that the workers are entering their respective office cells).

5.4 Summary

In *Building 1*, 26 and 30 office cells in *Organisation A* and *Organisation B* respectively, were monitored for one year. *Organisation A* work with special need education services for children, young people and grown-ups. *Organisation B* is a public university college.

The daily $\overline{OFz}^{06-18,wd}$ levels are approximately normally distributed when holidays periods are disregarded, ranging from 0 up to 0.43 (*Organisation A*) and 0.36 (*Organisation B*), with 20 minutes *TD-OFF*. The shape of the occupancy profile differs considerably from day to day, i.e. peaks and drops in *OFz* occur on different times of the day. It indicates that the pattern of *OFz* for zones with many office cells is difficult to predict. Table 5.7 summarise the results on organisational level.

Table 5.6 Summary of detected occupancy (OFz) with 20 minutes TD-OFF, for the entire monitoring period (holiday periods included)

$OFz^{06-18,wd}$	*Organisation A*	*Organisation B*
Average	0.25	0.19
90th percentile	0.54	0.40
95th percentile	0.62	0.47
98th percentile	0.65	0.50
Maximum	0.85	0.97

There is a relatively large variation in utilisation rates (*URs*) among the office cells in both organisations. The low average *OFz* can be explained by the fact that most employees works many days outside the office premises. The distribution of the duration of detected occupancy periods and the distribution of the duration of detected vacancy periods are both heavily skewed. A typical duration of a detected occupancy period is approximately 55 minutes and a typical duration of a detected vacancy period is approximately 20 minutes, with 20 minutes *TD-OFF*. Most office cells have 2 to 4 occupancy periods per day, when only days with at least one occupancy period is included. The result on individual room level are summarised in Table 5.7.

Table 5.7 Summary of detected occupancy pattern with TD-OFF equals 20 minutes on individual room level, with averages and standard deviations for 26 and 30 office cells in Organisation A and B respectively

	Organisation A		*Organisation B*	
	Average	Std	Average	Std
UR (hours/day), holidays excluded	3.4	1.6	2.6	1.7
Fraction of working days with *UR* = 0	0.37	0.19	0.45	0.24
UR (hours/day), days without occupancy excluded	4.6	1.1	3.8	1.3
Median duration of occupancy periods (minutes)	56	18	53	22
Median duration of vacancy periods (minutes)	19	8	23	11
Mean number of occupancy periods per day[1]	3.7	1.2	3.1	1.2

[1] Only days with occupancy included.

6 *Building 1* to 5

This chapter provides results similar to what were presented in Chapter 5 for *Organisation A* and *B* for the room samples from all five buildings. In addition, the results from the 11 case organisations are compared to occupancy monitored in other buildings (summarised in Chapter 3). Results for *Organisation A* and *Organisation B* are included also here, although some of them already presented in Chapter 5, to facilitate the illustration of differences and similarities between the cases.

6.1 Description of buildings and organisations

Building 1, housing *Organisation A* and *B*, is described in Chapter 5.1.

Building 2 is an office building of about 15 000 m^2, plus parking areas, located in the central part of a city. The building is occupied by several different governmental departments. The 31 monitored cellular offices, from four zones of the building, were selected by operation personnel. The selection was blinded to the author, meaning that the author does not know from which organisational unit, or units, the workers occupying these rooms belong to. What is here called *Organisation C* is therefore a room sample that may include workers from different departments. No meeting rooms were monitored.

Building 3 is the main office for *Organisation D*. The building consists of one older and one newer part. It is in the new part that the monitored office cells and meeting rooms are located. This part has a three office floors with a total floor area of just over 3 000 m^2. Three of the rooms have more than one workstation (to, three or four workstations). Because this is 3 out of 86 rooms, the outcome on *OFz* will be minimal. The premises also have several small common areas in addition to the cellular offices and meeting rooms. *Organisation D* is working with transportation of gas, including operation and development of gas transport systems and administration of available capacity in the system. The employees in the monitored office cells have working tasks that require use of a PC much of the working hours. The motion detectors are mounted to the ceiling, in a position that leads to a risk for false-positive detection, due to people passing by in the corridor if the door is open. However, detection through an open door of someone passing by in the corridor will, due to *TD-OFF*, only change the occupancy state of the room if it has been unoccupied for more than 20 minutes. Is it assumed that the workers normally close the door when they are absent for more than 20 minutes. In addition, the fire instruction for the building requires that the occupants close the doors when they leave their respective offices (Alsaker, 2007).

Building 4 is a combined office and laboratory building at a university campus. A few cellular offices in one corridor, together with a meeting room, were selected for monitoring of occupancy, by temporarily installation of motion detectors. The office cells are occupied by employees that either works at the university (professor or PhD-student) and/or in an independent research organisation (scientist) that has some of their departments located on the university campus. Three of the office cells were occupied by two workers; in two of them on permanent basis and in one of them for one day per week. All monitored office cells had two motion detectors, except for one office that had all three tested types of detectors.

The detector performance in the office with all three types of detectors was investigated by manual registration of occupancy during seven working days. The results from the comparison of the manual registrations and the logged occupancy from the motion detectors are summarised in Table 6.1.

Table 6.1 Occurrences of false-detection in one investigated room in Building 4 (based on seven days of manual registration of occupancy)

Detector	*TD-OFF* (minutes)	Frequency of false-positive detection (number/day)	Frequency of false-negative detection (number/hour of actual occupancy)
Servodan	20	0	0
CALECTRO	20	0.43	0
ceiling mounted	10	0.43	0
CALECTRO	20	0.14	0.16
wall mounted	10	0.14	0.77

The false-positive detections occurred when the door was closed, and were consequently not a result of people passing by in the corridor. The wall mounted detector was the one with highest frequency of false-negative detection. This detector had 10 minutes *TD-OFF* during the monitoring period, but the investigation indicated that 20 minutes would have been a more suitable delay, at least with the chosen detector position. It was mounted near the door, facing the right shoulder or the back of the occupant, dependent on where at the desk he was sitting. This is the same detector as in *Building 1*. The position, both angle and distance, in relation to the occupant is also approximately the same. The frequency of false-negative detections in the investigated room is in the same magnitude as found in observations in *Building 1* (0.84 and 0.26 false-negative detections per hour of actual occupancy for all observed rooms aggregated, with 10 and 20 minutes *TD-OFF* respectively).

Building 5 is a relatively new office building of around 12 000 m^2 distributed over nine floors, which houses several organisations. The office premises consist of a combination of cellular offices and open plan offices. In addition to some meeting rooms, occupancy has only been monitored in cellular offices. Not all parts of the building had been rented out when the monitoring period started. Rooms from six different organisations were included in the data set: *Organisation F* is a company that delivers data and telecommunication services; *Organisation G* offers audit, tax and advisory services; *Organisation H* is a radio station for maritime radio communication; *Organisation I* is an organisation that has operational responsibility for search and rescuing operations; *Organisation J* has responsibility for ambulance transport that requires airplane or helicopter; and *Organisation K* is a real estate investing company. The motion detectors are mounted on the wall in the corner beside the door; except for a few office cells and all the meeting room, which have ceiling mounted detectors. However, the risk for false-positive detection due to people passing by an open door to an empty room with ceiling- mounted detector is considered to be low, at least for the office cells, because of the relatively long time-delay (20 minutes).

Monitoring periods and number of monitored rooms

The data set included 247 cellular offices and 16 meeting rooms, distributed on five buildings and eleven organisations. As mentioned before, the monitored rooms are only samples from the organisations and do not include all workstations in all organisations. Table 6.2 gives an overview of the number of monitored rooms and the duration of the monitoring period in each of the five case buildings.

Table 6.2 Overview of monitored case buildings and organisations

	Number of monitored rooms		Selected monitoring period [a]			
Building – org.	Cellular offices	Meeting rooms	Duration (weeks)	Holiday periods [b] included (weeks)	Remaining days, holiday periods excluded	
					Working days	Weekend days [c]
1 – A	26	1	52	7	211[4]	97 [d]
1 – B	30	1	52	9	201[4]	93 [d]
2 – C	31	0	17	4	65	26
3 – D	86	8	6 [e]	0	30	12
4 – E	10 [f]	1	6	0	29	13
5 – F	20	3	22.5	5	87	35
5 – G	11	2	22.5	5	87	35
5 – H	11	0	22.5	4	92	37
5 – I	4	0	22.5	7	77	31
5 – J	12	0	22.5	3	97	39
5 - K	6	0	22.5	3	97	39

[a] *Building 1*: 01.10.2005 - 31.09.2006; *Building 2*: 30.05.2005 - 25.09.2005; *Building 3*: 07.02.2007 - 20.2003.07; *Building 4*: 21.05.07 - 01.07.07; *Building 5*: 06.05.08 - 09.10.08.

[b] Periods with significant lower occupancy, including a period in the summer where many workers simultaneously take most of their holidays (*Building 1*, *2* and *5*) and week 52 and the week before Easter (*Building 1*).

[c] Including public holidays.

[d] Remaining days after exclusion of days with a stop in the logging (nine working days and two days on weekends).

[e] In addition to these six weeks, occupancy were monitored for five days, three of them working days, with a shorter *TD-OFF*.

[f] The ten rooms include four two-person offices and six one-person offices.

6.2 Results on organisational level

Chapter 6.2 presents result only for office cells, i.e. meeting rooms are not included. The occupancy in the monitored meeting rooms is presented in chapter 6.3. The presented results are based on 20 minutes *TD-OFF*, if nothing else is specified.

6.2.1 Long-term variations

The monitoring period in three of the buildings, *Building 1*, *2* and *5*, covered the part of the summer in Norway where most people take the main part of their holidays. No other cases than *Organisation A* and *B* were monitored during week 52 or the week before Easter; two weeks that normally have low occupancy. The period defined as holiday period during the summer was selected by inspection of a plot of weekly $\overline{OFz}^{06-18,wd}$ levels of the organisation in question and then choosing a period of several successive weeks with lower occupancy than the general level. This was done without using any specific numeric selection criterion common for all organisations; for example, a certain percental decrease in occupancy from one week to another.

Figure 6.1 shows a box and whisker plot of the daily $\overline{OFz}^{06-18,wd}$**,** holiday periods excluded, for all cases. The range from the case with lowest to highest median is large: from 0.218 (*Organisation B*) up to 0.579 (*Organisation K*). The difference regarding the dispersion of daily $\overline{OFz}^{06-18,wd}$, here illustrated by the interquartile range, are large between some cases, while some cases have rather similar dispersion. The probability distributions of the daily $\overline{OFz}^{06-18,wd}$ are symmetric, or close to symmetric, and the deviation between the mean and median are small for all cases, less than 0.02. Either the mean or the median of the daily $\overline{OFz}^{06-18,wd}$**,** holiday periods excluded, can be a representative daily average level for what can be considered as normal conditions.

The distribution of daily $\overline{OFz}^{06-18,wd}$, holiday periods excluded, were tested graphically (cumulative probability function and normal probability plot) against a normal probability distribution. The distribution of daily $\overline{OFz}^{06-18,wd}$ fits reasonably well with a normal distribution for most of the eleven cases. In some cases, the fit improves if more weeks is considered as holiday periods and are excluded (e.g., if two more weeks are excluded for *Organisation G*).

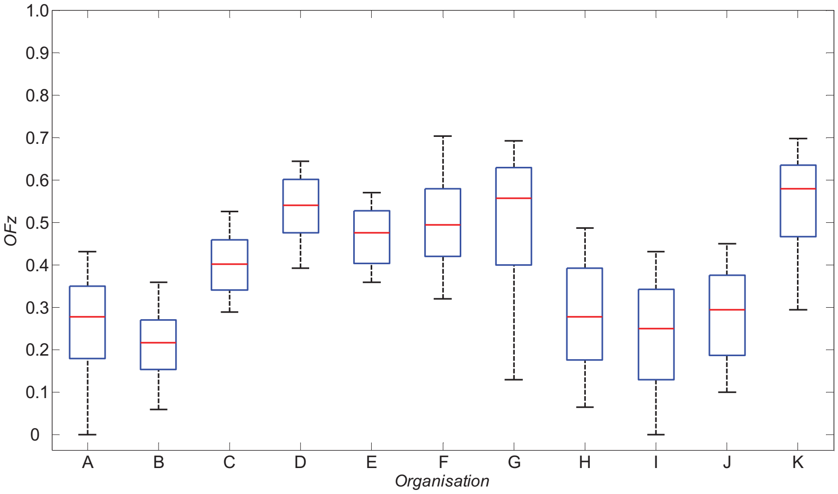


Figure 6.1 Box and whisker plot of the distribution of daily $\overline{OFz}^{06-18,wd}$*, holiday periods excluded. The whiskers mark the maximum and minimum values and the boxes the upper quartile, median value (red line) and lower quartile.*

It is worth noticing that the maximum daily $\overline{OFz}^{06-18,wd}$ can be more than 0.2 higher than the median. This can, for example, be of interest for cooling load considerations. For instance, if one estimates the $\overline{OFz}^{06-18,wd}$ to be 0.5 during a normal day, it can according to the monitored cases be over 0.7 on a peak day; a day that may coincide with unfavourable climate conditions from a cooling load point of view. Hence, using a profile or a daily mean value representative for normal conditions may in some cases result in a significant under-estimation of the peak cooling load, when the simultaneous cooling load in several sub-zones are considered. In addition, it is important to remember that the average for the peak day is higher if only the core working hours are considered. In the three cases with highest maximum daily $\overline{OFz}^{06-18,wd}$, the average between 8 a.m. and 5 p.m. is: 0.872 for *Organisation F* with *OFz* reaching 1.0 several times; 0.821 for *Organisation G* with *OFz* reaching 0.9 for main parts of the day; 0.825 for *Organisation K* with *OFz* reaching 1.0 several times. However, the risk for the day with highest average *OFz* to occur on one of the days with most critical outdoor climate conditions from a cooling load point of view is small. If for instance the 95th percentile of the daily $\overline{OFz}^{06-18,wd}$ is considered instead, it is 0.618, 0.675 and 0.647 for *Organisation F*, *G* and *K* respectively, which is around 0.02 to 0.09 lower than the maximum for these organisations. Using a certain percentile (below maximum) as a sort of occupancy design day for cooling load calculations means that one calculates with a risk (5 % in the case of the 95th percentile); a risk that *OFz* is higher than the level of the percentile in question on the day that from a outdoor climate point of view is a design day for cooling load calculations. This of course, provided that the daily *OFz* averages can be assumed rather stochastically distributed over the year (holiday periods excluded). It is worth mentioning that because the sample range usually increases with the sample size, the maximum levels found from the monitoring are probably deviating more from the true long-term value (a year or more) than, for example, the median or the 95th percentile does, especially in the cases with shorter monitoring period (e.g., *Organisation D* and *E*). Here, only *OFz* with 20 minutes *TD-OFF* is considered. However, both or either of (a) *OFz* with *TD-OFF* included and (b) the actual *OFz* levels can be of interest for such considerations. This depends on which type of system(s) that provides cooling to the rooms and whether the ventilation flow rates and/or the set-point temperature for cooling is occupancy-sensing controlled or not.

6.2.2 Daily profiles

Figure 6.2 shows 24-hour profiles of average *OFz* on working days, holiday periods excluded, for all 11 cases. The shapes of the profiles are in some aspects rather similar for many of the cases and differ in other aspects. The increase in occupancy in the morning is centralised around approximately 8 a.m. for all cases and the decrease in the afternoon starts around, or just after, 3 p.m. for most cases. The gradients of both the increase in the morning and the decrease in the afternoon are rather similar for most cases, but especially *Organisation A* diverges with steeper gradients. For most cases, the average level of *OFz* is relatively constant between around 9 a.m. and 3 p.m., with exception for lunch and in some cases a drop in occupancy around, or just after, 2 p.m.

The profiles show that there are disparities in lunch routines. In some cases (*Organisation A*, *E*, *G*, *H* and *K*) many of the workers take their lunch simultaneously and often on approximately the same time day after day, resulting in a distinct drop in the average profile. In other cases the drop in the profile is less distinct and in cases like *Organisation D* and *J* the lunch is nearly not shown on the profile at all. This means that (a) the workers to a less degree take their lunch simultaneously with their colleagues; and/or (b) that the time that many of the workers take their lunch varies much from day to day; and/or (c) that the workers have a very short lunch break. The lunch break appears more clearly when looking at a plot of the average profiles with approximate zero *TD-OFF* (20 min logging). In two of the cases, it seems like it is common that the workers in the monitored rooms goes to lunch in two rounds. This is most evident in *Organisation C*, but can be seen also for *Organisation F*. For *Organisation C*, this can indicate that the monitored rooms belong to at least two different organisational units. Figure 6.2 also shows that the average *OFz* drops around, or just after, 2 p.m. in some of the organisations, which most probably is a result of coffee breaks.

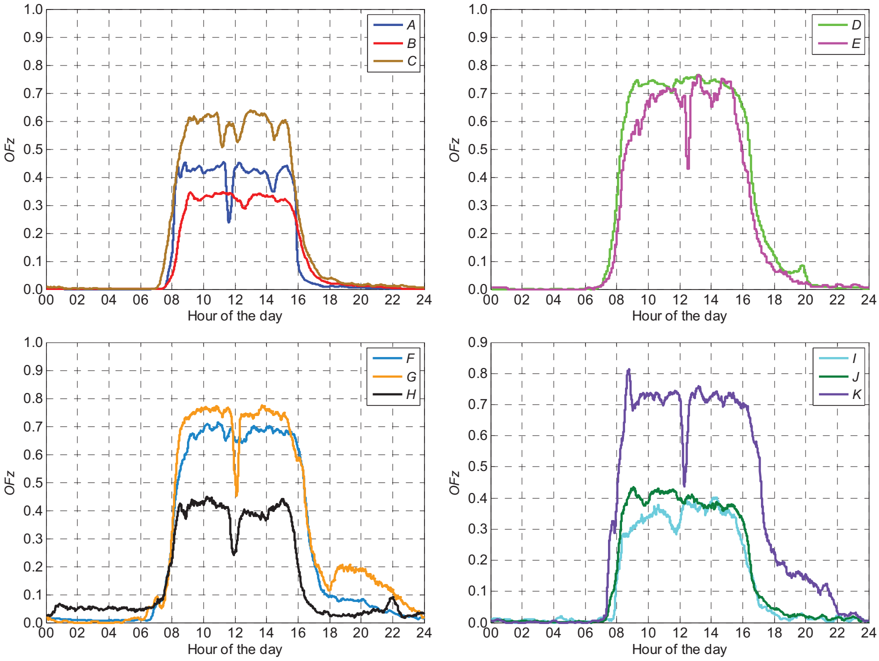


Figure 6.2 Average OFz on working days, holiday periods excluded.

As Figure 6.2 shows, and as already indicated by the median values of daily $\overline{OFz}^{06-18,wd}$, there is a large spread in $\overline{OFz}^{06-18,wd}$: from 0.219 (*Organisation B*) to 0.564 (*Organisation K*). The occupancy before 6 a.m., and also until 7 a.m., is negligible in all cases except for *Organisation H*. The occupancy levels are less consistent among the cases after 6 p.m., but still low in most organisations. Two organisations have however a significant higher occupancy on evenings than the others: *Organisation G* and *Organisation K*. In such cases like *Organisation K*, using occupancy-sensing control of the ventilation, and utilise it also after 6 p.m. can be advantageous compared to a conventional CAV system. The occupancy is low, so using CAV with the same air flow rates as during the normal working hours in all office cells may be considered as waste from an energy and operation cost point of view. On the other, the occupancy is not negligible (e.g., on average, 20 % of the cellular offices are occupied between 18.30 and 20.30 in *Organisation G*) and the workers that are present will appreciate if the quality of the indoor climate is on the same level as during normal working hours. Whit occupancy-sensing control, it will not cost much to increase the air flow rate during occupancy also in the evening, compared to a CAV system, because the average occupancy after 6 p.m. is still low ($\overline{OFz}^{18-24,wd}$ equals 0.13 and 0.10 in *Organisation G* and *K*, respectively). This becomes a discussion of how large part of the day one can expect the building to provide a satisfactory indoor climate for the occupants.

Figure 6.3 summarise the average occupancy levels, holiday periods excluded, expressed both in terms of $\overline{OFz}^{06-18,wd}$ and in terms of the fraction of the total occupancy hours on working days that occurs within the time period 6 a.m. to 6 p.m. The figure also shows the levels that from the available raw data is the best estimate of the actual occupancy levels, with 5 minutes *TD-OFF* for *Organisation A* and *B* and approximate zero *TD-OFF* (20 minutes logging) for the other cases. The averages for the estimated actual occupancy were computed for the time period 8 a.m. to 5 p.m. to match the summary of measured occupancy found in the literature, presented in Chapter 3.2.

The cases can roughly be divided into two groups, one with lower and one with higher occupancy. The detected $\overline{OFz}^{06-18,wd}$ with 20 minutes *TD-OFF* and the estimated actual occupancy level $\overline{OFz}^{08-17,wd}$ are both in the range from about 0.2 to 0.3 for the group with lower occupancy (*Organisation A*, *B*, *H*, *I* and *J*), and in the range from about 0.4 to 0.6 for the group with higher occupancy (*Organisation C*, *D*, *E*, *F*, *G*, *K*).

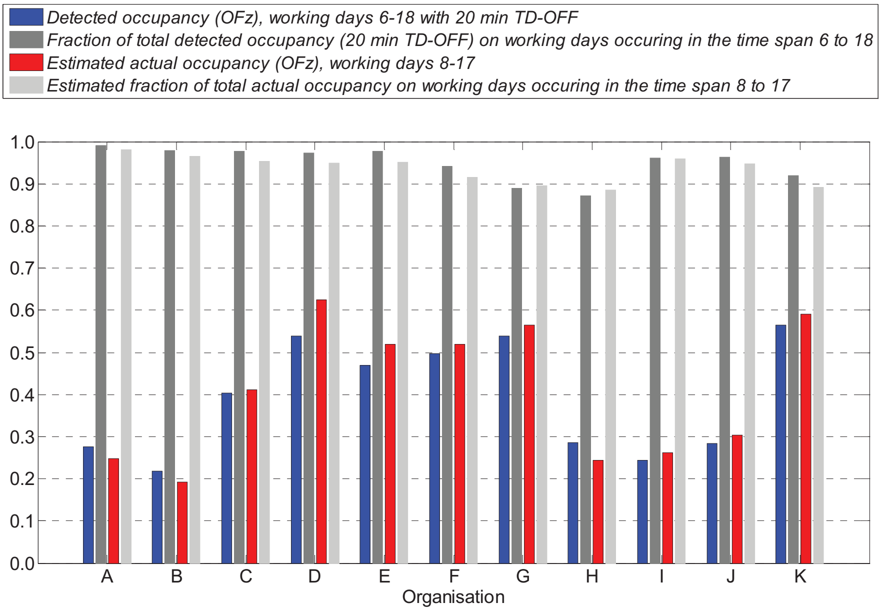


Figure 6.3 Summary of average OFz levels in the monitored cellular offices in the 11 case organisations, holiday periods excluded.

The room sample from *Organisation E* included three rooms with two workstations, which means that *OFz* is somewhat higher than if the workers on these rooms had been sitting in one-person office cells instead. The probability for a two-person office cell to be occupied at one specific time of the day can be expressed as:

$$p_{occ} = 1-(1-p_1)\cdot(1-p_2) \tag{6.1}$$

where

p_{occ}	Probability for the room to be occupied
p_1, p_2	Probability for being present in the room, for occupant 1 and occupant 2 respectively

The probability p_2 can be replaced with $f \cdot p_1$, where f equals p_1/p_2. The probability of being occupied (p_{occ}) on working days was computed for each 5 minute time step between 6 a.m. and 6 p.m. for the three rooms with two workstations. The factor f was set to 1 for two of the rooms and 5 for the room where one of the occupants worked in the office only one day per week. For each time step, Equation 6.1 was solved for p_1, which means that also p_2

could be found. Then, two utilisation rates were computed for each of the three rooms, by taking the average of all time steps for p_1 and p_2, respectively. A new average *OFz* could thereby be computed for a fictitious case with only one-person office cells. With the assumptions mentioned above for *f*, $\overline{OFz_D}^{06-18,wd}$ is estimated to have been 0.39 if all the 13 employees from *Organisation E* had been working in one-person office cells. This is 0.08 lower than in the actual situation ($\overline{OFz_D}^{06-18,wd}$ equals 0.47) where six employees work in two-person office cells.

24-hour profiles with hourly averages

In energy and indoor climate calculations, especially in dynamic simulations, 24-hour profiles of diversity factors for occupancy and occupancy related load are needed as input. Two types of profiles were constructed: (a) profiles with 20 minutes *TD-OFF;* and (b) profiles with approximate zero *TD-OFF*, representing the actual occupancy levels. The profiles with detected occupancy levels can be used to represent the control of lighting and HVAC systems with occupancy-sensing control; both for specifying the heat generation from lighting fixtures and to control the on/off switching and change of air flow rates and room temperature set-points with control functions in a simulation tool. The curve representing the actual occupancy levels can be used to specify the heat generation from occupants and plug-loads (e.g., a PC with stand-by function). The profiles were constructed so that the shape of them represents the occupancy in one organisation, rather than the average of many.

Figure 6.4 shows three sets of constructed 24-hour profiles of occupancy in office cells, representing organisations with high, medium and low occupancy respectively. These profiles can be combined with the data in the box and whisker plot in Figure 6.1, showing the daily averages of *OFz*. By multiplying with a factor, the profiles can be corrected so that the daily average *OFz* corresponds to a day with peak or close to peak occupancy loads, for instance, as input to a cooling load simulation. A daily average of approximately 0.7 between 6 a.m. and 6 p.m. can according to the data be a suitable occupancy load in a calculation or simulation of a day with peak, or close to peak, average occupancy. To get a 24-hour profile for a day with $\overline{OFz}^{6-18}$ equal to 0.7, the profiles representing high average occupancy have to be multiplied with 1.35. Then, the hourly *OFz* reaches a peak of 0.98 (20 minutes *TD-OFF*) and just below 0.9 (actual occupancy) between 11:00 and 12:00 and between 14:00 and 15:00.

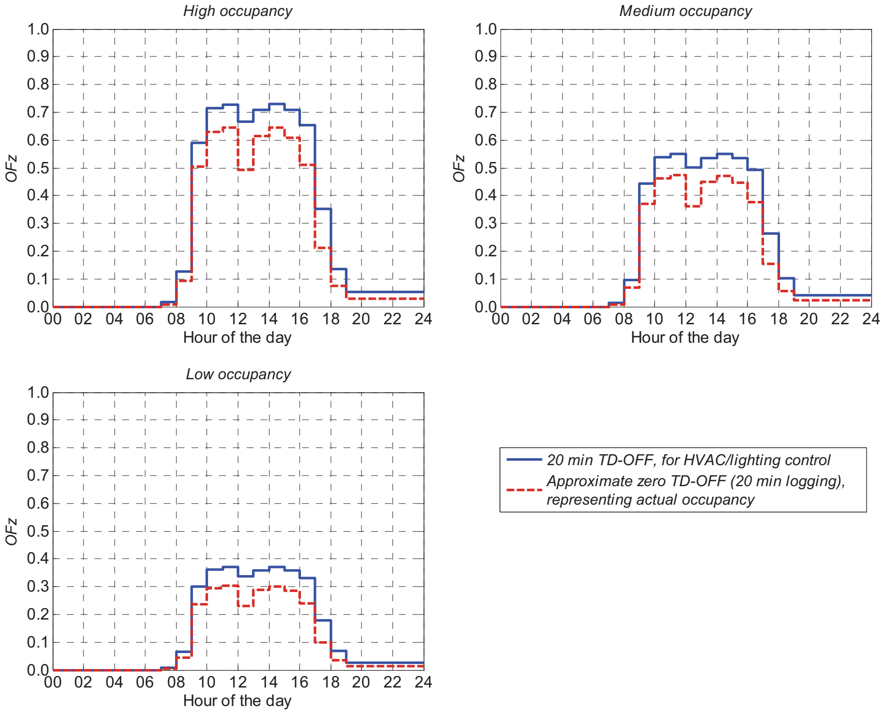


Figure 6.4 Three sets of 24-hour profiles for occupancy in office cells during working days, representing organisations with high, medium and low occupancy, respectively.

The construction of the profiles followed the following procedure:

1. *Organisation E* was excluded because three out of ten rooms were two-person office cells. The remaining ten room samples were divided in two groups: one with high occupancy (*Organisation A*, *B*, *H*, *I* and *J*) and one with low occupancy (*Organisation C*, *D*, *F*, *G* and *K*).
2. The yearly average profile for each of the organisations was adjusted so that lunch occurred simultaneously for all ten profiles. All ten profiles were then averaged and recalculated to hourly averages. This was done both for the profiles with 20 minutes *TD-OFF* and the profiles with approximate zero *TD-OFF*. This resulted in the two profiles representing a medium occupancy level. To simplify the profile somewhat, the hourly averages between 00:00 and 07:00, which all where close to 0, were approximated to 0. In addition, the small variations after 19:00 were eliminated by taking the average of all five hours from 19:00 to 00:00.

3. The two medium occupancy profiles were then multiplied with a factor, so that the profiles representing a high occupancy level have a 24-hour average equal to the average of the five room samples in the group with higher occupancy. This means that the levels of the profiles were increased but the shape of the profiles remained the same. The same procedure was then repeated to construct the profiles representing organisations with low occupancy.

6.2.3 Influence of *TD-OFF*

Figure 6.5 shows the effect of changing *TD-OFF* on the average *OFz*. The gradient of the curve is decided by the occupancy pattern (frequency and duration of actual occupancy and vacancy periods) and the occurrence of false-detections. In *Building 3*, housing *Organisation D*, the data were logged with 5 minutes *TD-OFF* during the first three working days of the monitoring period. These days are not included in the other results, but are included here to show the effect of a lower *TD-OFF*. Three graphs are shown for *Organisation E*. The results presented so far and in the remaining part of this chapter are based on the detector that was used in all of the monitored rooms. Here, results for the other two types of detectors are also included. The graph for *Organisation A*, labelled “no false detection” is based on estimates of a fictitious perfect detector completely without false-detections.

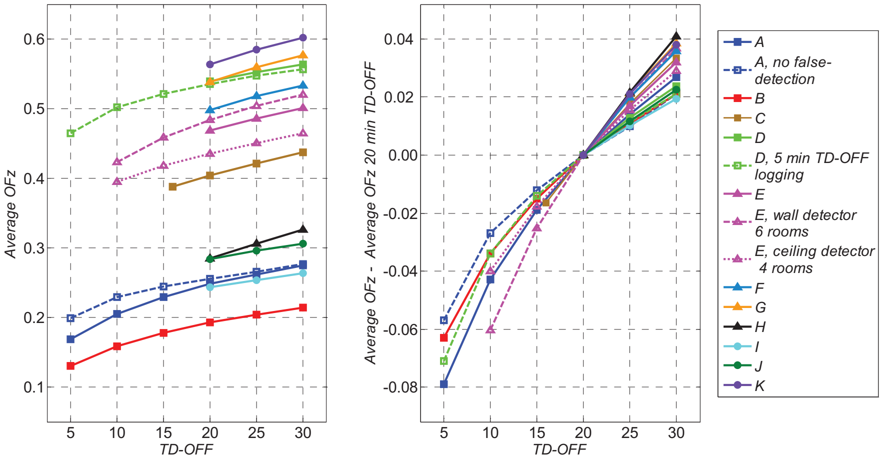


Figure 6.5 *The effect of changing TD-OFF on* $\overline{OFz}^{06-18,wd}$.

The differences between the cases, regarding the effect of changing *TD-OFF*, are small. The figure indicates the following rule of thumb: a modification of *TD-OFF* in the range from 10 to 30 minutes will lead to a change of $\overline{OFz}^{06-18,wd}$ with between 0.01 and 0.02 for every 5 minute increase or decrease of *TD-OFF*. Increasing *TD-OFF* from 20 to 30 minutes, to reduce the risk for false-negative detection, will not increase the average *OFz* by more than 0.04 in any of the cases, and thereby not have any large impact on annual operation hours of the building services that the detectors control.

6.2.4 Weekly profiles

None of the organisations have an occupancy profile that shows a considerably higher or lower average occupancy on some of the weekdays; the average occupancy is rather evenly distributed from Monday to Friday. The occupancy during weekends is low for all organisations.

6.2.5 Duration curves and peak loads

Figure 6.6 shows duration curves for *OFz*, where the percentages on the x-axis represent the fraction of operation hours for a ventilation system that operates between 6 a.m. and 6 p.m., on working days only.

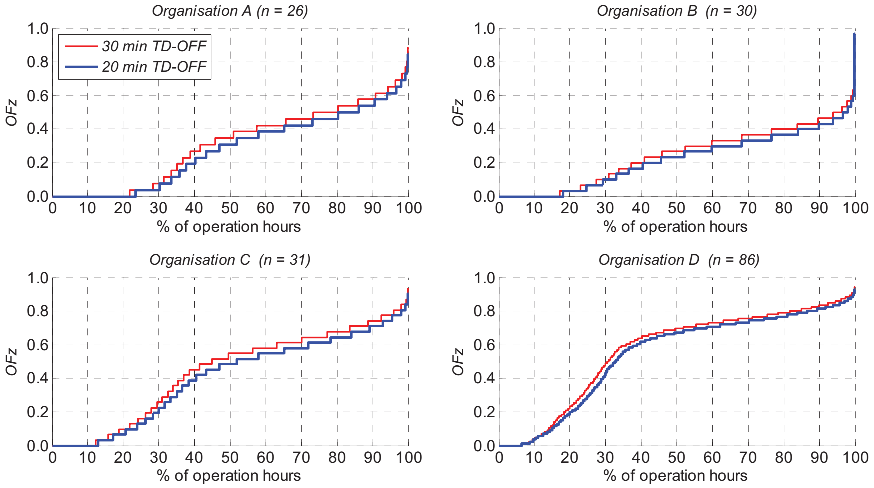


Figure 6.6 Duration curves for OFz for working days between 6 a.m. and 6 p.m.

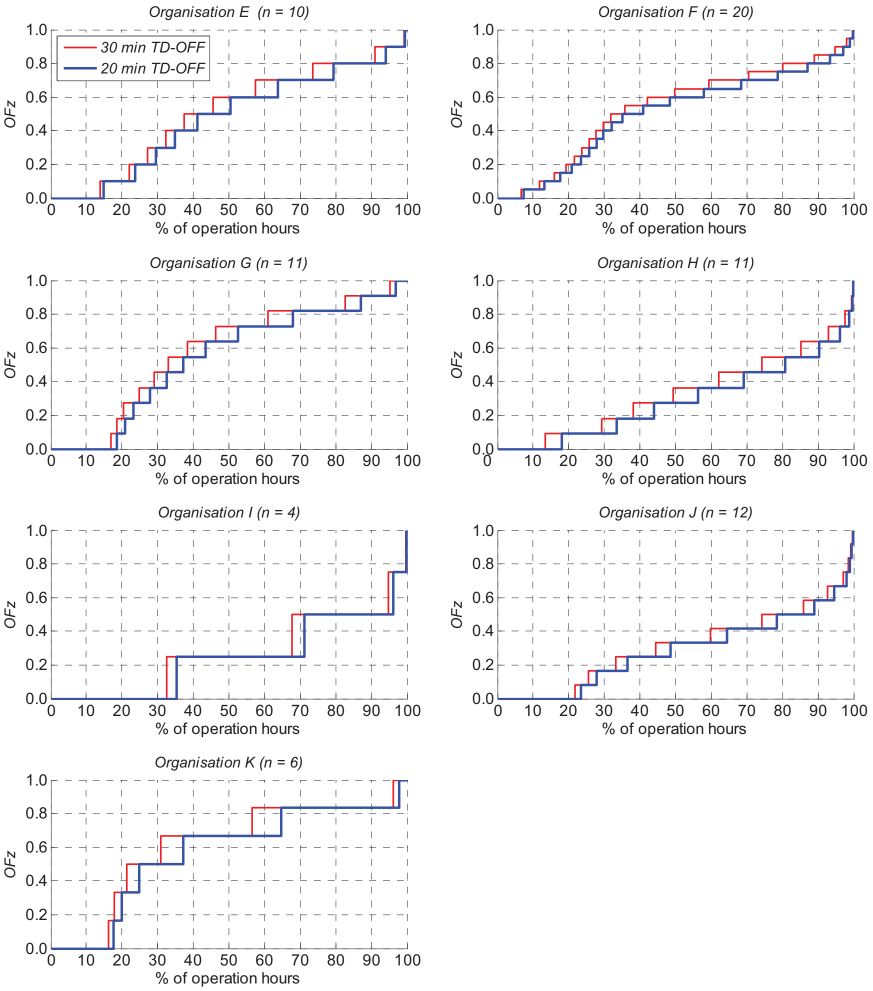


Figure 6.6 continued.

The duration curves for the different organisations should not be compared without having in mind that the size of the room samples differs considerably. The probability for a high peak level of *OFz* will decrease if the number of rooms in the zone it refers to is increased. The peak levels, or close to peak levels, of *OFz* will probably be a function of (a) the average level of *OFz*; (b) the number of rooms; and (c) to what extent co-ordinated activities takes place, such as scheduled meetings.

The influence of the number of rooms on peak or close to peak levels of *OFz* was investigated by randomly selecting room samples with different size. The procedure is here described for the data from *Organisation D*, which included 86 office cells. From the 86 rooms, a sample of 10 rooms was selected randomly. This was repeated 100 times, resulting in a set of 100 samples, each containing 10 rooms. The 95th percentile, 98th percentile and the maximum $OFz_D^{06-18,wd}$ were then computed for each of the 100 samples and the median for each of these three measures was saved. This procedure was then repeated with 15, 20, 25, 30, …. , 75 and 80 rooms in each of the 100 randomly selected room samples. Figure 6.7 shows a plot of the medians for the 95th percentile, 98th percentile and the maximum $OFz_D^{06-18,wd}$.

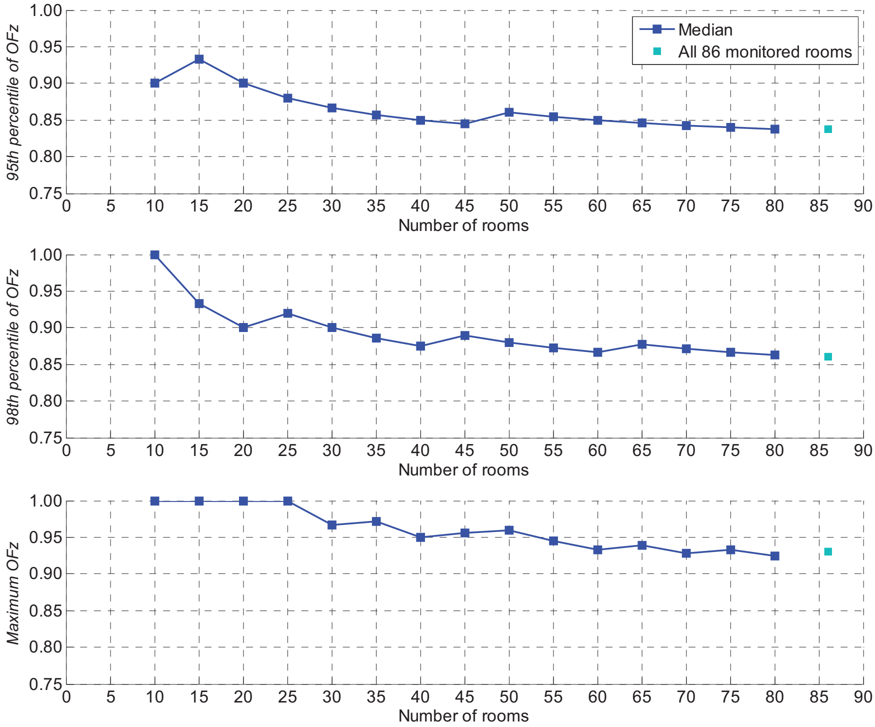


Figure 6.7 The influence of number of rooms on peak, or close to peak, occupancy ($OFz_D^{wd,6-18}$) in Organisation D.

The median decreases when the size of the room samples increases. The graphs are not smooth because the median is a discrete variable with number of possible values equal to the number of rooms it refers to. Taken this into account, then the median reaches the same level as monitored for all 86 rooms on a room sample size of 30, 35 and 55 rooms for the

95th percentile, 98th percentile and maximum *OFz*, respectively. For instance, the 95th percentile is 0.837 for all 86 rooms included, corresponding to 72 occupied rooms. With 0.837 · 30 rooms, we get 25.1 rooms. Hence, we can say that with 30 rooms, the median of the 100 samples should be 0.833 (corresponding to 25 occupied rooms) or 0.866 (corresponding to 26 occupied rooms) to have approximately the same 95th percentile of *OFz* as for all 86 rooms. As expected, it requires a higher number of rooms for the maximum *OFz* than for the 95th percentile to reach a point where a further increase in number of rooms do not have any affect on the outcome.

The computation procedure described above was used on the data from all organisations, except for *Organisation I* and *K* because of the low number of monitored rooms. The results of these computations are shown in Figure 6.8. The variation among the organisations is higher for the 95th percentile and the 98th percentile than for the maximum *OFz*.

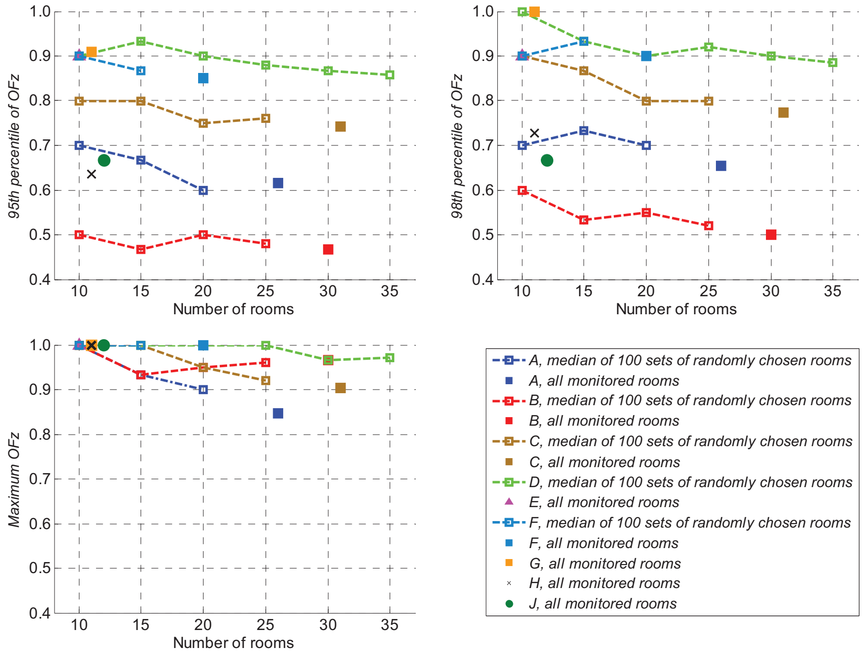


Figure 6.8 Peak, or close to peak, occupancy levels ($OFz^{wd,6-18}$) as a function of number of rooms in nine of the case organisations.

6.3 Results on individual room level

6.3.1 Utilisation rates

Figure 6.9 shows the utilisation rates in nine of the case organisations. The organisations shall not be compared with each other regarding the average level of *UR*, because the holiday periods are not excluded. This means that some of the cases have typical holiday periods included and some have not. However, the shape of the distribution and the sample range can be compared.

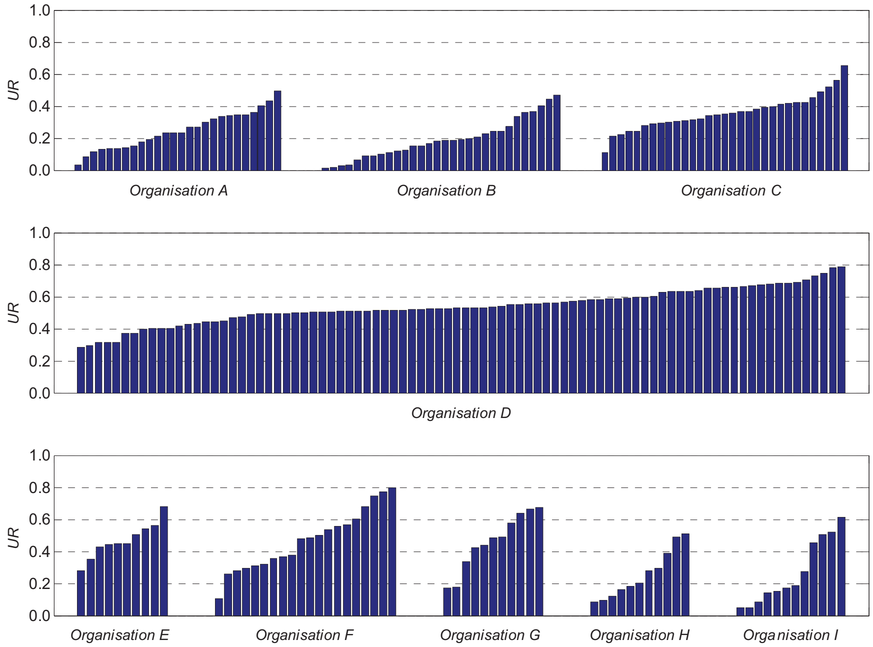


Figure 6.9 $UR^{wd,6\text{–}18}$*, with 20 minutes TD-OFF, for the monitored cellular offices in nine of the case organisations.*

Meeting rooms

Figure 6.10 shows utilisation rates for working days, both with 20 minutes *TD*-OFF and as estimates for actual occupancy levels, with 5 minutes *TD-OFF* for the rooms from *Organisation A* and *B* and approximate zero (20 minutes logging) *TD-OFF* for the remaining rooms. The exact *TD-OFF* for meeting room E-1 is unknown. It is between 20 and 25 minutes, and most likely closer to 20 minutes. The meeting rooms are, as for the office cells, seldom in use outside normal working hours (8 a.m. to 5 p.m.).

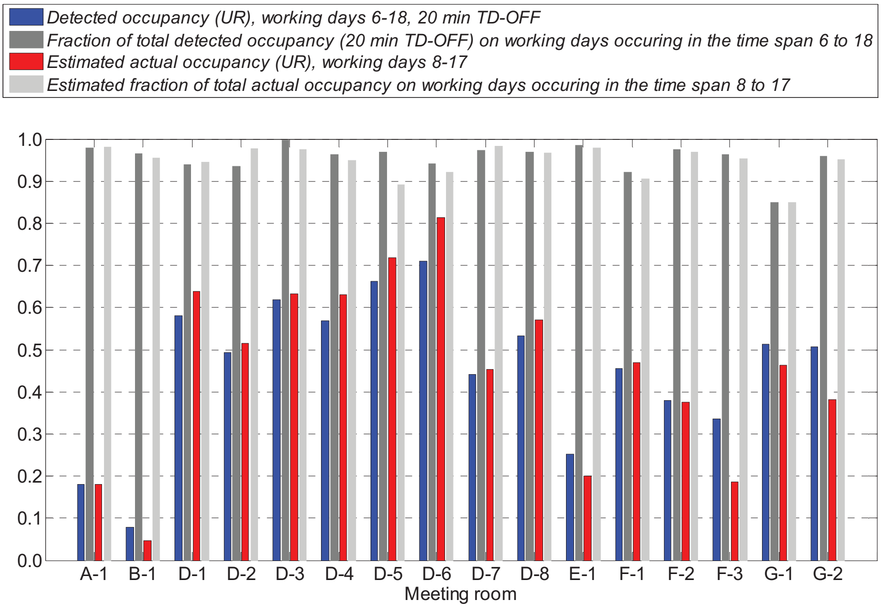


Figure 6.10 *Summary of the occupancy in the 16 monitored meeting rooms.*

6.3.2 Influence of *TD-OFF* for meeting rooms

The effect of changing *TD-OFF* on *UR* for the meeting rooms, shown in Figure 6.11, is somewhat higher than the effect on *OFz* for the office cells, i.e. the gradients of the graphs in Figure 6.11 is steeper than the ones in Figure 6.5. One exception is the meeting rooms in *Building 1* which are seldom in use, and with few occupancy periods, the effect of changing *TD-OFF* is small. This means that with 20 minutes *TD-OFF*, the detected occupancy patterns in most of the monitored meeting rooms were more intermittent than in most of the office cells.

The results fore meeting rooms indicate the following rule of thumb: a modification of *TD-OFF* in the range from 10 to 30 minutes will lead to a change of $UR^{6-18,wd}$ with between 0.01 and 0.04 for every 5 minute increase or decrease of *TD-OFF*.

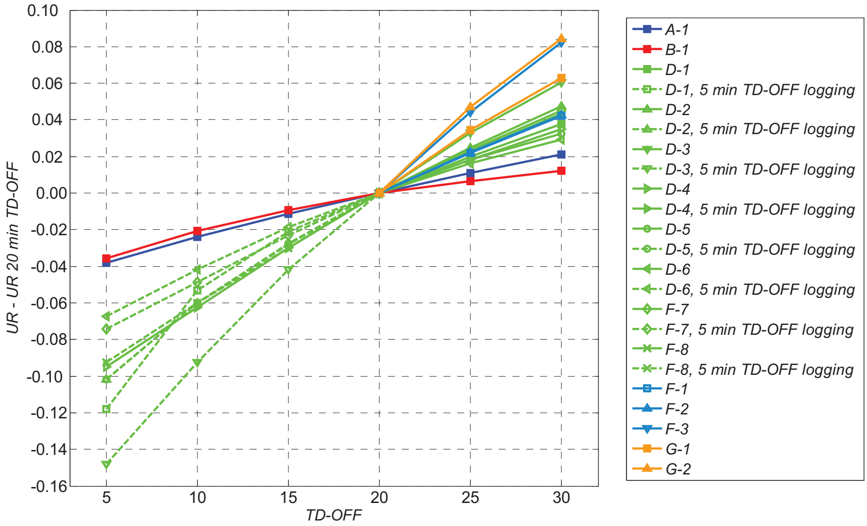


Figure 6.11 *Effect of changing TD-OFF on* $UR^{6-18,wd}$.

6.4 Comparison with other studies

In Chapter 3.2, published data of measured occupancy in office buildings were summarised. Case studies where occupancy has been measured in offices were searched for in the literature. A limited number of studies from Europe, Japan and North-America were found. These studies include too few cases to draw a conclusion valid for a large population of organisations. However, the studies indicate that most spaces for individual work, occupied by workers from one and the same organisation, have an average *OFz* between 0.25 and 0.55, with a mean somewhere around 0.4, measured over nine hours per working day.

Figure 6.12 shows a frequency distribution of both the 11 cases organisations presented in this chapter and other cases published in the literature. As the figure shows, the average *OFz* of the 11 cases presented here is close to what is presented in the reviewed case studies presented in chapter 3; around 0.4 for working days between 8 a.m. and 5 p.m., estimated to represent actual occupancy levels (approximate zero *TD-OFF*). While the cases presented in Chapter 3 indicate a symmetric distribution of *OFz*, the eleven cases presented in this chapter are more spread and separated in two groups, one with lower *OFz* levels and one with higher *OFz* levels. However, with only 11 room samples, it can not be concluded on the distribution of Norwegian office organisation in general.

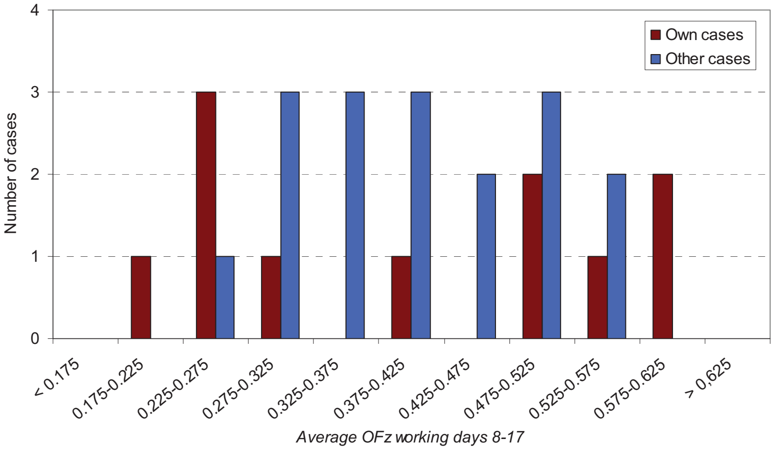


Figure 6.12 Comparison of $\overline{OFz}^{8-17,wd}$*, estimated to represent actual occupancy levels, in the 11 case organisations (own cases) and other cases reported on in the literature (reviewed in Chapter 3).*

Measurements from five different university buildings (two located in Sweden, one in Austria, one in USA and one in Canada) were consistent regarding *OFz*. According to these measurements, a guideline value for *OFz* for individual workspace in university buildings could be 0.35, as an average over nine hours per working day, during periods of the year with normal occupancy. *Organisation B*, a university college, had an $\overline{OFz}^{8-17,wd}$ equal to 0.25, i.e. lower than the other similar organisations, but at the same time confirming that the occupancy in university buildings is low. In *Organisation E*, a combination of scientists in a research organisation and academics at a university is estimated to approximately 0.4 if all occupants would have been working in one-person office cells, i.e. close to 0.35.

The published data referred to in Chapter 3 indicate that most meeting and conference rooms seem to have low utilisation rates; seldom higher than 0.45, and an average around 0.25 to 0.30, for the core occupancy hours on working days. The variation regarding *UR* among the monitored meeting rooms presented in this chapter is large. Many of the meeting rooms, especially the eight rooms in *Organisation D*, have higher utilisation rates than what is reported in the cases presented in Chapter 3. However, compared to individual workspace, the utilisation of meeting and conference rooms are to a higher degree dependent on spatial parameters of the building, i.e. the number and size of available rooms for group work. Hence, the variation can be caused both by differences in space layout and by differences in work style.

6.5 Summary

Occupancy has been monitored in cellular offices and meeting rooms in 11 case organisations, distributed on five Norwegian office buildings. The data set included 247 cellular offices and 16 meeting rooms The average occupancy factor for the 11 cases is approximately 0.4, both for estimated actual occupancy during working hours ($\overline{OFz}^{8-17,wd}$) and for detected occupancy with 20 minutes *TD-OFF* between 6 a.m. and 6 p.m. ($\overline{OFz}^{6-18,wd}$). This is consistent with the occupancy data presented in other case studies, referred to in Chapter 3. The cases can roughly be divided into two groups, one with lower and one with higher occupancy. $\overline{OFz}^{06-18,wd}$ with 20 minutes *TD-OFF* and the estimated actual occupancy level $\overline{OFz}^{08-17,wd}$ are both in the range from about 0.2 to 0.3 for the group with lower occupancy (five cases) and in the range from about 0.4 to 0.6 for the group with higher occupancy (six cases).

The results for close to peak levels (95th and 98th percentiles of *OFz*) are not directly comparable between cases. First of all, one has to keep in mind that *OFz* is a discrete variable, with number of possible values equal to the number of rooms it refers to. The choice of percentile can have a large effect on the outcome, especially for a small room sample. For instance, the 98th percentile of $OFz^{wd,6-18}$ is 1.0 for the six rooms in *Organisation K* and drops down to 0.83 for the 97th percentile. Second, the sample size will influence the probability for a high peak occupancy level to occur. However, when taking the effect of the sample size into account there are still significant differences between the organisations regarding peak levels of *OFz*. The data from the nine case organisations with ten monitored office cells or more indicate that in a zone with between 10 and 30 office cells, we can expect roughly the following close to peak levels of $OFz^{6-18,wd}$:

- 10 rooms: 0.50-0.95 for the 95th percentile and 0.60-1.00 for the 98th percentile
- 20 rooms: 0.50-0.90 for the 95th percentile and 0.55-0.90 for the 98th percentile
- 30 rooms: 0.45-0.85 for the 95th percentile and 0.50-0.90 for the 98th percentile

Table 6.3 summarise the occupancy in the 11 monitored case organisations. All results in the table are with holiday periods excluded.

Table 6.3 Summary of monitored occupancy in 11 case organisations, holiday periods excluded

Org.	Room sample size: Office cells/ meeting rooms	Cellular offices				Meeting rooms
		$\overline{OFz}^{8-17,wd}$	$\overline{OFz}^{6-18,wd}$	95th percentile of $OFz^{wd,6-18}$	98th percentile of $OFz^{wd,6-18}$	Average $UR^{6-18,wd}$
		TD-OFF (minutes)				
		Approx. 0	20	20	20	20
A	26/1	0.25	0.28	0.62	0.65	0.18
B	30/1	0.19	0.22	0.47	0.50	0.08
C	31/0	0.41	0.40	0.74	0.77	-
D	86/8	0.62	0.54	0.84	0.85	0.58
E	10/1	0.52	0.47	0.90	0.90	0.25
F	20/3	0.52	0.50	0.85	0.90	0.39
G	11/2	0.57	0.54	0.91	1.00	0.51
H	11/0	0.24	0.28	0.64	0.73	-
I	4/0	0.26	0.24	0.50	0.75	-
J	12/0	0.30	0.28	0.67	0.67	-
K	6/0	0.59	0.56	0.83	1.00	-
Average		0.41	0.39	- [a]	- [a]	0.46

[a] Not relevant due to large differences in room sample size (which influences peak levels of *OFz*).

Finally, the monitored occupancy indicates the following rule of thumb regarding *TD-OFF*: a modification of *TD-OFF* in the range from 10 to 30 minutes will lead to a change of $\overline{OFz}^{06-18,wd}$ with between 0.01 and 0.02 for cellular offices and a change of $UR^{6-18,wd}$ with between 0.1 and 0.04 for meeting rooms, for every 5 minute increase or decrease of *TD-OFF*.

PART III:

EXAMPLES OF APPLICATION AND CONCLUSIONS

Part III consists of two chapters:

Chapter 7 addresses different topics related to selection and sizing of components in ventilation systems, with special emphasis on demand controlled ventilation systems, and uses the occupancy data from the *Building 1*, presented in Chapter 5, to illustrate some potential sectors of application of empirical occupancy data.

Chapter 8 presents the main conclusions that can be drawn from the work and provides some suggestions for further research.

7 Selection and sizing of ventilation system components

The aim of this chapter is to show some examples of application of the occupancy data collected and presented in Part II. The data from *Organisation A* and *B* is used for that purpose.

7.1 The simultaneous factor (*S*)

During sizing of a ventilation system and selection of components, not an occupancy level, but the air flow rate passing through the components, is what the designer base the sizing on. Therefore, it is convenient to convert the occupancy load to a simultaneous factor related to the air flow rates in the ventilation system. The simultaneous factor *S* was defined by Mysen et al. (2003) for evaluation of energy saving potential for DCV systems. In the case of cellular offices where the ventilation is controlled by motion detectors, *OFz* together with the air flow rate when an office is occupied and unoccupied respectively, are needed to compute *S*.

The simultaneous factor S_I, defined in Definition 7.1**,** is simply a rate that expresses the total ventilation flow rate in a zone compared to the flow rate required if all sub-zones of zone *I* is occupied simultaneously.

Definition 7.1: For zone *I*, consisting of sub-zones with ventilation controlled by motion detectors and with equal air flow rates in all sub-zones; let OFz_I be the zone based occupancy factor and *b* the ratio between the air flow rate of an unoccupied sub-zone and the air flow rate of an occupied sub-zone ($b = q_{unocc}/q_{occ}$). Then, the simultaneous factor *S* of zone *I* can be expressed mathematically:

$$S_I = OFz_I + b - b \cdot OFz_I \qquad (7.1)$$

with limits:

$$0 \le S_I \le 1.0$$

Definition 7.1 is only valid for systems with motion detectors, and where the ventilation flow rate is altered between two levels. It is important to stress that S is not synonymous with the ratio between the total air flow rate supplied to a zone and the design ventilation flow rate for that zone, because the design ventilation flow rate can be chosen lower than the flow rate corresponding to S equals 1.0.

Equation 7.1 is only valid if the ventilation flow rates for occupied and unoccupied offices are identical in all sub-zones. If this is not the case, sub-zones having equal q_{occ} and q_{unocc} shall be grouped together and thereby dividing the zone I into several smaller zones. Then, S_I can be computed according to Equation 7.2:

$$S_I = \frac{\sum_{x=1}^{N} S_{Jx} \cdot n_{Jx} \cdot q_{occ,Jx}}{\sum_{x=1}^{N} n_{Jx} \cdot q_{occ,Jx}} \qquad (7.2)$$

where

S_I Simultaneous factor for zone I, which constitutes of N smaller zones, i.e. $I = \{J1, J2, \dots, JN\}$

S_{Jx} Simultaneous factor for zone Jx, which constitutes of n_{Jx} sub-zones, i.e. $Jx = \{i_1, i_2, \dots, i_n\}$, computed according to Equation 7.1

$q_{occ,Jx}$ Ventilation flow rate in the sub-zones belonging to zone Jx, when occupied

In this chapter, only S values for offices with equal q_{occ} and q_{unocc} in all sub-zones are presented.

The total air flow rate $q_{DCV,I}$ supplied to zone I in a DCV system with motion detectors for ventilation flow rate control, can be expressed as:

$$q_{DCV,I} = q_{occ} \cdot n_I \cdot S_I \qquad (7.3)$$

where

n_I Number of sub-zones in zone I

Consequently, $q_{DCV,I}$ is proportional to S_I and will vary as the occupancy state of the sub-zones of zone I changes. In the following, the air flow rate that corresponds to a certain level l of S_I will be denoted $q_{DCV,I}(S=l)$. In Equation 7.3, $q_{occ} \cdot n_I$ is equal to $q_{DCV,I}(S=1.0)$.

Hence, if it is decided to take the simultaneous factor into account when sizing a component in the ventilation system, the air flow rate that the sizing shall be based on can be found by: first, decide the value of S_I for the zone I that the ventilation air that flows through the component is supplied to/extracted from; and second, multiply S_I with $q_{DCV,I}(S=1.0)$. Of course, other correction factors can be used in addition, so that the final computed design air flow rate is further adjusted. If zone I, in addition to having DCV with motion detectors, also has zones with CAV, then S_I can easily be calculated with Equation 7.2, by using Jx equals 1.0 for the zones having CAV.

The focus in this chapter has so far been mostly on cellular offices. However, as mentioned earlier, the approach of using an occupancy factor in sizing procedures can also be relevant in, for example, open plan offices. In Norway and also many other countries, the ventilation flow rate is often calculated as a sum of two parts: one part expressing the air flow rate per person (q_P) and one part expressing the air flow rate per unit area (q_A). For an open plan office, S_I can therefore be expressed as:

$$S_I = \frac{OFp_I \cdot np'_I \cdot q_P + q_A}{np'_I \cdot q_P + q_A} \tag{7.4}$$

where

np'_I Number of persons per square meter

A duration curve of S, based on measured data of OFp and computed according to Equation 7.4, will represent the distribution of the ventilation flow rate demand rather than the air flow rates that a DCV system will deliver. None of the conventional control strategies for DCV in open-plan offices, using CO_2-sensor(s) or motion detectors covering more than one workstation (less common), will supply air flow rates that exactly match the demand expressed by Equation 7.4 at every time, even though the sensors works as intended. Finding a representative S for sizing of a DCV system with CO_2-sensor(s), based on expected occupancy levels, may require dynamic calculations.

7.2 Sizing

For buildings with DCV systems, there is an opportunity to use an occupancy factor as a correction factor when sizing centrally located components, such as main ducts and AHUs.

This approach can, however, also be relevant for CAV systems supplying ventilation to one or several larger open zones. These are zones where it could be expected that *OFz* never reaches the design occupancy load (e.g. equal to the number of workstations in an open plan office) or at least only have short-lived occupancy peaks reaching up against or equal to the design load. Moreover, a special case for CAV systems where this approach could be conceivable is in buildings with cellular offices that have supply air only, and transferred air to a larger zone with both supply and extract air. If it is assumed that all office cells never, or very seldom, are occupied simultaneously, there may be a possibility to decrease the design supply flow rate in the larger zone, because the transferred air from an empty office is less polluted than from an occupied office. This is the same way of thinking as proposed in a Swedish guideline for office design already in 1967 (Byggnadsstyrelsen, 1967). It was suggested that the amount of outdoor air in offices could be reduced in systems with recirculation, because a fraction of the extract air (equals 1 - *OFz*) origins from unoccupied offices and is consequently not polluted by humans, which at that point of time was considered to be the main indoor pollution source in offices.

The presentation of the data in this part is focused on DCV systems where the ventilation flow rate is controlled exclusively by people being present or not. However, DCV systems in most office buildings in Norway with cellular offices have motion detectors in combination with temperature sensors for control of the ventilation flow rate in the office cells. In these buildings, temperature control is determinant for the size of the AHUs and distribution system. However, the occupants themselves are a non negligible part of the internal heat loads in an office building and the use of office equipment and artificial lighting are to some extent dependent on the occupancy level as well. In addition, manual control of, for example, venetian blinds and windows are related to occupancy and influence the solar gain. Furthermore, the set-point for cooling can be automatically adjusted when the room is unoccupied. All together this means that the occupancy level can have a significant influence on the cooling demand. Consequently, the peak levels of *OFz* are of interest in the sizing procedure also when requirements related to thermal indoor climate is the determining factor for the design ventilation flow rate of a DCV system. In the same way, peak levels of *OFz* are also of interest for CAV systems supplying ventilation to, for example, open plan offices, where the air flow rate is decided by the cooling demand. Because the distribution of *OFz* is only one of several inputs to a cooling demand and thermal climate calculation, no attempt has been made to present data that could have been used directly as a correction factor for such systems.

7.2.1 Duration curves for *S*

Figure 7.1 shows the duration curves for *S*, computed from the corresponding duration curves for *OFz*, for *Organisation A* and *B* respectively. The area above the curves up to *S* equals 1.0 represents the reduction in annual amount of ventilation air for a DCV system with occupancy-sensing control compared to a CAV system, presumed that the air flow rate in the CAV system q_{CAV} equals $q_{DCV}(S=1.0)$. To illustrate the effect of changing *b*, results are presented for four values of *b* (0, 0.25, 0.50 and 0.75). For *b* equals zero, *S* is identical to *OFz.* If the reader is interested in *S* for other values of *b*, it can easily be computed from the curve with *b* equals 0 in Figure 7.1, by the use of Equation 7.1.

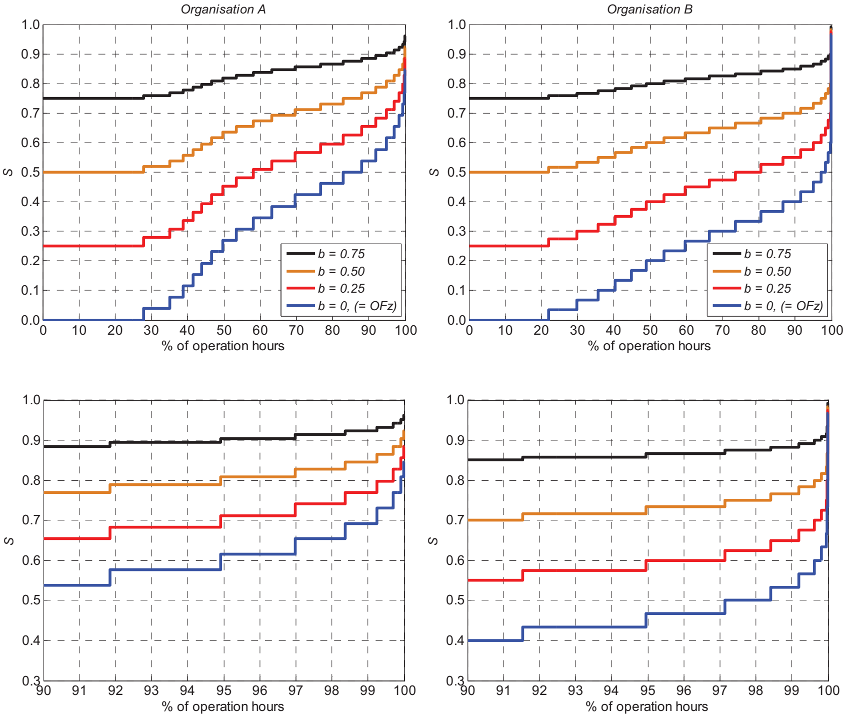


Figure 7.1 Duration curves for S for the operation hours (6 a.m. to 6 p.m. on working days), with different values of b for Organisation A (upper left) and Organisation B (upper right) with extracts showing the last tenth of the duration curves below.

There is an interesting difference between the graphs of *Organisation A* and *Organisation B* in Figure 7.1 from a ventilation design point of view. For instance, imagine that these data were available when designing a ventilation system in *Building 1*, and it was decided on 20 minutes *TD-OFF* and ventilation air flow rates that resulted in a *b* of 0.5. With these prerequisites, *Organisation B* has a maximum *S* of 0.984, which is higher than for *Organisation A*, with a maximum *S* of 0.923. If centrally located components are sized based on these maximum *S* values instead of *S* equals 1.0, the potential to reduce the size of these components is larger in *Organisation A* than in *Organisation B.* However, if it is accepted to size the components based on an *S* smaller than the expected maximum *S*, then the situation is the opposite, with a larger potential for size reduction in *Organisation A*. This is because *Organisation B* has a few short-lived peaks and consequently a very steep ending of the duration curve. For example, if a level of 97.5 % of the normal working hours is used as design criterion, *S* is reduced down to 0.827 in *Organisation A* and down to 0.750 in *Organisation B*.

As already mentioned, a CAV system with capacity corrected for *S* may in some cases be a suitable solution in open plan offices. In that case, Equation 7.4 can be used to evaluate the necessary capacity of the system. For instance, imagine that the curve for *b* equals 0.5 for *Organisation B* in Figure 7.1 instead represented the ventilation demand in an open plan office. Then, the design ventilation flow rate in that zone could, for example, be set to 75 % of the flow rate that conventional design practice would have given, i.e. corresponding to *S* equals 1.0. For a CAV system fixed at this ventilation flow rate, it means that there will be a shortage of ventilation air in 2.5 % of the annual operation hours, compared to the demand. The consequences of that are dependent on several factors and must of course be carefully evaluated. One important factor is how this shortage of ventilation is distributed over time.

7.2.2 Safety margins

It is common practice to use a safety factor (*sf*) in sizing procedures in general, and sizing of ventilation systems is no exception. One example is selection of an AHU among a couple of size alternatives from one and the same producer. The AHU must have enough capacity to deliver the design air flow rate at the computed design pressure drop. In addition, it has to be able to condition the air to a specified state (temperature and humidity) during summer and winter design conditions. Moreover, other prerequisites and requirements, such as space limitations and noise, and of course economical evaluations, will influence the choice. For a given design pressure drop, the fan system, i.e. the combination of the fan, transmission, motor and motor control equipment, decides the air flow capacity. For one and the same AHU size, there may be more than one fan size to choose between and for each fan size, more than one motor alternative. This means that there can be two or more AHU sizes, and for each of these it can be several fan and motor alternatives, that can deliver a specific air flow rate at a given pressure drop.

The required ventilation flow rate is calculated based on requirements for indoor air quality (IAQ) and thermal indoor climate. This can be adjusted by multiplying it with a safety factor and/or other correction factors to find the design air flow rate. The simultaneous factor can be one such other factor. The safety factor can either be used directly when calculating the required ventilation flow rate, i.e. that the system is balanced and adjusted to operate with a larger air flow rate already from the start, or as a spare capacity that can be used later on if it shows to be necessary. Although there may be several fan system alternatives to choose between, the capacity will seldom match the design air flow rate perfectly. Hence, there will often be some degree of safety margin independent on whether an intentional safety factor is used or not.

Safety factors and fan systems

The safety factor can take several aspects into account. First, either the calculated design ventilation flow rate does not match with the actual demand or the calculated pressure drop is to low. This can be discovered either during testing and balancing of the system or after the handover when the system has been in operation for a while. Second, the ventilation demand can change in the future, for example, due to higher expectations or changing needs regarding the indoor environmental quality (IEQ) among the building occupants, more stringent authority requirements or alterations in the use of the premises. The safety margin also functions as a spare capacity if the selected size of the fan system was based on a simultaneous factor below 1.0 and the assumptions made about *OFz* proved to be incorrect, i.e. peak level of *OFz* turned out to be higher than expected. This results in a need to move the operating point of the fan at design air flow rate which can be done either by changing the fan characteristic or by changing the system characteristic. The possibility for doing that is dependent on the fan system, i.e. type and available spare capacity, and on the location of any potentially installed dampers.

Example 7.1

A new large office building is under construction. It will be the new head office for a company. It is decided to use motion detectors to control ventilation flow rates in cellular offices, with b equals 0.5. It is assumed that the maximum *OFz* is below 0.7, based on one week of observations at the office premise where the organisation is located before moving into the new building. The designers decide to use an *OFz* equals 0.7, resulting in an S equals *0.85*, when selecting the AHUs. The designers select fans with asynchronous motor and frequency converter for fan speed control. For the selected fan system in one of the AHUs, the estimated operation point of the fan at $q_{DCV}(S=0.85)$ is at approximately 75 % of the motor load at maximum speed. The resulting *sf*, expressed in terms of motor power and in terms of air flow rate is approximately 1.3 and 1.1, respectively. This means, provided that the pressure drop calculations are correct, that the maximum capacity of the selected fan system is $q_{DCV}(S=0.935)$, i.e. 6.5 % below the ventilation demand if all office cells were in use simultaneously, i.e. $q_{DCV}(S=1.0)$.

With the choices made by the designers, *OFz* has to exceed 0.87 for a shortage of air flow rate capacity, compared to the demand, to occur. Although, the assumed maximum *OFz* level involves a certain degree of uncertainty, it is understandable if the design team considers the probability for *OFz* exceeding 0.87 to be low. However, the data for *Organisation A* and *B* indicates that the maximum occupancy level easily can be underestimated in some organisations where *OFz* in most of the time is low. *OFz* is equal to or less than 0.47 and 0.62 in 95 % of operation hours, while the maximum, on the other hand, is as high as 0.85 and 0.97, in *Organisation A* and *B* respectively. Another possibility is that the design team considers the possibility for *OFz* exceeding 0.87 high enough not be disregarded, but assumes that the peaks are short-lived and therefore considers the consequences for the IEQ to be acceptable if it occurs. In *Organisation B, OFz* exceeds 0.87, but this occurred only a few times during one year of monitoring.

If there for some reason shows to be a need for increasing the ventilation flow rates in the office cells and it is decided to adapt the system to higher flow rates, part of the safety margin is consumed, and the possibility for a shortage of capacity to occur is increased. For instance, if the flow rate in both occupied and unoccupied offices is increased by 10 %, the whole safety margin is used up, and the risk for the demand exceeding the capacity has increased significantly. Now, *OFz* only have to exceed 0.7 for this to happen. Again, returning to *Organisation A* and *B* as examples, this occurs only for 40 minutes in *Organisation B,* but for 23.4 hours during one year in *Organisation A*. The consequences of a potential shortage of air flow rate capacity has to be weighted against the potential gain of selecting a smaller fan and potentially also a smaller AHU.

Safety factors and duct sizing

The simultaneous factor can also be used when sizing other components than fans, such as main ducts. The standard duct sizes used in Europe follows approximately a Renard series with a factor of $10^{0.1}$ between each standard diameter from 63 mm up to 1600 mm. This is standardised in Europe, but sometimes a few other diameters outside this series are used in some countries (Malmström et al., 2002). Hence, a duct with a standard diameter will seldom match the design criterion exactly. Because it is common to select the larger of the two diameters with velocity or pressure drop closest to the design criterion, there will generally be a safety factor also for ducts.

Example 7.2

Assume that the designers use 8 m/s as a rule of thumb for sizing main ducts in the same building project as in Example 7.1. Moreover, assume that they use the same *S* (0.85) as for the fan, when sizing the first duct section of the supply side after the AHUs. First, assume that the air flow rate $q_{DCV}(S=0.85)$ for the selected duct size gave an air velocity of 7.27 m/s, resulting in a safety margin of 10 % up to the design criterion (the same as for the fan). Then, if *OFz* reaches 0.87, the velocity in the duct will be equal to 8 m/s. However, if *OFz* rise above 0.87 the velocity will not increase further, because the maximum capacity of the fan is reached. If $q_{DCV}(S=0.85)$ instead gave a higher velocity than 7.27 m/s, the velocity can exceed 8 m/s and this will occur at a lower *OFz* than 0.87, because now the safety margin for the capacity of the fan is larger than the safety margin of the duct. The maximum velocity that can occur is 8.8 m/s, which is possible if $q_{DCV}(S=0.85)$ results in a velocity of exactly 8 m/s and *OFz* exceeds 0.87. If $q_{DCV}(S=0.85)$ gave a lower velocity than 7.27 m/s, the velocity will never reach 8 m/s, independent on the value of *OFz*.

If we at last, look at what happens if the fan is not sized according to an *S* below 1.0, but the main duct is. Comparing two ducts with the same duct size and the same air flow rate at *S* equals 0.85, but in the first case with a fan sized according to *S* equals 0.85 and *sf* equals 1.1; and in the second case according to *S* equals 1.0 and *sf* equals 1.1. Then, the maximum velocity that can occur in the duct is higher in the latter case. For instance, if $q_{DCV}(S=0.85)$ gave an air velocity of 7.27 m/s, the maximum velocity that can occur is increased from 8 m/s in the first case to 8.55 m/s (7.27·1.0/0.85) in the second case. Hence, evaluating the consequences for sizing the duct work or other static components, such as outdoor air intakes, according to an *S* below 1.0 has to take the approach used for selection of the fan, regarding simultaneous and safety factor, into account.

7.2.3 Design level of *S*

In Definition 7.2 the level of *S* that the sizing of a component is based on if a simultaneous factor is taken into account is defined. To simplify and to avoid using more than one factor, the safety margin is included in this level.

Definition 7.2: During design of a ventilation system a simultaneous factor *S* can be used as a correction factor when selecting the size of some of the components. The design level of *S* is denoted $S\text{-}dl_I^c$ and can be different for different components *c,* where each component is connected to a certain zone *I* of the building. The chosen level of $S\text{-}dl_I^c$ can take into account the fact that there never or seldom is a need for the ventilation flow rate corresponding to all sub-zones of zone *I* reaching their design load simultaneously. In addition, $S\text{-}dl_I^c$ may include a certain level of safety margin, expressed by the safety factor sf^c. The time fraction denoted *T(S-dl)* expresses the percent of operation hours or number of hours within a specified time period (e.g., one year) in which *S* exceeds *S-dl*.

In addition to sizing of new ventilation systems, *S-dl* can also be relevant in some cases for evaluation of the size of components in existing systems. For instance, if one wants to increase the ventilation flow rates in a DCV system or an existing CAV system that will be rebuilt to a DCV system, it may be necessary to evaluate the size of the ductwork and thereby make some judgements of the simultaneous factor, in order to estimate the maximum expected air flow rate through the distribution system.

The maximum value on the y-axis of the duration diagram for *S* is 1.0. This is the reference point for *S-dl*. In the case of motion detectors for control of ventilation, this corresponds to the ventilation flow rate required if all sub-zones are occupied simultaneously. The value of *S-dl* must be related to the $q_{DCV}(S=1.0)$ that is decided on at the time for the selection of *S-dl*, because any potential future changes of the air flow rate is often unknown at that point in time. Returning to Example 7.1 and sizing of fans. In that example, *S-dl* is 0.935, including a safety factor of 1.1 for the fan system. The designers do not know at the time for the selection of the fan whether this safety margin will be used in the future or not. If this safety margin instead was added to the air flow rates (q_{occ} and q_{unocc}) and the same fan system was selected, then *S-dl* is decreased to 0.85 because $q_{DCV}(S = 1.0)$, which is the point of reference, is increased. Because the design level *S-dl*, as defined in Definition 7.1, includes the safety factor, it can have a value above 1.0. If the selected *S-dl* is above 1.0, it does not mean that there never will be a demand for the ventilation flow rate corresponding to *S-dl*. The fraction above 1.0 is a spare capacity that can be used later, if necessary.

Estimating *S-dl* for a fan system

For fans, *S-dl* corresponds to the maximum flow rate that the fan system can deliver through the air distribution system it is part of. The air flow rate capacity is dependent on where the system characteristic crosses the fan curve at maximum fan speed. There is always some degree of uncertainty in the pressure drop calculation, which makes it difficult to establish the exact location of the operating point for a fan. Moreover, if the estimate of *S-dl* is based on an *S* below 1.0, i.e. it is expected that all sub-zones never will be occupied simultaneously; then, the difficulty of establishing the value of *S-dl* is dependent on the type of flow rate control in the VAV-system. If the fan speed is controlled to keep a constant static pressure somewhere in the ductwork, it may be easier to estimate *S-dl* if the pressure sensor is located in the start of the main duct compared to if it is located longer away from the fan, for instance, at the start of the branch assumed to have the air path with the highest pressure drop. The latter location can be preferable to decrease the level of the constant static pressure, in order to save energy. However, if *S* is below 1.0, then the pressure drop calculation in the latter case must include an assumption of the air flow rate distribution in the system. One possibility is to assume that the air flow rates, relative to the design flow rates, are evenly distributed between the branch ducts. Another possibility is to base the estimate on the flow distribution giving the lowest value of *S-dl*. Then the safety margin is probably underestimated, rather than overestimated.

7.2.4 Using simultaneous factors in connection with duct sizing

The simultaneous factor changes with the position in the distribution system. More centrally located duct segments near the AHU have in general lower peak values of *S* than those located nearer the terminal ducts. Therefore, the use of a simultaneous factor for sizing of ducts is most relevant for main runs and possibly for the first duct segments of branch ducts having many terminal ducts attached. The criterion for selecting the size of a duct segment, is usually a maximum velocity or pressure drop, which is important foremost to limit the generation of noise. This also restricts the power demand for the fan system. In addition, the sizing aims at finding a pressure balance between different segments of the system and to limit the number of transitions. Furthermore, the available space is a limiting factor. A number of methods have been developed as guidance during sizing, such as the equal friction method and Bahcos 1/3-method (Stensaas, 1980). At times, the size of branch ducts is kept constant, which simplifies mounting and increase the flexibility, i.e. makes it easier to add new terminal ducts.

Independent of the selected approach for duct sizing, the starting point is always the air flow rate passing through the duct segment. For ducts, *S-dl* corresponds to the level of *S* that gives an air flow rate which exactly matches the design criterion for the selected duct size. This interpretation of *S-dl* is also valid for other components like outdoor air intakes and filters where one wants to keep the air velocity below certain limits. However, the following discussion will focus on ducts only.

In Example 7.2, *S-dl* is 0.935, which means that the air flow rate giving 8 m/s in the selected duct is 93.5 % of $q_{DCV}(S=1.0)$. In that example, the duct size was computed based on an *OFz* equals 0.7, giving an *S* of 0.85. As already discussed, it may be difficult to estimate *OFz* if no measurements of the organisation(s) have been carried out. Another possible approach, instead of first choosing a level of *S*, is to find the duct size that matches the design criterion with *S* equals 1.0 and afterwards find which level of *S* that is required to reduce the duct size and make a judgement based on that.

Figure 7.2 shows which level of *OFz* that is required to go one or two sizes down and still fulfil the design criterion. The figure is only valid if a maximum air velocity is used as design criterion and for circular ducts with a factor of 1.25 between the available standard diameters. This factor is not exactly 1.25 for the whole span of duct diameters used in Europe, but close to 1.25 (1.25-1.28) and the deviation from the curves in Figure 7.2 is therefore small. With a factor of 1.25 between two standard diameters, it is possible to get an air velocity that is between 64 % and 100 % of the design criterion. A corresponding figure for the other common design criterion, pressure drop per meter duct, can be found in Appendix A.3.

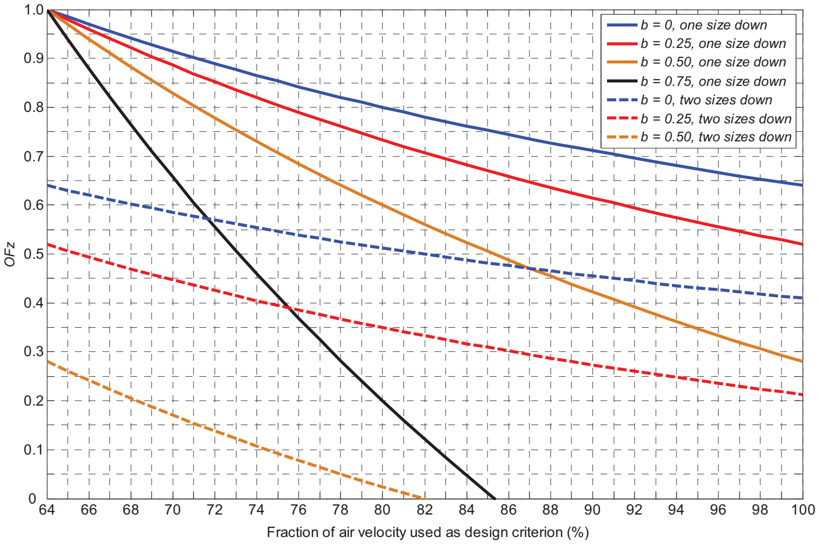


Figure 7.2 OFz levels needed to go one or two sizes down for circular ducts and still fulfil the maximum air velocity used as design criterion, as a function of the fraction of the design criterion that $q_{DCV}(S=1.0)$ *gives.*

The diagrams have been adapted to fit systems using motion detectors to control the ventilation flow rates between two flow rates (q_{unocc} and q_{occ}). However, if other sensors is used for flow rate control, then the blue curves (*b* = 0) can be used and the value on the y-axis shall be interpreted as *S*, i.e. the fraction of $q_{DCV}(S=1.0)$.

As seen by Figure 7.2, it is very seldom realistic to go two sizes down if the ventilation flow rates are controlled based on occupancy only. If we use *Organisation B*, which must be considered as having low occupancy, as an example and accept that the design criterion is exceeded for 5 % of the annual operation hours, which according to Figure 7.1 corresponds to *OFz* equals 0.467. Then, for *b* equals 0, i.e. no ventilation in unoccupied zones, there is a relatively large possibility to go two sizes down. However, *b* equals 0 is not a common solution in offices in Norway. With *b* equals 0.25, which also can be considered as low, the fraction of the design criterion has to be lower than approximately 68 %. This corresponds to a probability of 1/9, assumed that the probability for a certain fraction of the design criterion is evenly distributed between 64 % and 100 % of the design criterion. For *b* equals 0.5, an even lower level of *OFz* is required with this approach, and for *b* equals 0.75 there will never be an opportunity to go two sizes down.

If it is considered as an advantage to reduce the size of a duct segment, the three step approach listed below is suggested. Because the pressure drop of the distribution system will change if the size of some duct segments are reduced and the pressure drop is an input for selecting the fan, the final selection of the fan should not be done before these steps. However, the level of *S* and the minimum required *sf* for selecting the size of the fan should already be decided.

1. If it is desirable with a safety margin, multiply *sf* with $q_{DCV}(S=1.0)$. Otherwise, use $q_{DCV}(S=1.0)$. The safety factor should be identical to the minimum *sf* required when selecting the fan. Then, find the duct diameter fulfilling the design criterion.
2. With the duct diameter found in step 1, calculate the resulting fraction of the design criterion.
3. Find the level of *OFz* required to go one and two duct diameters down, according to the principles in Figure 7.2 (maximum air velocity as design criterion) or Figure A.3.7 (maximum pressure drop as design criterion). Make a judgment of the probability that this level will be exceeded or not, and then take a decision.

It is the last part, making a judgment on the probability for an *OFz* level to occur, which is the difficult part. Hence, this approach does not avoid the need for estimating such levels. However, if the second step shows that the fraction of the design criterion is high, i.e. far to the right in the diagram, there is most likely no need for an estimate because the necessary level of *OFz* is not realistic as design levels. If instead, the fraction of the design criterion gives an *OFz* which seems more realistic, the designer may consider going one size down. This *OFz* level do not necessary have to be identical to the level that the selection of the fan is based on. First, and as already mentioned, peak levels of *S* are in general lowest near the AHU, i.e. it is logical to increase *S-dl* throughout the distribution when moving away from the AHU against the terminal ducts. Second, the consequences if *S* is exceeding *S-dl* can be evaluated as being different for the ductwork and the fan. For instance, if the design criterion is 8.0 m/s for main ducts, it is most likely not critical if the air velocity is reaching 8.2 m/s for short periods.

In Norway, some designers make use of computerised tools to size the ductwork, while some designers make the calculation without such tools and instead use diagrams and tables to easily find velocities and pressure drops for different combinations of air flow rates and duct diameters. In Figure 7.2 and Figure A.3.7 curves are plotted for a limited number of values of *b*. To be useful in a sizing procedure, such a diagram should have curves for more values of *b*. In addition, four diagrams are suggested, one for each of the factors 1.25, 1.26, 1.27 and 1.28 between two standard diameters. The suggested approach could also easily be implemented in a computerized tool as part of the overall sizing and pressure drop computation procedure. With more data available than today, such tool could have included guidance of peak values of occupancy for different building categories and type of organisations. In a computerised tool, the sizing can first be carried out without trying to reduce the size of any of the ducts sections, i.e. based on *S* equals 1.0. Then, the suggested approach can be used on duct segments where it is considered as an advantage to reduce the size. After fulfilling that, the pressure drop can be calculated, as input to the fan selection.

In Table 7.1, three scenarios are shown, with examples of input and output data following the suggested approach for a duct segment located directly after the AHU. The rows in the table correspond to the inputs and outputs required if the approach shall be implemented in a computerised tool. In all three scenarios, the same *b* and *OFz* is used as input for selecting the fan, and the same design criterion is used for selecting the duct. If compared to Figure 7.2, the required *OFz* to go one size down in Table 7.1 is identical for *Scenario 1* while there is a deviation of approximately 0.05 for *Scenario 2* and *3* because the factor is 1.27 between the standard diameters (800 mm and 630 mm) instead of 1.25. In *Scenario 1,* the decision will most probably be easy to take, which is not to go one standard diameter down, because it requires an *S* of 0.71, corresponding to *OFz* equals 0.42. In *Scenario 2* and *3*,

$q_{DCV}(S=1.0)$ is resulting in a lower fraction of the design criterion. In these cases it may be reasonable to go one standard diameter down.

Table 7.1 Three scenarios showing examples of suggested approach to select duct size and control the opportunity to go one size down based on expected peak values of OFz

	Scenario 1	*Scenario 2*	*Scenario 3*
Input:			
$q_{DCV}(S=1.0)$	1.25 m^3/s	2.60 m^3/s	2.60 m^3/s
If motion detectors only: *b/OFz* for fan	0.5/0.7	0.5/0.7	0.5/0.7
If other sensors: *S* for fan	-	-	-
Min. required sf^{fan}	1.1	1.1	1.1
Design criterion	8.0 m/s	8.0 m/s	8.0 m/s
Output:			
Min. required $S\text{-}dl^{fan}$	0.94	0.94	0.94
Standard duct diameter	500 mm	800 mm	800 mm
Velocity	7.01 m/s	5,69 m/s	5,69 m/s
Fraction of design criterion	87.6 %	71.2 %	71.2 %
One standard diameter down	400 mm	630 mm	630 mm
Required *OFz/S*	0.46/0.73	0.74/0.87	0.74/0.87
$S\text{-}dl^{duct}$ one standard diameter down	0.80	0.96	0.96
Min. required $S\text{-}dl^{fan} / S\text{-}dl^{duct}$	1.16	0.98	0.98
Max. velocity	9.3 m/s	7.8 m/s	7.8 m/s
Input for selected fan			
Capacity selected fan		2.48 m^3/s	2.65 m^3/s
Output for selected fan			
sf^{fan}		1.12	1.20
$S\text{-}dl^{fan}$		0.95	1.02
$S\text{-}dl^{fan} / S\text{-}dl^{duct}$		0.99	1.06
Max. velocity		7.94 m/s	8.51 m/s

Scenario 2 and *3* are identical with one exception; the capacity of the selected fan. It is convenient to differ between two safety factors for the fan: (a) the minimum required safety factor specified as input for selecting the fan and (b) the actual safety factor for the chosen fan. The chance of finding a fan that exactly matches the minimum required *S-dl* is small. Therefore, after finishing the sizing of the ductwork, calculating the pressure drop in the

distribution system and selecting the fan, it may be advantageous to control the maximum possible velocity with the estimated *S-dl* for the selected fan in the ducts where it was chosen to reduce the diameter. However, in many cases, sizing the distribution system and carrying out the pressure drop calculations is made by a consultant, while selecting the AHU is made by the contractor, based on specifications from the consultant. This may complicate such a procedure. In *Scenario 2*, the selected fan has a safety factor that is almost equal to the minimum required safety factor. This results in a ratio between *S-dl* for the fan and the duct that is below 1.0, keeps the maximum velocity below the design criterion. In *Scenario 3*, on the other hand, the safety factor of the selected fan gives a ratio between *S-dl* for the fan and the duct equal to 1.06, resulting in a maximum velocity that is 6 % above the design criterion. The minimum required safety factor specified for selecting the fan system is set to a level that seems reasonable for meeting any potential future needs to increase the air flow rates (or correcting for increased pressure drops). However, there is no guarantee that the full capacity of the fan not will be utilised sometime in the future. Therefore, it should be written in the operation manual that the distribution system is sized based on a possible increase of the air flow rates up to a certain specified level (e.g., 10 %, like in the scenarios in Table 7.1).

Finally, it is important to stress that this section regarding duct sizing shall not be interpreted as it always is advantageous to decrease the size of ducts. It will increase the pressure loss and consequently the energy use for fan operation and the risk for potential noise problems. Although reducing the duct size will decrease the first cost, the most important motive is probably, in most cases, the reduced space demand. Reducing a circular duct with one standard diameter may for instance be an alternative to the use of two parallel ducts or a rectangular duct.

7.2.5 Distribution of occupancy peaks and potential consequences for IAQ

Published data on peak levels of *OFz*, and especially detailed data presented as duration curves, are very limited. Consequently, and as already mentioned, an approach where the sizing is based on an *S* below 1.0 must usually be based on assumptions with a relatively high degree of uncertainty involved. Therefore, it is of great importance to carefully evaluate the potential consequences if *S* during operation of the ventilation system exceeds *S-dl*. There are two in principal different choices that can lead to this situation:

- An *S-dl* higher than the expected *S* maximum is chosen. If either the maximum *S* prove to be higher than expected or the air flow rates are increased, or a combination of these two, then *S* may exceed *S-dl*.
- An *S-dl* lower than the expected *S* maximum is chosen. If the estimated maximum level of *S* proves to be correct, then *S* will exceed *S-dl*.

In the following, peaks will be considered as periods when *S* is exceeding *S-dl*. Figure 7.3 shows the distribution of peaks in *Organisation A*, computed for *S-dl* equals 0.827 and *b* equals 0.5, which corresponds to *T(S-dl)* equals 50 hours per year. This distribution will look exactly the same for all combinations of *S-dl* and *b* that gives a *T(S-dl)* of 50 hours per year. This level of *T(S-dl)* shall not be interpreted as any recommendation for design, just an example.

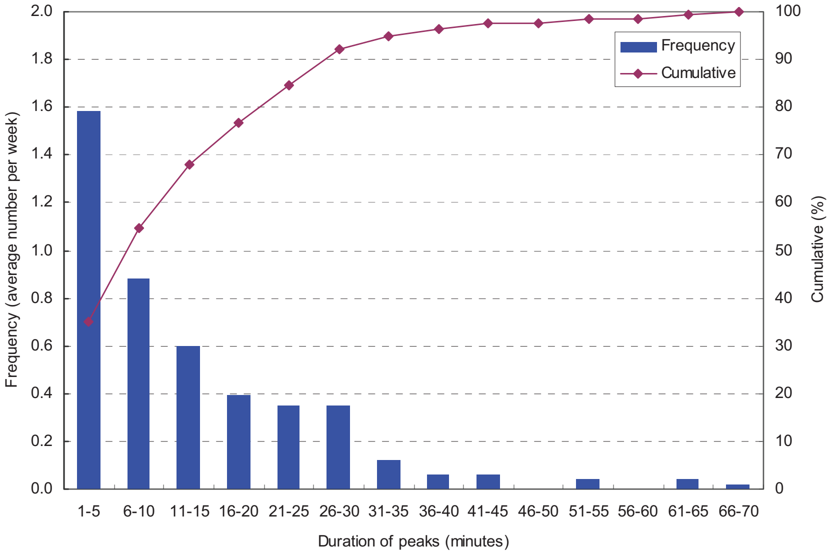


Figure 7.3 Distribution of occupancy peaks where S exceeds S-dl in Organisation A, for T(S-d) equals 50 hours per year.

With *T(S-dl)* equals 50 hours per year, it is on average 4.5 peaks per week, most of them short-lived. As the cumulative graph in Figure 7.3 shows, approximately 55 % of the peaks are lasting 10 minutes or less and 92 % are lasting 30 minutes or less. However, even though most peaks are short-lived it does not guarantee that there are not some days with large part of the day where *S* is exceeding *S-dl*, because Figure 7.3 does not give any information about how the peaks are distributed over time. For every single peak that the distribution in Figure 7.3 consists of, the scatter plot in Figure 7.4 shows the time to the next peak. Some dots mark a time interval of more than 480 minutes (8 hours) between two peaks. Because all peaks are occurring within the normal working hours, these marks means that the next peak did not occur the same day. The scatter plot shows that there often is a short time interval until the next peak is occurring, indicating that there may be days where *S* exceeds *S-dl* for a rather large part of the day.

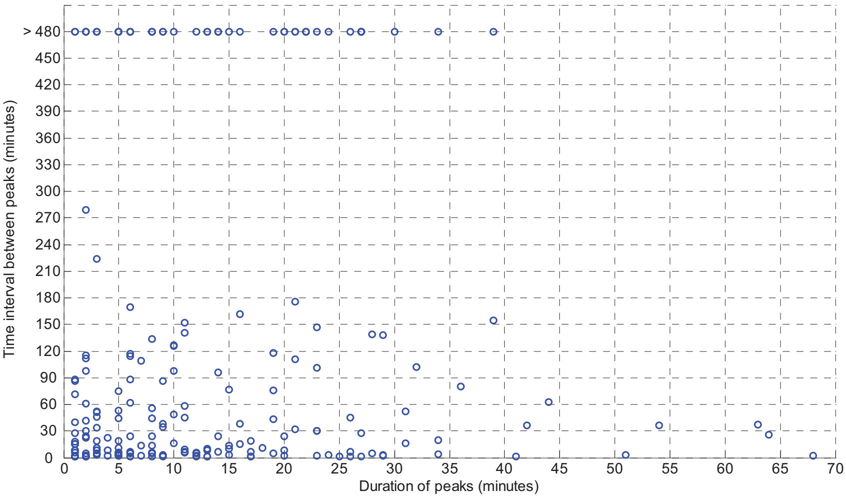


Figure 7.4 The duration of occupancy peaks where S exceeds S-dl versus the time to the next peak for T(S-dl) equals 50 hours per year in Organisation A.

Figure 7.3 and Figure 7.4 do not give a complete picture of how the peaks are distributed over time. With *T(S-dl)* equals 50 hours per year, 20 % of the working days have at least one peak. It could be of interest to find one of these approximately 50 days annually that can be considered as the design day. The question is what criterion that can be used to decide which day that should be? The day with highest average *S* in not necessary a day where *S* exceeds *S-dl* during large part of the day, or even at all, because this can be a day where *S* is constantly high just below *S-dl.* One alternative is to choose the day with the highest instantaneous value of *S*. However, this may be a very short-lived peak, and is not necessarily occurring on a day having high values of *S* during other parts of the day. For evaluating the consequences of reducing the air flow rate capacity of a fan system, an alternative is to find a measure that represents the shortage of ventilation air during the operation hours of each day. Here, shortage means the deficit when the amount of ventilation air supplied by a fan system with maximum capacity equals *q(S=S-dl)* is compared to the actual ventilation demand (which here is a function of the detected occupancy state in the office cells). Figure 7.5 shows the four days with most shortage of ventilation air in *Organisation A*, for *b* equals 0 and 0.5 and *T(S-dl)* equals 50 hours per year. The total daily shortage of ventilation air corresponds to the sum of the areas between *S* and *S-dl* in the time intervals where *S* is higher than *S-dl* between 6 a.m. and 6 p.m. The denomination for this area is minutes, or any other suitable time unit.

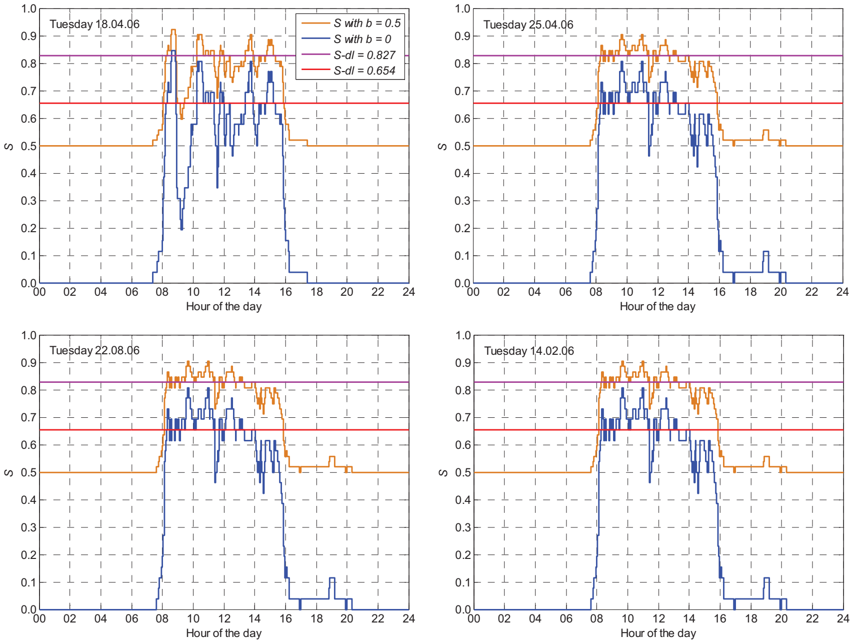


Figure 7.5 The four days with most shortage of ventilation air in Organisation A, when T(S-dl) equals 50 hours per year and b equals 0 and 0.5.

For the day in the upper left part of Figure 7.5 (Tuesday 18th of April 2006) the area between *S* and *S-dl* amount to 7.08 minutes (425 seconds) for *b* equals 0.5. Multiplying this area with q_{DCV} *(S=1.0)* will give us the shortage of ventilation air that day. For instance, assume that an AHU is selected to supply ventilation air to the office cells in *Organisation A* with an estimated *S-dl* of 0.83, and that $q_{DCV}(S=1.0)$ is 1 m^3/s and *b* is 0.5. Then, for 18th of April, there will be a 425 m^3 shortage of supplied ventilation compared to the ventilation demand detected by the motion detectors. The day having most shortage of ventilation air can change if *T(S-dl)* is altered. This corresponds to moving the curve for *S-dl* vertically in Figure 7.5. Furthermore, in contrast to the distribution of the duration of the peaks and the time between peaks, the shortage of ventilation air is not only dependent on *T(S-dl)*, but also on the value of *b*. For equal values of T(S-dl), the shortage of ventilation air is higher for smaller values of *b*, which can be seen in Figure 7.5 when comparing the areas between the curves representing *S* and *S-dl* for *b* equals 0.5 and 0.

In Table 7.2, different quantitative measures for describing days with occupancy peaks are presented for the four days in Figure 7.5, for *b* equals 0.5 and *S-dl* equals 0.827. The shortage of ventilation air expressed in minutes, or any other time unit, is difficult to interpret. Therefore, Table 7.2 also includes the shortage of ventilation air expressed as percent of actual ventilation demand, which is computed by dividing the area between *S* and *S-dl* by the area below *S* in the time span 6 a.m. to 6 p.m. Although Tuesday 18th of April has higher shortage of ventilation air expressed in minutes, Tuesday 22nd of August has the same shortage expressed in percentage, because the average *S* for 22nd of August is lower than for 18th of April.

Table 7.2 Different quantitative measures describing days with occupancy peaks, when b equals 0.5 and S-dl equals 0.827, corresponding to T(S-dl) equals 50 hours per year

Day	Shortage of ventilation air		$\overline{S}^{6-18}$	Max. *S*	Number of peaks
18.04.06	7.08 minutes	1.4 %	0.704	0.923	9
25.04.06	6.41 minutes	1.2 %	0.716	0.904	16
22.08.06	6.37 minutes	1.4 %	0.651	0.923	7
14.02.06	6.14 minutes	1.2 %	0.691	0.923	8

The different measures in Table 7.2 will not all result in the same day as the design day. For instance, the day with most shortage of ventilation air is not the one with highest average *S*. By using shortage of ventilation air as a selection criterion for the design day, both the amplitude of the peaks and the duration of them are considered. For sizing of fan systems and consequences for the IEQ, this measure has been considered as the most convenient, and is the one focused on in the following.

It is not the reduction in supplied amount of ventilation itself that matters; it is the consequence for the IEQ that is important. Hence, it is natural to look at the shortage of ventilation on room level, where the worker's perception of the indoor environment takes place. The IAQ will be affected negatively in both occupied and unoccupied office cells. It is important to maintain a good IAQ also when the office cell is unoccupied, so that the worker perceives the IAQ as good when entering the office after being absent. Establishing ventilation flow rates to maintain a certain level of IAQ based on assumed pollution sources and their source strength is difficult. For instance, consider a scenario where the selected q_{unocc} proves to be to low, resulting in an IAQ that is significant lower than intended in unoccupied offices, while q_{occ} gives a satisfying IAQ in occupied offices. Then, the consequences may be worse for an unoccupied office where the worker is entering a zone normally having low IAQ (that is now being even lower), than for an office cell where the worker is present, and the normally good IAQ still may be considered as satisfying. Of course, the situation can be the other way around, with q_{occ} being to low instead. Which of the office cells that is the most exposed office, i.e. where the consequences are largest for the perceived air quality (PAQ), is consequently not only decided by the occupancy pattern in the individual sub-zones, but also on the air flow rates q_{occ} and q_{unocc} relative to the strength of the pollution sources.

The following approach was selected, aiming at finding a numeric measure of the consequences of *S* exceeding *S-dl* on a sub-zone (cellular office) level. Because the purpose was not to apply the occupancy data on any specific building and ventilation system, but just to compare different levels of *S-dl* and *b* and different organisations on general basis, some assumptions was necessary. First, how the shortage of ventilation capacity will spread between the different sub-zones is dependent on the system architecture and type of flow rate control equipment and may therefore differ from system to system. Here, it is assumed that the relative reduction in supplied air flow rate when *S* is exceeding *S-dl* is equal in all sub-zones, independent on the sub-zone being occupied or not. Second, it is assumed that the only thing differing between the office cells regarding pollution sources is the occupancy pattern. Third, it is assumed that q_{occ} and q_{unocc} is selected so that the IAQ in unoccupied and occupied office cells is approximately equal. Computations were made for four values of *b* and six levels of *S-dl* with a script written in MATLAB. First, the shortage of supplied amount of ventilation air between 6 a.m. and 6 p.m. on working days was computed for each day of the monitoring period in the same way as described for the values in Table 7.2. The day with most shortage of ventilation air, expressed in minutes per day, is considered to be the design day. With the assumptions mentioned above, the most exposed office has been considered to be the one having most shortage of ventilation, measured in total air volume, during periods when the office is occupied on the design day. When *S* exceeds *S-dl*, the shortage of ventilation is larger in occupied than unoccupied offices, provided that the relative shortage is equal in all sub-zones. As a consequence, the sub-zone *i* having most shortage of ventilation during all operation hours on the design day, is also the one having most shortage of ventilation when only periods with occupancy are considered. Therefore, for each of the n_i monitored office cells the daily shortage of ventilation air, expressed in minutes, was computed according to Equation 7.5:

$$Vsh_i = \sum_{t=1}^{720} Vsh_i^t$$

$$Vsh_i^t = \begin{cases} S - S\text{-}dl & \text{if } (S - S\text{-}dl) > 0 \;\&\; occ_i^t = 1 \\ (S - S\text{-}dl)\cdot b & \text{if } (S - S\text{-}dl) > 0 \;\&\; occ_i^t = 0 \\ 0 & \text{if } (S - S\text{-}dl) \le 0 \end{cases} \tag{7.5}$$

where

Vsh_i	Shortage of air for sub-zone *i,* (minutes)
Vsh_i^t	Shortage of air for sub-zone *i* at time step *t,* (minutes)
t	Time step. The summation uses one minute time step and $t = 1$ corresponds to 06:00-06:01, and $t = 720$ corresponds to 17:59-18:00
occ_i^t	Occupancy state of sub-zone *i* at time step t, equals to 1 if occupied and equals to 0 if unoccupied

The most exposed office is the sub-zone having the highest value of Vsh_i. As already mentioned, the shortage of ventilation expressed in minutes can be difficult to interpret if not applied to a specific ventilation system. The result is therefore presented as the percental decrease of ventilation relative to the demand in the most exposed office cell, i.e. relative to a system with capacity corresponding to the maximum *S*, and is computed according to Equation 7.6:

$$Vsh\text{-}r_i^{dd} = \frac{Vsh_i^{dd}}{\overline{S}_i^{6-18,dd} \cdot 720} \cdot 100 = \frac{Vsh_i^{dd}}{(UR_i^{6-18} + b - UR_i^{6-18} \cdot b) \cdot 720} \cdot 100 \tag{7.6}$$

where

$Vsh\text{-}r_i^{dd}$	The relative shortage of ventilation air on the design day (*dd*) for sub-zone *i*, (%)
$\overline{S}_i^{6-18,dd}$	The average of *S* on the design day between 6 a.m. and 6 p.m. for sub-zone *i*
$UR_i^{6-18,dd}$	The utilisation rate on the design day between 6 a.m. and 6 p.m. for sub-zone *i*

The result for the most exposed office in *Organisation A* is presented in Table 7.3. The corresponding results for *Organisation B* can be found in Appendix A.3. In Table 7.3, the corresponding *T(S-dl)* for each value of *S-dl* and *b* is presented. The values of *T(S-dl)* are corrected to represent 252 working days per year and operation hours between 6 a.m. and 6 p.m. on working days only, i.e. 3024 annual operation hours. The values for shortage of ventilation air when *T(S-dl)* exceeds 300 hours have been left out because more than approximately 10 % of the annual operation hours is considered to be a level far from acceptable.

Table 7.3 For six values of S-dl, the corresponding T(S-dl) and maximum shortage of ventilation air for one office during one day (the design day), in Organisation A

	T(S-dl) (hours per year)				Relative daily shortage of ventilation air for the most exposed office (%)			
	b				*b*			
S-dl	0	0.25	0.50	0.75	0	0.25	0.50	0.75
0.70	22.5	153.6	> 300	> 300	1.6	4.2	-	-
0.75	9.3	49.2	> 300	> 300	0.7	1.7	-	-
0.80	2.9	9.3	153.6	> 300	0.2	0.6	2.5	-
0.85	0.0	2.9	22.5	> 300	-	0.1	0.6	-
0.90	0.0	0.0	2.9	153.6	-	-	0.1	1.1
0.95	0.0	0.0	0.0	2.9	-	-	-	0.0

Even in cases where *S-dl* exceeds *S* for approximately 150 hours per year in *Organisation A*, the resulting maximum shortage of ventilation in one office cell is small, and not more than 4.2 % compared to the demand on that day. For corresponding levels of *S-dl* and *b*, the relative shortage of ventilation is even smaller in *Organisation B*. Both the day considered as the design day and the office cell being the most exposed one may change when *S-dl* is changed and also for the same *S-dl* when *b* is changed. Paper III (Appendix A.4) addresses the situation with a shortage in capacity compared to the demand, and shows that a shortage of ventilation in the same order of magnitude as in Table 7.3 will have a negligible effect on the perceived air quality in the room in question.

7.3 Distribution of *S* and consequences for fan selection

The previous section focused on the maximum capacity of a fan system. However, when choosing between several alternatives in a VAV system, also the expected distribution of *S* should be taken into account in order to optimize the energy performance of the fan system. The annual energy use for operation of a fan system can be expressed by Equation 7.7 and 7.8:

$$E_{fan} = \frac{q \cdot \Delta p_t}{\eta_t} \cdot t_{fan} \tag{7.7}$$

$$\eta_t = \eta_f \cdot \eta_d \cdot \eta_m \cdot \eta_c \tag{7.8}$$

where

E_{fan}	Annual energy use for fan operation, (kWh/year)
q	Air flow rate through the fan, (m^3/s)
Δp_t	Total pressure rise of the fan, (kPa)
η_t	Total efficiency of the fan system, (-)
t_{fan}	Annual operation hours of the ventilation system, (h/year)
η_f	Efficiency of the fan (-)
η_{tr}	Efficiency of fan to motor drive (-)
η_m	Efficiency of the motor (-)
η_c	Efficiency of equipment for fan speed control (-)

In a VAV system, the air flow rates, and thereby also Δp_t, vary with time. In addition, the efficiency of the fan system varies as the air flow rate and pressure rise of the fan change. If it is possible to express the pressure rise of the fan during operation and the efficiency of the fan system as a function of the air flow rate, then the energy use in a VAV system can be expressed by dividing the air flow rate spectre up to $q_{VAV}\ (S=1.0)$ into a number of bins:

$$E_{fan,VAV} = q_{VAV}(S = 1.0) \cdot t_{fan} \cdot \sum_{k=1}^{x} \left(\frac{S_k \cdot \Delta p_t(q)_k \cdot y_k}{\eta_t(q)_k} \right) \tag{7.9}$$

where

$E_{fan,VAV}$ Annual energy use for fan operation in a VAV system, (kWh/year)

x Number of bins, (-)

y_k Fraction of t_{fan} for bin k

A description of different alternatives for air flow rate control in VAV systems can be found in, for instance, Maripuu (2006). A common solution is to adjust the fan speed with a variable frequency inverter to keep the static pressure constant at one position in the main duct. The VAV diffusers or terminal units can be classified as either pressure independent or pressure dependent, because they have different requirements for control of the pressure in the distribution system in order to work properly (Maripuu, 2006). In a system with pressure dependent VAV diffusers the static pressure before the unit has to be controlled more strictly. While a system with pressure independent VAV diffusers/terminal units works with static pressure control in the main duct only, systems with pressure dependent VAV diffusers/terminal units in addition need control of the static pressure in the branch ducts. This can be achieved by using control damper at the start of each branch duct having VAV diffusers/terminal units. The total pressure rise of the fan as a function of the air flow rate in a VAV system with static pressure control can be expressed (Maripuu, 2006, p. 20):

$$\Delta p_t = f(c + q_{VAV}{}^{r}) \tag{7.10}$$

If the pressure sensor for fan speed control is located in the start of the main duct, the operating point of the fan will roughly follow one and the same system curve when the air flow rate varies. Moreover, the exponent r in Equation 7.10 will in that case mainly depend on the flow conditions in the AHU, equal to 1.0 for laminar flow and 2.0 for turbulent flow. While the flow conditions in the ductwork often is turbulent and the pressure loss is proportional to approximately the square of the air flow rate (r = 2), the value of r can deviate considerably from 2.0 for the AHU. Sørensen (2002, p. 74) made a review of catalogue data for different components and found the following values of the exponent r: 1.8 for heating/cooling coils (water to air); 1.2-1.3 for heat recovery wheels; 1.8-2.0 for silencers; and 1.4 for filters (EU7). The value of the constant c in Equation 7.10 is decided by the level of the constant static pressure. This level is chosen to maintain the static pressure level in the branch duct within the limits required by the VAV diffusers/terminal units to work as intended at the design air flow rate. It is usually between 20 % and 40 % of the total pressure rise of the fan at the design air flow rate (Maripuu, 2006).

For a fan system with capacity equal to, or above, S equals 1.0 ($S\text{-}dl^{fan} \geq 1.0$), the total pressure rise of the fan at a certain level S compared to the pressure rise at S equals 1.0 can be expressed:

$$\frac{\Delta p_t}{\Delta p_t(S = 1.0)} = a + (1 - a) \cdot S^r \tag{7.11}$$

By replacing $\Delta p_t(q)$ in Equation 7.9 with Equation 7.11 and computing the numerator behind the summation sign for each of the x bins, the relative importance of $\eta_t(q)$ at different fractions of S for the total energy use can be analysed. Although a simple polynomial as in Equation 7.10 and 7.11 not necessary gives a curve fit close to the actual system characteristic, it may be precise enough for the purpose of illustrating in which part load segment of S that high fan system efficiency is most important.

The left hand side of Figure 7.6 shows two examples of the total pressure rise of the fan as a function of S according to Equation 7.11. The right hand side of Figure 7.6 shows the frequency distribution of S within the annual operation hours, with b equals 0.5 for *Organisation B*. The bin width in the histogram is 0.01, but because S only has 30 possible values, equal to the number of monitored rooms in *Organisation B*, the frequency is zero for some of the bins. The right hand side of the figure also shows the relative importance of the fan system efficiency at different air flow rates for the total energy use. Even though the pressure curves differs considerably, the two curves for the relative importance of the fan system efficiency is very similar, having peaks occurring at the same levels of S. In both cases one should aim at finding a fan system that has high efficiency when the system operates with minimum air flow rate, i.e. $q(S=0.5)$, and around 65 % of the maximum air flow rate $q(S=1.0)$. However, for finding an optimal fan, these two air flow rate segments corresponds to operation points that differs significantly for the two pressure curves. As marked in the left hand side of Figure 7.6, these two air flow rates corresponds to approximately 40 % and 55 % versus 70 % and 80 % of $\Delta p_t(S=1.0)$. For instance, if two or more fans are compared regarding their expected total energy use according to this approach, the accuracy of the estimated system characteristic may therefore be decisive for the selection. Moreover, estimating the distribution of S may constitute a large element of uncertainty. More available data of measured occupancy distributions could hopefully contribute to make such type of evaluations easier.

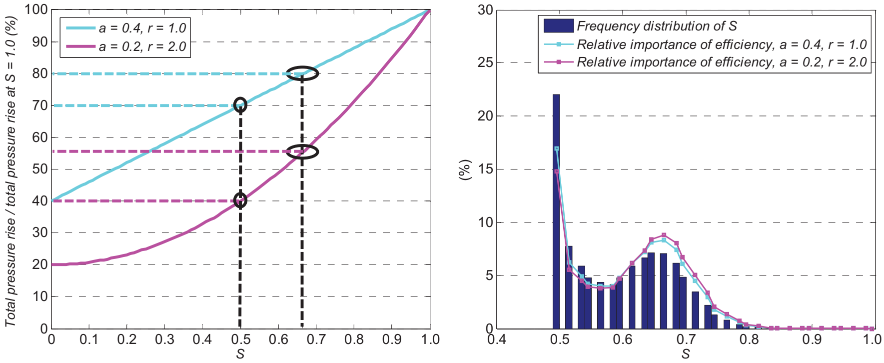


Figure 7.6 Left: Two examples of total pressure rise of the fan as a function of S. The marked areas represent operation points on the system curves where high efficiency of the fan system is important for the energy performance. Right: Frequency distribution of S within the annual operation hours, with b equals 0.5 in Organisation B, together with curves representing the relative importance of fan system efficiency for total energy use in different segments of S.

Figure 7.7 shows the frequency distribution of S for four values of b in *Organisation A*. The relative importance of the fan system efficiency is here based on a constant static pressure that is 30 % of the total pressure rise at S equals 1.0, i.e. a equals 0.3, and r equals 1.5. In organisations like *Organisation A* and *B* where most of the workers arrive at around 8 a.m. and leave the office at around 4 p.m. on most days, and the ventilation system is in operation for 12 hours per day, the frequency of *OFz* equals zero becomes high. The relative importance of the fan system efficiency is, as a consequence, highest at the value of S corresponding to *OFz* equals zero, when b is 0.25 or higher. Because of higher air flow rates and pressure rise of the fan when *S* increases, the importance of a high efficiency when *OFz* is zero increases as *b* rises.

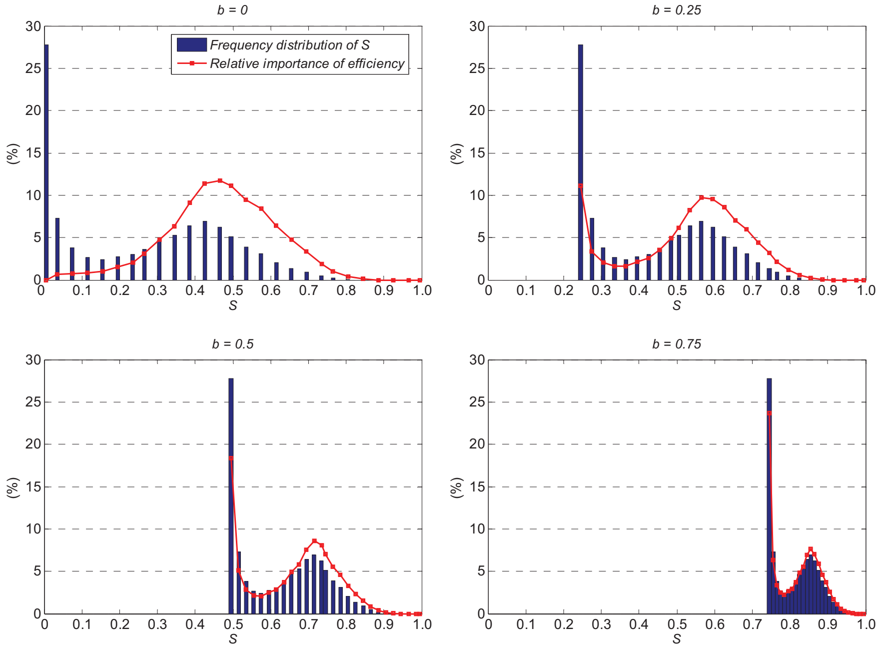


Figure 7.7 Frequency distribution of S within the annual operation hours for different values of b in Organisation A. The red curves represent the relative importance of fan system efficiency for energy use in different segments of S. They are based on a system characteristic that can be described with Equation 7.11, with a equals 0.3 and r equals 1.5.

7.4 Frequency of occupancy state changes in office cells

The number of changes in occupancy state of an office cell can be of interest for considerations regarding the life span of equipment, such as VAV terminal units, and is twice the number of detected occupancy periods. To get the yearly number of occupancy periods, the numbers in Figure 5.19 in Chapter 5 (frequency of occupancy periods) have to be combined with the numbers in Figure 5.15 in Chapter 5, showing the fraction of days without occupancy. On a yearly basis, with only working days included, the average of all office cells is 602 detected occupancy periods per year in *Organisation A*, and 481 per year in *Organisation B*. The office having most occupancy periods has 1463 per year in *Organisation A* and 1353 per year in *Organisation B*.

Consider a ventilation system with pressure dependent VAV terminal units operating with three damper positions: (1) fully closed outside the operation hours, (2) one position to supply an air flow rate when the office cell is unoccupied, and (3) one position when the office cell is occupied. In *Building 1* and with operation hours between 6 a.m. and 6 p.m. on working days only, the yearly number of position changes of the damper is roughly: two times the yearly number of occupancy periods, plus two times the number of working days. The exact number which is presented in Table 7.4 differs somewhat from that, because some of the occupancy periods are occurring outside the operation hours and some days the worker is present when the ventilation system starts or stops.

Table 7.4 Number of changes in damper position for a pressure dependent VAV terminal unit altering between three positions as function of TD-OFF, in Organisation A and B

Organisation/ *TD-OFF*	Number of damper position changes per year[1]	
	Average of all office cells	Office cell with highest value
Org. A/15 min	1997	3959
Org. A/20 min	1690	3161
Org. A/25 min	1488	2601
Org. B/15 min	1690	4028
Org. B/20 min	1443	3192
Org. B/25 min	1283	2671

[1] Based on 243 monitored working days, and corrected to be valid for 252 working days/year.

The average values of all office cells are higher in *Organisation A*, while the office cells with most frequent damper position changes in the two organisations have quite similar levels. Based on the latter, i.e. the most exposed office, and with an expected life span of for instance 30 years, the VAV terminal units must stand approximately 120 000, 95 000 and 80 000 damper position changes for 15, 20 and 25 minutes *TD-OFF* respectively. This of course, provided that the monitored year is representative for the whole life span.

7.5 Summary

This chapter has provided a series of examples showing how the distribution of the occupancy factor can be used as input to decisions regarding sizing and selection of centrally located components like main ducts and fan systems. In connection with sizing, a prediction of the peak, or close to peak, occupancy load can be used as a correction factor to reduce the size of the components. It can be combined with a safety factor, which takes other uncertainty factors into account. It is important when sizing ducts to also consider the approach used for the sizing of the fan. If the dimensions of the ductwork is reduced, and not the fan capacity, a higher peak occupancy than expected can lead to air velocities or pressure drops that exceeds the design criterion. For selection of fans, it is important to make judgements regarding the consequences for the indoor climate if the demand exceeds the capacity of the fan system. However, the data from *Organisation A* and *B* indicate that occupancy peaks are often short-lasting; hence, even if the capacity of the fan has been selected based on a low *OFz* (e.g., corresponding to the one that is exceeded in 150 hours/per year), it will still result in a shortage of ventilation air supply that is small and which only have minimal effect on the air quality. It is important to stress that aiming at reducing the size of components is not an objective in itself. Many factors have to be weighted against each other in such considerations: pressure drops and energy efficiency at part-load operation, affecting annual operation cost; first costs; space limitations; capability to handle future changes, i.e. the adaptability of the system; and as already mentioned, the consequences if the demand for ventilation exceed the predicted level that the sizing is based on.

8 Conclusions and suggestions for further work

This chapter summarise first the main conclusions that can be drawn from this work, and then gives some suggestions for further research. Additional conclusions are presented in the three papers in Appendix A.4.

The main conclusions are based on measured occupancy in office buildings, performed by logging of signals from motion detectors. Some abbreviations are frequently used throughout the thesis. Those are explained below, making it possible to fully understand the conclusion without having to read previous chapters.

A few numerical measures have been used to describe different aspects of the occupancy pattern. The zone based occupancy factor (*OFz*) expresses the ratio between the number of occupied sub-zones/rooms in a zone and the total number of sub-zones/rooms in the zone. *OFz* does not take the number of people into account, only whether a sub-zone/room is occupied or unoccupied. *OFz* can be used both to express instantaneous occupancy levels and averages over time. Superscript is used to specify the time, or time period, that the measure refers to. For instance, $\overline{OFz}^{06-18,wd}$ means the average *OFz* between 6 a.m. and 6 p.m. on working days, while the 95th percentile of $OFz^{6-18,wd}$ means the 95th percentile of all instantaneous values (one or five minute averages in the case studies) of *OFz* that have occurred during the same time period. The utilisation rate (*UR*) expresses the fraction of time that a room is occupied within a specific time period.

It is important to distinguish between the actual occupancy state of a room (occupied or unoccupied) and the detected occupancy state, which is the one monitored in the case buildings presented in this thesis. The detected occupancy state can differ from the actual occupancy state, because of false-detection and time-delay of the detector. The OFF-delay (*TD-OFF*) is the time from the last detected motion occurred until the detector changes the output signal, and the zone is recorded as unoccupied in connection with logging. It is however possible to make some corrections regarding *TD-OFF* to estimate the actual occupancy levels.

8.1 Main conclusions

Based on a literature study, the following main conclusions can be drawn:

- There is a need for more empirical basic data on occupancy in offices, with measurements from a wide spectre of organisations. In particular, detailed data describing variations between zones/rooms in one and the same building and short- and long-term fluctuations are very limited. In addition, there is a lack of data on peak, or close to peak, occupancy levels, relevant for HVAC system design.
- A limited amount of published occupancy data from Europe, North-America and Japan indicate that most spaces for individual work, occupied by workers from one and the same organisation, have an average *OFz* between 0.25 and 0.55, with a mean somewhere around 0.4, measured over a nine hour period per working day. Furthermore, the data indicate that most meeting and conference rooms have a low *UR*; seldom higher than 0.45, and on average between 0.25 and 0.30, measured over the core occupancy hours on working days.

Occupancy has been monitored in room samples from eleven organisations in five Norwegian office buildings. The data set contained 247 office cells and 16 meeting rooms. The case studies indicate that:

- $\overline{OFz}^{06-18,wd}$ with 20 minutes *TD-OFF* and actual occupancy during working hours ($\overline{OFz}^{8-17,wd}$) for one-person cellular offices is on average around 0.4, and somewhere between 0.2 and 0.6 in most Norwegian organisations. There is a large variation in utilisation rates for meeting rooms, with $UR^{6-18,wd}$ ranging from 0.1 to 0.7.
- In a zone with office cells, we can expect roughly the following close to peak levels of $OFz^{6-18,wd}$, with 20 minutes *TD-OFF*:
  - 10 rooms: 0.50-0.95 for the 95th percentile and 0.60-1.00 for the 98th percentile
  - 20 rooms: 0.50-0.90 for the 95th percentile and 0.55-0.90 for the 98th percentile
  - 30 rooms: 0.45-0.85 for the 95th percentile and 0.50-0.90 for the 98th percentile

  - > 30 rooms: Approximately the same levels as for 30 rooms

- The following rule of thumb can be used if *TD-OFF* is adjusted: a modification of *TD-OFF* in the range from 10 to 30 minutes will lead to a change of $\overline{OFz}^{06-18,wd}$ with between 0.01 and 0.02 for cellular offices and a change of $UR^{6-18,wd}$ with between 0.1 and 0.04 for meeting rooms, for every 5 minute increase or decrease of *TD-OFF*.

The findings listed above, implies that:

- There is a large potential for energy savings with demand controlled ventilation (DCV) in many office buildings, both in spaces for individual work and in spaces like meeting rooms.
- There is a potential to reduce the size of main ducts, air handling units and other centrally located components in DCV systems, and potentially also for constant air volume systems supplying air to large zone, such as open plan offices, by taking into account that all occupants seldom, or never, will be present simultaneously. Many factors have to be weighted against each other in such considerations: pressure drops and energy efficiency at part-load operation, affecting annual operation cost; first costs; space limitations; capability to handle future changes, i.e. the adaptability of the system; and consequences if the demand for ventilation exceed the predicted level that the sizing is based on. Because of the large variation in peak, or close to peak, occupancy loads found in the case buildings, it is recommended to use a somewhat conservative approach; for instance, based on *OFz* equals 0.9 when occupancy is the determining factor for the design air flow rates.

8.2 Suggestions for further work

- Collection of more empirical occupancy data from a broad spectre of organisations to establish a more solid data material relevant for indoor climate and HVAC considerations. More data on both average occupancy loads and peak, or close to peak, loads, as well as short- and long-term variations are needed.
- Collection of more reliable data regarding the occupancy pattern on room level, where also the short lasting vacancy periods (less than 20 minutes), which occurs frequently, are included. This can be done either with detectors with low risk of false-detection and thereby possibility to use a short *TD-OFF*, or by performing observations on-site and combine it with more long-term logging with motion detectors. This is to some extent done in one of the case buildings *(Building 1)*, but more data is needed.
- Perform a parametric study, based on the collected data from the eleven case organisations presented in this thesis; aiming at quantifying the energy saving potential with DCV in office buildings and find optimised solutions for different parameter combinations (space layout, occupancy pattern, outdoor climate, building shape etc.).
- Studying different potential approaches for dealing with occupancy and occupancy related loads in cooling demand calculations/simulations in connection with HVAC system design. Make recommendations for peak occupancy levels and for division of the building in zones to take diversity in occupancy, and occupancy related loads, into account.
- Analyse the consequences of typical occupancy patterns in office cells, to make recommendations for suitable control parameters in control-on demand systems involving occupancy-sensing, such as length of *TD-OFF* and ventilation flow rates for unoccupied offices. Implement occupancy prediction in feed forward control; for instance, changing supply air temperature and ventilation flow rate before someone is expected to arrive to a room.

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APPENDIX

A.1 Description of PIR motion detectors

The following summery of PIR motion detectors and their manner of operation is mainly based on the description by Fraden (2004).

The PIR motion detector belongs to a group of detectors called optoelectronic motion detectors, which are based on detection of electromagnetic radiation with wavelengths in the range of about 0.4 to 20 µm. Common for the optoelectronic detectors are that they consist of a lens or mirror to focus the radiation, a light-detecting element and a threshold comparator. A PIR motion detector with the purpose to detect the presence of people has a detecting element that responds to infrared radiation with wavelengths between about 4 and 20 µm, because most of the radiation emitted by humans is concentrated within this spectral range. The detector is passive; it senses infrared radiation emitted by objects with a temperature that deviates from the surroundings. This means that no additional radiation source is needed, in contrast to an active motion detector where the detected radiation originates from a light source (e.g., daylight or electric lamp) and is then reflected by the moving object.

Sensing element

The sensing element is usually a pyroelectric element. A pyroelectric material responds to a temperature change with generation of electric charge. By placing electrodes on each side of the pyroelectric element and connect them to an electric circuit, a temporary change in the amount of infrared radiation received by the surface of the sensing element can be measured in terms of a voltage.

All pyroelectric materials are also piezoelectric materials, generating electric charge when exposed to mechanical stress. Hence, if the detector is exposed to such stress (e.g., vibrations), there is a risk for this being interpreted as infrared radiation. In order to avoid this misinterpretation and to distinguish between infrared radiation from moving objects and infrared radiation emitted by stationary heat sources changing their surface temperatures (e.g. radiators), the sensing element is divided in two sections. When a human is moving into the coverage area of the sensor it will create a thermal image on the surface of the pyroelectric sensing element resulting in a temperature increase and, as a consequence, generation of electric charge. The electrodes and the electric circuit are arranged in such way that a positive voltage is produced when the thermal image covers one of the sections and a negative voltage when it covers the other section. If a human moves inside the detection field of the detector, the thermal image will travel from one section over to the other, resulting in a positive and a negative voltage signal that occur separated in time (out of phase). A mechanical stress or stationary radiation source will, on the contrary, most likely affect both sections of the sensing element simultaneously, resulting in the signal being cancelled.

Threshold comparator

The analog signal produced by the sensing element is amplified in the electric circuit before reaching a window comparator. The converter produce a digital output signal based on a comparison of the analog voltage signal with an upper and lower threshold. This digital output has two voltage levels: one indicating motion being detected and one indicating no motion. To summarize, the requirements for the detector to indicate motion are: (1) a radiation source that deviate enough from its surroundings when it comes to emission of infrared radiation; and (2) that it affects first one and then the other section of the sensing element, so that the produced signal crosses the thresholds in the window comparator.

Mirror or Fresnel lens

A concave mirror or a Fresnel plastic lens focuses the radiation onto the detecting element, where the Fresnel lens is the most common alternative today. A filter for visible light (0.4-0.7 μm) is used in front of the sensing element. Both PIR motion detectors and ultrasonic motion detector have several characteristics that distinguish one detector from another, and make them more or less suitable in different types of premises. Important characteristics are: coverage area (m^2), coverage pattern (square, circle etc., only relevant for PIR), field of view (vertical and horizontal angle, only relevant for PIR), sensitivity, and time delay (NLPIP, 1998). The lens has many sections which divides the detection field into several smaller detection zones. Increasing the number of zones increases the sensitivity to small movements, which is import in office premises. A PIR motion detector is most sensitive to movement perpendicular to the detection zones, in contrast to an ultrasonic motion detector which is most sensitive to objects moving straight against or away from the detector.

A.2 Investigation of data acquisition procedure and detector performance in *Building 1*

This appendix presents results from on-site observations in *Building 1*. In this building, described in chapter 5, passive infrared (PIR) motion detectors control lighting (3 x 35 W fluorescent lamps in office cells), ventilation and room temperature set-point. The office cells are, with a few exceptions, 7.5 m^2 (2.2 m x 3.25 m). The short side walls are the external wall and the partition wall including the door to the corridor. The detector is placed on the wall, just beneath the ceiling, in approximately 2.4 m height, in the corner to the right of the door opening (seen from the corridor). Figure 5.2 in Chapter 5 shows a picture of one of the office cells.

Some variables with the following abbreviations are defined and/or explained in previous chapters and are essential for understanding the results of the observations:

OFz:	The zone based occupancy factor, which in the case of the observations means the number of office cells occupied divided by the total number of office cells that *OFz* is computed for (defined in Chapter 2.1). $\overline{OFz}$ is the average of *OFz* over a specific time period.
UR:	The utilisation rate of a room, which is the portion of a specific time period that the room is occupied (defined in Chapter 2.1). *UR* is either expressed as a factor between 0 and 1 (or %), or as the number of time units within a specific time period (e.g., minutes per hour or hours per day).
TD-OFF:	The time delay of the detector. The OFF-delay means the time from the last detected movement until the detector quits the alarm output signal (discussed in Chapter 3.1.3).

In order to investigate the performance of the PIR motion detectors and to detect any failure in the data acquisition procedure, observations of the office workers were carried out three times in *Building 1*. In addition, the purpose of the observations was to investigate the difference between the actual and the logged *OFz*. The logged occupancy is the primary focus in this thesis because that occupancy level is the one relevant for analysing the consequences for the operation of a DCV system. However, the actual occupancy level is also of interest; for instance, when using a simulation tools to predict the quality of the indoor environment and the energy demand of a building, since the occupants themselves and some equipment used by the occupants constitute a substantial part of the internal heat and pollution load. For this reason, the observations were carried out also as an attempt to find an estimate of the actual occupancy level in *Building 1*.

Two different methods were used. The first method was used one time (*Observation 1*) and the second two times (*Observation 2* and *Observation 3*). The observed occupancy was then compared with the logged occupancy. Here, and in the following, observed occupancy are synonymous with actual occupancy and logged occupancy with the recorded occupancy in the log files generated in the data acquisition procedure.

There are four possible sources to a deviation between observed and logged occupancy:

1. False-detection with false positive outcome: The motion detector indicates occupancy although there is no one present (see Chapter 3.1.3 for more details), which results in a higher logged than observed *OFz*.
2. False-detection with false negative outcome: The motion detector fails to detect a present worker for a period longer than *TD-OFF* (see Chapter 3.1.3 for more details), which results in a lower logged than observed *OFz*.
3. *TD-OFF*: Each time the worker is leaving her/his office there will be registered that the office is occupied for a time period equal to *TD-OFF*, although it is unoccupied, resulting in a higher logged than observed *OFz*. There are two variants:
    a. Vacancy longer than *TD-OFF*: The previous occupancy period will be prolonged in the log file, and the vacancy period shortened, with a time equivalent to *TD-OFF*.
    b. Vacancy shorter than *TD-OFF*: Such vacancy periods will not be registered in the log file.
4. Failure in the data acquisition system: Can affect the deviation in both directions, either higher or lower logged than observed *OFz*, dependent on the nature of the failure.

In addition to these four, the persons who carry out the observations can fail; either miss an event (a person leaving or entering an office cell) or register the wrong time for an event. In the following, the deviations will be divided into *Type 1*, *2*, *3a*, *3b* and *4 deviations*, referring to the list above. As long as the data acquisition system uses a *TD-OFF* unequal to zero there will always be deviations between the observed and the logged occupancy, even though the detectors and the log procedure is functioning perfectly, because of *Type 3 deviations*.

Figure A.2.1 shows the observed versus logged occupancy state with 5 minutes *TD-OFF* for one of the offices cells, denoted *Room 11*, in *Observation 3*. This is an example where several *Type 2*, *Type 3a* and *Type 3b deviations* are involved.

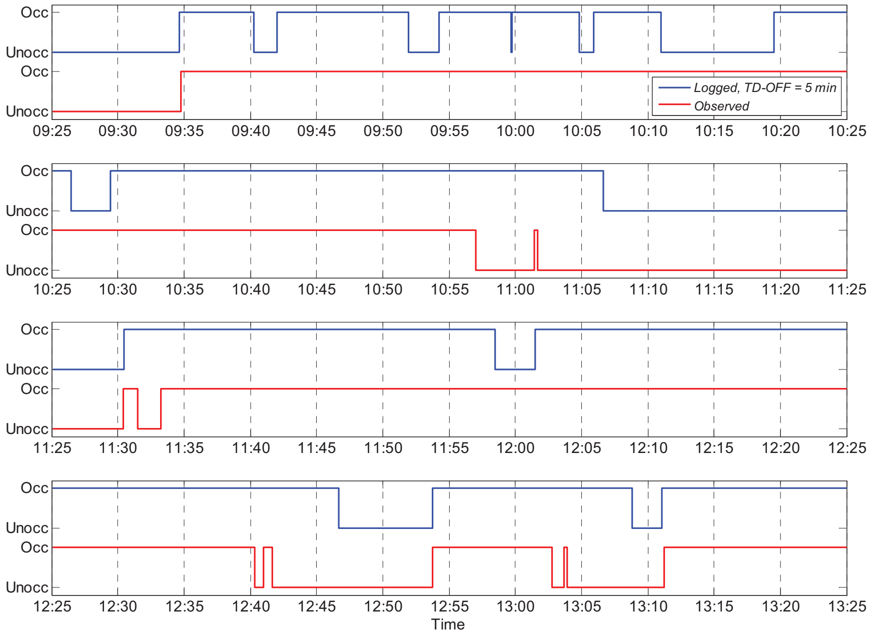

Figure A.2.1 Logged occupancy with 5 minutes TD-OFF versus observed occupancy for room 11 in Observation 3.

The logged *UR* with 5 minutes *TD-OFF* equals 74.0 % while the observed *UR* is 72.6 %. This means that the total duration of *Type 3a* and *3b deviation* are somewhat higher than the total duration of *Type 2 deviation*. As shown in Figure A.2.1, there are seven occurrences of false-negative detection (*Type 2 deviation*), six of them occurring between 09:40 and 10:30. If *TD-OFF* had been increased to 10 minutes, six of these deviations would not have occurred and none if *TD-OFF* had been further increased up to 15 minutes. The worker in *Room 11* left the office cell seven times during *Observation 3*. Four of these vacancy periods were shorter than 5 minutes and were therefore, as shown in Figure A.2.1, not registered in the log file (*Type 3b deviations*). The remaining three vacancies resulted in *Type 3a deviations*.

A.2.1 *Observation 1*

Objective: The intension of the observation was to investigate the deviation between the actual occupancy and the logged occupancy.

Method: Two persons, one on each floor, walked quickly through the corridors in the office wing occupied by *Organisation A* and counted the number of occupied rooms (office cells) every fifth minute during two hours. This was done simultaneously for both floors. Only the number of occupied offices was observed, not which of the offices that were occupied.

The occupancy data in *Building 1* was logged with 5 minutes *TD-OFF*, while the control of the lighting, heating and ventilation used 20 minutes *TD-OFF*. It is possible to compute occupancy profiles with increased *TD-OFF*. However, it is impossible to compute how the logged occupancy would have looked like if *TD-OFF* was less than 5 minutes, because the frequency of vacancies less than *TD-OFF* is unknown. By subtracting 5 minutes from each registered occupancy period, an occupancy factor with a *TD-OFF* denoted approximate zero (approx. 0) is computed. This is an attempt to compute an occupancy factor approximately equal to the actual occupancy factor by excluding every *Type 3a deviation*. *Type 3b deviations* are, however, not excluded.

The results of *Observation 1* are summarised in Table A.2.1. The computed $\overline{OFz}$ with an approximate zero *TD-OFF* is very close to the observed occupancy factor, as an average of the whole observation period. However, as shown in Figure A.2.2, which presents the observed versus the logged *OFz* values every fifth minute, there is a deviation for some of the instantaneous values in the second half of the observation period.

Table A.2.1 Summary of Observation 1, observed versus logged $\overline{OFz}$

	$\overline{OFz}^{Observ.1}$	Deviation from observed (%)	Difference, logged - observed
Observed	0.15		
Logged:			
TD-OFF = approx. 0	0.16	6.9	0.01
TD-OFF = 5 min	0.21	40.6	0.06
TD-OFF = 10 min	0.25	65.3	0.10
TD-OFF = 20 min	0.30	101.0	0.15

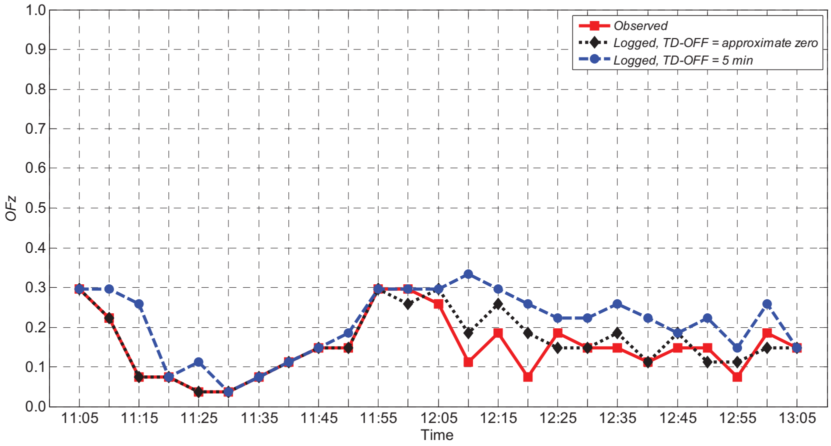

Figure A.2.2 Observed versus logged OFz with TD-OFF equal to approximately 0 and 5 minutes respectively, computed for all 26 office cells in Observation 1.

Because of the selected method used for *Observation 1* the sources to the deviation shown in Figure A.2.2 could not be identified. However, *Observation 2* and *3* showed no occurrence of *Type 1* or *4 deviation*. If it is assumed that this is also the case for *Observation 1*, then the deviations consist of *Type 2* and *3b deviation* when the observed and the logged occupancy with approximate zero *TD-OFF* is compared. *Type 2* and *3b deviation* affects the difference between actual and logged *OFz* in opposite direction and compensate for each other. Because the averaged *OFz* is slightly lower for the observed than for the logged occupancy with approximate zero *TD-OFF*, the frequency of *Type 3b deviation* (vacancies shorter than 5 minutes) is somewhat higher than *Type 2 deviation* (false-negative detection).

Sometimes the observed *OFz* is lower than the logged (e.g. four times in a row in the time period between 12:05 and 12:20). The most likely explanation is that some of the workers are leaving their office cells for a time period of less than 5 minutes, and these vacancies are coinciding with the time for the observations. Workers frequently leaving and entering their office cells also decrease the risk for false-negative detection because these are large movements easy to detect. Sometimes the observed *OFz* is higher than the corresponding *OFz* logged with approximate zero *TD-OFF*, most probably because of false-negative detection (*Type 2 deviation*). The observed *OFz* is closer to *OFz* with 5 minutes *TD-OFF* than *OFz* with approximate zero *TD-OFF* for a few times (e.g., 12:00). The explanation is that *OFz* logged with 5 minutes *TD-OFF,* in contrast to approximate zero *TD-OFF*, also include *Type 3a deviation* which can compensate if there are some *Type 2 deviation* at this point of time.

A.2.2 *Observation 2* and *3*

Objective: In addition to investigate the deviation between actual and logged occupancy, also study the sources to the deviation, and thereby evaluate the detector performance.

Method: Some office cells in the office wing occupied by *Organisation A* were observed by sitting in the corridor and register the point in time each time someone was leaving or entering an office cell.

In *Observation 2*, six office cells were observed constantly for one hour. Offices located nearby each other, making it possible for one person to observe them, were selected. In addition, offices occupied at the start of the observation were given priority. In *Observation 3*, the procedure of *Observation 2* was repeated, but this time for 4 hours and with two persons observing 12 office cells in total. Four of the six office cells in *Observation 2* were also observed during *Observation 3.*

The observed and the logged $\overline{OFz}$ for *Observation 2* and *3* are shown in Table A.2.2 and Table A.2.3, respectively. The $\overline{OFz}$ values in Table A.2.2 and Table A.2.3 are higher than for a normal day in *Organisation A*, because they are computed only for the observed rooms which were selected because most of them were occupied at the start of the observations. According to the log files, seven and three other offices than the observed offices in *Observation 2* and *3* respectively, had one or more occupancy periods during the observation periods. The logged $\overline{OFz}$ for all office cells of *Organisation A* were 0.46 in *Observation 2* and 0.39 in *Observation 3* with 20 minutes *TD-OFF*, which correspond well with typical levels for these periods of the day. However, unoccupied rooms does not affect the relative deviation between actual and logged $\overline{OFz}$, only the level of $\overline{OFz}$. The level of the observed $\overline{OFz}$ in *Observation 2* is between the logged $\overline{OFz}$ with 5 and 10 minutes *TD-OFF*. In *Observation 3* the observed $\overline{OFz}$ is close to the logged $\overline{OFz}$ with 5 minutes *TD-OFF*.

Table A.2.2 Summary of Observation 2, observed versus logged $\overline{OFz}$

	$\overline{OFz}^{Observ.2}$	Deviation from observed (%)	Difference, logged - observed
Observed	0.876		
Logged:			
TD-OFF = approx. 0	0.608	-30.6	-0.268
TD-OFF = 5 min	0.820	-6.4	-0.056
TD-OFF = 10 min	0.930	6.1	0.053
TD-OFF = 20 min	0.980	11.8	0.103

Table A.2.3 Summary of Observation 3, observed versus logged $\overline{OFz}$

	$\overline{OFz}^{Observ.3}$	Deviation from observed (%)	Difference logged - observed
Observed	0.538		
Logged:			
TD-OFF = approx. 0	0.377	-29.9	-0.161
TD-OFF = 5 min	0.532	-1.1	-0.006
TD-OFF = 10 min	0.646	20.1	0.108
TD-OFF = 20 min	0.751	39.6	0.213

In Figure A.2.3 the observed and the logged *OFz* with 5 minutes *TD-OFF* are plotted for *Observation 3*. Both graphs in the upper plot fluctuate strongly and there is often a deviation between the two *OFz* levels. However, the two graphs roughly follow each other when it comes to the large fluctuations. For instance, both graphs show a clear dip in *OFz* level around lunch-time, between approximately eleven o'clock and half past eleven. Most building energy simulation tools uses occupancy profiles with a time resolution of one hour. The lower part of Figure A.2.3 shows the four hourly averages of *OFz.* The averaging have evened out the fluctuations and the two *OFz* profiles are very similar both when it comes to levels and shape.

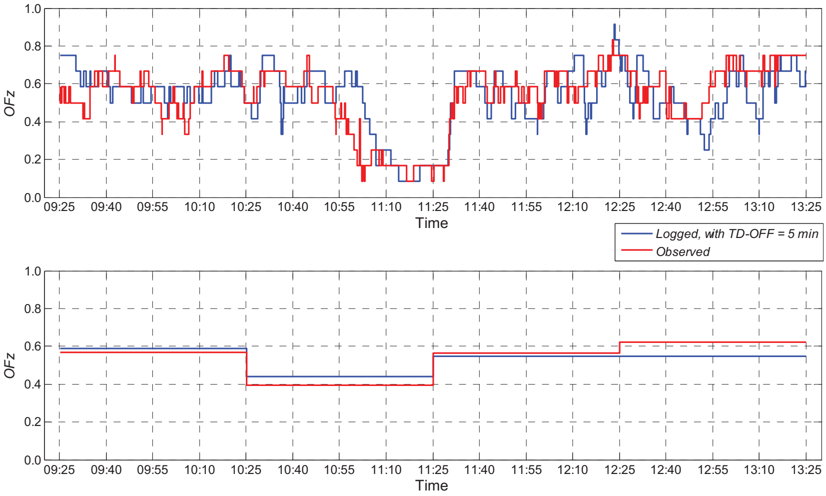

Figure A.2.3 Observed versus logged OFz with TD-OFF equals 5 minutes computed for the 12 observed rooms in Observation 3. Upper: computed with a time resolution of 5 seconds. Lower: one hour averages.

A.2.2.1 *Type 1* (false-positive detection) and *Type 4 deviations* (data acquisition failure)

The occurrence of *Type 1* and *Type 4 deviations* was investigated by comparing the observed occupancy state with the logged occupancy state with 5 minutes *TD-OFF*, for each office cell separately. As already mentioned, no *Type 1* or *Type 4 deviations* were identified, in neither of the observations. For *Type 1 deviation*, this means no occurrence of an office being logged as occupied at the same time as it was observed as unoccupied for 5 minutes or more. Two of the offices (*Room 9* and *14*) during *Observation* 3 had a very low *UR* (0.6 % and 1.4 %) and thereby gave no information about *Type 2 deviations*. However, the observations of these two rooms were useful because of the long-lasting unoccupied periods, which showed no occurrence of *Type 1 deviation*. Because all the logged time stamps agreed well with the observed, taking *TD-OFF* into account, no *Type 4 deviations* were identified. Consequently, the data acquisition procedure seems to have worked as intended.

A.2.2.2 *Type 2 deviation* (false-negative detection)

Before looking at the observed occurrence of false-negative detection, the influence of the lighting control as an uncertainty factor for the computed frequency and duration of false-negatives when altering *TD-OFF* is discussed. The next part deals with the factors having potential to cause differences between individuals regarding the occurrence of false-negative detection, before a short summary regarding false-negative detection are presented.

The impact of lighting control on computed occurrence of false-negative detection for different levels of *TD-OFF*

As already mentioned, the logging was carried out with 5 minutes *TD-OFF* and afterwards new results have been computed for other values of *TD-OFF*. The results computed for *TD-OFF* equals 20 minutes represent the actual situation, i.e. the situation the workers in *Building 1* perceive. The consequences of false-negative detection during normal operation, i.e. with 20 minute *TD-OFF*, are unwanted changes related to lighting and HVAC components. These changes are intended to occur when the worker is absent for a period longer than *TD-OFF,* but in the case of false-negative detection they occur when the worker is present. The changes include the lighting being switched off, the set-point for room temperature being moved and the ventilation flow rate being reduced, provided that there is no cooling demand. The worker will probably notice the lighting being switched off, and maybe make movements large enough to switch the light on again. However, if the worker is satisfied with the lighting conditions without the occupancy-controlled lighting switched on, it is possible that the worker ignore the false-detection. This will depend on whether any additionally artificial lighting is used and on the daylight availability. The worker’s reaction will consequently vary with the hour of the day and season. There is probably also other factors influencing how the worker react, making the reaction to vary from time to time, such as the type of working tasks performed and possibly also the mental condition at the moment. Moreover, their may be individual differences regarding the acceptance of the lighting being switched off due to false-detection. In contrast to the lighting, the worker will probably not notice the change of the ventilation flow rate and room temperature set-point immediately.

There were in total eight occurrences of *Type 2 deviation* with *TD-OFF* equals 20 minutes for *Observation 2* and *3,* distributed on three different workers. The duration of these eight deviations was between 55 seconds and 16 minutes and 25 seconds. This means that none of these false-negative detections resulted in the workers to respond instantaneously to the lighting being switched off by making movements to switch the light on again. This indicates that the result for other *TD-OFF* than 20 minutes would not have been affected significantly if also the lighting used another *TD-OFF*. False-negative detection was, however, also observed in nine of the other rooms, but none of these lasted longer than 20 minutes. Hence, their reaction if the lighting had been switched off is unknown. In addition, *Observation 2* was carried out on 30th of March 2006 between 12:34 and 13:34 and *Observation 3* on 30th of June 2006 between 09:25 and 13:25, with relatively good daylight availability. If the observations were carried out during a period with less daylight availability, the result may have been different.

The frequency distribution of the logged vacancy periods for the whole monitoring period (one year) shows a clear tendency of falling frequency when the duration of the vacancy periods increases. With a bin width of 1 minute, the frequency of vacancy periods lasting between 15 and 16 minutes when *TD-OFF* equals 5 minutes, constitute a break in this tendency. This applies both for *Organisation A* and *B*. Figure A.2.8 in Chapter A.2.2.4, shows that the distribution of vacancy periods in *Organisation A* lasting up to 40 minutes with 5 minutes *TD-OFF*. The annual frequency of vacancy periods with duration between 15 and 16 minutes is 28 % and 59 % higher than for periods lasting 14-15 minutes and 16-17 minutes, respectively. This is most probably explained by false-negative detection and the workers' reactions to the lighting being switched off, which occurs 20 minutes after the last detected movement and consequently 15 minutes after it is registered as unoccupied. Throughout the year, vacancy periods lasting 15-16 minutes are occurring most frequent in the time period October to January and, for example, more than twice as frequent in January compared to May, two month having similar average occupancy factors. This indicates, in contrast to the observations, that the workers in *Building 1* react to false-negative detection that results in the lighting being switched off by making movements, especially in periods of the year with less daylight availability.

The computed results for other values of *TD-OFF* than 20 minutes do not represent the actual operation situation perceived by the workers. If *TD-OFF* was changed also for control of the lighting, it would probably not have affected the results for *Type 2 deviations* during *Observation 2* and *3* significantly, or even at all. However, it would probably have had an effect on a yearly basis and the results presented in PART II, foremost for *TD-OFF* less than 20 minutes. With *TD-OFF* equals 5, 10 or 15 minutes, some of the false-negative detections would have been shortened because of the workers' reactions to the lighting being switched off. In that case, the total duration of false-negative detection would have decreased. The frequency of false-negatives on the other hand, would have increased. For *TD-OFF* equals 25 and 30 minutes the results would probably also have looked somewhat different, due to:

1. Some of the logged vacancy periods that are a result of false-negative detection may have been prolonged. For instance, with *TD-OFF* equals 25 minutes *Room 13* had two false-negative detections during *Observation 3*, one of them lasting 1 minute and 40 seconds. This means that the lighting had been switched off for 6 minutes and 40 seconds before the worker made a movement large enough to be detected. Although it did not occur close to the lighting was switched off it is still possible that it was a movement intended to switch the light on. In most cases when the lighting has been off for several minutes or more followed by a detected movement, it is most probably not a result of the lighting condition. However, in some cases, for instance, during work requiring a high level of concentration, it may take some time before the worker notice that the lighting has been switched off. Consequently, some of the false-negative detections lasting long enough to result in a vacancy period in the data record with 25 or 30 minutes *TD-OFF* may have been prolonged, if the lighting was switched off 5 or 10 minutes later.
2. New vacancy periods would have been added. The overrepresentation of vacancy periods with duration between 15 and 16 minutes compared to the general trend would have been moved 5 and 10 minutes, for *TD-OFF* equals 25 and 30 minutes, respectively. As already mentioned, the reason for this overrepresentation is the workers' reactions to the lighting being switched off. If the control of the lighting used 25 instead of 20 minutes *TD-OFF*, this reaction would have occurred 5 minutes later. It does not mean that all of these vacancy periods would have been prolonged 5 minutes, because some of them could have ended before they had lasted long enough to result in a logged vacancy period.

Occurrence of false-negative detection

Instead of looking at the two observations as two separate observations, Table A.2.4 summarises the occurrence of *Type 2 deviation* as one observation. This means that the results are based on five hours of observation for four offices, four hours of observation for six offices, and one hour of observation for two offices. The offices are sorted in falling order after the total duration of *Type 2 deviation* with 5 minutes *TD-OFF*. Due to the low *UR*, *Room 9* and *14* can not have *Type 2 deviation* and are therefore disregarded.

The occurrence of *Type 2 deviation* expressed as percent of time observed as occupied varied significantly among the observed rooms, from 0.3 % to 54.2 %, for 5 minutes *TD-OFF*. When increasing *TD-OFF* the occurrence and the variation among the offices are reduced gradually. The detection in most offices worked well during the observations with a potential to decrease *TD-OFF* from the normally used 20 minutes down to 15 or even 10 minutes, and still avoiding false-negatives. A few offices, on the other hand, needed 20 minutes *TD-OFF* or even more, in order to avoid false-negatives. Rooms with higher total duration of false-negatives did not necessarily also have a higher number of false-negative periods than others. For instance, *Room 13* had a significant higher total duration of false-negative detection than the other offices. However, with *TD-OFF* equals 5 or 10 minutes, several other offices had more frequent occurrence of false-negatives. Instead of many short-lasting false-detections, *Room 13* had some false-negative detections that lasted long.

Table A.2.5, which presents the hourly duration of false-negative detection, shows that there in most office cells were large periodic variations regarding the difficulty of detecting the present worker. It illustrates that short-lasting observations may give a result that deviates significantly from the typical situation in one specific room. For instance, if *Room 5* were observed only for one of the observed hours, as for *Room 2* and *3*, it could have resulted in an observed duration of false-negatives between 0.0 and 44.3 % of the time observed as occupied. Observing for 4 or 5 hours is most likely not enough to give a good estimate of the long-term average in one specific room. Consequently, the levels in Table A.2.4 should not be interpreted as a representative sample for the variations among individual office cells regarding false-negative detection.

Table A.2.4 Summary of Type 2 deviations, i.e. false-negative detection, Observation 2 and 3 included

Room	Frequency (number per hours observed as occupied[1])						Duration (% of time observed as occupied)						Duration (% of time observed as occupied and exposed to false-negative detection)					
	TD-OFF						*TD-OFF*						*TD-OFF*					
	5	10	15	20	25	30	5	10	15	20	25	30	5	10	15	20	25	30
13	1.5	1.5	1.5	1.5	0.6	0.3	54.2	42.1	29.9	17.7	6.4	3.1	54.2	45.0	32.0	19.0	6.8	3.3
4	2.8	1.5	0.8	0.3	0.0	0.0	33.4	14.8	4.3	0.4	0.0	0.0	33.7	15.4	4.8	0.4	0.0	0.0
6	2.8	1.7	0.9	0.6	0.3	0.0	31.0	13.6	7.6	3.5	0.1	0.0	31.5	15.4	8.6	4.9	0.1	0.0
5	2.4	1.2	0.3	0.0	0.0	0.0	19.5	6.8	0.5	0.0	0.0	0.0	20.5	7.2	0.7	0.0	0.0	0.0
10	2.3	0.8	0.0	0.0	0.0	0.0	13.0	0.5	0.0	0.0	0.0	0.0	13.5	0.5	0.0	0.0	0.0	0.0
11	2.4	0.3	0.0	0.0	0.0	0.0	11.3	2.0	0.0	0.0	0.0	0.0	11.4	2.1	0.0	0.0	0.0	0.0
1	3.0	0.3	0.0	0.0	0.0	0.0	10.3	0.2	0.0	0.0	0.0	0.0	11.0	0.2	0.0	0.0	0.0	0.0
7	1.3	0.4	0.0	0.0	0.0	0.0	8.5	3.2	0.0	0.0	0.0	0.0	9.8	4.7	0.0	0.0	0.0	-
12	1.5	0.0	0.0	0.0	0.0	0.0	1.7	0.0	0.0	0.0	0.0	0.0	1.8	0.0	-	-	-	-
8	0.3	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.9	0.0	0.0	0.0	0.0	0.0
2	1.3	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0
3	1.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0

[1] Observation time (hours)/*UR* (%): *Room 13*: 4/85.6; *Room 4*: 5/77.9; *Room 6*: 5/70.4; *Room 5*: 5/66.1; *Room 10*: 4/64.8; *Room 11*: 4/72.6; *Room 1*: 5/74.0; *Room 7*: 4/55.7; *Room 12*: 4/16.2; *Room 8*: 4/75.5; *Room 2*: 1/77.1; *Room 3*: 1/100.0.

Table A.2.5 Hour-to-hour variation of false-negative detection with 5 minutes TD-OFF

Room	Duration (% of time observed as occupied) Hour of observation				
	1st	2nd	3rd	4th	5th
13	-	35.2	59.4	38.4	87.9
4	13.2	27.0	62.6	44.1	45.1
6	55.9	19,6	10,1	13,2	37,7
5	23.9	0.0	0.0	30.5	44.3
10	-	10.5	25.5	17.3	13.6
11	-	27.4	9.0	5.7	0.0
1	16.4	0.0	3.9	4.1	21.6
7	-	0.0	33.1	2.6	2.1
12	-	0.0	7.2	0.0	0.0
8	-	0.0	0.0	2.9	0.0
2	0.4	-	-	-	-
3	0.3	-	-	-	-

Parameters influencing occurrence of false-negative detection

The frequency of false-negative detection is dependent on detector performance, including potential adjustments as e.g. sensitivity settings, and detector location in proportion to furnishing, room geometry and location of the person/persons it is expected to detect. The observed office cells in *Building 1* are almost identical regarding these parameters, except for the location of the workers in the office cells, which are further discussed later on. Furthermore, the office denoted *Room 7* is larger than the other observed offices. In addition, three other parameters will also affect the frequency of false-negatives:

1. *The utilisation rate*: The probability of a worker being exposed to false-negative detection is increased with increasing *UR*. For instance, if a worker is constantly present for 3 hours without leaving the office before lunch and just 1.5 hours after lunch, the probability is highest for more false-negatives before than after lunch, provided the same motion pattern inside the office cell.
2. *The distribution (frequency and duration) of occupancy periods*: If a worker has many vacancy periods that shorten the occupancy periods, the risk for false-negatives will decrease if these vacancies make some of the occupancy periods shorter than *TD-OFF*. For example, two hours of a working day can be compared,

where the worker is present for half an hour in total for both of these hours (*UR* equals 0.5). For the first hour, the worker is present constantly for half an hour and then absent for half an hour. For the second hour, the worker is present for two times fifteen minutes. If *TD-OFF* equals 20 minutes, then for the first hour, the worker is exposed for the risk of false-negative detection. For the second hour, there is no risk for false-negative detection, as long as the worker is being detected when entering and leaving the office cell. During the observations the detectors never failed to detect a worker who was entering or leaving an office cell.

3. *The worker's motion pattern inside the office cell*: The way the workers are moving at their desks is a determining factor for the risk of false-negatives. In addition to the type of work performed (reading, typing, talking in telephone etc.), the motion pattern is also decided by the room geometry and furnishing.

As mentioned above, the duration of the occupancy periods compared to *TD-OFF* can affect the occurrences of false-negatives. The last 6 columns to the right of Table A.2.4 shows the total duration of false-negatives expressed as percent of observed occupancy exposed to false-negative detection. For instance, with *TD-OFF* equals 30 minutes, an occupancy period shorter than 30 minutes will not be counted as an occupied period exposed to false-negatives. These values are computed with the intention to also exclude, in addition to *UR*, the effect of differences in distribution of occupancy periods. *Room 12* had no occupancy periods with duration of 15 minutes or more and therefore has empty cells for these values of *TD-OFF*. This was also the case for *Room 7* with *TD-OFF* equals 30 minutes.

As Table A.2.4 shows, there were still significant differences between the rooms regarding occurrence of false-negatives when only occupancy periods exposed to false-negatives is used as the basis of comparison. Hence, during the observations there were significant differences when it comes to the motion pattern inside each individual office cell, making it easier to detect some workers than others. The shape of the office desk makes it possible for the worker to take different positions at the desk, in relation to the detection field of the motion detector. The two outer positions are: (1) the detector facing the back of the worker (the worker is facing the external wall) and (2) facing the chest/right shoulder of the worker. Movement perpendicular to the detection field is easier for the PIR motion detector to detect than movement straight against or away from the detector. This means that the risk for false-negative detection was not only dependent on how much the worker was moving but also where at the desk the worker was sitting. The position of personal computers can differ somewhat between the office cells. If it was placed at the window, the detector was facing the back of the worker and small horizontal arm movements or wrist movement during typing at the keyboard could have been difficult to detect. Neither the position of the personal computers nor the exact position of the workers inside each observed office cell were registered during the observations.

Summary of occurrence of false-negative detection

The motion pattern inside the office cell, including the activity level and the workers' position in the room, is decisive for the occurrence of false-negatives. Both the working tasks and the position at the desk will vary with time. Because the office cells were only observed between one and five hours each, it is likely that most of the workers had a motion pattern, and in turn an exposure to false-detection, during the observations that more or less deviate from their average situation. There will probably be some differences between individual office cells regarding exposure to false-negative detection also in the long-run, but it is most likely less than during the observations. However, the limited observation time makes it difficult to predict the variation among the offices.

Instead of consider the frequencies and durations in Table A.2.4 as a sample with a sample range, or another measure, describing the variability among the office cells, it is probably better to consider these results as a sample of periods reaching from high to low occurrence of false-negatives, which most workers will experience. Therefore, adding all false-negative detection periods from both observations and divide it with the total number of observed occupancy hours[1], as presented in Table A.2.6, is considered to be a better estimate of the long-term average situation for a typical office cell in *Organisation A,* than the average of the observed offices. However, due to limited observation time this estimate involves some degree of uncertainty. Moreover, if the observations had been carried out with less daylight availability, such as a winter morning, the results may have looked somewhat different. All or some of the false-detections that lasted long enough to result in false-negatives with *TD-OFF* equals 20 minutes or more, could have been shorten due to the workers response to the lighting being switched off. In that case, it would have resulted in less total duration, but somewhat higher frequency of false-negatives.

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[1] Just over 31 hours of observed occupancy in total.

Table A.2.6 *Occurrence of false-negative detection during Observation 2 and 3*

TD-OFF (min)	Occurrence of false-negative detection	
	Frequency (number per hours observed as occupied)	Duration (% of time observed as occupied)
5	2.09	19.8
10	0.84	9.2
15	0.39	4.7
20	**0.26**	**2.4**
25	0.10	0.7
30	0.03	0.3

While the numbers in Table A.2.6 for 20 minutes *TD-OFF* represents the actual operation situation, the other levels of *TD-OFF* involves one additional element of uncertainty. As already mentioned, the control of the lighting in *Building 1* use 20 minutes *TD-OFF*, while the detected occupancy state was logged with 5 minutes *TD-OFF*. As a consequence, when altering *TD-OFF* it represents a situation where *TD-OFF* is changed for control of the ventilation (provided that a change in ventilation rate is not noticed instantaneously by the workers), but where the control of the lighting still uses 20 minutes *TD-OFF*. This is not a common solution. If *TD-OFF* was changed also for the lighting control, it would however probably not have affected the results during the observations significantly, or even at all. Nevertheless, if the numbers in Table A.2.6 are assumed fairly representative for the long-term average, it should be kept in mind when studying them that if *TD-OFF* was changed also for the lighting control it would probably had the following effect: for *TD-OFF* equals 15 minutes or less, the frequencies would have been higher and the total duration lower; for 25 or 30 minutes *TD-OFF*, the frequency would increased, but not much, and a few false-negatives would been prolonged. Based on that, it is also likely that the yearly averages *OFz* levels presented in Chapter 4.2.3 for different values of *TD-OFF* would have been somewhat higher for *TD-OFF* less than 20 minutes and somewhat lower for 25 and 30 minutes *TD-OFF*, if *TD-OFF* was changed also for the operation of the lighting.

In spite of the elements of uncertainty, the observations give a good indication of the performance of the detectors. The false-negative detection rate of 0.26 per hour of actual occupancy means on average one false-negative detection approximately every fourth hour that the worker is present. With an estimated actual occupancy of only 2 hours per day as average of all 26 office cells (see Chapter A.2.2.4), this correspond to approximately 2.5 false-negative detections per week. Moreover, the frequencies in Table A.2.6 give an indication of how the detector would have worked with other *TD-OFF* values than 20 minutes, and illustrate clearly the fact that the occurrence of false-negative detection increases strongly when *TD-OFF* is decreased down to 10 or 5 minutes.

A.2.2.3 *Type 3a* and *Type 3b deviations* (caused by *TD-OFF*)

The frequency and duration of *Type 3a* and *Type 3b deviation* are decided by the number and duration of actual vacancy periods, i.e. when the worker leaves the office cell, and the value of *TD-OFF*. Figure A.2.4 shows the frequency distribution of the observed (actual) vacancy periods[2], both *Observation 2* and *3* included. For one specific level of *TD-OFF*, the bars to the left of that value on the x-axis represents *Type 3b deviations* and the bars to the right represents *Type 3a deviations*.

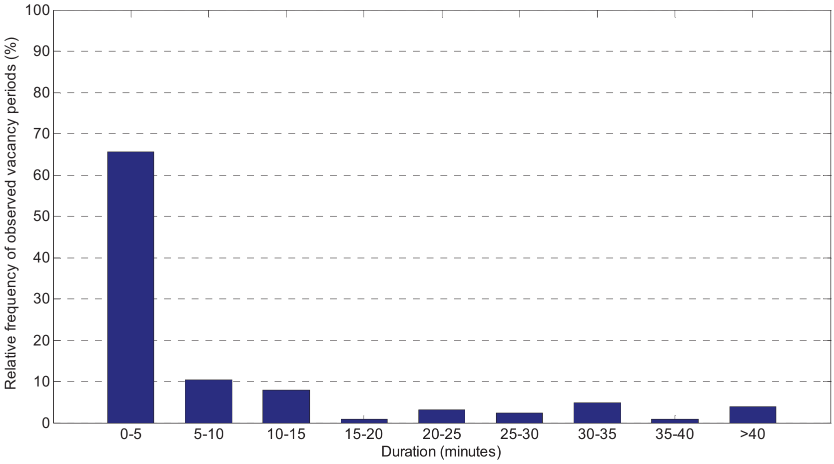

Figure A.2.4 Frequency distribution of observed vacancy periods, Observation 2 and 3 included.

Because the data were logged with 5 minutes *TD-OFF*, the *Type 3b* deviations lasting less than 5 minutes are not shown in the data record. As seen by Figure A.2.4, they were during the observations the most common ones and with 20 minutes *TD-OFF* they constituted 32 % of the total duration of *Type 3b deviations*, in spite of their short duration. The frequency

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[2] A few vacancy periods starts or ends outside the start or end of the observation period. The duration of these vacancy periods have not been cut at the start or end of the observation. Instead, the time for the start or end of the vacancy period registered in the log file have been used. Because no *Type 1* or *4 deviations* were observed, it can be assumed that it gives the correct duration.

of vacancy periods lasting less than 5 minutes were 2.6 per occupied hour and had a total duration corresponding to 4.1 minutes per occupied hour.

The distribution in Figure A.2.4 is most probably not completely representative for a typical day. Because the observations only covered segments of the day, some types of the typical vacancy periods are included and some are not. *Observation 3* covered the lunch time but none of the observations covered the typical time for coffee-breaks in the morning and afternoon. As a result, vacancy periods lasting 15 to 20 minutes are most likely underrepresented.

A.2.2.4 Implication of observed *Type 2* and *Type 3* deviations

The first part of this section discuss briefly the consequences of altering *TD-OFF*, and the second part computations carried out to estimate the occupancy logged with imaginary ideal detectors completely without false-detection.

Consequences of changing *TD-OFF*

In systems with control based on motion detectors, the energy use for lighting and ventilation is a function of *OFz*; and *OFz* in turn, a function of *TD-OFF*. The fact that *OFz* decreases when *TD-OFF* is reduced is explained by *Type 2* (false-negatives) and *Type 3 deviation*. First, the frequency and duration of *Type 2 deviation* increases when *TD-OFF* is reduced. Second, when *TD-OFF* is reduced, more and more *Type 3b deviations* is transformed to *Type 3a deviations* and each logged vacancy periods is prolonged. The time delay is needed to avoid, or at least limit, the occurrence of false-negative detection. However, decreasing *TD-OFF* reduce the energy demand of the lighting and ventilation system. The choice of *TD-OFF* is consequently an optimisation between the comfort of the workers on the one hand and the energy demand and operating costs on the other hand. When it comes to ventilation and comfort, not only the risk for false-negative detection but also the need for ventilation after a person has left the office has to be taken into account.

Another side effect when decreasing *TD-OFF*, in addition to increased risk for false-negative detection, is that the frequency of *Type 3a deviation* increases. Each *Type 2* and each *Type 3a deviation* represents a logged vacancy period that results in the lighting first being switched off and then switched on again. In the same way will the ventilation rate first be reduced and afterwards be increased, which implies two position changes for the damper(s) controlling the air flow rate. The number of times the lighting is switched on and off and the number of damper position changes may affect the length of life of the light sources and damper units. This is an additional factor that should be taken into account when deciding *TD-OFF*. The lifetime reduction for fluorescent and compact fluorescent lamps caused by frequent on and off switching can, however, be reduced by dimming the light down to a minimum level, instead of switching them completely off (Hansen and Fosse, 2004). This will cost some extra energy, and this loss has to be weighted against the gain of longer lamp lifetime.

If we think of an ideal detector without any false-negative detection, the decrease in *OFz* when *TD-OFF* is reduced will be less than for the detectors in *Building 1*. This is exemplified by Figure A.2.5, showing *OFz* for the 12 rooms in *Observation 3* with and without false negatives, together with the number of occupancy state changes, which is a function of the amount of *Type 2* and *Type 3a deviation*.

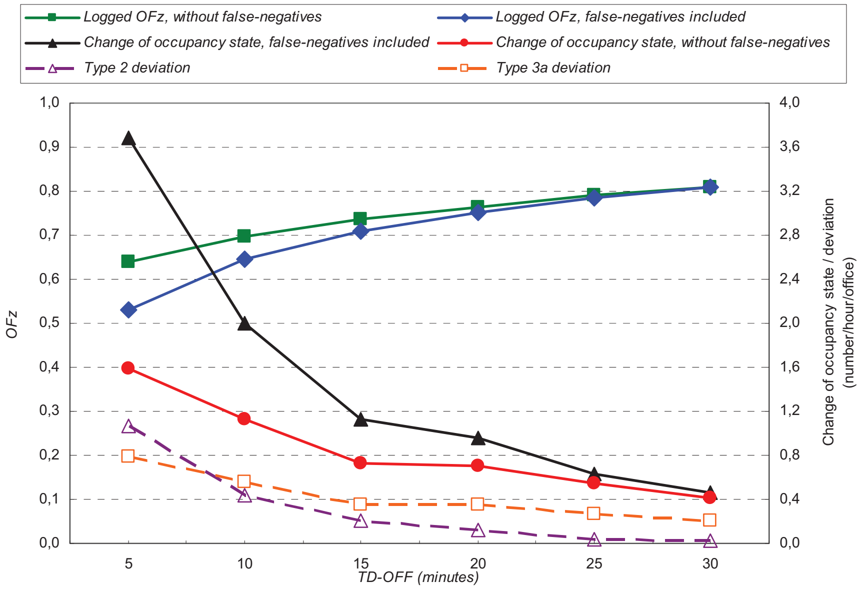

Figure A.2.5 OFz and average number of occupancy changes with and without false-negative detection included, in Observation 3 as a function of TD-OFF, illustrating the difference between the detectors in Building 1 and imaginary ideal detectors. In addition, the average number of Type 2 (false-negatives) and Type 3a deviations.

The exact numbers in Figure A.2.5 is not what is important, since it is based on only 4 hours of observation. However, it illustrates the compromise that has to be done between energy use (*OFz*) and the workers' comfort (*Type 2 deviation*) when choosing *TD-OFF*, and depending on the type of installations, also taking life time of components into account (number of occupancy state changes). The workers' comfort should have first priority, but some degree of false-detection has to be accepted when using PIR motion detectors in offices.

In *Observation 3*, the number of occupancy state changes increases strongly when *TD-OFF* is reduced below 15 minutes (black curve). For an ideal detector without false-negatives, the number of changes as a function of *TD-OFF* (red curve) has a gradient that is significant flatter, because it is only dependent on the actual number of vacancy periods lasting longer than *TD-OFF* (*Type 3a deviations*). With a detector having very low frequency of false-negative detection (e.g., one with dual technology), one has the opportunity to use a short *TD-OFF* in order to limit the energy demand. The distribution in Figure A.2.4 strongly indicates that reducing *TD-OFF* below 5 minutes will increase the number of times the lighting will be switched on and off and the damper will change position significantly. Consequently, setting *TD-OFF* below 5 minutes would not have been a suitable solution, even for a detector with very good performance regarding false-negatives.

Above, *Type 2 deviation* is mentioned as a disadvantage with motion detector regarding the workers' comfort. For ventilation, also *Type 3a* and *3b deviation* will impact the air quality and consequently the comfort of the workers, because it is important to supply ventilation also when the office cells are unoccupied in order to achieve an acceptable air quality when the worker returns after being absent for a while. Figure A.2.6 shows the total duration of these three types of deviation during *Observation 2* and *3*.

During *Type 2 deviations* the concentration of all pollutants in the indoor air will rise, resulting in a deterioration of the air quality. During *Type 3a* or *Type 3b deviation* the concentration of pollutants generated by the worker, and potentially also pollutants generated by the workers activities, will diminish. This is of course provided that no additional changes is taking place simultaneously (pollutant concentration in supply air, ventilation efficiency etc). As Figure A.2.6 shows, the total duration of *Type 3a* and *3b deviation*, which improve IAQ, exceeded the total duration of *Type 2 deviation*, with the opposite effect on IAQ, during the observation for *TD-OFF* equals 10 minutes or more. However, it does not automatically mean that the *Type 3 deviations* more than compensate for the *Type 2 deviations* and their negative effect on the IAQ, because the time when worker is exposed to this either improved or reduced air quality is not the same. During *Type 2 deviation,* the worker is exposed to the shortage of ventilation during the whole false-detection period and an additional period until the steady-state concentrations for an occupied office is reached. The worker will during *Type 3b deviation* only benefit from the somewhat improved IAQ when returning to the office and the time until the steady-state concentrations is reached. For a *Type 3a deviation*, the absence from the office cell can be long enough for the concentration of a pollutant to reach the steady-state level for an occupied office before the worker returns. The worker will in that case not benefit at all from the period with increased IAQ. This is dependent on how much ventilation that is supplied when the office cell is registered as unoccupied. Moreover, the consequences of the deviations for the IAQ are also dependent on when they occur in relation to each other, i.e. the distribution of occupancy and vacancy periods.

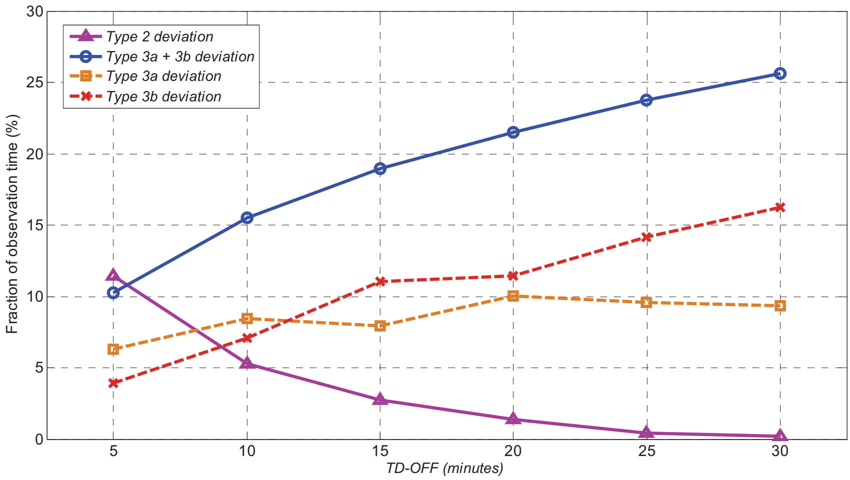

Figure A.2.6 Total duration of Type 2, Type 3a, Type 3b and the sum of Type 3a and 3b deviation, during Observation 2 and 3 as a function of TD-OFF.

Estimates of a ideal detector without false-detection

In order to estimate the yearly average *OFz* with an ideal detector without false-negative detection, the observations were used as an attempt to find the percental distribution between false-negatives and actual vacancies on a yearly basis. As mentioned above, the distribution of observed vacancy periods in Figure A.2.4 is not representative for an average day. Instead, it is assumed that the distribution of false-negatives observed in the two observations constitute an approximately representative mix for the average situation in *Organisation A*.

A branch of statistics called survival analysis deals with methods for analysing survival time data, which are measurements of the time elapsed until a certain event occurs; for instance, death, convalescence, relapse to or development of a specific disease in biomedical studies and failure of a component in a technical system (Lee and Wang, 2003). The duration of false-negative periods, and also the duration of actual vacancy periods and occupancy periods can be regarded as survival time data, where the event is a detection ending a false-negative detection period or the worker leaving or entering the office cell, respectively.

As a simplification, the process of false-detection is modelled as an exponential distribution, which is the simplest and the most important distribution in survival time studies (Lee and Wang, 2003). This distribution is related to the Poisson process where the survival time (also called waiting time) T to the next event A is exponentially distributed with rate parameter λ. The exponential distribution has the following probability density function f and cumulative distribution function F:

$$f(t) = \lambda \cdot e^{-\lambda \cdot t} \qquad \text{for } t > 0 \tag{A.1}$$

$$F(t) = 1 - e^{-\lambda \cdot t} \qquad \text{for } t > 0 \tag{A.2}$$

Here, the event A is a movement large enough to be detected by the motion detector, which ends a false-negative detection period when *TD-OFF* equals 5 minutes. The maximum likelihood estimate (MLE) for λ (without any censored observations) is the reciprocal of the observed mean waiting time (Lee and Wang, 2003), i.e.:

$$\hat{\lambda} = \frac{n}{\sum_{i=1}^{n} t_i} \tag{A.3}$$

The mean duration of the $n = 65$ false-negative detections that occurred during *Observation 2* and *3* was 5.92 minutes, resulting in an estimated λ of 0.169.

A graphical method for checking if a theoretical distribution provides an adequate fit to the observed data is to construct a probability plot. For survival time data, this means plotting the observed survival times, or a function of *t,* against a function of the sample cumulative distribution function[3]. If the tested distribution provides a god fit, the points will lay on an approximately strait line. For the exponential distribution, Equation A.2 shows that there is a linear relationship between t and the function $ln[1/(1-F(t))]$. The left hand side of Figure A.2.7 shows such exponential probability plot, while the right hand side of the figure shows the cumulative distribution function.

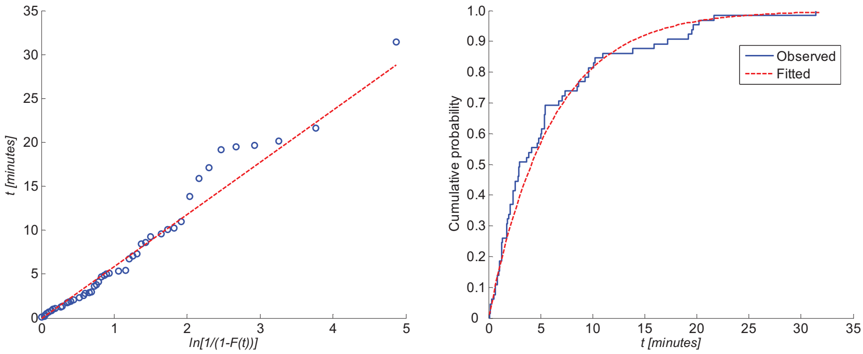

Figure A.2.7 Observed versus modelled distribution of the duration of false-negative periods. Left: Exponential probability plot. Right: Cumulative distribution function. (The red curves does not represent a graphical fit (by eye), it is the fitted distribution based on the MLE).

Assume we are studying the duration of a process where we measure the survival time T until a defined event A that ends the process occurs; then, the hazard rate is the probability per unit time of A to occur in the short time interval $[t, t + \Delta t]$, given that the process has already survived until *t.* One of the prerequisites for the Poisson process and the validity of the exponential distribution is that the hazard rate is constant, i.e. independent of t, and equal to λ (Løvås, 2004; Lee and Wang, 2003). In this case, it means that during a false-negative detection period, the probability for being detected within the next time period Δt

---

[3] The sample cumulative distribution function can be estimated by first sort the n observed survival times in ascending order, then compute $F(t)$ with either $(i - 0.5)/n$ or $i/(1+n)$, where i is the order index ($i = 1, 2, \dots n$). If two or more observations have identical survival time, they are given different order index and only the one with highest index is plotted (Lee and Wang, 2003).

is independent of how long the false-negative detection period has lasted. For example, a worker that have not be detected for the last 6 minutes has the same probability of being detected within the next second as if she/he had not been detected for the last 20 minutes. To which degree this prerequisite is fulfilled is uncertain, however, the observed duration of false-negatives seems to fit reasonable well with the exponential distribution.

In situation where it is not realistic to expect a constant hazard rate, other distributions have to be tested and one of the most used in case of time-dependent hazard rate is the Weibull distribution (Løvås, 2004). Several common used theoretical distributions within survival data analysis was tested in addition to the exponential distribution. A Weibull distribution was the one that graphically seemed to fit the empirical data best, however the improvement compared to the exponential distribution was small. To test appropriateness of a theoretical distribution as a model for the empirical data it can be compared to a nested and more general distribution; for example, by computing the log-likelihood ratio statistics. For instance, the Weibull distribution[4], which is a two-parameter distribution with scale parameter (λ) and shape parameter (*k*), includes the exponential distribution as a special case when *k* equals 1. In the case of testing for the exponential distribution, the log-likelihood ratio statistics X_L becomes (Lee and Wang, 2003):

$$X_L = 2[l_w(\hat{\lambda},\hat{k}) - l_w(\hat{\lambda}(1),1)] \qquad \text{A.4}$$

The term $l_w(\hat{\lambda},\hat{k})$ is the value of the log-likelihood function for a Weibull distribution with the MLEs for λ and *k*, and $(\hat{\lambda}(1))$ the MLE for λ given *k* equals 1. The term $l_w(\hat{\lambda}(1),1)$ equals $l_E(\hat{\lambda})$, which is the value of the log-likelihood function for an exponential distribution with MLE for λ. The statistics X_L in equation A.4 has an asymptotic chi-square distribution with one degree of freedom. The null hypothesis H_o that the underlying distribution, explaining the observations, is an exponential distribution is rejected with significance level α if X_L exceeds the α-quintile of the chi-square distribution with one degree of freedom, i.e. $X_L > \chi^2_{1,\alpha}$. With the fitted exponential and Weibull distribution (performed in MATLAB (2007), based on MLE), X_L = 0.54, which is less than $\chi^2_{1,0.05}$ =

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[4] Probability density function: $f(t) = k\lambda\left(\lambda t\right)^{k-1} e^{-(\lambda t)^k}$ for $t \geq 0$ and $\lambda, k > 0$

3.84. Consequently, the null hypothesis could not be rejected with 5 % significances level ($p = 0.46$). Hence, because the Weibull distribution does not provide a significant better fit, the exponential distribution was preferred due to its simplicity.

In order to find an estimate of the frequency distribution of false-negative detection periods for the whole year, the percental distribution between false-negatives and actual vacancy periods has to be estimated for one value or one segment of the time scale. The left hand side of Figure A.2.8 shows the frequency distribution of logged vacancy periods with duration up to 40 minutes, partly for the observations and partly for the whole year. The durations on the x-axis (also for the right hand side of the figure) correspond to 5 minutes *TD-OFF*. Because of the limited number of observed vacancy periods, a time resolution of 5 minutes was chosen. The distribution of vacancy periods in the observations corresponds rather well with the annual distribution, with one exception; 10 to 15 minutes duration is underrepresented in the observations. Because of the highest number of observations, the percentage distribution between false-negatives and actual vacancies with duration between 0 and 5 minutes was chosen to fit the modelled distribution in Figure A.2.7 with the annual data. In addition, it is assumed that the frequency of vacancy periods with short duration is the one least affected of the fact that only segments of working days were observed.

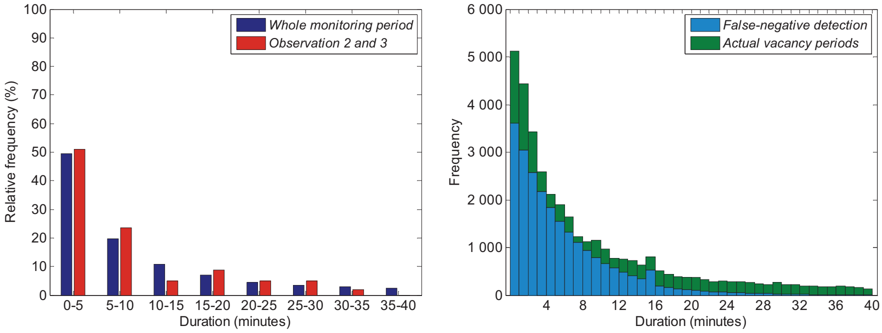

Figure A.2.8 Left: Comparison of the frequency distribution of logged vacancy periods with duration up to 40 minutes between Observation 2 and 3 and the whole year. Right: Modelled annual frequency distribution of vacancy periods due to false-negatives and actual vacancy periods respectively. The annual distributions include all working days between 6 a.m. and 6 p.m. and TD-OFF equals 5 minutes.

With 75 % of the total logged vacancy periods with duration between 0 and 5 minutes assumed to be false-negatives (equal to the percentage in the observations), the right hand side of Figure A.2.8 shows the estimated annual frequency distribution of false-negatives and actual vacancy periods respectively, for working days between 6 a.m. and 6 p.m. The modelled probability distribution of false-negatives do not take into account the effect of the lighting being switched off 20 minutes after the last detected movement (15 minutes after the room is counted as unoccupied with 5 minutes *TD-OFF*). It is assumed that the increase in total number of vacancy periods with duration equals 15 and 16 minutes compared to the general trend, shown on the blue part of the bars in the right hand side of the figure, is completely a result of false-negatives, due the reaction of the lighting being switched off. Therefore the surplus on the blue curve compared to a linear reduction between 14 and 17 minutes is added to the frequency distribution of false-negatives. To compensate for this addition of false-negatives with 15 and 16 minutes duration, it is assumed a corresponding decrease in frequency for periods up to 25 minutes, compared to the exponential probability distribution. It is assumed the highest reduction for 17 minutes duration and then a linear decline up to 25 minutes duration.

If the frequency of false-negative detection during the observation shall be compared to the estimates for the whole year, it is logical to base it on the number of occupied hours with approximate zero *TD-OFF*. This is the time when the worker is present and at the same time detected[5], which is a prerequisite for a false-negative detection period to start. During the observations, there were 2.59 false-negatives per occupied hour[6] with approximate zero *TD-OFF*. With 75 % of the logged vacancy periods lasting up to 5 minutes assumed to be false-negatives and λ equals 0.169, the model gives an annual rate of 2.52 false-negatives per occupied hour with *TD-OFF* equals approximate zero.

The estimation of using ideal detectors, without false-negative detection, on an annual basis is presented in Chapter 4.2.3. The increase in *OFz* with ideal detectors compared to the

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[5] This is not completely correct, because when the worker is absent less than five minutes the room is still logged as occupied, so it slightly overestimates the time when false-negative detections can be initiated. The comparison between the observation and the estimated rate of false-negatives assumes therefore that the frequency of such short lasting vacancy during the observations is representative for the annual situation.

[6] If an occupancy period started before and/or ended after the observation, the duration was calculated from the time stamps in the data log, i.e. it was not cut at the start and/or end of the observation. A continuous time interval was selected for each observed room, reaching from the start of the first to the finish of the last occupancy period on the day of the observation where the cause to the ending of the occupancy period could be established (whether the worker left the room or was the start of a false-negative detection period). This means that some of the counted occupancy periods occurred partly or completely outside the observation time. This was done to increase the accuracy of the estimated false-negative detection rate.

ones used in *Building 1* is 18 percent for 5 minutes *TD-OFF* and only 3 % for 20 minutes *TD-OFF*. The outcome of changing the distribution between false-negatives and actual vacancy periods for the logged vacancy periods lasting up to 5 minutes (with 5 minutes *TD-OFF*), and thereby the rate of false-negatives, was tested. Changing it from a 75/25 % distribution to an 80/20 % or a 70/30 % distribution[7], corresponding to 2.69 and 2.35 false-negatives per occupied hour with approximate zero *TD-OFF*, had a very small effect; +/- 0.002 and +/- 0.001 units on *OFz* for 5 and 20 minutes *TD-OFF* respectively. There is of course also a certain degree of uncertainty in the modelled probability distribution of the duration of false-negatives. A 95 % confidence interval for λ (Løvås, 2004) is [0.128, 0.212]. Reducing λ down to 0.128 gives an increase of *OFz* by 0.017 and 0.011, while increasing λ to 0.212 decreases *OFz* by 0.005 and 0.004, for 5 and 20 minutes *TD-OFF* respectively. Hence, none of the changes had more than a minimal impact on the results.

Finally, the estimates of using ideal detectors together with the observed occurrence of (actual) vacancy periods lasting less than 5 minutes are used to estimate the actual annual *OFz* level, i.e. the occupancy level of the workers without the effect of the detectors. First, *OFz* in the case of ideal detectors with approximate zero *TD-OFF* (eliminating *Type 2* and *Type 3a deviations*) was computed in the same way as explained above. Second, this *OFz* level was reduced to eliminate *Type 3b deviations*, by assuming the same fraction between the duration of short vacancy periods (< 5 minutes) and number of occupied hours as in *Observation 2* and *3* (4.1 minute per hour of presence). The actual annual *OFz* level for working days between 6 a.m. and 6 p.m. was estimated to 0.166. Like for the observations, this is close to the *OFz* level with 5 minutes *TD-OFF*, which on annual basis is 0.169.

A.2.3 Discussion

The observations indicate a false-negative detection rate of 0.26 per occupied hour with 20 minutes *TD-OFF*. It is difficult to state what can be considered as acceptable performance regarding false-negative on a general basis. What is perceived by the workers as acceptable is probably individual to a great extent. In addition, the acceptance will probably vary with time, dependent on factors like daylight availability, use of other artificial lighting sources

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[7] Using a 77/23 distribution gives an estimated annual rate of false-negatives per occupied hour (with approximate zero *TD-OFF*) equal to the one during the observations.

and what kind of working task is performed at the moment for the false-detection. The workers in *Organisation A* first complained when moving into *Building 1*. However, when the manner of operation and the application of the detectors were explained by the operating personnel, the performance and the fact that they have to move the arm to switch the light on again have been accepted by the workers. Nevertheless, based on the high observed occurrence of false-negatives in a few rooms (especially *Room 13*), it would most likely not have been suitable to decrease *TD-OFF*, even though it probably would have worked well in most of the time with, for example, 15 minutes *TD-OFF.* Detection of sedentary office work with almost no motion is a week point of PIR motion detectors. Improving the performance and decrease the false-negative rate can be done, as an alternative to increasing *TD-OFF*, by using another type of detector; for example, one that uses dual technology which combines a PIR and a high frequency Doppler (microwave) sensor. The disadvantage is that these sensors are more expensive.

If the observed occurrence of false-negative detection, summarised in Table A.2.4, is considered as representative for the typical situation in the individual rooms, it strongly indicate that individually adapted *TD-OFF* settings could be suitable in order to reduce the average *UR* without impairing the comfort of the workers. The settings could be based on feed-back from the workers, either by asking each worker if she/he is satisfied with the prevailing *TD-OFF*, or instead or as a complement, asking them to make notes of the number of false-negatives during a few days. An advantage of this approach is that the individual differences regarding the acceptance of false-detection is taken into account. A disadvantage is that it requires some effort to find the new settings and to adjust them. If the detector is connected to a room controller as part of a computerized building automation and control system, it facilitates the adjustment. However, this argumentation is based on observations with a very limited duration. The motion pattern inside the office cells, both the position at the desk and the activity level, decided by the type of work performed, will change for each individual during the day and/or from day to day. Thus, workers that had few false-negatives during the observations may have significant more frequent occurrence of false-negative detection during other periods. Hence, the potential to reduce *UR* with an individual *TD-OFF* setting may be much smaller than indicated here. However, like in the observations, there are probably some individual differences regarding the average frequency of false-negatives also in the long-run, so that some energy saving can be expected with individual *TD-OFF* setting. If the differences between individual offices regarding false-negative detection are to be studied, observations covering a longer time period (e.g., one week) are preferable. This was however not the main purpose of the observations presented here.

Another possible solution, both taking any potential differences between individuals and time-varying motion pattern for each individual into account, is PIR motion detectors with self-adaptive time delay. This means that *TD-OFF* is decided by the previous detection frequency, i.e. the time interval between the detected motions during a certain specified time period. The purpose is to save energy and at the same time decrease the all over false-negative detection rate compared to a detector without self-adapting timed delay. Products with this kind of control logic are available; either built into the detector or in a controller unit that a motion detector can be connected to. However, one disadvantage is that it results in more on and off switching of the lighting and more damper position changes. Moreover, if the ventilation is controlled with this varying *TD-OFF*, the period with a higher level of ventilation will also vary. No published tests of commercial available detectors with self-adaptive *TD-OFF* are known by the author.

Algorithms for adaptive time delay for motion detection were studied by Garg and Bansal (2000) and Leephakpreeda (2005). Garg and Bansal used a PIR motion detector placed near the PC monitor and facing the user, in order to detect small movements. The detector controlled both fluorescent lamps and compact fluorescent lamps. When the user was not detected for a period equal to the prevailing *TD-OFF*, the compact fluorescent lamps were dimmed and in addition the detector gave a beep sound for 15 seconds before the fluorescent lamps were switched off. *TD-OFF* was changed based on the reaction during these 15 seconds, i.e. a detected movement or no detection (interpreted as the area being unoccupied). In that way the detector learned the pattern of activity level during the day. This process was repeated for 5 days. Two methods were tested. In the first method, the day was divided into 10 minute intervals and the longest logged inactivity period (time between two detections) was selected as *TD-OFF* for that time interval. In the second method, a statistical model was derived from the logged data which modelled the probability distribution of inactivity periods. With that, the probability for false-negative detection was taken into account. The *TD-OFF* values found with the two methods were applied on a typical 9.5 hour working day, with 7 hours occupancy. With the second method, one *TD-OFF* was selected for the whole day (with 99.5 % probability to avoid false-negatives). However, as mentioned by the authors it could instead have been done with different *TD-OFF* values for different time periods of the day. Compared to no lighting control at all, it was computed that both methods saved approximately 5 % more energy than a detector with a constant 5 minutes *TD-OFF*. Two disadvantages were mentioned with the first method; longer learning period and no control of the probability for false-negatives. Both methods assume that the activity level of the worker follows a similar trend on every day. This assumption was confirmed to be valid in the study. However, it was based on a limited logging period and only one person.

The assumption that the activity level follows the same pattern from day to day for one specific worker was pointed out by Leephakpreeda (2005) as a limitation in the method proposed by Garg and Bansal (2000). Leephakpreeda also modelled the probability distribution of inactivity periods, based on measurements, in the same way as Garg and Bansal. However, Leephakpreeda proposed lighting control based on Grey prediction, which tries to predict *TD-OFF* based on the trend of the pattern of activity level during the past days, resulting in *TD-OFF* to change from day to day.

A.2.4 Conclusions

All together, the three observations gave the following conclusions:

- It seems that the data acquisition procedure worked as intended, so that the collected data from *Building 1* is reliable.
- Some results in Chapter 5, PART II, are presented as a function of *TD-OFF*. For other values than 20 minutes *TD-OFF*, they do not represent the actual operation conditions, because they are all based on the same data, where the lighting control used 20 minutes *TD-OFF*. If *TD-OFF* was changed also for the lighting control it would probably had the following effect on annual basis: *OFz* would have been somewhat higher for *TD-OFF* less than 20 minutes and somewhat lower for 25 and 30 minutes *TD-OFF*. The effect on both *OFz* and the distribution of logged occupancy and vacancy periods would have been largest for 5 minutes *TD-OFF*. For *TD-OFF* equals 15 minutes or more, the effect is considered to be small.
- The observations strongly indicated that the difficulty in detecting a present worker will vary significantly from time to time, where the occurrence of false-negatives mainly is dependent on the motion pattern inside the office cell, decided both by the type of work performed, and the workers' position at the desk in relation to the

> detection field of the detector. Using a *TD-OFF* as low as 5 minutes would have resulted in occurrence of false-negative detection during most hours. With 20 minutes *TD-OFF*, false-negative detection is not completely avoided and during some type of work it can occur relatively frequent. Consequently, decreasing *TD-OFF* below 20 minutes is not considered to be a suitable solution in *Building 1*.

Besides that, it is difficult to draw conclusions due to the limited total observations time. However, the observations also indicated that there are no problems with false-positive detection.

A.3 Complementary results to Chapter 5 and 7

Appendix A.3 contains complementary results to Chapter 5 in Part II and Chapter 7 in Part III. No further explanation of the results in addition to the figure and table text is provided. The figure and table texts include a reference to the chapter that the result is linked to.

A.3.1 *Building 1* – organisational level

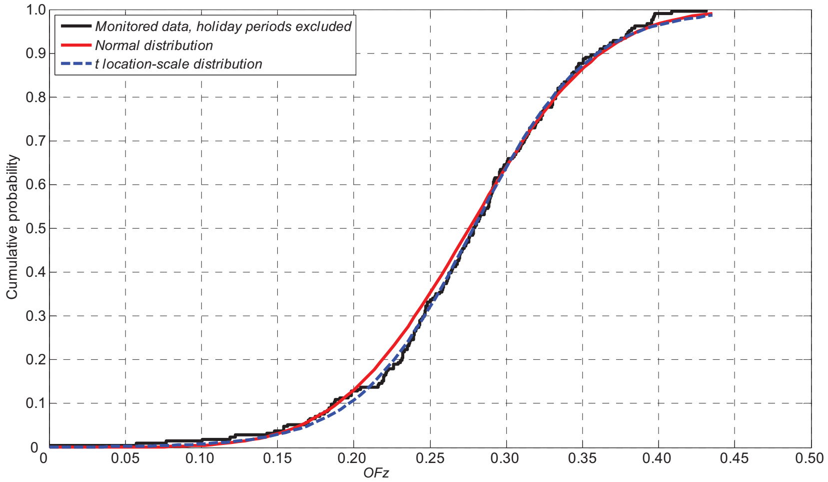

Figure A.3.1 Cumulative distribution function (CDF) for $\overline{OFz}^{06-18,wd}$ *in Organisation A, for monitored data versus fitted distributions. (Chapter 5.2.1)*

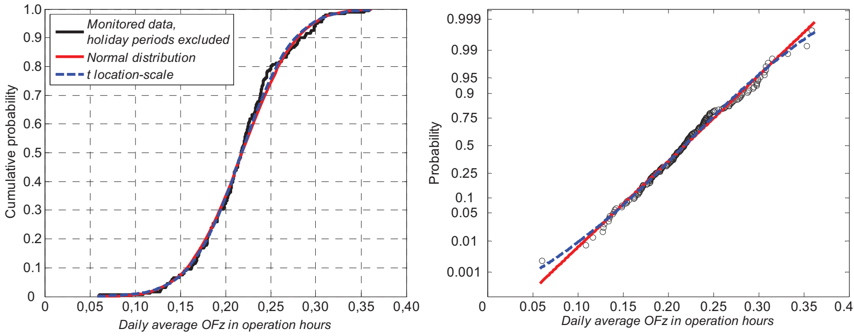

Figure A.3.2 Monitored data versus fitted distributions of $\overline{OFz}^{06-18,wd}$ *for Organisation B, holiday periods excluded. Left: CDF. Right: Probability plot. (Chapter 5.2.1)*

A.3.2 *Building 1* – Individual room level

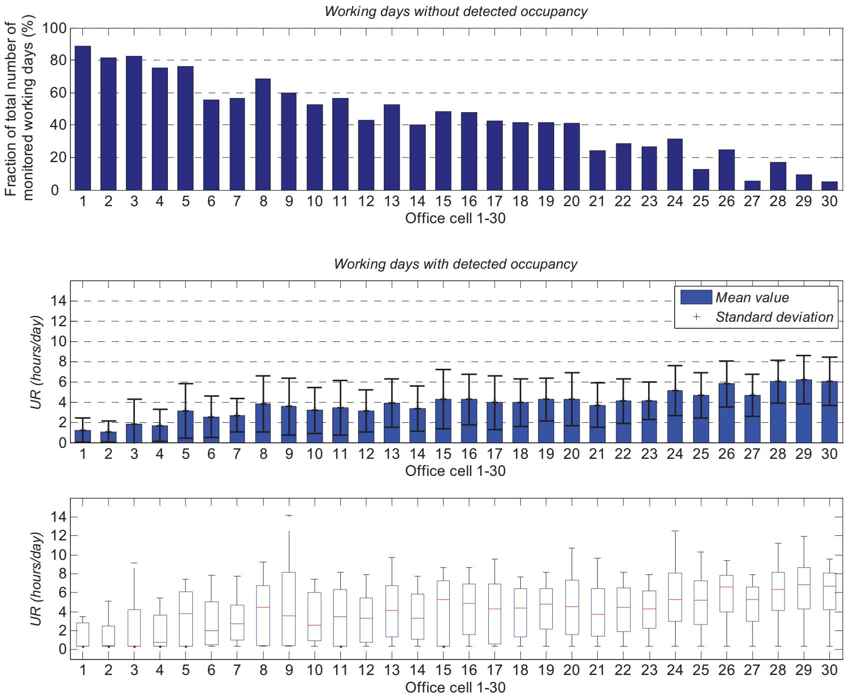

Figure A.3.3 Upper: Number of working days with UR equals zero as fraction of total number of monitored working days, in Organisation B. Middle: Mean and standard deviation of daily UR, when days with UR equals zero are excluded, in Organisation B. Lower: Box and whisker plot illustrating the distribution of daily UR when days with UR equals zero are excluded in Organisation B. The whiskers mark the maximum and minimum values and the boxes the upper quartile, median value (red line) and lower quartile. (Chapter 5.3.1)

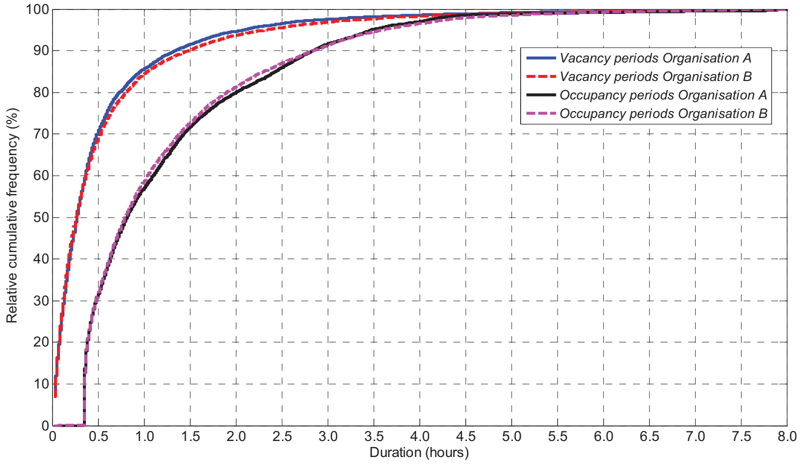

Figure A.3.4 Cumulative frequency distribution of the duration of (detected) occupancy and vacancy periods in Organisation A and B. (Chapter 5.3.2)

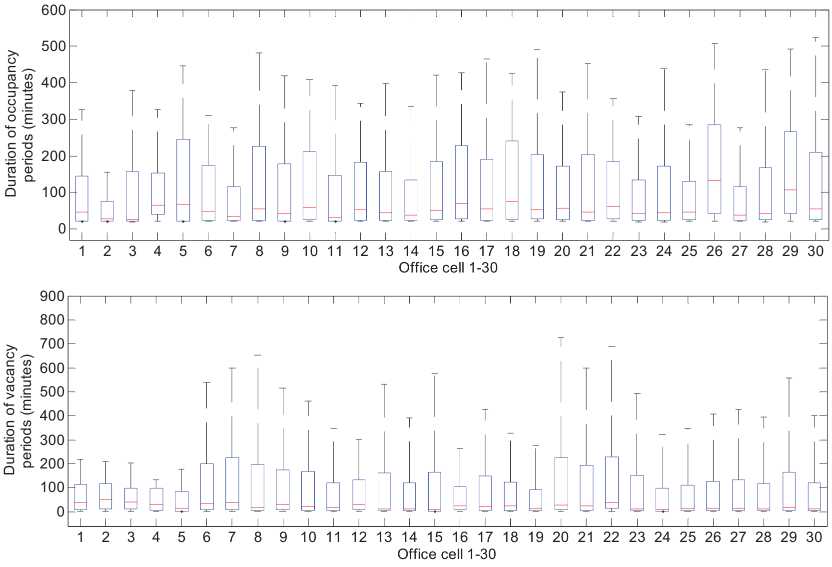

Figure A.3.5 Distribution of the duration of occupancy periods (upper) and vacancy periods (lower) for the office cells in Organisation B. Box and whisker plot showing maximum and minimum (whiskers) together with upper quartile, median and lower quartile (boxes). (Chapter 5.3.2).

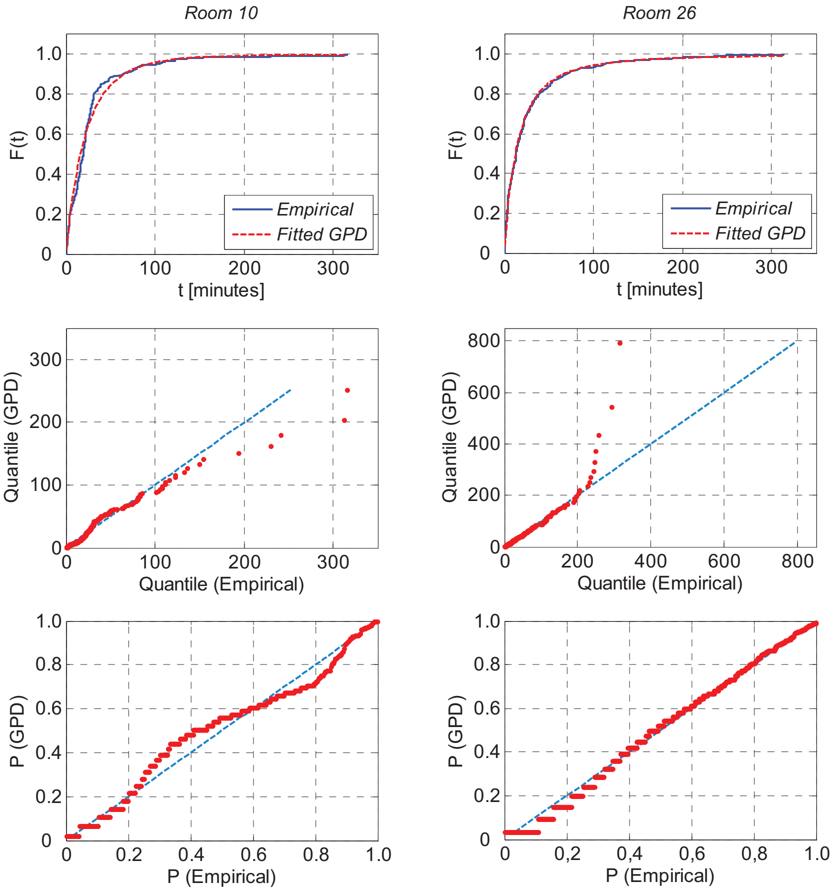

Figure A.3.6 Test of fitted generalised Pareto distribution to the duration of vacancy periods in two rooms in Organisation A.

A.3.3 Chapter 7

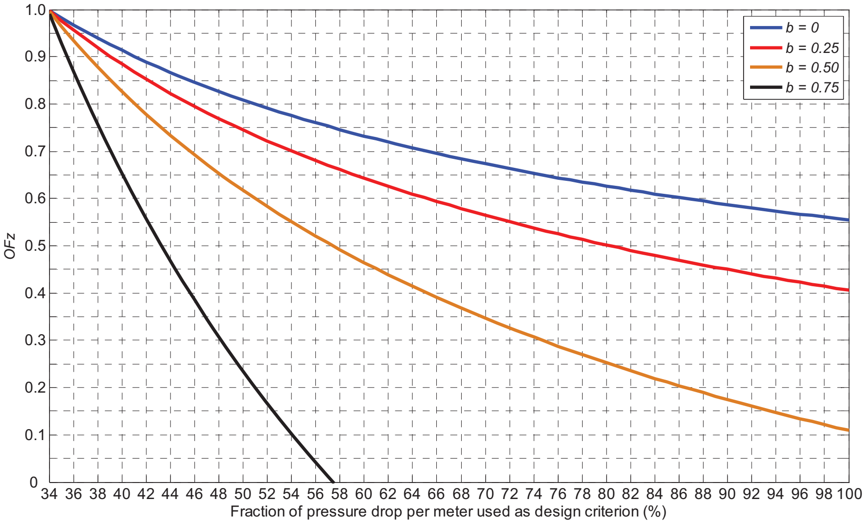

Figure A.3.7 OFz levels needed to go one standard diameter down for circular ducts and still fulfil the maximum pressure drop per meter duct used as design criterion, as a function of the fraction of the design criterion that $q_{DCV}(S=1.0)$ *gives. The equation used for the pressure drop is* $\Delta p = 0.0158 \cdot \rho \cdot q^{1.8376}/d^{4.8541}$ *(Pa/m), which is used in the PFS (Program Flow Systems) program (referred to in Johansson, 2005). (Chapter 7.2.4)*

Table A.3.1 For six values of S-dl, the corresponding T(S-dl) and maximum shortage of ventilation air for one office during one day (the design day), in Organisation B. (Chapter 7.2.5)

	T(S-dl) (hours per year)				Relative daily shortage of ventilation air for the most exposed office (%)			
	b				*b*			
S-dl	0	0.25	0.50	0.75	0	0.25	0.50	0.75
0.70	0.6	5.5	256.2	> 300	0.5	0.6	5.1	-
0.75	0.4	0.8	48.0	> 300	0.3	0.4	2.1	-
0.80	0.1	0.4	5.5	> 300	0.2	0.2	0.3	-
0.85	0.1	0.2	0.7	256.2	0.1	0.1	0.2	2.3
0.90	0.1	0.1	0.1	11.8	0.0	0.1	0.1	0.1
0.95	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0

A.4 Papers

Paper I:	Halvarsson, J., Hanssen, S. O. and Mathisen, H. M. (2005) Rationale for IAQ regulations in Scandinavia. *Proceedings of Indoor Air 2005*, Beijing, 3459-3463.
Paper II:	Mathisen, H. M., Halvarsson, J., Wachenfeldt, B. J., Hanssen, S. O. and Berner, M. (2005). A comparison of central and decentralized air handling units. *Proceedings of Clima 2005 – 8th Rehva World Congress*, Lausanne, 1-6.
Paper III:	Halvarsson, J., Mathisen, H. M., Hanssen, S. O. and Kolsaker, K. (2006) Measured occupancy in an office building. *Proceedings of Healthy Buildings 2006*, Lisboa, Vol V: 55-58.

(Paper III, Figure 3: correct is 0, 100, 200 % on the x-axis)

RATIONALE FOR IAQ REGULATIONS IN SCANDINAVIA– SIMILARITIES AND DIFFERENCES

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ABSTRACT

Most ventilation regulations and standards are descriptive, meaning that they require ventilation flow rates which are assumed to dilute pollutants to acceptable concentrations. The required ventilation flow rates differ considerably between regulations and standards worldwide. This paper compares regulations in Scandinavia. These countries should be quite similar with respect to culture, building tradition, climate etc. In spite of similarities, the difference in required or recommended outdoor air flow rates is significant between the countries. A possible explanation may be uncertainties about indoor air quality and the necessary level of ventilation, in combination with different views on the balance between indoor air quality and energy use.

INDEX TERMS

Regulations, Ventilation, Indoor air quality, Outdoor air flow rate

INTRODUCTION

Construction of buildings involves large amounts of money and great responsibilities (Wouters et al. 2003). In this context, it is important that the customer and the supplier have a mutual understanding of quality. For some aspects of a system, the expected performance is evident. For other aspects, for instance indoor climate and energy efficiency, the needs are often not obvious and clearly stated requirements are important. Regulations and standards can be a helpful tool to handle these requirements and to create buildings with a quality level which satisfies the needs of the users and the society. (TIP-Vent 2001)

A recent meta-analysis (Wargocki et al. 2002) showed a correlation between ventilation flow rates and health, comfort (perceived air quality) and productivity. However, the ventilation flow rate is just one of several factors that decide the pollutant concentration in the indoor air. The steady state concentration in a room can be calculated from Equation 1 (Seppänen et al. 1999).

$$C_{in} = C_s + \frac{S/V}{\lambda_v + \sum \lambda_{other}} \tag{1}$$

C_{in} is the indoor concentration, C_s is the concentration in the supply air, S/V is the pollutant generation rate per unit air volume, λ_v is the supply air flow rate divided by the room volume and $\sum\lambda_{other}$ is the sum of all other pollutant removal rates. Equation 1 assumes perfect mixing ventilation, which is not always the case. In addition, the quality of the supply air is dependent on several factors, for example ambient air quality, location of the air intake, cleaning of supply air and pollution sources in the ventilation system. Furthermore, the indoor pollutant concentration is in practice not constant over time, because of varying pollutant generation rate and adsorption and desorption of pollutants by room surfaces. Many buildings have variable ventilation flow rates, controlled by for example temperature or occupancy. Moreover, the operation schedule, 24 hours a day operation or intermittent operation, affects the indoor pollutant concentration (Seppänen et al. 1999). Consequently, the ventilation flow rate is only one of many factors that influence the indoor air quality (IAQ). Idealistically, all the factors mentioned should be taken into consideration when deciding the flow rates.

There are in principle two different ways of expressing requirements for appropriate levels of ventilation. Most existing regulations and standards are *descriptive*, meaning that they require ventilation flow rates which are assumed to dilute pollutants to acceptable concentrations. The *performance based approach* is based on that

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acceptable concentration levels for different pollutants are stated (Wouters et al. 2003). In many cases, regulations and standards set exposure levels for CO_2 or a few pollutants and additionally requires minimum flow rates.

Reviews by Olesen (1997 and 2004) show that there are large differences between ventilation standards worldwide. In the framework of the European TIP-Vent project (2001) ventilation requirements in different countries were compared. The conclusion was that existing regulations and standards worldwide differ considerably both in comparable values and in the way the requirements are expressed. Furthermore, no accepted criteria to define ventilation flow rates based on health considerations exist. As a result, each country defines requirements to ventilation flow rates based on different criteria. Three potential reasons for the difference in requirements are suggested in the TIP-Vent project. First, finishing materials and therefore the pollution loads, are not the same in different countries. Second, higher ventilation rates can be required in some countries because they compensate with other requirements, for instance compulsory heat recovery. Third, different political attitude towards the trade-off between energy use and IAQ. The energy consequences are evidently different between regions because of the climate differences. In addition, it seems logical that people in different countries can have different expectations to IAQ, especially to perceived air quality. The countries in Scandinavia should be quite similar in respect of culture, building tradition, climate and so on. Therefore, the difference in ventilation requirements between the Scandinavian countries could be expected to be small. In the following, requirements and recommendations given by authorities in the Scandinavian countries, regarding indoor air quality and ventilation flow rates, will be compared. The work is limited to commercial and public buildings and requirements for mechanical ventilation systems.

RESULTS

The Nordic Committee on Building Regulation (NKB), a committee for the national building authorities in the Nordic countries, has published guidelines within the indoor climate area. The purpose was that the guidelines should constitute a foundation for national requirements in these countries. The guideline published in 1981 (NKB 1981), required an outdoor air flow rate per person which was dependent of the room volume. A room volume less than 4 m^3/person required 10 l/s per person. For larger volumes, the required flow rate decreases proportionally to the room volume per person until 13.5 m^3/person. For rooms larger than 13.5 m^3/person, 4 l/s per person was required. These values were based on the research work of Yaglou in the 1930s in USA (NKB 1981). As well known, Yaglou found a strong correlation between the required ventilation rate to control the perceived body odor to a certain level and the net room volume per occupant (Janssen 1999). The values in the NKB guideline correspond to a moderate odor intensity perceived by a person entering the room. The minimum amount of 4 l/s per person was based on the hygienic limit value for CO_2 of 5000 ppm (activity level 1.2 met and safety factor of 3). The guideline also required an outdoor air flow rate of at least 0.35 l/s per m^2 per floor area, to take pollutants from materials into account. For rooms with large volume per person, this requirement can exceed the occupant-dependent flow rate. The basis for this requirement is explained in the guideline. With a room height of 2.5 m, a supply rate of 0.35 l/s per m^2 corresponds to 0.5 air changes per hour. The group working with the NKB guideline evaluated that 0.5 air changes per hour in dwellings was a reasonable value based on what was known about emission of radon and formaldehyde and on the uncertainty within this area. Furthermore, 0.5 air changes per hour were considered a reasonable value to keep the moisture content at a level that prevents mite and mould growth.

In 1991, a new NKB guideline (1991) for indoor air quality was published. The ventilation rates from 1981 were adjusted, now recommending a minimum outdoor air flow rate of 3.5 l/s per person + 0.7 l/s per m^2 floor area. This recommendation assumes sedentary activity (1.2 met) and low polluting materials and furnishing. These values are based on the research work by Fanger (NKB 1991). According to Fanger (1988), 7 l/s per person is required to achieve 80 % satisfied with the perceived air quality, when humans with sedentary activity level are the pollution source. This is based on the first impression when people enter a room. Based on the work by Fanger et al. (1988), 0.7 l/s per m^2 was chosen, corresponding to a low-olf building with pollution load of 0.1 olf/m^2 and 20 % dissatisfied (NKB 1991). The 1991 NKB guideline uses an approach, where the occupant-dependent air flow rate is multiplied with 0.5, and then added to the material-dependent air flow rate (0.5 x 7 l/s per person + 0.7 l/s per m^2). There is no documentation behind this factor of 0.5.

Present Regulation in Norway

The Norwegian Building Code states that the necessary air supply shall be determined from the number of occupants, use of materials (building material, furnishing and installations) and contamination from processes and activities. For commercial and public buildings, a minimum outdoor air supply rate of 7.0 l/s per person is recommended for low activity levels. An additional amount of minimum 0.7–2.0 l/s per m^2 floor area shall be added. This amount is for well-tested and documented low-emitting materials 0.7 l/s per m^2. If mainly known and well tested materials are used; 1.0 l/s per m^2, and for not documented or high-emitting materials; 2.0 l/s per m^2. The outdoor air flow rate required by processes and activities shall be compared with the one required by persons and materials (7.0 l/s per person + 0.7-2.0 l/s per m^2) and the dimensioning shall be based on the largest of those two. Filtration of the supply air is required if the outdoor air is not sufficiently clean with respect to health hazard and contamination of the ventilation installations. However, no requirement or recommendation about filter class is given. In Norway, the different authorities have coordinated their regulations in order to achieve corresponding requirements and recommendations. A guideline to the Working Environment Act deals with indoor climate and gives recommendations to ventilation rates. The recommendations are much the same as in the Building Code, but there is one important difference. The guideline recommends that a safety factor of 1.3 shall be used, meaning that the ventilation system shall be dimensioned with a minimum of the required flow rate multiplied with 1.3. This will ensure the need for increased ventilation in new building and in addition, flexibility regarding future change in use of the premises.

Present Regulation in Sweden
The Swedish Building Code refers to the Working Environment provisions and recommendations regarding air quality in working premises, which recommends a minimum outdoor air flow rate of 7.0 l/s per person + 0.35 l/s per m^2 floor area, provided sedentary work. The same recommendation is given by National Board of Health and Welfare for schools and child care premises. The air change efficiency should be at least 40 % (50 % for perfect mixing ventilation) and low pollutant materials should be used. No recommendation about filter class is given. Instead, the Building Code recommends that the concentration of pollutants in the supply air does not exceed the normative values for outdoor air given by the Swedish Environmental Protection Agency.

Present Regulation in Denmark
The Building Code states requirements to minimum outdoor air flow rates provided low polluting materials. For classrooms and premises in school buildings, 5.0 l/s per person + 0.4 l/s per m^2 floor area is required. For daycare centre and residential institutions, 3.0 l/s per person for children and 5.0 l/s per person for adults, and in addition 0.4 l/s per m^2 floor area, is required. These requirements shall be seen in conjunction with requirement for minimum space, for instance 2 m^2/child in kindergartens and a volume of 6 m^3/person in classrooms. For ventilation flow rates in other premises as office buildings and for cleaning of the supply air, the building code refers to Danish Standard DS 447. The recommendation to outdoor air flow rates in DS 447 is the same as in the NKB guideline from 1981. DS 447 is under revision, and the revised standard will be published during 2005.

The outdoor air flow rate for a 10 m^2 single office and a 60 m^2 classroom with 30 persons is calculated using the requirements and recommendations in the Scandinavian countries, and presented in figure 1. For Norway, the three recommended flow rates, which are dependent on the use of materials, are used in the calculation.

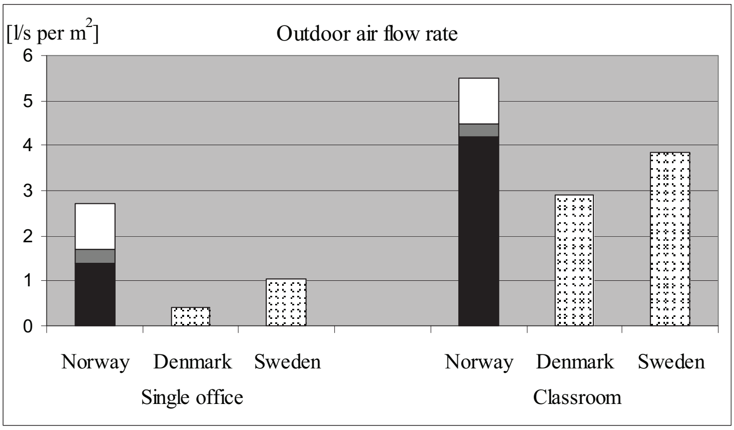

Figure 1. *Required or recommended outdoor air flow rates in a single office and a classroom.*

DISCUSSION

The result shows a considerable difference in required or recommended outdoor air flow rates between the Scandinavian countries. So, what are the reasons? It is difficult to give an exact answer. Some possible explanations are mentioned in the introduction. The climate differences from north to south are greater in Norway and Sweden respectively, than the difference in climate between those two countries. Denmark has a warmer climate than Norway and Sweden, so that can not explain why the requirements are lower in Denmark. The requirements for energy efficiency are not more stringent in Norway than Sweden and Denmark. Therefore, energy efficiency requirements to compensate for higher ventilation flow rates are not considered to be an explanation. Low pollutant materials are recommended in all three countries. A significant difference in use of materials between the countries is not likely. Different political view of the balance between IAQ and energy use, can be a potential and more plausible explanation. The energy price has been, and still is, higher in Denmark than Sweden and Norway. This can result in a stronger focus on energy saving.

The recommendation in NKB guideline from 1981 and the Danish standard takes the room volume per occupant into account. The recommended 7.0 l/s per person in Norway and Sweden can, as for the NKB guideline from 1991, be assumed to be based on the research work by Fanger (Fanger 1988). The research by Fanger and also research by Cain et al. (1983) confirmed most of the work by Yaglou except for the effect of air volume per occupant (Janssen 1999). Furthermore, the research work by Yaglou is from the 1930s. If the results are relevant today can be questioned. The hygienic habits and sensory pollution load from a person was probably different 70 years ago and also the frame of reference of the person judging the air quality. In the Danish Building Code, the required air flow rates per person in schools and daycare centres are lower than in Norway and Sweden. The rationale for the values is not mentioned in the building code. One possible explanation is that these values are based on a certain degree of adaptation, and not the first impression of the air quality. This can be an applicable approach in spaces were people enters simultaneously and the people are the main polluters, for instance classrooms (Gunnarsen and Fanger 1992).

The air flow rates required for pollutants from building materials, furnishing and installations also differ between the countries. The recommendation of 0.35 l/s per m^2 in Sweden can be assumed taken from the 1981 NKB guideline. The use of building materials have changed over the years. The reason for adjusting this value in the 1991 NKB guideline was the finding by Fanger (Fanger et al. 1988) indicating that 0.35 l/s per m^2 was to low. However, using an addition of the flow rates like in the 1991 NKB guideline, but with 7.0 l/s per person + 0,5 x 0.7 l/s per m^2 instead, gives the value recommended in Sweden. It is difficult to find a logical explanation for selected values in Norway and Denmark. For the values recommended (0.7-2.0 m^2) in Norway and required (0.4 l/s per m^2) in Denmark, no documentation was found, and it is difficult to find a logical explanation for the selected values.

The lack of knowledge is mentioned as a problem in the two NKB guidelines and it is stated that that minimum air flow rates only can be established with great uncertainty. These uncertainties make it difficult to set requirements, and can be assumed to be a part of the explanation why the requirements and recommendations are different in the Scandinavian countries. Nevertheless, as stated in the ECA Report no. 23 (Wouters et al. 2003), “There clearly are uncertainties with respect to the indoor air quality and ventilation requirements for buildings. However, this cannot be used as an argument for not having standards and/or regulations”. In the Tip-Vent project (2001), ventilation design procedures among HVAC designers were studied. The conclusion was that air flow rates are in most cases determined from regulations or standards and separate calculations are seldom carried out. This further underlines the need for appropriate regulations and standards.

CONCLUSION

- Differences in required and recommended outdoor air flow rates between the Scandinavian countries may mainly be explained by the uncertainties about IAQ and the necessary level of ventilation, in combination with different political views on the balance between energy use and IAQ.
- The present requirements and recommendations stated by the authorities seems to be based on “good engineering practice” more than scientific documentation, and it is difficult to find a rationale for the values. Consequently, it is important that HVAC designers make a more qualified evaluation than only using the minimum outdoor air flow rates in the building codes or working environment legislation.

Reviews of regulations and standards indicate that these conclusions may be valid world wide. A harmonization of the methods in regulations and standards seems to be needed.

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A COMPARISON OF CENTRAL AND DECENTRALIZED AIR HANDLING UNITS

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ABSTRACT

The objective of the paper is to compare central and decentralized air-handling units with regard to costs and suitability. It is mainly based on a calculation model for Life Cycle Costs (LCC), which has been used on two cases, one high-rise and one medium-rise office building. Qualitative evaluation of non-quantifiable factors supports the comparison. The results show that the decentralized solution in general has higher LCC, but buildings with side wings and fewer floors tends to even out the differences. Less need for shafts and large fan rooms make space available that can give income from rent that exceeds the extra LCC for the decentralized solution.

KEYWORDS: Ventilation, Life Cycle Cost, Decentralized Air Handling Units

INTRODUCTION

Due to indoor climate requirements, building rehabilitation often involves replacement of the old ventilation plant by a new mechanical system with higher capacity. If one or a few large central air-handling units (AHUs) are used, lack of space can be a problem. Another option is to use decentralized air handling units and ducts with smaller dimensions that are easier to fit into the building. Decentralized air handling units can also be a suitable solution in new buildings. This is especially the case in buildings where changes in the required airflow rates do not occur simultaneously in different zones (floors/façades) of the building.

The objective of this paper is to compare central and decentralized air-handling units with regard to costs and suitability. It is mainly based on a calculation model for Life Cycle Costs (LCC), which has been used on two cases, one high-rise and one medium rise office building. This has been supported by some qualitative evaluation of non-quantifiable factors.

METHODS

The work has been carried out as a case study of two fictitious buildings, where central and decentralized AHUs were compared. One building has 17 floors on a rectangular floor plan while the other has four floors distributed on three wings connected by a main building. The study uses LCC for comparing the different cases. The LCC calculation is implemented in a spreadsheet that calculates sizes and costs of ductwork, AHUs, shafts and fan rooms.

Description of the spreadsheet model:

- Input to the model:
    - Dimensions of the building (total area, depth of building, number of floors, number of wings etc.).
    - Layout of the ductwork (number of vertical shafts, number of horizontal parallel ducts, etc.).
    - Choice between central and decentralized solutions and number of AHUs.
    - Airflow rate per square meter.
    - Maximum allowed air velocities.
- Length of ducts, size of shafts and fan rooms are generated from the input.
- The duct diameter is calculated from a given velocity and the closest standard diameter above the calculated value is selected.
- Only costs that are influenced by the choice between central and decentralized solutions are included. This implies that ductwork from corridors to rooms, air terminal devices, local dampers etc. not are included.
- The ventilation airflow rate is kept constant (CAV).
- The pressure loss for the ductwork is calculated from the distribution path with the highest pressure drop (from outdoor air intake to the air terminal device in the room). Duct sizing was done by a velocity-reduction method (Bahco's 1/3-method [1]). The pressure drops for the AHUs were found in manufacturers' data sheet. Supply and exhaust ductworks are assumed to have equal pressure loss.
- The LCC calculation is separated in four groups with costs for: Ductwork, AHUs, building related parts of shafts, and fan rooms. Input variables are: Investment cost, maintenance cost, operating costs (energy and filter exchange), lifetime expectancy, and real interest rate [2], [3].

To make the work manageable, several simplifications have been made:

- The layout of the ventilation ducts is straightforward without the complications often found in real buildings.
- For calculation of duct costs, a simplified model using the surface area of the duct is used. The cost includes both material and labour. In addition, bends, attenuators, size reductions, branches and joints are included. Only supply air ducts are insulated. Outdoor ducts are jacketed.
- To represent the reductions of diameter in the duct system, a truncated cone has been used to estimate the total surface area.
- Only energy costs for operating fans are included, i.e. heating and cooling demand are assumed equal in all cases.

Table 1 shows the costs that have been used in the calculations. These are estimated from cost data collected from a consultant and a contracting company.

Table 1. Costs used in the calculations and comparison of solutions, all prices in Norwegian kroner/m^2 (NOK/m^2). NOK 100 equals EUR 12.

Circular ducts	200	Shaft walls	350
Insulation of ducts	180	Fan room walls	900
Jacketing for outdoor ducts	450	Fan room floor	400

The costs for AHUs range from NOK 137,000 for 6,000 m^3/h up to 837,000 for 90,000 m^3/h.

Description of cases:

- Each floor in the two buildings consists of 2.4 m x 4.2 m office modules along the two long sides and larger offices at the corners. The corridors are located between the offices and the core areas where meeting rooms, toilets, printing rooms and open spaces are situated.
- The ventilation system is operated 2,600 hours per year.
- The layout of the ductwork in the corridors is similar for central and decentralized solutions.
- The airflow rates are typical values for buildings where air is used to cool the building, 9 m^3/hm^2 net area.
- The air velocities are chosen to avoid noise, 8 m/s in main ducts in the shafts and at the roofs, 6 m/s in horizontal main ducts transporting air along corridors and 3 m/s in ducts connecting ducts in corridors with supply and exhaust air terminals.
- The diameters of the horizontal ducts at each floor are kept below 315 mm to allow duct crossings without reducing the visual ceiling height. Vertical ducts are kept below 1250 mm to use standard circular ducts.
- The expected lifetimes used in the calculations are 30 years for ductwork, 25 years for AHUs and 60 years for shafts and fan rooms. The real interest rate is set to 6.3%.
- The energy cost is set to NOK 0.50 per kWh. The maintenance cost is set to 15 % of the investment cost. Maintenance is executed every 15 year. The cost for changes of filters is set to 4 hours at NOK 500 per hour per AHU.

In Figure 1 the building for Cases I and II is shown to the left and for Cases III and IV to the right. Both buildings have a net floor area of 16,000 m^2.

Table 2 shows the number of shafts and AHUs for each case.

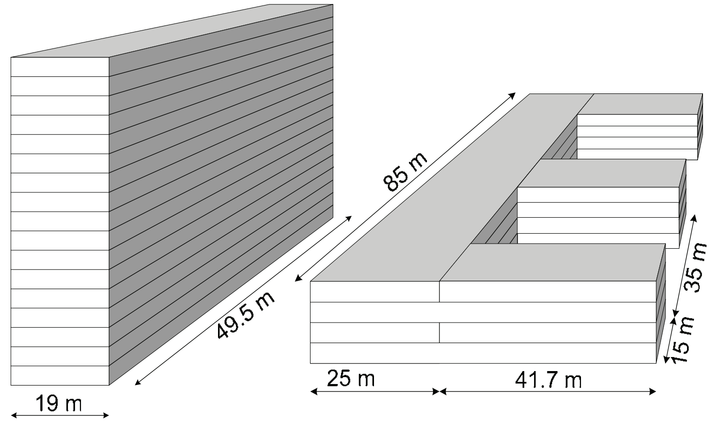

Figure 1. Buildings used in the simulations. 17 floor building used in Cases I and II to the left and the four floor building with three wings used in Cases III and IV to the right.

Table 2. Number of shafts and AHUs in the different cases.

	Case I	Case II	Case III		Case IV	
			Main wing	Side wing	Main wing	Side wing
AHU roof	3	0	1	1 per wing	0	0
AHU/floor	0	3	0	0	3	1 per wing
Shafts	3	0	3	1 per wing	0	0

RESULTS

Table 3 shows the variation in cost for the different alternatives. Decentralized solutions reduce the cost for ductwork relative to AHUs.

Table 3. Costs for different alternatives, prices in NOK.

	Case I, Central AHUs	Case II, Decentral-ized AHUs	Case III, Central AHUs	Case IV, Decentral-ized AHUs
Investment costs				
AHU	1 381 530	5 438 481	1 566 754	2 912 940
Ductwork	843 827	1 178 734	1 855 849	1 172 544
Energy costs				
AHU	57 366	139 849	76 685	109 909
Ductwork	64 676	25 371	41 898	26 906
LCC				
AHU	165 120	564 026	198 885	337 105
Ductwork	131 756	119 075	189 430	120 118
Total incl. AHU, ductwork, shafts and fan room	463 242	874 733	524 782	606 241

Figure 2 shows how the annual cost for the ductwork varies with the air velocity in the ducts. The curves are somewhat erratic because only standard duct diameters are considered in the analysis. It can be seen that the central solution has the highest annual cost at reference velocity (100%). Another observation is that an optimum diameter exists. When the diameter increases the investment cost increases more than the fan energy cost decreases. A reduction in the diameter increases the costs related to fan energy consumption more than the investment cost decreases. Figure 3 shows the relation between air velocity and specific fan power (SFP) for ducts and AHUs.

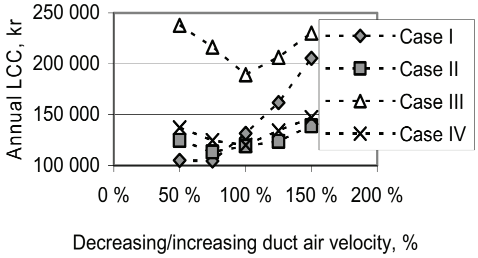

Figure 2. Annual life cycle cost as a function of the air velocity in the ducts. The air velocities used in Table 3 equals 100% in the figure. AHU sizes are kept unchanged.

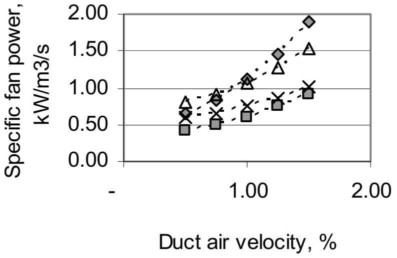

Figure 3. Specific fan power as a function of air velocity.

Figure 4 compares buildings with different number of floors with equal floor areas, i.e. the total floor area is proportional to the number of floors. The building has three shafts and AHUs positioned at the roof. The number of AHUs is adapted to the total airflow rate, the two and four floor buildings have one AHU, and the eight and seventeen floor buildings have three. The decentralized solution with three AHUs at each floor has an annual cost independent of the number of floors.

A calculation done in the spreadsheet shows that if two AHUs at each floor had been used in the decentralized solution, costs had been reduced considerably. However, this solution requires ducts that exceed 315 mm.

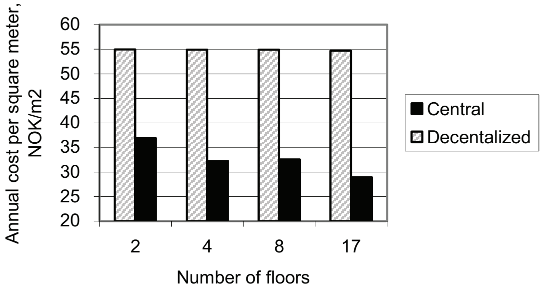

Figure 4. Comparison of buildings with different number of floors. All floors in all buildings have equal areas.

Table 4 discusses some parameters that are not included in the calculation model [4]. Indicators are used to show the advantages of the decentralized solution compared to the central solutions.

Table 4. Other quantitative and qualitative parameters that influences the choice between solutions.

	Evaluation of decentralized versus central air handling units + = advantage for decentralized - = disadvantage for decentralized	
Efficiency - Shaft area - Fan room area	 + +/-	 Reduces need for shafts More fan rooms, but not necessarily larger total area
Capacity - Demand control - Noise	 + -	 Increased opportunity for zone division that takes the thermal and pollution load variation into consideration. Shorter distance between fan room and users makes it difficult to deliver high amounts of air without noise.
Accessibility	-	More fan rooms means more labour intensive maintenance
Adaptability (Generality, flexibility and elasticity)	+	The ventilation can easily be upgraded in one part of the building without interference with the rest of the system. Reconstructions in one part of the building can easier be done without disturbance.
Aesthetics	+	AHUs placed in fan rooms at roof can be avoided
Safety in operation	+ - -	If one component breaks down it will influence only a smaller part of the building More components that can break down More complex system to survey

DISCUSSION

The results show that the decentralized solution in general has higher LCC, but buildings with side wings and fewer floors tends to reduce the differences. The main explanation is that the layout and dimensions of the low buildings results in fewer decentralized AHUs than in the high-rise building.

If the number of AHUs at each floor is reduced in the decentralized solution, the total investment cost is considerably reduced while the energy cost increases moderately. This makes the decentralized solution more favourable compared to the central solution.

For buildings with few floors the differences becomes small between central and decentralized solutions, but variances in the annual costs between building layouts indicate that it is necessary to conduct calculations in each case.

The results are strongly influenced by energy costs, airflow rate per square meter and allowed maximum duct sizes. In this study, only circular ducts have been considered. More use of rectangular ducts could have influenced the costs in favour of decentralized solutions.

A certain velocity minimizes the annual cost. This optimum velocity or SFP differ between the different solutions. This indicates that the SFP should not be the only parameter considered in duct sizing processes.

Reduced areas for shafts and fan rooms in decentralized solutions could mean increased income from rent, which may exceed the increased annual LCC for the ventilation system.

A vast number of parameters are needed to describe buildings and their HVAC systems in detail. Optimised solutions for the air-handling units cannot necessarily be achieved through a mathematical approach due to the substantial number of qualitative parameters that has to be taken into account. In addition, establishing a mathematical optimisation procedure that includes all parameters would be very complex. Nevertheless, mathematical procedures can provide information that, combined with qualitative evaluation, can help achieve optimised solutions. The qualitative evaluation can include the parameters mentioned in Table 4 among others. In addition, other factors, such as work pattern, interior layout and outdoor environment, also influence the design of the ventilation system and the choice between one main or several subsystems.

ACKNOWLEDGEMENTS

The work has been initiated and funded by a joint project between Norwegian contracting firms (YIT Building Systems and Gunnar Karlsen AS), equipment vendors/manufacturers (Systemair and Swegon), consultants (COWI), property management enterprises (Forsvarsbygg) and the The Research Council of Norway.

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Measured Occupancy in an Office Building

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Summary: *This paper presents collected occupancy data for 58 rooms, of which 56 are cellular offices, in a Norwegian office building. The data covers a time period of approximately three and a half months. Many modern office buildings have demand controlled ventilation (DCV) systems. Optimal design requires knowledge about how the building will be used. Taking into account that all rooms are not occupied simultaneously gives the opportunity to decrease the size of central components of a DCV system. The presented results for occupancy include both mean values and how occupancy is distributed over time and between different groups of occupants. The results show that the maximum occupancy factor in the building, with all rooms included, is below 0.5.*

Keywords: *HVAC, Occupancy pattern, Occupancy factor, Case study*
Category: *Case Study, Field investigation, HVAC*

1 Introduction

When designing HVAC systems, information about some aspects of the expected use of the building is required. The most obvious is the occupancy density that each room or zone is designed for. In addition, information about how the occupancy is expected to vary with time can be useful. Sensors and detectors can be used for control of different installations in buildings, for example lighting and control of thermal climate and indoor air quality (IAQ). It is important to be able to prognosticate the occupancy pattern in advance, to fully take advantage of the opportunities of sensor technology. The distribution of occupancy intervals and vacation intervals, studied by Wang et al. [1], are of interest for choosing an appropriate control strategy. These are aspects of interest both for lighting and ventilation control. For these purposes, movement detectors can be a possible solution. The delay time, that is the time duration from the latest detected movement until the lighting is switched off or the ventilation rate is decreased, should be based on this type of knowledge. This is also essential in relation to what extent the ventilation rate should be reduced during unoccupied periods, in order to achieve an acceptable IAQ when the occupant returns to the room.

In addition to the occupancy profiles on an individual room level, the resulting occupancy profile for all rooms, or a group of rooms, are helpful information if a demand controlled ventilation (DCV) system is considered. The occupancy factor is the actual number of occupied rooms, divided by the total number of rooms [2]. The occupancy factor is one of several factors that affects the energy saving potential of DCV, as shown by Mysen et al. [2], and should be taken into consideration in cost benefit analysis of such systems. The occupancy factor can also be used as a correction factor when calculating the dimensions of central components as air intakes and exhausts, air handling units (AHUs) and main ducts.

This study is part of an ongoing project were occupancy data are collected in three office buildings in Norway with movement detectors installed. The objective of this project is to analyze different aspects of the occupancy pattern in these building and the consequences this has for design of HVAC systems. This paper presents results for one of these buildings, based on data collected so far, approximately three and a half months. The limitations and uncertainties in the collected data and presented results are discussed.

2 Method

The investigated building is a combined office and education building located in the middle part of Norway. It has one main wing and to side wings, distributed on 3 700 m^2 and two floors. The two side wings consists of offices premises. Both side wings have individual cellular offices on both sides of the corridor. There are two organizations located in the office premises, one in each side wing. The side wings are here named zone A and zone B.

All offices have a movement detector installed to control lighting and ventilation. Occupancy data has been collected from the building energy management system (BEMS). Those data can not be analyzed directly. The raw data must be preprocessed in order to get a useful format before it can be further analyzed. The detection from a movement detector is registered as a point in time, given with accuracy in seconds. The processed data on the other hand, is divided into five minute intervals. However, the total time that an office has been occupied in the analyzed period has been compared between the raw data and the processed, for some randomly collected offices. This comparison shows a negligible difference.

When a person enters the office, the detector detects movement and this will be registered as an unoccupied-to-occupied event together with the time for the event. If the detector does not detect movement for a period of five minutes, the office is regarded as unoccupied. The time for this occupied-to-unoccupied event is then registered. Because of this time delay, five minutes have been subtracted in the processing of the data each time it has been registered an occupied-to-unoccupied event.

This paper presents data for the period 27th September 2005 to 17th January 2006, except for the last week in 2005, where most of the employees are not working full week. In addition, one weekday had to be excluded because of errors in the registration, probably due to a power outage. The data collected so far includes 105 days, of which 75 days are working days. Data for 56 cellular offices are included, 26 in zone A and 30 in zone B, and in addition, two meeting rooms, one in each zone.

3 Results

Figure 1 shows the occupancy factor for zone A+B, for all working days. The normal working hours seem to last approximately between 08:00 and 16:00 and the normal period of occupancy between 07:00 and 18:00. Normal probability plots show that the occupancy factor for a certain time of the day follows a normal distribution in the working hours.

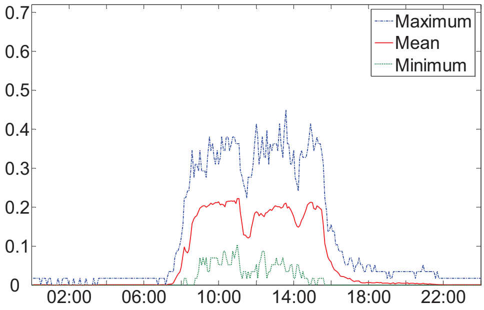

Figure 1. Occupancy factor for all working days.

The occupants are spending only a small part of the working days in their office cell, in average 15 % of the normal period of occupancy (17 % for zone A and 13 % for zone B). This can explain the low occupancy factor shown in Figure 1. However, there are large variations among the occupants, as shown in Figure 2.

The distribution of the occupancy factors for all working days in the normal period of occupancy are illustrated in Figure 2. The maximum occupancy factors are 0.62, 0.47 and 0.46 for zone A, B and A+B respectively. In 90 % of the time the occupancy factor is equal to or less than 0.35 (zone A), 0.23 (zone B) and 0.27 (zone A + B).

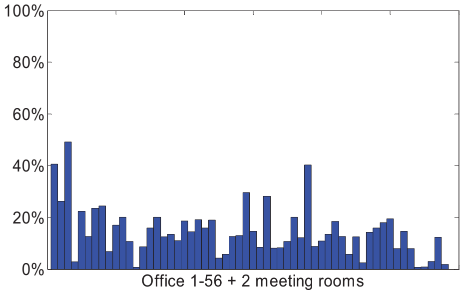

Figure 2. Percentage of the normal period of occupancy that each room are occupied.

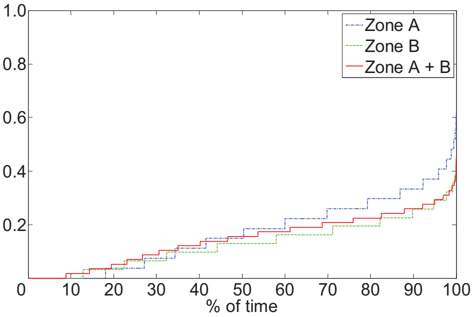

Figure 3. Distribution of the occupancy factor for all working days.

Interesting to investigate is how often peaks with an occupancy factor that exceeds a certain value occurs. Figure 4 shows how the peaks with occupancy factor larger than 0.4 are distributed for zone A. This is illustrated as percentage share of total number of peaks as a function of the duration of the peaks. The peaks of 15 minutes or less occurs most frequently. However, a few peaks are 45-60 minutes. In this context, it can also be interesting to study the time between the peaks. Figure 5 shows that many of these periods are short, meaning that it can be a series of several short peaks with short time separation.

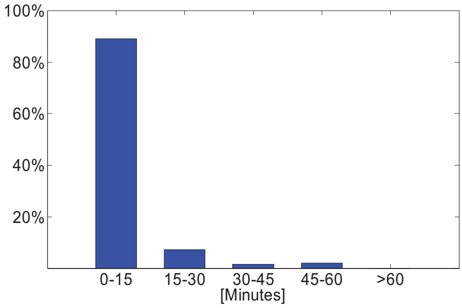

Figure 4. Peaks with occupancy factor > 0.4.

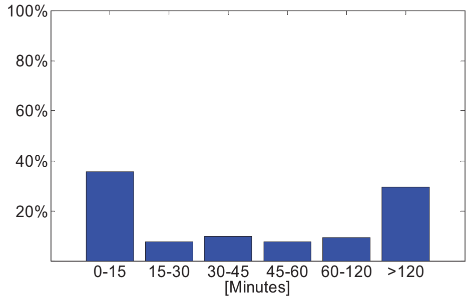

Figure 5. Time separation between peaks with occupancy factor > 0.4. The periods longer than 2 hours includes periods between working days and over weekends.

However, Figure 4 and 5 do not give a complete picture of the situation, because Figure 4 does not tell anything about which time separations and which peaks that belongs together. On average, there is approximately 25 minutes per day with an occupancy factor > 0.4. There are large differences between the working days. In almost half of the days, the occupancy factor never exceeds 0.4, but in a few days it exceeds 0.4 in approximately 30 % of the normal period of occupancy.

4 Discussion

There are some uncertainties involved in the registered occupancy factors which can affect the accuracy in the presented results. As described, there is a time delay of five minutes from the last detected movement until the room is registered as unoccupied. This means that an office can be unoccupied in up to five minutes without the room being registered as unoccupied. The second uncertainty is related to the detectors, which are detecting movement, and no movement indicates that the room is unoccupied. However, in short periods the occupant can be sitting without doing any moves large enough to be detected. The deviation between the actual and the registered occupancy is affected by the accuracy of the detectors. How strongly these two aspects are influencing the results, is difficult to estimate. A manual counting in the building showed good agreement with the registered occupancy, but a somewhat higher occupancy than what is registered.

The occupancy factor in this building is low, which implies a considerable energy saving potential for a DCV system compared to a constant air volume system (CAV). To consider potential savings, a simultaneous factor s can be defined according to Equation 1, as done by Mysen et al. [2]:

$$s = o + b - bo \tag{1}$$

where o is the occupancy factor and b the ventilation rate for an unoccupied office divided by the ventilation rate for an occupied office. For zone A, based on the results in Figure 3, a possible solution could be to dimension the central components of a ventilation system delivering air to this zone according to an occupancy factor of 0.6. In this building, each office cell is ventilated with 12 l/s when the office is occupied and 7 l/s when it is unoccupied. For Equation 1, $s_{0.6}$ equals 0.83. If the dimensioning is based on an occupancy factor of 0.4 instead, which means that there will be a shortage of supply air during 4.1 % of the time, $s_{0.4}$ becomes 0.75. Based on the presented results, a possible scenario is that a one-hour peak in occupancy occurs, where the occupancy factor reaches 0.6 at its maximum. Regarding the consequences, this is a realistic, but somewhat conservative scenario, because most of the peaks have a shorter duration. In this situation there will be a 10% shortage of air in the main duct:

$$1 - \frac{s_{0.4}}{s_{0.6}} = 0.1 \tag{2}$$

The following assumptions are made:

- A constant sensory pollution load of 1.9 olf (0.1 olf/m^2 which corresponds to a low-olf building and 1 olf/person [3]).
- The ventilation rate decreases linearly from 12 l/s to 10.8 l/s during 15 minutes; is constant for 30 minutes; and then increases linearly up to 12 l/s again during the next 15 minutes. The ventilation effectiveness is 1.0
- The shortage of air in the main duct is distributed evenly between the offices.

Figure 6 shows the resulting consequences for the perceived air quality (PAQ).

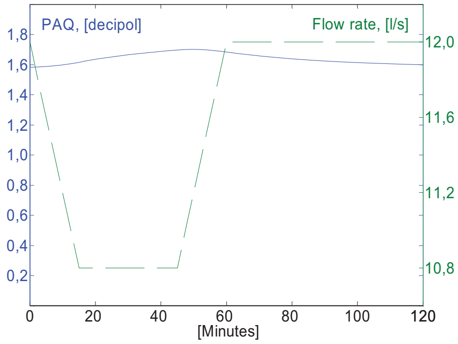

Figure 6. Consequenses for perceived air qulity (PAQ) when the ventilation rate is varied. Computed nummericaly.

When the ventilation rate is reduced, the decipol value starts to increase from its initial value of 1.58 and reaches its maximum of 1.70 after approximately 50 minutes. This corresponds to an increase in percentage dissatisfied (PD) from 21.7% to 22.9% [3]. Such a short-lived reduction in ventilation rate will therefore not impair the PAQ significantly, and probably not affect the occupants' health or performance. Estimates of the relationship between percentage dissatisfied with IAQ and performance shows an approximately 1 % change in performance for every 10 % in PD [4]. In this case this means a 0.1 % decrease in performance.

The maximum occupancy factor is dependent on what kind of organizations that are using the building. The employees in both of the organizations in this building have work tasks which require that they are away from the office for longer periods of the day. The occupancy factor is consequently low. However, this situation can be changed if a new organization is moving into the building or due to changes in one of the organizations now using the building. Dimensioning the ventilation system according to an occupancy factor of 0.4 can therefore be a risky approach and a factor of 0.6 is a more realistic solution. The result in Figure 6 is also valid if central components are dimensioned according to *o* equals 0.6. Then, the peak in occupancy corresponds to an occupancy factor that reaches a maximum of 0.82. This kind of consideration tends to become a trade-off between many interests. Decreasing the dimensions of central components like AHUs and main ducts will reduce the investment costs. On the other hand, this will increase the pressure drop and the energy use for fan operation. Likewise, ducts with large dimensions can be difficult to fit into the building, for example due to limited space above the ceiling. Similarly, decreased dimensions of the AHU will result in the possibility for reducing the size of the fan room. On the contrary, decreasing the dimensions will reduce the generality of the ventilation system. Changes in the need for ventilation can occur due to organizational changes or new knowledge leading to more stringent requirements for ventilation rates. If the size of the fan room and height above the ceiling also is reduced, the adaptability of the building is further reduced. This is an example of one of the big challenges in design of office buildings, as stated by Blakstad [5]; “The buildings must be both general enough to accommodate different users, and at the same time have the ability to be fitted out to support the actual user organisation in the best possible way.”

Many Norwegian office buildings has a cooling demand during parts of they year. This demand is often met by supplying ventilation air with a temperature some degrees below the room air. The design ventilation rate in many office buildings is decided by the cooling load. This is also the case in this building [6]. Dimensioning the central components according to the expected maximum occupancy, or alternatively to an occupancy level that occurs during for example maximum 5 or 10 % of the normal period of occupancy during one year, can in many ways be a favourable solution for DCV systems. However, the cooling demand may require higher ventilation rates than required by the expected occupancy. In that case, the cooling demand has to be reduced or met by other means than the supply air, if the system is to be dimensioned based on the expected occupancy. Irrespective of which solution that is chosen is it important to keep control of the temperature. Thermal climate is essential for both comfort, including PAQ [7], and performance [4], and is of vital importance for the occupants’ satisfaction.

5 Conclusion

To fully take advantage of the opportunities that DCV systems offers, the occupancy factor can be considered as a possibility to decrease dimensions of central components like AHUs and main ducts. Short peaks with an occupancy factor exceeding the design value, will result in a shortage of supply air. This does not have to impair the IAQ significantly due to the high ventilation rates in new office buildings in Norway. The occupancy factor is low in the examined building, and probably not representative for most other office buildings. More data on typical occupancy factors would make it easier to use this kind of consideration in practice.

Acknowledgment

This work is part of a project funded by Statsbygg – The Directory of Public Construction and Property. The authors would like to take the opportunity to thank Statsbygg for the permission to collect and analyze the data.

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