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# **Assessing the impact of the indoor environment on productivity**

A case study in a university building in Stockholm

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## ABSTRACT

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The impact that the indoor environment has on productivity is a topic that has been investigated in numerous studies. There are a variety of different methods that have been used to evaluate productivity with. There are quantitative methods and there are qualitative ones, and both have been used in the literature as indicators or real productivity. The quantitative ones are for instance short arithmetical or linguistic performance tests or measurements of the actual quantitative output of a job. Qualitative assessments of productivity consist of different ways of allowing the subjects to rate their own productivity. Both these two approaches of evaluating productivity are claimed to be subject to different issues, and the question of which way is preferable is a matter of contention among the researchers. The quantitative approach is claimed to be unable to reflect the complex and qualitative output of many modern jobs, while the qualitative one is believed to be highly influenced by bias. This master's degree project has investigated the associations between the two approaches and conducted a qualitative assessment of the impact of the indoor environment on the productivity in a university building in Stockholm.

Numerous studies have been reviewed that include *both* quantitative evaluations of productivity and qualitative evaluations of the indoor environment. Qualitative evaluations are for instance evaluations of environmental satisfaction, as well as evaluations of healthiness and productivity. The relationship between the quantitative measurements and the subjective evaluation is indeed complex. However, there appears to be a consistency to some extent between the two, and the trend seems to indicate that occupants who are more productive are also more satisfied with the indoor environment *or* perceive themselves to be healthier *or* more productive.

A working hypothesis has been formulated; that subjective evaluations of the indoor environment may act as indicators of productivity. This approach has been used in a university building in Stockholm, where the productivity of the students has been evaluated through a survey, together with physical measurements of the indoor environment. The survey is designed based on the current literature within the field. It has a large emphasis on productivity, with several questions concerning it directly and indirectly. The physical parameters that were measured were radiant temperature, air velocity, relative humidity, CO<sub>2</sub>- concentration and sound pressure level. Considerable correlations were observed between perceived productivity and environmental satisfaction, perceived environmental control and between different ways of evaluating productivity subjectively. The correlations between the physical measurements and the subjective evaluations were in general considerably weaker than the ones between the different subjective parameters. The correlations between the mean CO<sub>2</sub>- concentration and productivity was weak, and similar findings were obtained concerning sound pressure level. This emphasise the importance of heeding the opinions of the occupants while evaluating the performance of a building, as physical measurements alone appear to be unable to reflect the users' perspective reliably. The correlation between the thermal parameters (evaluated by the PMV- value) and the subjective evaluations were, on the other hand, considerably stronger. This may indicate that the thermal parameters are among the most influential ones in creating a productive workplace.

Furthermore, the study discusses different methods that have been used to evaluate productivity with. It discusses their weaknesses and strengths and what elements they contain that may be used for future studies of productivity.

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# 1 INTRODUCTION

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## 1.1 BACKGROUND

One of the main objectives of buildings is to provide a comfortable, safe, and healthy indoor environment for its occupants. There are numerous variables of the indoor environment that need to fulfil certain criteria to be able to achieve this. For instance, we need comfortable temperatures, sufficient amount of lighting, satisfying acoustics and air that has low concentrations of pollutants. There are building standards that specify what levels should apply to these variables to obtain a safe and healthy indoor environment. To ensure that the standards actually do promote healthy buildings, it is vital that buildings that are already constructed are evaluated based on the quality of their indoor environment. Evidence suggest that there are many buildings that do not to function as intended, for instance by HVAC systems (heating, ventilation, air- conditioning systems) that suffer operation dysfunctions (Fanger, et al., 1988), or moisture related problems (Spengler, et al., 1994). Evaluation of existing buildings may provide a feedback loop that is vital in the design of future buildings and for the development of the building regulations. The evaluations need to be conducted in a systematic manner when the building has been occupied for some time. This approach of evaluation has been referred to as *post occupancy evaluation* (Preiser et.al 1988). It has been proposed that *post occupancy evaluations* should be incorporated as a mandatory procedure in the design and commissioning of buildings, where the findings from the evaluations can be utilized in other stages of the buildings lifetime (Meir et.al 2009).

The quality of the indoor environment may significantly influence the health and wellbeing of the occupants, but it may also influence their productivity at work (Clements-Croome, 2015). The productivity aspect is of special interest, because productivity gains could be accompanied by economic benefits. If evidence can be found that high productivity is related to high quality indoor environment, this could create stronger incentives to design and construct buildings that promote health, comfort and productivity. There is evidence that suggest that even relatively small improvements of productivity within an organisation should have the potential to outweigh the potential costs of the improvement. De Dear et.al (2013) claims that it is “accepted wisdom” that the cost of energy and maintenance is greatly exceeded by the salary costs in a typical commercial building, and that the difference between energy and salary costs often is of two orders of magnitude. De Dear et.al (2013) further present data from a few articles that show the relation between staff costs, HVAC-systems running costs and energy costs. The ratio between staff and energy costs is between 87 and 200, which means that a productivity gain between 0,5% and 1,2% would be economically equivalent to the entire energy costs. This would imply that even a relatively small increase of productivity could have the potential to outweigh the higher costs that may be necessary to create the environmental improvement, for instance operating a larger ventilation system. Today, productivity benefits are not commonly included in the economic calculations of buildings (Seppanen, et al., 2006). The long-term objective of this research would be to develop a method that can be incorporated in the economical calculations of a building, which will create incentives to design, build and operate healthy and productive buildings.

The following question arises: how has productivity been evaluated in the existing literature and how should future productivity evaluations be conducted? Productivity is commonly defined as the output of an activity divided by its input. There are many different methods that have been used by researchers to evaluate how productivity is influenced by the indoor environment. Wyon (1996) describes a few general ways:



- Simulated work - an artificial but realistic task
- Diagnostic tests - a test that is unlike any real task
- Embedded tasks - a test derived from part of an existing task
- Existing measures - existing outcome metrics that are available
- Absenteeism - records of sick leave
- Perceived productivity - subjects estimate and report their productivity according to their self-estimation.

A number of studies regarding productivity will be reviewed in the literature review, and all of the above-mentioned ways of measuring productivity will be covered. The methods of measuring productivity can either be carried out in the field or in a laboratory environment. There are different opinions on which of the methods that should be used to properly assess what impact that the indoor environment has on productivity. Wargocki & Wyon (2017) maintains that climate chamber experiments (environments that have very precise control of several environmental parameters) are essential for understanding cause and effect relationships between the environment and productivity. However, they also recognize that the productivity of real work in real offices might not be affected to the same extent as in the more controlled studies. The authors don't consider perceived productivity as a valid indicator of actual productivity.

Humphreys & Nicol, (2007), have a quite different opinion. They doubt the usefulness of objective measurements of productivity due to the complexity of many real office tasks that may not be reflected by simulated office tasks. Leaman (1995) states that the difficulty of measuring productivity is due to the high variety of tasks of most office work and the difficulty to identifying clear output measures. It has been claimed by Fang et.al (2004) that productivity in real life is almost impossible to measure, and Antikainen & Lönnqvist (2006) states that the qualitative work of knowledge organisations cannot easily be measured by quantitative means and should instead be evaluated by more subjective methods. McCarney & Humphreys (2002) mentions that a strength of subjective evaluations of productivity is that the results easily can be compared between different organisations and different work tasks, which Leaman & Bordass (1999) claims to be difficult to do between different quantitative productivity metrics. Humphreys & Nicol (2007) mentions a few skills that are required in most office work, such as intellectual, social, creative and analytical skills, but also skills of ordinary routine work. They further state several advantages of using subjective productivity evaluations, such as the simplicity of assessing productivity by one single question and ability to easily compare the results with that of other buildings. A few of the drawbacks of perceived productivity that they mention are the remaining uncertainty whether perceived productivity and real productivity are closely associated, and the difficulty in formulating questions that may accurately reflect real productivity. Another difficulty is that the reception, perception, and responses to environmental conditions is highly individual and depend for instance on psychological, physiological and contextual differences (Bluyssen, et al., 2011). McCartney and Humphreys (2002) recognise that subjective evaluations of productivity are inevitably influenced by bias, and they require a methodology that can incorporate both the simplicity of the self-assessed productivity as well as the scientific robustness of performance tests.

Although there are disagreements among the researchers whether subjective or objective evaluations of productivity is preferable, there is a general agreement that the quality of the indoor environment can affect the productivity of building users (Humphreys & Nicol, 2007).

## 1.2 OBJECTIVES

By analysing the findings of both quantitative or qualitative studies, the current study aims to explore the connection between different ways of evaluating productivity, and the connections between

productivity and subjective evaluations of the indoor environment. Based on the findings from the literature, the study will develop a method that will be used to evaluate how much the productivity is influenced by the indoor environment in a university building in Stockholm. To do this, physical measurements of the indoor environment will be conducted, and the subjective perceptions of the occupants will be investigated through a survey. The relationship between perceived productivity, environmental satisfaction, health symptoms and physical measurements will be explored.

The hypothesis is that subjective evaluations may be used to evaluate productivity. Examples of subjective evaluations are feelings of health, productivity and environmental satisfaction. A few research questions have been formulated based on the hypothesis and on the difficulties described above concerning productivity evaluations.

- Are there any connections between real productivity, quantitatively measured productivity and perceived productivity?
- Are there any connections between environmental satisfaction and perceived productivity?
- Are there any connections between health symptoms and perceived productivity?
- Are there any connections between the physical properties of the indoor environment and perceived productivity?
- Are there any other interesting connections between productivity and how the users perceive the building?
- What different methods of evaluating productivity quantitatively exist?
- What different methods of evaluating productivity subjectively exist?
- How can we evaluate the impact of the indoor environment on the productivity in a real building in operation?
- How can the current ways of measuring productivity be developed?

### 1.3 SCOPE AND BOUNDARIES

*This section will present an outline of the study and introduce what topics that will be covered. It will also present some adjacent topics that have not been included.*

The first part of the study contains a literature review. It will begin by addressing the fundamentals of thermal climate and air quality. The literature review will further investigate the connection between quantitative measurements of productivity and subjective evaluations of the indoor environment. Alternative ways of evaluating productivity quantitatively will also be presented, and lastly studies including subjective productivity evaluations will be reviewed.

Relevant papers were identified through internet searches on the university library search tool Primus. The search was mainly conducted by searching for articles with any the following keywords: *productivity, performance, office, indoor environment, self-assessed productivity, perceived productivity, thermal comfort, thermal climate, air quality, air pollutants*. Relevant literature has also been identified by reading literature reviews of similar topics, and by exploring their references in detail.

Based on the findings from the literature review, a survey has been developed to be used in a university building in Stockholm to evaluate the indoor environment and its impact on the building users' perceived productivity. The survey was conducted during lectures of bachelor and masters students of different engineering programmes simultaneously as physical measurements of the indoor environment were conducted. The measurement and survey procedures are described in detail in chapter 3.2 and 3.2.

There are numerous parameters of the indoor environment that may influence the productivity of the occupants. The indoor environment is typically divided into four physical parameters, namely acoustics, lighting, thermal climate, and air quality. The study was mainly limited to thermal comfort and air quality. Lighting and acoustics will only be covered briefly. Thermal comfort and air quality are strongly interconnected to one another, and therefore they are commonly evaluated together. For instance, the temperature may influence the perception of air quality (Fang et.al 2004) and the ventilation rate may impact the air movement that influence the thermal balance of a body.

There are numerous other variables in a building that may influence the productivity, for instance facility features, job satisfaction, ergonomics, aesthetics and facility management. The report will not cover these aspects more than just briefly. Productivity will only be evaluated for office work, and not for manual work. Manual jobs are considered to have quite different characteristics, for instance more physical. They may require other types of skills that are believed be influenced differently by the quality of the indoor environment. It is also possible that the work output of manual work may be easier to quantify, which reduces the need for subjective evaluations. Nevertheless, it must be maintained that there are physical elements in typical office work as well, for instance dexterity which may be reflected in the speed and accuracy of text typing and could be influenced by cold hands for instance (Zhang et.al 2009).

The literature reviewed has not included articles that are more than approximately 25 years old, unless they are considered to be very unique in some sense. This restriction has been implemented because within the extent of this master's degree project it was necessary to make some restrictions, and very old articles are deemed as less relevant than newer ones. Of course, the old articles have laid the foundation to the more recent research and may therefore be reflected in them.

Although the literature review in this master's thesis is quite extensive, it is not claimed that it provides the full picture of the research that is available. Some topics regarding the indoor environment and productivity have been attempted to be covered as entirely as possible while other topics are only included by reviewing a few of the available articles. The findings from those briefer sections of the literature review should not be generalised and assumed to be applicable in a broader context. However, they may provide some insight in an interesting topic, for instance concerning what research methods that have been used, and to show examples of what results that may be obtained from such methods. In a more extensive literature review, it would be desirable to explore every aspect of how productivity is influenced by the indoor environment in detail. In the beginning of every major chapter in the literature review it is stated whether the topic is attempted to be covered entirely or if the section is merely a brief insight into the field.

Even within the topics that are attempted to be covered more entirely, there are inevitably many scientific papers that may be of some relevance that are not included. This may be due to a number of reasons. Several potentially relevant papers have been not been included because they could not be found either via the database or via a free internet search. Some of those articles are incorporated anyway, by citing another article that have reviewed them, although this method is avoided if possible. It is clearly stated when that is the case.

The topic of how the indoor environment influence the occupants is a complex and multidisciplinary matter. There is a need to analyse the topic from various viewpoints, for instance physiological, behavioural, technical, and economical perspectives. This study will not go into depth about the physiological and psychological mechanisms behind how the indoor environment influence the occupants, although the topic is certainly of high relevance (for instance to be able to understand how

a headache is developed by poor air quality, and how it influences the occupants physically and mentally).

The study will not cover what long term effects that poor indoor environment may cause. There are numerous studies concerning this, and it is reasonable to assume that negative long-term health impacts may influence productivity as well. For instance, the cleanliness, maintenance and the level of humidity in building are associated with the prevalence of communicable respiratory illnesses, according to a literature review by Fisk, (2000). The review also present evidence indicating that allergies and asthma is associated with the prevalence of dust mites, pets, fungi, insects, pollen, moisture, and insufficient cleaning. The quality of the indoor environment may also influence the sleep of the building occupants. Wargocki & Wyon (2017) reviews a couple of studies that show that the ventilation in a bedroom is associated with the quality of sleep, and MacNaughton et.al (2016) provides evidence suggesting that improved lighting conditions during the day may improve the sleep duration and sleep quality. The prevalence of communicable respiratory illnesses, allergies, asthma and sleep problems are shown to be influenced by the indoor environment, and it is likely that a person that experience any of these symptoms will suffer decreased productivity. It has been shown by Smith (1990) that even subclinical respiratory illnesses can influence the performance of simulated work tests. These long-term effects of poor indoor environment have been considered to be beyond the scope of this study, but it will briefly cover a few articles that have investigated the association between sickness absenteeism and the quality of the indoor environment. So, the study will mainly investigate what direct and short-term impacts that the indoor environment may have on productivity.

#### 1.4 THE EDUCATIONAL BUILDING

*This section is a short introduction to the building that will be evaluated, along with the certification that it is accredited by.*

The building is a university building in Stockholm by the name *The Educational Building*. The building is located at Brinellvägen 28A and is used by *KTH- Royal Institute of Technology* for education and research. The building is owned by *Akademiska Hus* who is a large property owner in Sweden that is owned by the Swedish government. The building has a floor area of approximately 4000 m<sup>2</sup> and houses lecture rooms, group rooms and open work spaces. The building will mainly be used by the School of Architecture and Built Environment at KTH, and it is designed to be a tool in the education with visible building services and structural elements. It is designed to enhance creativity and to be a part of the vision to create a sustainable and vivid campus. As a sign of the strive towards sustainability, the building has been certified according to the Swedish building certification system *Miljöbyggnad*, and it was accredited the highest rating. The building was completed in 2017. (Akademiska Hus, 2015).

The building is a part of *KTH Live- In Lab* which is a project with the aim to increase the innovation rate within the building sector, and the building will be used as a testbed for future research within the field. It is equipped with hundreds of sensors that measures electricity, water, ventilation flow, CO<sub>2</sub> - concentration as well as relative humidity and occupancy in some sections of the building (KTH, 2018). The sensors are connected with a computerized monitoring system that can be overviewed by individuals with the access to that data. The building is also equipped with various features that may influence the indoor environment directly or indirectly. For instance: the electrical lighting can be controlled and dimmed by the occupants, the shading system of the windows may be adjusted manually as well as automatically, there are movable sound barriers available and the windows are operable. There are temperature and CO<sub>2</sub> – concentration displays in some rooms, although the settings of those parameters cannot be adjusted by the students (except by opening the windows or folding down the window shading system, for instance)

As mentioned, The *Educational Building* is certified according to the highest rating in the Swedish certification system *Miljöbyggnad*. The purpose of the certification system is to ensure that buildings are healthy to the occupants as well as environmentally friendly. The system is widely used in Sweden, with more than 1000 certified buildings within different building types. The system is developed for the Swedish market and is thus based on Swedish building codes, regulations and best practice. (SWGBC, 2018). The system exists in a few different versions, and the version used in the buildings consists of 15 different areas of sustainability within the topics of indoor environment, energy and building materials. Among the 15 areas, 11 of them are related directly to the indoor environment in the version that The *Educational Building* is certified according to (New buildings- version 2.2). Those areas are acoustic climate, ventilation, nitrogen dioxide, thermal climate in the summer, thermal climate in the winter, daylight, legionella, radon, moisture safety, material documentation and use of dangerous substances. The remaining four areas concern energy efficiency and energy sources. It is evident that the indoor environment is a prioritized area that receive considerable attention in the certification system. Despite this, there is evidence that suggest that the indoor environment in certified buildings is not necessarily superior that of non-certified ones (Thatcher & Milner, 2016). This makes it interesting to evaluate how good the indoor environment in the *Educational Building* really is, and if it promotes healthy and productive occupants.

## 1.5 TERMINOLOGY

*This section will clarify and define some of the terms that will be used in the study.*

The word *productivity* will be used to represent several other words that has a similar meaning, such as *work efficiency* and *work performance*.

*Perceived productivity* is the term that will be used to assess the subjective evaluation of the building users of their ability to perform their work. Other terms that are used in the literature is *self- assessed productivity*, *perceived performance*, or *self- assessed performance*.

The term *quantitatively measured productivity* will be used to refer to productivity/performance that is evaluated quantitatively and *not* subjectively, for instance through simulated office work, cognitive performance tests or real work outputs such as number of phone calls per minute. There should be a very important distinction between *quantitatively measured productivity* and *real productivity*. Real productivity concerns the total output of an activity, and that contain both quantitative and qualitative elements and is highly individual depending on numerous contextual circumstances.

When referring to a difference that is *statistically significant*, only the word *significant* will be used in the literature review. If the difference is large, regardless if it is statistically significant or not, the word *significant* will thus not be used. Instead words like *considerable* or *substantial* will be used to indicate if the difference is considered to be large.

The words *acute health symptoms* will be used to represent short- term symptoms that the subjects may experience as a result of residing in the building. The word *acute* is used to distinguish between short term symptoms and long-term diseases or symptoms. An acute symptom is one that arise relatively suddenly, for some reason, but may also disappear relatively fast if the condition that evoked the condition disappears. The built environment may cause both types of symptoms, and long- term symptoms may also influence the productivity of the person suffering from it, as previously described. Another word of similar meaning that is frequently used in the literature is *SBS- symptoms (sick building syndrome symptoms)*. If SBS- symptoms or any other similar term is used, they will be referred in this paper as *acute health symptoms* because this is considered to be a slightly broader and more

correct term. Also, the symptom may arise both due to the building or not, and it is often difficult to know what *caused* the symptom and the term SBS- symptoms should therefore be avoided.

The words *occupants* and *building users* will both be used to describe the people who are using a building, mainly for work purposes in this context. It does not include the people who are working *with* that particular building, for instance facility managers and cleaners.

The term *green building* may be used to refer to a building that is designed and/or constructed with a green intent, but that is not accredited a formal certification. A certified green building will be referred to as *certified building* (for instance according to LEED, BREEAM or Miljöbyggnad certification systems). A building that is not considered “green” will be referred to as *conventional*, and a building that is not certified will be referred to as non- certified. “Green” will also be used to refer to buildings that are *either* “green” or certified, as opposed to *conventional*.

## 2 LITERATURE REVIEW

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*The literature review contains five parts.*

*The first and second part will address the fundamentals of thermal climate and air quality. Fundamental knowledge about the indoor environment is required to be able to understand the subsequent articles about how the productivity of the occupants is influenced by the indoor environment.*

*The third part reviews studies that have investigated both how quantitative measurements of productivity and subjective evaluations of the indoor environment is influenced by the indoor environment simultaneously. Consistencies and inconsistencies between the evaluations will be the emphasis of that chapter.*

*The fourth part will provide additional insight into how productivity can be evaluated by quantitative means, for instance by measurements of educational achievements and sickness absenteeism.*

*The fifth part will review studies that have investigated how the indoor environment influence the subjective perception of productivity.*

### 2.1 THERMAL CLIMATE

*This chapter will present some fundamentals about the thermal climate that may be required to be able to understand subsequent sections.*

*The main factors that directly influence how we perceive the thermal climate are:*

- *Air temperature (the dry bulb temperature, measured with an ordinary thermometer)*
- *Room surface temperatures (through radiation and natural convection)*
- *Air movement (the velocity and turbulence of the air)*
- *Air humidity (the water vapour content of the air)*
- *The human metabolism (which varies with activity level)*
- *The insulation from the clothing*

### 2.1.1 Thermal balance of a body

The thermal balance is essential in our perception of the thermal climate. If the heat produced by the metabolism is equal to the heat dissipated to the environment we typically feel thermally comfortable. If the heat produced is greater we feel hot, and if it is lower we feel cold. (Bluyssen, 2009)

By assuming that the temperature of the body remains constant (for ordinary activities the body maintains its ideal temperature around 37 °C ) the following heat balance equation can be formulated: (Kreider, et al., 2010)

$$q = q_{con} + q_{rad} + q_{evap} + q_{resp,sens} + q_{resp,lat} [W]$$

The left side represent the heat produced by metabolism, and the right side the way we dissipate energy to our surrounding. The q- terms represent the heat loss by convection, radiation, sensible respiration and latent respiration.

#### 2.1.1.1 Convection

The convection part can be calculated by the formula: (Kreider, et al., 2010)

$$q_c = A * h_c * (T_{surface} - T_{air})$$

- A is the surface area [m<sup>2</sup>]
- T:s are the temperatures of the surface and of the surrounding air.
- The factor h<sub>c</sub> is the heat transfer coefficient for convection [W/m<sup>2</sup>K]

In theory, h<sub>c</sub> depends on the Nusselt number, which in turn depends on the properties of the flowing media (the heat transfer coefficient for conduction and the kinematic viscosity) as well as of the turbulence of the flow, and on whether the flow is induced by natural or forced convection. In indoor environment applications the flowing media is air, the flow is mainly turbulent, and the convection can be both natural or forced. (Ekroth & Granryd, 2006)

The convective part is thus increased when the following parameters are increased: the temperature differences, the surface area, and the velocity and turbulence of the surrounding air (Ekroth & Granryd, 2006).

The ISO standard 7730 (ISO, 2006) prescribes a more applied way of how the convective heat transfer coefficient can be calculated of a human body, by using the following set of equations.

$$h_c = \begin{cases} 2,38 \cdot |t_{cl} - t_a|^{0,25} & \text{for } 2,38 \cdot |t_{cl} - t_a|^{0,25} > 12,1 \cdot \sqrt{v_{ar}} \\ 12,1 \cdot \sqrt{v_{ar}} & \text{for } 2,38 \cdot |t_{cl} - t_a|^{0,25} < 12,1 \cdot \sqrt{v_{ar}} \end{cases}$$

$$t_{cl} = 35,7 - 0,028 \cdot (M - W) - I_{cl} \cdot \left\{ 3,96 \cdot 10^{-8} \cdot f_{cl} \cdot \left[ (t_{cl} + 273)^4 - (\bar{t}_r + 273)^4 \right] + f_{cl} \cdot h_c \cdot (t_{cl} - t_a) \right\}$$

$$f_{cl} = \begin{cases} 1,00 + 1,290 I_{cl} & \text{for } I_{cl} \leq 0,078 \text{ m}^2 \cdot \text{K/W} \\ 1,05 + 0,645 I_{cl} & \text{for } I_{cl} > 0,078 \text{ m}^2 \cdot \text{K/W} \end{cases}$$

- t<sub>cl</sub> is the clothing surface temperature, in degrees Celsius [°C]
- M is the metabolic rate [W/m<sup>2</sup>]. The metabolic rate for different activities is decided by the ISO standard 8996
- W is the effective mechanical power [W/m<sup>2</sup>]. Often W can be neglected, as the work done by a body during normal activity levels represent only a few percent of the total metabolism. (Kreider, et al., 2010)

- $I_{cl}$  is the clothing insulation [ $m^2 K/W$ ]. The clothing insulation for different clothing is decided by ISO standard 9920 (ISO, 2007).
- $v_{ar}$  is the relative air velocity [m/s]
- $f_{cl}$  is the clothing surface area factor [-]
- $t_a$  is the air temperature ( $^{\circ}C$ );
- $t_r$  is the mean radiant temperature ( $^{\circ}C$ ), later calculations will show how it is calculated

The calculation of  $h_c$  by these formulas require some iteration to solve, as  $h_c$  has to be given a start value in the formula for  $t_{cl}$  which in turn is used to calculate  $h_c$ .

### 2.1.1.2 Radiation

The radiation part is caused by surface temperatures that emit radiation to the body. The radiation part can be calculated by using the shape factor of the surrounding surfaces in relation to the body. The shape factor is a geometrical property and it is the fraction of the radiation leaving a specific surface that reaches the body. To simplify further calculations, one can use the mean radiative temperature of the room  $T_r$  to calculate the radiation exchange. The mean radiant temperature is the uniform surface temperatures that would result in the same radiative exchange as in the real situation. This can be expressed by the equation: (Kreider, et al., 2010)

$$\sigma * (T_{body}^4 - T_r^4) = \sigma * \sum_n F_{body-n} (T_{body}^4 - T_n^4)$$

$\sigma$  is the Stephan- Boltzmann constant.  $F_{body-n}$  is the shape factor between the body and surface  $n$ .

Solving for  $T_r$

$$T_r = \sqrt[4]{\sum_n F_{body-n} * T_n^4}$$

The radiative temperature can be used in the equations above to calculate the convective heat transfer coefficient  $h_c$ .

The heat loss due to radiation becomes:

$$q_{rad} = A * h_c * (T_{body} - T_r)$$

$h_c$  is the connective heat transfer coefficient [ $m^2K/W$ ]

### 2.1.1.3 Convection and radiation- Operative temperature

To simplify the calculations, the sum of the energy flows from convective and radiation is calculated by the use of what is called *operative temperature*. It is defined as the uniform temperature that the air temperature and the surfaces would have that would result in the same heat exchange as in the real situation. This can be expressed by the following equation: (Kreider, et al., 2010)

$$(T_{op} - T_{body}) * (h_{con} + h_{rad}) = h_{con} * (T_{air} - T_{body}) + h_{rad} * (T_{rad} - T_{body})$$

Solving the equation for  $T_{op}$ :

$$T_{op} = \frac{h_{con} * T_a + h_{rad} * T_r}{h_{con} + h_{rad}}$$



In buildings for many practical purposes  $h_{con}$  and  $h_{rad}$  are of similar magnitude, and thus the operative temperature simply becomes the average of the mean radiative temperature and air temperature. (Kreider, et al., 2010)

#### 2.1.1.4 Evaporation

The heat loss due to evaporation of sweat can be described by the following equation: (Bluyssen, 2009)

$$q_{evap} = 0,42 A \left( -58 + \left( 1 - \frac{W}{M} \right) \left( \frac{M}{A} \right) \right)$$

Where  $W$  is the mechanical power that the body produces [W].  $M$  is the metabolic rate [W] and  $A$  is the surface area [ $m^2$ ]

#### 2.1.1.5 Respiration

Sensible respiration heat loss can be calculated by the equation: (Bluyssen, 2009)

$$q_{resp,sens} = \dot{m}_{air} * c_p * (T_{exit} - T_{in})$$

$\dot{m}_{air}$  is the massflow of air [kg/s],  $c_p$  is the specific heat of dry air at constant pressure, and the  $T$ :s are the temperatures of the air that exit and enter the body.

The latent respiration heat loss can be calculated by the equation: (Bluyssen, 2009)

$$q_{resp,lat} = \dot{m}_{air} * c_{ev} * (H_{exit} - H_{in})$$

$c_{ev}$  is the heat of evaporation of water [J/kg],  $H$  is the humidity ratios of the exiting and entering air [kg/kg]

#### 2.1.2 Predicted mean vote and predicted percentage dissatisfied

To predict the thermal balance of a person one can use the PMV (predicted mean vote) index. It is based on a 7- point thermal sensation scale (from hot to cold) and a set of equation that estimates how a large group of people in average will perceive their thermal comfort according to this scale. The equation is: (ISO, 2006).

$$PMV = [0,303 \cdot \exp(-0,036 \cdot M) + 0,028] \cdot \left\{ \begin{array}{l} (M - W) - 3,05 \cdot 10^{-3} \cdot [5\,733 - 6,99 \cdot (M - W) - p_a] - 0,42 \cdot [(M - W) - 58,15] \\ -1,7 \cdot 10^{-5} \cdot M \cdot (5\,867 - p_a) - 0,0014 \cdot M \cdot (34 - t_a) \\ -3,96 \cdot 10^{-8} \cdot f_{cl} \cdot [(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4] - f_{cl} \cdot h_c \cdot (t_{cl} - t_a) \end{array} \right\}$$

- $h_c$ ,  $t_{cl}$ ,  $f_{cl}$  are calculated according to the equations in the section about convection
- $p_a$  is the water vapour partial pressure, which is a way of expressing the water vapour content in the air

As with the heat balance calculations above, the PMV value only applies for steady state conditions where the body temperature remains at a relatively constant temperature. The formula only applies within reasonable limits of all the parameters, which applies for most indoor environments. (ISO, 2006). As an example of this is that the evaporation of sweat becomes an increasingly important factor at higher activity levels, which the PMV calculations does not regard. (ASHRAE, 2010)

The thermal sensation scale that is used is:

**+3 hot, +2 warm, +1 slightly warm, 0 neutral, -1 slightly cool, -2 cool, -3 cold**

There are many subjective factors that influence how an individual perceives thermal comfort, but the PMV method is considered a useful tool to be able to estimate the mean value of the responses of a large group of individuals (Kreider, et al., 2010).

Another way of expressing the output of the PMV calculation is to express it as percentage of people dissatisfied. The definition of dissatisfaction in this case is if your vote is outside the range of -1 to +1, and it is calculated by the formula:

$$PPD = 100 - 95 \cdot \exp(-0,033 53 \cdot PMV^4 - 0,217 9 \cdot PMV^2)$$

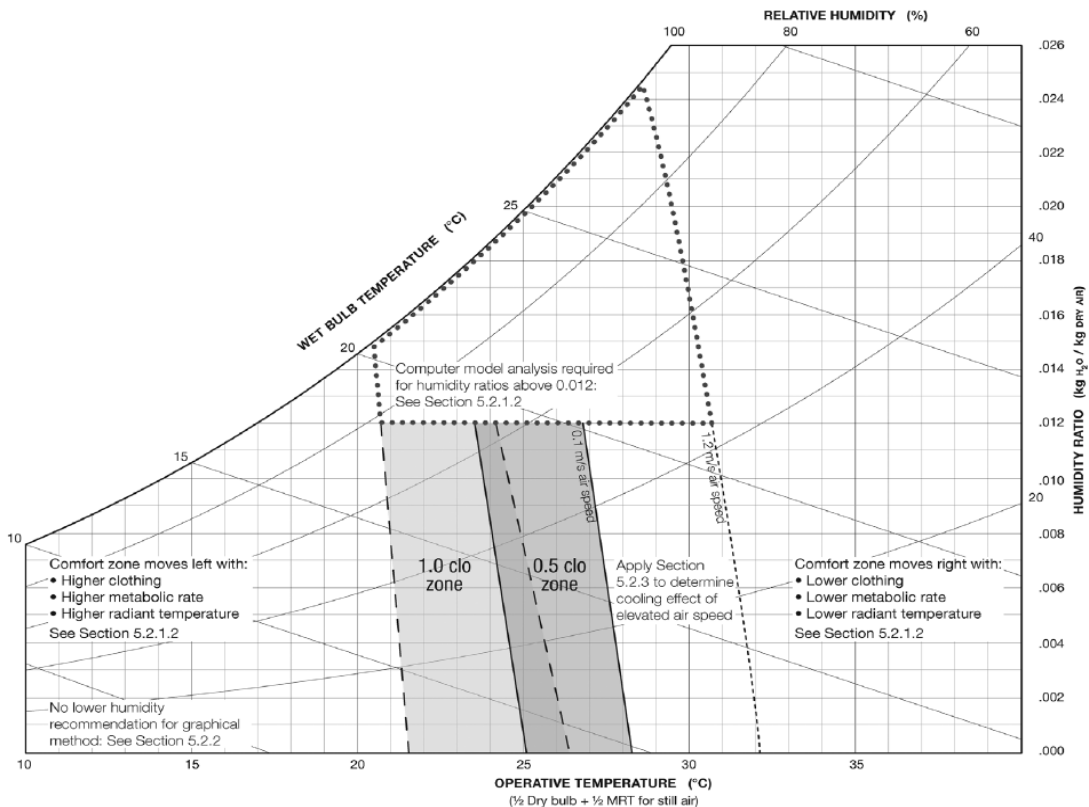
According to the formula, the number of dissatisfied will never be below 5% even if the PMV is 0. By the recommendation of ASHRAE standard 55 the thermal environment should not have a PPD- value above 10% to be able to create an acceptable environment (ASHRAE, 2010).

### 2.1.3 Comfort charts

The ASHRAE standard 55 provides support in evaluating some of the properties that affect the perception of thermal comfort. It specifies combinations of factors that will create a thermal environment that is perceived as acceptable to most building users, often 80% satisfaction rate (ASHRAE, 2010). The standard provides mainly graphic methods for deciding an adequate relationship between different parameters. Some of them will be presented below.

#### 2.1.3.1 Operative temperature and humidity

Fig. x presents the levels of humidity and operative temperature that the indoor environment should be within to create an adequate thermal environment, based on PMV and local thermal discomfort calculations. The grey shaded areas in the psychrometric chart are within an acceptable thermal climate.

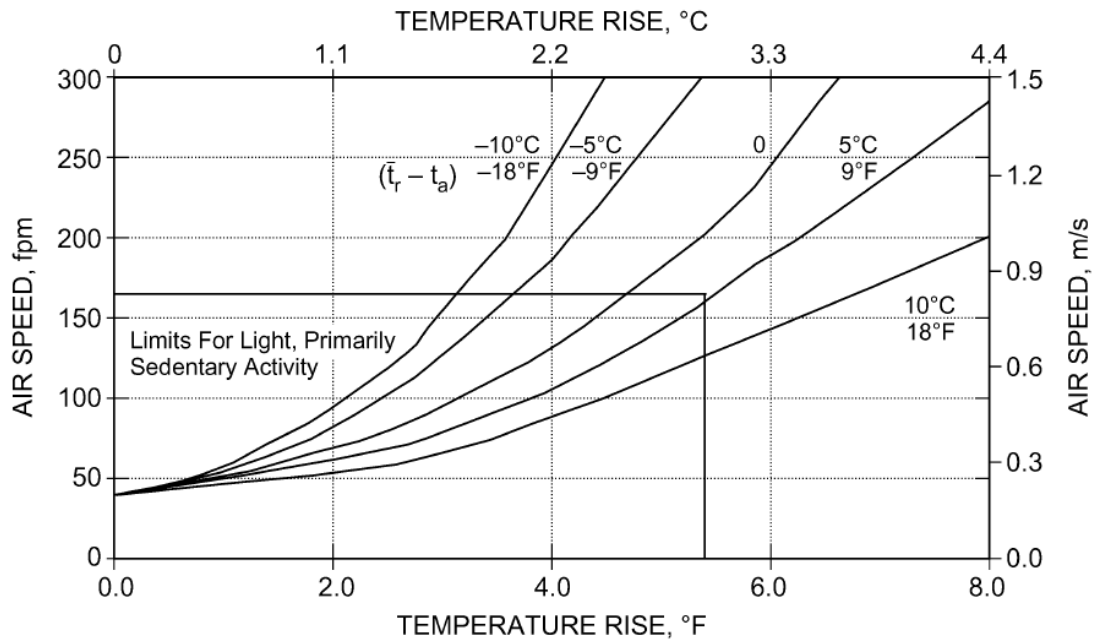


Graphic method of acceptable ranges of operative temperatures and humidity levels. (ASHRAE, 2010). This applies at metabolic rate of  $64 \text{ W/m}^2$  (1,1 met, sedentary activities)

The figure displays two different cases of clothing that corresponds to summer and winter clothing. That allows greater flexibility in temperature fluctuations over the seasons, which also corresponds to the behavioural tendency that people in general wear lighter clothing in the summer. The summer clothing has the insulation value of  $0,0775 \text{ m}^2\text{K/W}$  (0,5 clo) and the winter clothing  $0,155 \text{ m}^2\text{K/W}$  (1,0 clo). It is possible to have a climate outside these recommended zones, but not without further analysis. Note that there is no lower limit for humidity from a thermal perspective, but there might be other comfort factors that set a limit, such as dry skin or irritated eyes.

### 2.1.3.2 Elevated air speeds

Acceptable thermal climate can be achieved even at higher operative temperatures by elevating the air speed in the room. That will increase the convective heat transfer coefficient  $h_c$  which will reduce the PMV- value. As mentioned above, the PMV- formula only applies for parameters within certain values and in the case of air velocity the upper limit is  $0,2 \text{ m/s}$ . It is however possible to elevate the air speed above  $0,2 \text{ m/s}$  by the aid of the graph in the figure below.

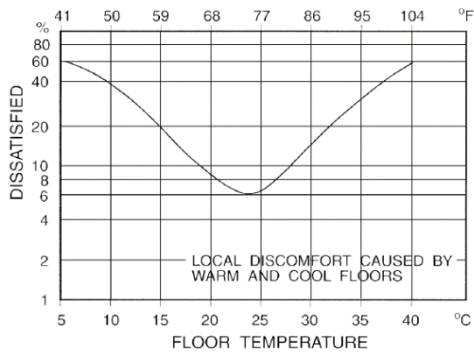
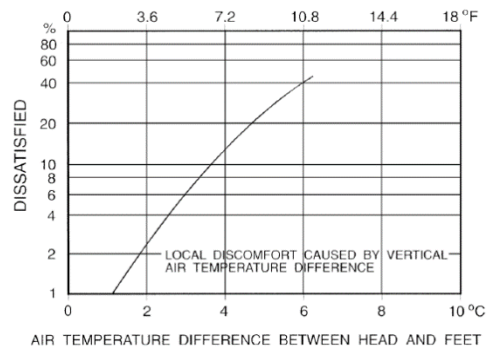
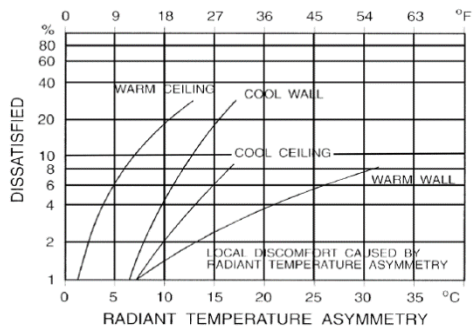


The combination of air speed, radiative temperature and air temperature rise that corresponds to equal levels of heat loss, with the air speed reference of 0,2 m/s (the upper limit of when the PMV formula applies). This applies for metabolic rates between 58,2 W/m<sup>2</sup> (1 met) and 75,66 W/m<sup>2</sup> (1,3 met) (sedentary activities) and for clothing insulation between 0,00775 m<sup>2</sup>K/W (0,5 clo) and 0,1085 m<sup>2</sup>K/W (0,7 clo) (medium clothing). For lighter clothing the increased air speed will have lower cooling effect, and for higher metabolism the cooling effect will be increased due to sweat evaporation. (ASHRAE, 2010)

### 2.1.3.3 Local thermal discomfort

Local thermal discomfort is another problem that ASHRAE standard 55 address. It can be caused by vertical temperature differences between the head and the feet, by draft, by radiative asymmetry or by cold floors.

Draft is defined by ASHRAE standard 55 as unwanted local cooling of the body caused by air movement. The disturbance of draft can be reduced by ensuring that air velocities are below 0,15 m/s, but more can be acceptable if the air temperature is above 22,5 °C. The disturbance becomes more severe at lower air temperatures and when the whole body thermal sensation is below neutral (ASHRAE, 2010). The following graphs in the following figures show some other graphic ways of assessing local thermal comfort problems.

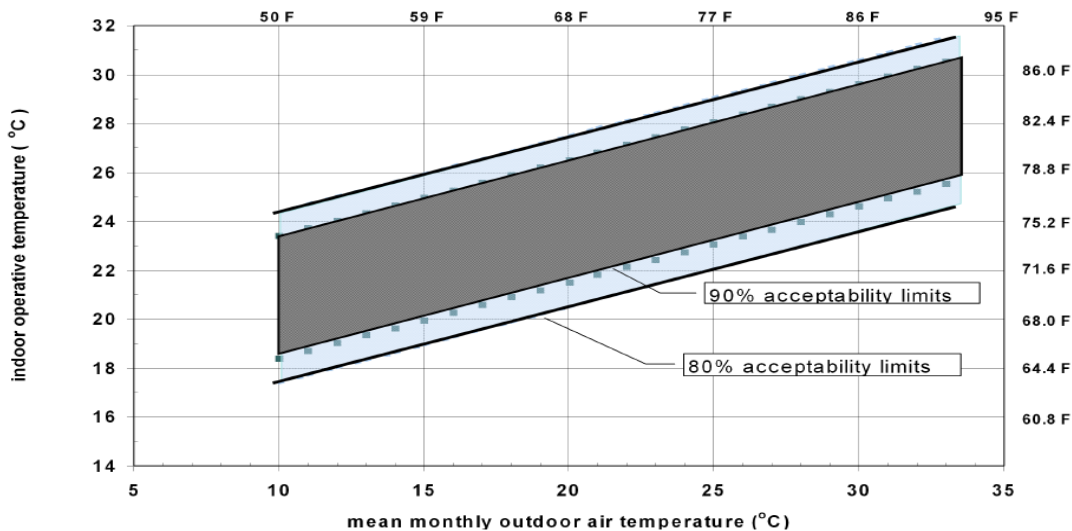


*How different local thermal comfort problems influence the percentage of people of dissatisfied. They apply for metabolic rates between 58,2 W/m<sup>2</sup> (1 met) and 75,66 W/m<sup>2</sup> (1,3 met) (sedentary activities) and for clothing insulation between 0,00775 m<sup>2</sup>K/W (0,5 clo) and 0,1085 m<sup>2</sup>K/W (0,7 clo) (medium clothing). (ASHRAE, 2010)*

### 2.1.4 Adaptive thermal comfort

Another way of approaching the topic of thermal climate is suggested by the adaptive thermal comfort model. The model builds on findings that suggest that the context and the thermal history of the occupants influence the perception of thermal comfort and that those parameters therefore should be included in the models that is used. It is predicted that people in warmer climate zones prefer warmer temperatures indoors than people from cold climates. It is also believed that people who have a higher degree of environmental control can tolerate higher variability of temperatures, because of psychological adjustments. For instance, occupants in naturally ventilated buildings are shown to be more tolerant. It was also found that the outdoor temperature may influence the thermal preference as well. So according to the model, the perception of the thermal comfort is influenced by past experiences of the thermal climate as well as the current climate and by the ability to control the indoor environment and by the outdoor temperature. (de Dear & Brager, 1998). Examples of individual control are for instance opening windows, adjusting shading systems, operating fans, hot/cold drinks or by adjust the clothing.

Some of those adaptive approaches have been incorporated into ASHRAE standard 55. By inserting the mean outdoor temperature in a graph, acceptable indoor temperatures are given. This only applies for buildings that are occupant controlled naturally conditioned spaces, for instance in buildings where the temperature is mainly is regulated by operating the windows, and thus not for HVAC equipped buildings. The model only applies for occupants of a metabolism between 1,0 and 1,3 met and in contexts where the occupants are allowed to adjust their clothing freely. The model should not be used when the mean monthly outdoor temperature is below 10 °C or above 33,5 °C. The air velocity or relative humidity is not regarded in the model. (ASHRAE, 2010). The graph is presented in the figure below.



How acceptable indoor temperatures are decided by the adaptive thermal comfort model in ASHRAE standard 55. (ASHRAE, 2010)

## 2.2 AIR QUALITY

Air quality is another environmental parameter that impact building users. Air quality concerns the pollutants that building users are exposed to in the indoor environments. The pollutants can have vastly different origins, for instance radioactive radon from the ground, compound released from furnitures, bacteria's and parasites that grow in damp materials and bioeffluents from the human body. These pollutants, and many more, are essential both to our health, well- being in the indoor environment.

An acceptable indoor air quality is defined by ASHRAE standard 62 as: (ASHRAE, 2007)

“air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction”

The standard has also established recommendations of upper limits for most contaminants, to provide guidance for system design, construction, and maintenance of ventilation systems.

The two main two groups of contaminants in the indoor environment are chemical and biological pollutants. The chemical ones can be divided into gases and particulate matter, and the biological pollutants are mainly particles from e.g. pollen, mould, insects, mites, viruses and bacteria. (Bluyssen, 2009). The chapter will not go into the depth of the topic and will not include any recent research.

### 2.2.1 Particulate contaminants

Airborne particular matter are small solid particles and liquid droplets. Particles that are small and light enough to stay suspended in the air are called aerosols, typically between 0,01 and 200  $\mu\text{m}$  in diameter. (Bluyssen, 2009). Dust, fumes and smoke are examples of solid particles, while fogs, smogs and mist are often suspended in liquid particles. Other examples of particles are bioaerosols such as virus, bacteria, fungal spores, and different particles from plants, animals, dust mites, and endotoxins (ASHRAE, 2013)

Especially the smaller particles with an aerodynamic diameter of below 10  $\mu\text{m}$  ( $\text{PM}_{10}$ ) and 2,5  $\mu\text{m}$  ( $\text{PM}_{2,5}$ ) have been shown to be particularly harmful as they are small enough to enter the lungs and be taken up by the body. (Klumpp & Ro- Poulsen, 2010). Particles can originate either from the primary source, as is most common with  $\text{PM}_{10}$  and  $\text{PM}_{2,5}$ , but also from chemical reactions between different

compounds such as gases and VOC:s. (Lavicoli, et al., 2010). The main source in the urban areas is from road traffic exhausted by the engine and from tire and brake friction (Almeida, et al., 2006). The coarse particles (2,5-10  $\mu\text{m}$ ) derives mainly from abraded soil, brake and tire friction, constructions and aggregates of smaller particles. The finer particles derive mainly from combustion processes. (Bernstein, et al., 2004)

The main way of taking in particulate matter is by inhalation, where particles often will deposit somewhere in the respiratory tract. Where and how they will deposit depends mainly on the aerodynamic properties of the particles, which depend on their size and shape. (Kappos, 2010). Smaller aerosols tend to penetrate deeper into the respiratory tract when inhaled, thus causing more severe health effects. Particles smaller than 10  $\mu\text{m}$  are considered respirable as they can penetrate into the thorax (Bluyssen, 2009). However, the boundary between what is respirable and non- respirable is not clear, as most particles with an aerodynamic diameter larger than 5  $\mu\text{m}$  settle at the large bronchi or earlier. Smaller particles will deposit deeper in the lungs, such as in the small bronchi, the bronchiole and the alveoli (Kappos, 2010).

There are different mechanisms of the respiratory system that act to prevent the particles from entering into the respiratory tract. The nose can filter away most of the particles above PM<sub>2,5</sub> and some of the particles between 1 and 2,5  $\mu\text{m}$ . The inside of the trachea and the bronchi are covered by hair- like structures that moves synchronously to transport the particles upwards (Kappos, 2010).

Particulate matter has been related to lung cancer and other deceases related to the lungs and the heart. (Cohen, et al., 2005). The evidence that PM<sub>2,5</sub> causes cardiovascular morbidity and mortality is considered strong by the American Heart Association (Brook, et al., 2010).

#### **2.2.1.1 Biological particular contaminants**

Bioaerosols originate from bacteria, viruses, protozoa, algae, fungi, mites, insects, plants, and animals. In general, they require a source of food to grow and survive as well as certain levels of temperature and humidity. In the indoor environment, different building components can work as amplifiers (allowing the contaminant to grow), disseminators (allow the contaminant to spread) or as reservoirs (allow the contaminants to survive). Most of these biological contaminants are dependent on a high humidity level. (ASHRAE, 2013). Due to the common cause, they often occur simultaneously, and it is therefore difficult to conclude what health symptoms that originate from which agent, though WHO states that "Exposure to microbial contaminants is clinically associated with respiratory symptoms, allergies, asthma and immunological reactions" (WHO, 2009). Beyond causing growth of microbes, dampness can also cause biological, chemical and physical degradation which can cause emittance of chemical and biological agents.

#### **Fungi**

Fungi exist in many different classes. They find nutrients in carbohydrates, proteins or lipids from e.g. wood building materials, paper products, textiles, paints, glue or in animal matter in dust. They also need high levels of moisture to thrive, which is measured in water activity. It is defined as the vapour pressure above a given surface divided by that of a water surface. The lowest water activity that can result in fungal growth is below 0,80 according to Grant et. al (1997), cited in WHO (2009). Relative humidity levels above 70% is often required for mould growth, and ASHRAE standard 62 recommends that RH shall be below 65%, (ASHRAE, 2007). It is essential to remember that a cold surface will increase the relative humidity of the surrounding air, and thus can there be a risk for fungi even when RH is below 70%. Most species of fungi in the indoor environment thrive at temperatures between 10 and 35 °C, but humidity is the critical factor as the nutrients and desirable temperatures are mostly

available in the indoor environment. Moisture problems in buildings can occur due to building technological errors such as moisture condensation in structures, faulty design of runoff water, remaining moisture from the construction process or inadequate ventilation (WHO, 2009). Many species of fungi produce allergens of different kinds. They originate from their spores (particles released during reproduction), hyphae (branching structure) and in fungal fragments (e.g fractured spores or hyphae). These allergens are released at higher rate during growth and germination, as is reviewed by WHO (2009). The spores can deposit in the whole respiratory system as they come in different sizes and densities and some aggregate and others are absorbed by water. The spores are typically 2-10  $\mu m$  and the fragments even smaller. Some of the spores can reach as deep as the alveoli, especially the smaller ones (Eduard, 2006). Another product of fungi are mycotoxins, which are products of some fungi's metabolism and can be toxic to humans in low concentrations. They can interfere with RNA synthesis and damage to DNA. (WHO, 2009). As reviewed by WHO (2009), most studies indicate that mycotoxins exist in higher levels in buildings that are fungi affected. Mycotoxins are extra dangerous to take in via food consumption, and can even result in death. (ASHRAE, 2013)

### **Bacteria**

Bacteria can be found on every surface in every building, but in order to grow they need a damp or wet surface. The temperature and nutrient demand is more often fulfilled indoors. It has been suggested, as reviewed by WHO (2009), that bacteria grow on the same surfaces as fungi does. Accumulating bacterial growth in the indoor environment are believed to negatively impact health. Endotoxins are molecules that exist in some types of bacteria and are released when the cells die. Substantial exposure to endotoxins can cause respiratory symptoms. (WHO, 2009). Infants wheezing has been shown to correlate with endotoxins, and increased asthma symptoms have been shown to correlate with increased levels of endotoxins for school children, as reviewed by Peden 2015, though emphasizing that the precise mechanisms are not well understood (Peden, 2015). One particularly bacteria that commonly causes severe health impacts by buildings is *Legionella pneumophila* that is associated with still standing water. (ASHRAE, 2013)

### **Animal allergens**

Allergens from animals are of course quite independent on the building itself, even though the cleanliness and the ventilation rate can have an impact on how severe the allergy symptoms appear.. The main sources of allergens from pets are dander, saliva and urine. (Lowenstein, et al., 1986). Allergy can easily develop into a severe asthma if a person is exposed during extended times. Cleaning of the building and of the furnitures are important means to reduce the allergens. (Astma och allergiförbundet, 2017).

### **Dust mites**

Dust mites live primary in damp and hut buildings with an optimum relative humidity of 70-80% and a temperature of 25-30 °C. Their source of food is mainly human skin flakes and fungi growing on the flakes. They live in dust that have accumulated in carpets, mattresses, and other fabrics. (Colloff, 2009).

#### **2.2.2 Gaseous contaminants**

There are many different gaseous contaminants that exist in the indoor environment and that can impact the building occupants. Some of them are released from materials while others are released during combustion processes.



### 2.2.2.1 Volatile organic compounds (VOC)

Volatile organic compounds are organic compounds with a boiling point at relatively low temperatures. This gives them a high vapour pressure at room temperatures which enables them to easily evaporate into the air. Compounds with very low boiling point are defined by WHO as very volatile organic compounds (VVOC), and they are considered to be so if the boiling point below 50°C. There are also semivolatile organic compounds (SVOC) that have a boiling point from about 240 °C (WHO, 1989).

The emissions of VOCs, VVOCS and SVOCs in the indoor air environment is mainly from building materials, furnitures, solvents and plasticisers and reagents in plastics, paints, cleaning products, combustion products from e.g. gas stoves and traffic, flame retardants, refrigerants, or be used as propellants in aerosols and expanders in plastic foams. VOC:s can also be produced by microorganisms (MVOC) such as fungi in water damaged buildings. (ASHRAE, 2013)

Especially new furnitures and building materials emit a lot of VOCs and the emittance will decay over time. ASHRAE 2013 reviews the findings of Morey & Singh (1991) and Sheldon et.al (1988) regarding the decay time of VOC emittance. The time until normal levels have been reached in a new or refurbished room can take several months, depending on the rate of air exchange and on the surface area. The concentration in new buildings can be as much as 100 times that of the outdoor air. After 5 months it can still be above 5 times that of the outdoor air, given a normal air exchange rate. Even in old buildings there can be 10 times the outdoor air concentrations of VOCs if the air exchange is low.

There are also materials in the indoor environment that can absorb VOCs, which can have a considerable impact on the concentration in a room over time. ASHRAE 2013 refer to Colombo et.al (1993), about the absorption effect. For a sudden rise of VOC: s in a room, e.g. from a newly painted wall, the peak concentration can be reduced by the absorption phenomena. However, it will also cause a subsequent desorption once the levels in the room are approaching normal values and this will prolong the time of the elevated VOC concentration. The sink materials in buildings could be carpets, gypsum boards and wall coating. (Colombo, et al., 1993).

To be able to quantitatively measure the total amount of VOCs the concept of total VOC has been introduced, to address the fact there are more different VOCs in the indoor air than can be measured individually. The concept is used to quantify the sum of all VOCs that have been detected by a certain method of detection. (ASHRAE, 2013). ISO standard 16000 does however accentuate that the value obtained from such a TVOC measurement depend much on the sampling and analytical methods used, and that the obtained value cannot speak for itself without regarding the methods used. (ISO, 2011). Most non- industrial buildings have a TVOC concentration below 1 mg/m<sup>3</sup> and rarely above 25 mg/m<sup>3</sup> (ECA, 1997). At levels of 3 mg/m<sup>3</sup> odours became significant in controlled experiments (ASHRAE, 2013). The emission of TVOC has been found to be quite independent on the temperature and humidity in the room (Fang, et al., 1999). The total amounts of volatile organic compounds (TVOC) have not been shown to be a very good way to measure the health and comfort issues regarding VOCs in non-industrial indoor air, even though an increased level of TVOC likely will result in increased sensory irritation (ECA, 1997).

Exposure to elevated levels of VOC can cause health effects of different forms. VOCs can be perceived by olfactory, gustatory and common chemical sensation (smell, taste and irritation) (Cain, 1989). Symptoms of elevated levels of VOCs are irritated mucous membranes, asthma, fatigue, poor concentration and cancer. VOCs are also known to cause bad odours, especially MVOCs have very low odour threshold. However, the overall health impacts of VOCs are not well understood (ASHRAE, 2013). The correlation between VOC concentration and complaints due to odour is weak, and there is therefore no simple method that can predict how the odour due to VOC is perceived. (ASHRAE, 2013)

Exposure to SVOCs have been associated with several severe health issues, which are reviewed briefly by ASHRAE 2013 (ASHRAE, 2013). The symptoms that are mentioned are endocrine disruption (interfere with the hormones), low semen number and poor motility and abnormal anogenital distance in newborns. SVOCs can be taken up by the body by inhalation, ingestion (diet or dust), or through the skin. SVOCs can be both gaseous and particulate (ASHRAE, 2013)

Most odorants provoke chemical irritation at high concentrations. Irritation of eyes and nasal pungency occur at approximately the same concentrations, while odour is detected at much lower concentrations (Cometto-Muñiz & Cain, 2002). Mixtures of odours are perceived as less intense than the sum of all the individual odours (hypoadditivity) according to the field of research on the subject, as reviewed by Cometto-Muniz & Cain (1997). Nasal pungency due to odour mixtures has, on the contrary, been shown to be additive or even hyperadditive. (Cometto-Muñiz & Hernández, 1990).

VOCs can react with nitrogen oxides in the presence of sunlight and form ground level ozone that may cause severe health impacts. (United States Environmental Protection Agency, 2017).

### 2.2.2.2 Bioeffluents, olf and decipol

Human generates pollutants that are called bioeffluents. High levels of bioeffluents are typically associated with dissatisfaction of the air quality. The emission rate of bioeffluents from a sedentary standard person at thermal comfort is defined as one olf. The emission of smell from other sources than humans can also be evaluated based on the olf unit, for instance the emission of smells from furnitures. The olf unit is thus a sensory unit and not a chemical one. The sensation of smell in an enclosure is measured in decipol, which is defined as the smell of a standard person with the ventilation rate of 10l/s unpolluted air (one olf per 10 l/s). (Fanger, et al., 1988)

The percentage of people dissatisfied by the air quality can be estimated based on the ventilation rate per olf in a room. The equations are presented below: (Fanger, et al., 1988) .

$$D = 395 \exp(-3,66q^{0.36}) \quad \text{for } q \geq 0,332$$

$$D = 100 \quad \text{for } q < 0,332$$

Where D is the percentage of persons dissatisfied, and q is the ventilation rate per olf. For instance, at the ventilation rate of 10l/s per olf the dissatisfaction rate is 15% and at 7 l/s per olf the dissatisfaction is 30%.

A person exercising at medium intensity corresponds to 10 olf, low polluting buildings have a value of approximately 0,1 olf/m<sup>2</sup> due to the material emissions, and the corresponding value of non-low polluting building is 0,2 olf/m<sup>2</sup>.

### 2.2.2.3 Carbon dioxide

CO<sub>2</sub> is a colourless gas that is naturally occurring in the air but is also produced as a by-product of metabolism. This results in a higher concentration of CO<sub>2</sub> in the indoor air than in the outdoor air. (Kreider, et al., 2010). The concentration of CO<sub>2</sub> in acceptable outdoor air is commonly 300 – 500 ppm, and it should not be more than 700 ppm more indoors than outdoors to satisfy 80% of the occupants. (ASHRAE, 2007). Toxic concentration is far higher than these levels, and severe health impact will in practice never occur in the indoor environment. However, as the CO<sub>2</sub>- concentration indoors are correlated with the occupancy density it can thus be used as an indicator of the total amounts of bioeffluents present in the room, causing the sensation of bad smell. ASRAE standard 62 recommends an air supply of 7,5 litres per person is to cause a dilution of the bad odours that would result in the recommended CO<sub>2</sub> levels above, given an activity level of 1,2 met (ASHRAE, 2007). The rate of CO<sub>2</sub> production is increasing linearly with increasing metabolism, resulting in higher requirements of

ventilation flows. At the activity level of 1,2 met the CO<sub>2</sub> production is 0,31 l/min, and the oxygen consumed is 0,36 l/min. The dilution of oxygen in the air is insignificant compared to the increasing concentration of CO<sub>2</sub>, as the concentration of CO<sub>2</sub> is much lower than that of oxygen, while the flows (0,31 and 0,36 l/min) are approximately equal, resulting in a higher percentage increase of CO<sub>2</sub> than the percentage of decreased oxygen. (ASHRAE, 2007). Oxygen levels will therefore remain fairly constant in the indoor environment, while the CO<sub>2</sub> concentrations may vary quite substantially depending on the ventilation rate and the occupancy.

#### 2.2.2.4 Ozone

Ozone is a colourless gas that is a strong oxidizing agent that may react with other compounds in the air. Ozone can be produced in the indoor environment by technical appliances such as air cleaners and printers. Exposure to ozone may cause decreased lung function and pain upon inhalation. (Health Canada, 2010). Ozone can also be created by the reaction between VOCs, nitrogen oxides and sunlight and is a contributor to acid rain and photochemical smog (United States Environmental Protection Agency, 2017)

#### 2.2.2.5 Other combustion products

This section will briefly mention a few gaseous contaminants that are produced mainly from combustion processes. These contaminants are mainly produced in the outdoors, but may reach the indoor air by inadequate air filtration, or if windows are opened, and may then affect the health of the building users. They may also be products of combustion processes indoors.

CO is a colourless, odourless, and tasteless gas that is produced by incomplete combustion of fuel that contain carbon, such as wood, petrol, natural gas and coal. Sources indoors are combustion processes such as gas stoves, wood stoves and tobacco smoke. It can also enter the building by infiltration from outdoor sources such as traffic, if the air intakes are inappropriately placed. If the building pressure is negative there is also a risk that CO enter the building from CO producing equipment, instead of being ventilated out. (ASHRAE, 2013). Incomplete combustion can occur if there is not enough air present in relation to the fuel. CO enters the body by inhalation, and is diffused easily by the alveolar membranes and is dissolved in the blood. Once in the blood, it binds to the protein haemoglobin which prevent them from carrying oxygen. (WHO, 2010). Symptoms of CO poisoning are e.g. headache, dizziness, feeling of confusion, abdominal pain, shortness of breath, and death (Haines, 2016). Long- term exposure to low concentrations of CO have been shown to cause pregnancy effects, such as decreased birth weight, preterm birth, and increased risk of intrauterine growth restriction, although the studies are inconsistent (Edwards, et al., 2015).

There are several oxygens of nitrogen that act as pollutants in the air. NO and NO<sub>2</sub> are products of combustion, and the greatest source is from traffic, and in the indoor environment from sources like fireplaces and unventilated heaters, or any other combustion process. NO<sub>2</sub> exists mainly in its gaseous form and has a pungent odour that can be detected from concentrations of 188 30  $\mu\text{g}/\text{m}^3$ , while in dense urban areas it can exceed 500  $\mu\text{g}/\text{m}^3$ . (Jarvis, et al., 2010). The concentration outdoors and indoors in offices and residential have been measured in several studies, for example in a study where the average NO<sub>2</sub> concentration in office buildings in Helsinki, Basel and Prague were measured to be 27, 36 and 30  $\mu\text{g}/\text{m}^3$  (Kousa, et al., 2001). NO<sub>x</sub> can cause severe airway symptoms (Bluyssen, 2009). NO<sub>2</sub> has been shown by several studies to cause severe changes in lung function e.g. airway responsiveness to allergens in allergic asthmatics (Peden, 2015). In a meta-analysis by Mustafic et.al it was shown that NO<sub>2</sub> was significantly associated with myocardial infarction (along with SO<sub>2</sub>, O<sub>2</sub> and PM<sub>10</sub> and PM<sub>2,5</sub>). Another way that NO<sub>2</sub> can cause severe health impacts is by being a component in the creation of ozone (WHO, 2010).

Sulfur dioxide is a colourless gas and is mainly produced by burning fossil fuels in industries. SO<sub>2</sub> can damage the human respiratory system and cause breathing problems, even from short term exposures. The sources that create SO<sub>2</sub> typically also lead to the creation of other sulfur oxides, SO<sub>x</sub> that may form small particles after reacting with other compounds in the air. (United States Environmental Protection Agency, 2016). The health problems that are associated with small particles have been described previously.

## 2.3 QUANTITATIVE PRODUCTIVITY ASSESSMENTS AND SUBJECTIVE EVALUATIONS

*This part of the literature review will review articles that have investigated whether either thermal climate or air quality is associated with quantitatively measured productivity and with the subjective perceptions of the occupants. The hypothesis is that higher productivity should occur simultaneously as higher environmental satisfaction, lower intensity/ prevalence of acute health symptoms or higher perceived productivity. This will be referred to as consistencies between quantitative assessments of productivity and subjective evaluations.*

*There are several of the reviewed studies that have included physiological measurements as well. The results from these measurements will only be covered briefly, although they are regarded as additional indicators of how the indoor environment may influence the occupants and their health, wellbeing and productivity.*

*The chapter is divided into two sections based on the two broad main categories defined by de Dear et.al (2013): field studies in real buildings and climate chamber studies. Both sections contain a variety of different ways of measuring productivity and evaluating the feelings of the subjects.*

### 2.3.1 Field studies

In a field experiment, Wargocki et.al (2004) have investigated the impact of two different ventilation rates and two filter conditions on the performance of call centre operators in their daily work. The ventilation rates were 2,5l/s-person and 25 l/s-person, and the filters were either new or six months old, resulting in 4 conditions that lasted 2 weeks each. The subjective perception of the indoor environment, perceived air quality and the prevalence acute health symptoms was collected by surveys every week, and the work productivity was evaluated based on call time. The results show that the high ventilation rate was associated with improved productivity only if the filter was new, and negative association was observed if an old filter was in place when the ventilation was increased. The results of the subjective assessments showed that new filters were associated with the perception of the air to be significantly more acceptable and fresher, and the subjects experienced less dry skin and less tired and they perceived the office to be more clean and bright. Increasing the ventilation rate with a new filter in place was associated with significantly decreased nose and eye irritation, improved the perception of brightness and cleanliness, and improved the general well-being. Higher ventilation rate was almost significantly correlated to improved performance ( $P < 0,055$ ). These findings support the hypothesis that quantitatively measured productivity correspond with subjective perceptions of the indoor environment and of acute health symptoms.

In another study of call- centre operators, Tham (2004) has investigated the impact on call time by altering the ventilation rate between 5l/s-person and 10l/s-person and the temperature between 22,5 and 24,5 °C. The four conditions were tested for a total time of nine weeks, by analysing talk time, hold time and evaluate the operators' responses to a questionnaire about the indoor environment, acute health symptoms and perceived productivity. The subjective results differed significantly between the conditions in several aspects. The higher temperature was significantly correlated with higher perceived warmth, headache, difficulty to concentrate, coldness of hands and feet, and a 9% lower

perceived productivity. It not stated in the report by what questions perceived productivity was evaluated. Higher ventilation rate was significantly associated with lower perceived air stuffiness. However, there were significant interaction effects between the temperature and ventilation, and a decrease in ventilation rate at the lower temperature resulted in an almost significant increase of headache. The filters in the ventilation systems were exchanged three months prior the experiment. Higher temperature and humidity was associated with a higher perceived air stuffiness and decreased air quality. To analyse the subjective responses further the symptoms were grouped together in four different clusters. The first cluster, neurobehavioral symptoms (such as headache and difficulty to concentrate) and the fourth cluster (dryness and nose related symptoms) were significantly associated with talk time. The results show quite good consistency between the productivity and the subjective perceptions of the indoor environment and acute health symptoms.

Tham et.al (2003) have conducted a very similar experiment as Tham (2004) and found that average talk time was significantly associated with lower temperatures and higher ventilation rate. Lower temperatures and higher ventilation rate was also associated with significant improvements of several acute health symptoms. The magnitude of the improvements were smaller than what was observed in the more recent study by Tham (2004); reducing the temperature from 24,5 to 22,5 °C was associated with an improved performance of 4,9% (compared to 15,5% improvement from the same temperature change in Tham (2004)) and by increasing the ventilation rate from 10 to 23 l/s-person the improvement was 8,8% (compared to the improvement of 11% by changing from 5 to 10 l/s-person in Tham (2004)). Interestingly, the thermal comfort was lower at the lower temperature despite the higher productivity. The higher ventilation rate was also associated with significantly lower headache intensity and significantly decreased difficulty in concentrating by 13%, and the lower temperature caused a significantly higher thermal comfort. The study is partly inconsistent with the hypothesis that subjective perceptions of the indoor environment should correspond with quantitatively measured productivity (as higher productivity occurred simultaneously as lower thermal comfort), but it also showed evidence that supported the hypothesis (higher productivity occurred simultaneously as less intense health symptoms appeared).

Toftum et.al (2005) have investigated the impact of temperature interventions in an office building on the productivity of the building users. The evaluation was based on the Remote Performance Measurement Tool (RPM- tool) which is designed to simplify productivity measurements in real office buildings. The tool is internet based and consists of several performance tests along with two questionnaires to be able to evaluate both the quantitatively measured productivity and the subjective perception of the indoor environment. The performance tests comprise three simulate office work tasks; text typing, proof reading and mathematical calculations that are all evaluated based on speed and accuracy. Similar performance tests have previously been used in laboratory experiments, but the authors state that they could be used in real offices as well. The tests are preferably taken in the afternoon, when the subjects have been exposed to the indoor environment for several hours which is believed to make them less alert and more sensitive to the environmental conditions. The questionnaires include questions about the thermal sensation, acute health- symptoms and perceived productivity. The whole RPM test takes between 20 and 30 minutes to complete. The tool was used in an office building complex that housed a Danish bank. Two different temperature conditions were created by adjusting the temperature setpoints in two buildings. Approximately 200 subjects were participating in the study, and they were instructed not to open the windows during the two-day intervention tests. The temperature conditions that were achieved were approximately 21 °C in the cool condition and 25 °C in the warm one, while the other environmental conditions were attempted to be kept constant. It was found that the performance in the addition task was significantly higher in the cooler condition, approximately 10%, but no other significant associations were observed between

the other performance tests and the temperature. Significant associations were observed between the temperature and the thermal sensation of the subjects, but no significant association between temperature and acute health symptoms or perceived productivity was seen. These findings show that the indoor temperature may influence productivity of office workers in some aspects, and that the thermal perception is consistent with the environmental condition. However, perceived productivity was unchanged between the condition despite the improved performance in the addition test. A cooler air temperature was associated with both higher productivity and higher thermal comfort, which support the hypothesis that subjective perceptions are consistent with quantitative productivity impacts.

In a field experiment, Murakami et.al (2006) have investigated the difference between quantitatively measured productivity and perceived productivity by changing the ventilation rate and the temperature in a classroom. The adult subjects were first watching a recorded lecture, and subsequently asked to answer questions regarding the lecture. The answers were evaluated based on the scores on theoretical and memorization tasks. The subjective evaluation of productivity was assessed based on questions regarding how the subject estimated that the environmental conditions affected their understanding of the lecture and estimation of how much time that was lost during the test due to the environmental conditions. The quantitative improvements from the better air quality and better thermal conditions were between 5,4% and 8,7% in the different types of tasks, while the subjective estimations of improvement were between 4,6% and 6,6% in estimated rate of improvement, and between 2,2% and 4% in estimated time loss. This shows a generally good consistency between the perceived productivity and the quantitatively measured one, which support the hypothesis that productivity can be evaluated subjectively.

In a subsequent experiment by Ito et.al (2006), similar conditions as described in Murakami et.al (2006) were tested in a climate chamber, with similar lectures, tests and questionnaire. The results from this study were more scattered as some of the subjective evaluations tended to over-estimate the performance, while other under-estimated it. The difference between the quantitative and the subjective results differed more in this study, but an improvement of perceived productivity corresponded to an improved test scores in all instances. Both studies showed significant associations between the scores and the two environmental conditions in most tests. These are interesting findings, as they indicate that perceived productivity can be used as an indicator of real productivity, although the magnitude of the environmental impact remains uncertain.

A similar experiment was conducted by de Visme (2006), who is reviewed by Humphreys & Nicol (2007). In that study, 109 students completed a 3-hour examination in mathematics and were then asked to rate their own performance. The correlation coefficient between their actual performance and their estimated one was 0,77 which indicates that subjective evaluations of performance are quite accurate in predicting actual performance which support the hypothesis.

The effect of ventilation rates and CO<sub>2</sub> concentrations on cognitive performance of primary school children has been investigated by Coley et.al (2007). By either having the windows closed or opened they generated two air quality conditions in a classroom with children between the ages 10 and 11. 18 children participated in the study, and their cognitive abilities were tested by a 10 minutes test after a few hours in the classroom under one of the conditions. The conditions resulted in CO<sub>2</sub>- concentrations of approximately 690 and 2909 ppm respectively. The results of the cognitive tests were evaluated based on speed and accuracy of response of several tasks and of one memory task. Subjective evaluations were also conducted by self-assessments of calmness, alertness and mood. The results showed significant improvements in the total speed, which is considered an indicator of high focussed attention. No significant impacts were observed in terms of accuracy, but the calmness was

significantly improved. This study shows that even by easy means the ventilation rate can be increased, resulting in significant improvements in the cognitive tests which is considered an indicator of concentration. The ability to concentrate is believed to impact the children's ability to learn on long term, and thus the output of their studies. The increased ventilation was associated with both higher quantitatively measured productivity and improved mood, which indicates that there is a connection between the subjective feelings and productivity, which support the hypothesis that productivity can be evaluated subjectively.

Wargocki & Wyon (2013) have presented their findings from a series of studies about the performance of children and their classroom conditions. They altered the outdoor air supply between 3 and 10 l/s, person and the temperature between 20 and 25 °C. The productivity was quantitatively evaluated through language and numerical tests based on accuracy and speed. The results show that increasing the ventilation rate two folded was associated with increases test scores of 8%, but also that the subjective perception of the air was significantly improved according to the children as well as by a sensory panel of adults. Reducing the temperature from 25 °C to 20 °C was also associated with significant improvements in four out of eight performance tests, along with the perception of fresher and less warm air. These findings support the hypothesis that there is a connection between subjective perceptions of the indoor environment and how productive a subject are. Another interesting finding was that the windows were only opened to decrease the classroom temperature when climate was perceived too warm, and not to improve the air quality when the CO<sub>2</sub>- concentrations were high. This indicates that the subjective evaluations of the indoor air quality may not provide the complete picture of the indoor environmental conditions, and that air quality is difficult to assess by subjects already present in the room when the air quality is changed. The study also showed that although the electrostatic air cleaners operated as intended, the reduction of particulate pollutants did not influence the productivity. It is speculated that gaseous pollutants have more negative short-term impacts on health and productivity than particulate pollutants.

A series of studies regarding productivity in schools have been conducted by Bakó-Biró, Clements-Croomea, Kochhara, Awbia and Williams, and their latest development of the study is presented in Bakó-Biró et.al (2012). By installing mobile mechanical ventilation system in mostly naturally ventilated school classrooms the ventilation rate is increased from between 0,6 and 4 l/s-person to 5,1 to 9,6 l/s-person in 16 school classrooms in the UK. 330 children participated in the study. The association between increased ventilation rate and the cognitive performance and the subjective perception of the environment and intensity of acute health symptoms was evaluated. There were significant improvements in 4 out of the 9 performance tests in either reaction time or accuracy, and the improvements were between 2,2 and 15%. Relatively few significant improvements from the subjective evaluations could be observed. The study also shows that the CO<sub>2</sub>-concentrations in most of the schools prior the intervention was quite high; the mean values of one week were in most cases above 1000 ppm and values as high as 5000 ppm was not uncommon, and the ventilation relied to a great extent on the routines for window opening. The authors suggest that the CO<sub>2</sub>-concentration is monitored so that additional ventilation can be provided when the value exceed 1000 ppm. The study supports previous findings that indicate that the air quality has a significant impact on subject's ability to work. The absence of significant improvements in the subjective evaluations surprises the authors, and they believe it could be due to too short exposure times or due to the regular school breaks that children often spend in the fresh air outdoors. The findings do not support the hypothesis that there is a strong connection between productivity and the subjective perceptions of the indoor environment.

Another more recent study of productivity in schoolwork was conducted by Petersen et.al (2016). The experiment was similar to that of Wargocki & Wyon (2013). Four classrooms from two school buildings

were used to expose pupils of ages 10-12 years to different ventilation rates. The different ventilation rates were achieved by ventilation units installed in the classroom. All other conditions remained constant. The four performance tests were the same as used by Wargocki & Wyon (addition, number comparison, grammatical reasoning and reading and comprehension). Subjective evaluations were conducted through questionnaires every Friday, including questions about acute health symptoms, perception of the indoor environment, motivation and tiredness. The high and low ventilation conditions created CO<sub>2</sub>- concentrations of approximately 900 and 1500 ppm respectively. The tests were evaluated based on number of correct answers, and number of errors. The authors chose to subjectively remove a few extremely poor test scores because it was obvious that some of the subjects did not attempt to complete the tests. By analysing the total sample there were significant improvements in all four tests between 3,2 and 7,4%. The only significant differences from the subjective evaluation were that the pupils experienced more eye pain and more air movement in the high ventilation condition. The increased symptoms are speculated to be caused too high air velocities or by too high air exchange (but they may also have occurred caused by chance). These findings indicate that ventilation rate has significant impact on the short-term productivity of children, but that the subjective perceptions do not necessarily correspond to the quantitatively measurements of productivity. This contradict the hypothesis.

MacNaughton et.al (2016) have investigated whether the indoor environment is better in “green” buildings than in conventional ones. Participants were recruited from 10 high performance buildings, of which some were accredited a certification and other not. The certified and non-certified were matched to each other by age and size, and the occupants from each building were matched by similarity of work. The health of the occupants physiologically measured by a watch that measured activity, heart rate and sleep quality among other factors. The health of the subjects was also assessed though a questionnaire about the work environment, health and acute health symptoms. The performance of the subjects was evaluated by a cognitive performance test, and several physical variables were monitored at the workplaces (such as temperature, humidity, carbon dioxide, luminance and sound pressure levels). The results from the physical measurements showed that the certified buildings were significantly drier, brighter, but had slightly higher sound levels. The cognitive performance was significantly better in seven out of nine domains, and in average 26% better in the certified building. The certified building had also 6,4% higher sleep scores, which is believed to be a result of the improved lighting conditions. The subjective evaluation of the indoor environment and of the acute health symptoms were also perceived as better in the certified buildings. The lighting, temperature, air movement, air odours and air humidity was perceived better, and the number of reported acute health symptoms were 30% fewer. There was an inconsistency between the physical measurements and how the subjects perceived the indoor environment. For instance, the temperature, air movement and the odours were perceived to be better, while the corresponding physical parameters were not significantly different. However, there was a consistency between the quantitatively measured productivity and the perception of the indoor environment and the perception of acute health symptoms. This support the hypothesis that there is a connection between subjective evaluations and productivity.

Quantitative relationships between the indoor environment and productivity have also been found by Kroner et.al (1992) who is reviewed in Heerwagen (2000). By allowing workers in a new building to have greater control of the environmental parameters of their workplace they found that quantitatively measured productivity was increased by 16% compared to a conventional building without personal control. However, it was found that the increased control itself caused an increase of only 3%. The workers were working at an insurance company, and their work output that was measured was the number of forms that they filled in per week. The higher controllability was



associated with improved thermal comfort for women. So higher control was both associated with higher productivity and with higher thermal satisfaction, which may be considered as a support for the hypothesis. The findings also suggest that high individual environmental control can cause increased productivity.

Kekäläinen et al. (2010) have investigated the associations between high temperatures and perceived productivity, measured productivity, dissatisfaction with the indoor environment and acute health symptoms. The employees of a knowledge intense organisation in an office building in Helsinki, Finland is evaluated before and after a renovation that improved the indoor environment in several aspects. Some of the improvements that the renovation included was installation of chillers in the HVAC system and in the ceiling, adjustable thermostats to the radiators, better air distribution and increased ventilation flow of fresh air. The occupant's perception of the indoor environment was evaluated by two surveys including perceived productivity, acute health symptoms and satisfaction with the indoor environmental parameters. Perceived productivity was evaluated by asking the subjects to estimate how their work efficiency has been the previous week, in relation to their average work performance. A 5- point scale was used that ranged between "clearly below my average efficiency" and "clearly above my average efficiency". The perception of the indoor environment was improved in all aspects, and significantly ( $P < 0,05$ ) concerning the following ones: air stuffiness (from 46% of subjects feeling dissatisfied to 22%), unpleasant odours (21% to 6%), draught (17% to 4%), low temperatures (14% to 2%) and varying temperature (13% to 2%). Interestingly, the percentage of subjects feeling dissatisfied with high temperatures was only reduced from 29% to 24%, which was not a statistically significant difference, despite the installation of cooling devices. Almost all acute health symptoms decreased after the renovation, and the following ones significantly ( $P < 0,05$ ): fatigue (26% reported the symptom before, and 6% after), nose symptoms (21% before to 9% after), throat dryness (16% before to 6% after) and cough (8% before to 0% after). In one of the surveys, the perceived productivity was improved after the renovation, from 21% reported work below average before renovation to 16% after the renovation, although the statistical significance of this change is not stated. However, significantly fewer reported that they were disturbed by the indoor environmental conditions after the renovation. In the other survey, significant improvements of perceived productivity were associated with the renovation. From the survey, it was also found that dissatisfaction with air quality and temperature increased considerably when temperature exceeded 25 °C, and the number of subjects reporting that their work efficiency was below average increased from between 10% and 20% (for temperatures between 21 and 24 °C) to between 50% and 80% (for temperatures between 26 and 29 °C). The quantitative measurements of productivity were conducted in a relatively small scale, as quite few of the employees had a clear measurable work output that could be evaluated quantitatively. The productivity was evaluated on two small groups of employees (fewer than 10 persons in each group), one which worked with salary calculations and the other one working with vouchers. The output was measured as number of receipts/vouchers handled. The renovation was associated with an improved productivity of 4,4%. The authors discuss several weaknesses with the study, such as that several environmental parameters were changed simultaneously and that the subjects were not blinded to the intervention. The findings are nevertheless interesting, as they show a consistency between the subjective evaluations of the indoor environment (satisfaction, acute health symptoms and perceived productivity) and the quantitatively measured productivity. This support the hypothesis that there is a connection between subjective evaluations and productivity.

Lamb & Kwok (2016) have investigated the association between inadequate indoor environmental conditions and environmental satisfaction, perceived productivity and cognitive performance in a simulated test. The survey included 2261 survey answers and test participations over a period of 8 months, and the subjects had been present in the offices at the time of the survey/test for at least 6

to 7 hours. The survey covered questions regarding the satisfaction with the thermal climate, noise and lighting, as well as questions regarding motivation, mood, tiredness/alertness, distractions, feelings, environmental annoyance, headache and perceived productivity. Productivity was evaluated on a scale between “much less productive than average” and “much more productive than average”, which is similar to the one used by Kekäläinen et.al (2010). The cognitive performance test was a so called “stroop test” which meant that the subjects were to report the colour of a word and not the colour that the word describes, and it was evaluated based on speed and accuracy. A factor called “environmental stress” was used to calculate the dissatisfaction rate of the environmental conditions, and it was calculated as the number of environmental parameters that the subjects rated as the lower possible grade of satisfaction. It was found that the stress level was associated significantly with perceived productivity (the higher stress the lower productivity), and the stress level was also associated with the prevalence of headache, the mood and “feeling off”. The mood (between unhappy and happy) was associated with the feeling of environmental annoyance. The subjective evaluation of motivation, mood and distraction was significantly associated with the results from the cognitive performance tests. The results from the cognitive performance tests was also associated with the feeling of mood and “feeling off”. These are interesting findings, as it connects several subjective evaluations with the quantitative measurements of productivity, which support the hypothesis.

### 2.3.2 Climate chamber studies

Wargocki et.al (1999) have investigated whether the air quality may be associated with the productivity of office workers. Perceived air quality, health symptoms and performance of simulated office work were evaluated during two different air pollution conditions in a climate chamber. The two different conditions were created by having an old carpet present or absent in the room, which would correspond to a low pollution building (0,2 olf/m<sup>2</sup>) and a non-low pollution building (0,1 olf/m<sup>2</sup>). The simulated office work was evaluated based on accuracy and speed of text typing, addition, search and recognition tasks, grammar logical reasoning, running memory among other tasks. The performance of the simulated office work was significantly correlated with the pollution load, concerning the speed of the text typing task and for the addition task. The subjective perception of the environment and of the acute health symptoms was evaluated upon entering, during the exposure and upon re- entering the room after a while (with a “fresh” olfactory sense). The subjective perception was significantly correlated to the pollution conditions regarding the perception of headache, the acceptability of the air quality upon re-entering the room and the subjects rated their effort to be higher when the pollution source was present. So the high pollution condition was associated with both lower quantitatively measured productivity and with poor environmental perception, which support the hypothesis that there is a connection between productivity and subjective evaluations.

The experiment was replicated in Sweden by Lagercrantz et.al (2000), and their findings are reviewed in Wyon (2004). Their results showed significant correlation between pollution load and speed of text typing and accuracy in addition. It was also found that the pollution load was correlated with the subjective perception of dizziness, fatigue, difficulty in thinking clearly, odour intensity, reduced air quality and more acute health symptoms of the nose, eyes and throat. Clearly, Lagercrantz et.al (2000) observed more aspects that were correlated to the pollution load, but the agreement between the studies was considered relatively high. The findings support the hypothesis.

In a meta- analysis of by Wargocki et.al (2002), they combined the results of Wargocki et.al (1999) and Lagercrantz et.al (2000) to increase the statistical material and increase the sensitivity of the analysis. Statistically significant correlations were found between air pollution level and speed and accuracy of text typing, acceptability of air quality (both upon entering the room initially and upon re-entering), odour intensity (both during exposure and upon re-entering), headache, dizziness, dryness of nose,

perceived dryness of air, irritation of throat (both during exposure and upon re- entering) and irritation of nose and eyes upon re-entering. The findings support the hypothesis that there is a connection between productivity and subjective evaluations, although it must be maintained that the outcomes of most tasks were not significantly associated with the air quality.

Wargocki et.al (2000) have conducted a similar experiment as Wargocki et. al (1999). Subjects were exposed to different pollution loads while performing very similar simulated office work and made the same evaluations of how they perceived the indoor environment and their health symptoms. The main difference compared to the previous study was that the air quality was controlled by varying ventilation flow between 3 l/s-person, 10 l/s-person and 30 l/s-person, while the same carpet was present in all three conditions to create a moderate background level of pollution. It was found that the speed of text typing and creative thinking was significantly associated with the ventilation rate. The subjective perception of air freshness, air quality acceptability and odour were also significantly associated with the ventilation rate upon entering the room initially. The symptoms of mouth and throat dryness were also significantly associated with the ventilation rate, as well as difficulty in thinking clearly and general feeling of well-being. The perception of increased dryness is interpreted as irritation due to elevated pollution levels. The association between the ventilation rate and the performance tests did not reach statistical significance in most test aspects, but a regression line was created that indicate that a two-fold increase of ventilation flow would be associated with a 1,4% improved performance. These results support previous findings that indicate that the air quality is associated with a number of subjective perceptions, as well as with a few aspects of quantitatively measured productivity. This support the hypothesis that there is a connection between them.

By analysing the findings of three studies (Wargocki et.al, 1999; Wargocki et.al 2000; Lagercrantz et.al 2000) Wargocki et.al (2000) have shown that reducing the pollution load in the room (by removing pollution source or by increasing the ventilation rate) significantly improves perceived air quality ( $P < 0,0001$ ) and performance of text typing ( $P = 0,0002$ ) and almost significantly improved addition ( $P = 0,056$ ) and proof reading ( $P = 0,087$ ). They also established quantitative relationships between good air quality and text typing ( $R^2 = 0.82$ ,  $P = 0,005$ ), proof-reading ( $R^2 = 0.70$ ,  $P = 0.08$ ) and addition ( $R^2 = 0.52$ ,  $P = 0.07$ ).

Another similar laboratory experiment as described in Wargocki et.al (1999) was conducted by Bakó-Biró et.al (2004). One difference was that the air pollution was created by introducing a 3 months old PC for each subject present in the room. The ventilation rate was kept constant at 10l/s-person, and the two conditions (source present or absent) were evaluated by simulated office work as well as subjective evaluations of perceived air quality, acute health symptoms, evaluations of the indoor climate and self-estimated ability to work. These subjective evaluations were evaluated upon entering and on several occasions during the exposure. The subjects were significantly more dissatisfied with the air quality, perceived significantly higher odour intensity and perceived the air to be significantly less fresh when the pollution sources were present. The higher pollution load was also significantly associated with increased symptoms intensity throughout the exposure concerning skin dryness, sleepiness and ability to work. It is not stated precisely how the subjective perception of ability to work is evaluated, but the ability to work is certainly closely connected to perceived productivity. Significant differences were also observed regarding the speed and accuracy of text typing, while proofreading and arithmetical calculations were unchanged. So, the air quality was significantly associated with both subjective perceptions and with the results from a few productivity tests, which support the hypothesis that there is a connection between subjective evaluations and productivity.

Both in Wargocki et.al (1999) and Bakó-Biró et.al (2004) it was found that CO<sub>2</sub>- concentrations were lower in the conditions with elevated pollution level. By analysing data from previous experiments

Bakó-Biró et.al (2005) showed that air pollution concentration is significantly associated with the CO<sub>2</sub> production of occupants. It was also found that an increase in the dissatisfaction rate from 8 to 40% corresponds to a reduction of CO<sub>2</sub> production of 13%. This effect is believed to be caused by more shallow breathing in polluted air, or that people tend to work slower in polluted air. Both these studies also showed that poor air quality is associated with poor environmental perception and with poor productivity. The finding suggests that metabolism is an indicator of perceived air quality and indirectly of productivity.

Another similar experiment was conducted by Witterseh et.al (2004), where they investigated whether room temperatures are associated with the perception of air quality, intensity of acute health symptoms and perceived productivity. They also investigated whether the room temperature was associated with a few physiological symptoms and the performance of simulated office work. Perceived productivity was evaluated by asking at what extent the subjects were able to work, from 0 to 100%. The different temperature conditions were 22, 26 and 30 °C, corresponding to PPD:s of 5, 26 and 72%. The subjects were initially clothed to be thermally neutral at 22 °C and they were thereafter not allowed to adjust the clothing throughout the 3-hour experiment. The absolute humidity was constant, corresponding to RH of 45, 35 and 28% which is supposed to represent normal office conditions without humidification or dehumidification. The simulated office tasks were the same that was used by Wargocki et.al (2000). The only task that was significantly associated with the thermal conditions was the error rate of the addition task. The physiological evaluations showed that elevated temperatures were significantly associated with increased finger skin temperatures, sweating on forehead and average metabolic rate. The thermal conditions were associated with how the subjects perceived the overall indoor environment, thermal sensation, thermal acceptability, perceived air quality upon entering, air stuffiness upon re-entering, odour intensity (both upon entering and re-entering), irritation of mucous membranes of the eyes, throat and nose, ability to work (at the beginning and after 120 min), and the severity of several acute health symptoms. The consistency between the subjective evaluation and the productivity tests was weak, because only one aspect of one test was significantly influenced by the thermal condition.

Maddalena et.al (2004) have investigated the association between ventilation rate and cognitive ability, perceived air quality and reported acute health symptoms in a simulated office environment. They simulated both pollutions from occupants (such as CO<sub>2</sub> and bioeffluents) and pollutants from building products (such as VOC: s) and controlled several other environmental parameters such as temperature and relative humidity. The cognitive performance was evaluated by a validated measurement tool, and the subjects' perception of the indoor environment and their well-being were evaluated in a survey concerning their acceptability of air quality and odours and acute health symptoms like headache, irritated eyes, fatigue and nose congestion. While the results from the cognitive tests were significantly improved during the higher ventilation rates, the subjective evaluation did not indicate any significant differences except in one aspect for one of the environmental conditions. The authors believe that the lack of subjective indications of the improved air quality was due to olfactory adaption. The lack of acute health symptoms is also believed to be a result of too short exposure durations. It is also speculated that it could be due to too little pressure during the test sessions, as higher pressure is believed to contribute to the development of symptoms like headache and fatigue. The air quality was significantly associated with the performance in the cognitive tests, but hardly with the subjective evaluations. These findings do not support the hypothesis that there is a connection between subjective evaluations and productivity.

Fang. et.al (2004) have investigated if any association could be observed between the air temperatures, levels of humidity and ventilation rate in buildings with the perception of air quality, acute health symptoms and the performance of simulated office work. They found no significant association between the performance of the simulated office work and the physical properties of the air. However, they did find significant associations between the environmental conditions and the subjective perception of air freshness, air acceptability, headache, and difficulty in thinking clearly. The dryer and cooler air was also perceived as dryer. It was also found that the temperature and humidity had much stronger associations with how the perception of air quality and intensity of acute health symptoms, than the ventilation rate had. The ventilation rate in the current study was only significantly associated with the initial perception of air quality, upon entering the room, but after a while the association became weaker probably due to sensory adaptation. The authors believe that the lack of significant associations between simulated office work and the environmental conditions are due to too short test duration and that the subjects might be “too motivated”, which could make the subjects perform well even in adverse conditions for a limited time. The higher intensity of headache, difficulty to concentrate and the perception of stuffy air is believed by the authors to have the potential to cause decreased productivity on long term. The authors claim that productivity in real life is almost impossible to measure, and they regard health symptoms as useful indicators of productivity. The results do not support the hypothesis, because the environmental conditions were associated with the subjective perceptions, but not with the outcomes of the quantitative productivity measurements.

Wyon et.al (2003) have conducted two experiments in a large climate chamber to test the impact of relative humidity and temperature on eye symptoms and productivity in simulated office work. The study is reviewed in Wyon (2004). The first experiment showed that low levels of relative humidity was significantly associated with the subjective perception of increased eye dryness and eye irritation. Low levels of humidity were also significantly associated with the objective measurement of decreased tear film mucous quality and increased blink rate at the lowest level of RH. Lower RH was also significantly associated with reduced performance in several simulated office tasks. This shows a consistency between the perceived symptoms and the measured productivity, which support the hypothesis. In the second experiment the absolute humidity was constant at 2,4 g per kg of dry air, while the temperature was altered between 18, 22 and 26 °C in the climate chamber. Typical levels of air pollutions were created by a carpet and linoleum. Tear film mucous quality was significantly decreased above 22°C, which could be a result of the reduced RH that is associated with higher temperature. The performance of simulated office work was significantly lower at 18 °C, despite the higher RH which could indicate that temperature has more significant impact on productivity than relative humidity. The association between the conditions and the symptoms were small.

Tsutsumi et.al (2007) have investigated the influence of different humidity levels on how the subjects perceive their environmental satisfaction, symptoms, perceived productivity. They also investigated the association between humidity and the results from a simulated office work of 12 Japanese adults in a climate chamber. A part of the study included a 180 minutes test session in a climate chamber where addition and text typing tasks were performed under different humidity and temperature conditions. The humidity levels were 30, 40, 50 and 70% RH, and the temperature was adjusted to achieve an effective temperature of 25,2 °C in all conditions. The performance tests lasted for a total of 115 minutes and was assessed based on the number of correct additions and the speed of typing. It was found that the thermal conditions were not significantly associated with any differences in addition or text typing. The subjects were also asked to answer questions about their subjective perception of the indoor environment, but no significant differences were observed regarding perceived productivity, thermal sensation, sensation of humidity and symptoms associated with concentration and physical comfort. The only significant difference that was observed was that

symptoms related to drowsiness and dullness were higher at humidities above 50% RH. The results indicate that the humidity level does not have so great impact on the productivity (neither measures or perceived) or on the thermal satisfaction. Although few significant association were observed, the lack of association was quite consistent between the quantitative measurements of productivity and the subjective evaluations.

Tanabe & Nishihara (2004) have presented an interesting approach to the topic of how to measure productivity. They believe that an evaluation of the fatigue of the subject performing a performance test can indicate something about how the indoor environment influence the subject. They believe that a test subject with high motivation can maintain focus for a relatively short time despite inadequate indoor environment. If this is true, this would make it more difficult to observe the effect of inadequate indoor environment on the productivity of the users, especially in climate chamber experiments which typically have a relatively short duration. Maintaining a high productivity despite inadequate indoor environment is believed to be more exhausting. So, by measuring how exhausted the subjects are by the performance tests is thus believed to provide supplementary information about how the indoor environment influence the subjects. On long term it is believed that higher fatigue will cause losses of productivity. Their experiment was carried out by controlling the temperature and illuminance in a climate chamber, while the subjects were performing a number of different performance tests, such as text typing, calculations and memory and learning exercises. The subject's feelings of fatigue were evaluated through a survey where different aspects of fatigue were included. Those aspects were mental fatigue, general fatigue and physical fatigue. Physiological measurements were carried out, in an attempt to evaluate the fatigue in a more objective way. The measurements were voice analysis where chaotic fluctuations in the voice was measured as an indicator of fatigue, and near infrared spectroscopy of the head where changes in haemoglobin in the brain were measured as an indicator of mental effort. The results showed that the different environmental conditions had little impact on the performance tests, while elevated temperatures were significantly associated with increased levels of two types of haemoglobin in the brain ( $\Delta O_2Hb$  and  $\Delta total Hb$ ) in most performance tests. This would indicate that the mental effort and fatigue was higher. The subjective evaluations showed that fatigue was perceived to be higher at elevated temperatures, and that the fatigue had more characteristics of "mental fatigue" rather than "general fatigue". The experiment with different lighting conditions gave similar results. Important to note is that quite extreme conditions were used in the experiments, without being able to observe any significant differences in productivity. The low illuminance level was only 3 lux, and the highest temperature was as high as 33 °C. The study does not directly support the hypothesis that subjective evaluations and productivity is associated, because no significant differences of productivity was observed. However, the aspect of evaluating productivity through fatigue is an interesting approach that managed to show that the subjects were indeed more exhausted in the poor environmental condition.

Nishihara et.al (2013) have conducted a similar experiment regarding productivity and fatigue, but this time concerning the air quality. The study included performance tests, physiological measurements (voice analysis and near red spectroscopy) and the subjects were asked about their perceptions of the air quality, thermal sensation, lighting conditions, acoustical climate, cleanliness, acute health symptoms, fatigue, and mental work load. The air quality was controlled by having an old carpet present or absent, while the other environmental conditions remained constant. The results showed that the subjective perception of the environment was significantly associated with the presence of the pollution source, such as perceived air quality, thermal sensation and several acute health symptoms. The subjective perception of fatigue and mental work was not significantly associated with the presence. The results from the performance tests were significantly associated with the air quality concerning one aspect of text typing, but not concerning the rest of the tests. The physiological

measurements (voice analysis and near infrared spectroscopy) were likewise unaffected by the pollution source, although both of them indicated a significantly increasing fatigue and mental during the progression of the test. That indicates that these measurements are in fact valid measurements of effort and fatigue, but that the difference in air quality was not enough to evoke any significant difference concerning fatigue. These findings are partly inconsistent with the findings of Tanabe & Nishihara (2004), as the current one failed to show any associations between the environmental conditions and perceived mental effort or physiologically measured fatigue. The study does not support the hypothesis that there is an association between productivity and subjective evaluations.

Lan et.al (2009) have investigated whether they could observe any associations between the thermal climate and quantitatively measured performance and subjective perceptions of the indoor environment. By altering the temperature in a field laboratory between 17, 21 and 28 °C, they attempted to achieve conditions that would correspond to what most perceive as slightly cold, thermally neutral, and slightly warm. The performance of the subjects was assessed by 13 neurobehavioral tests in combination with subjective assessments of the environment, thermal comfort, self-rated effort, as well as the subject's feelings and mood. They did not find any significant difference in most performance aspects, except in two tests which indicated better performance at 17 °C than 21 °C, although most tests were performed best at 21 °C and least good at 28 °C. They classified the different tests into two categories, and found that verbal/symbolic tests were performed most accurately at lower temperatures and fastest at neutral, while slower at slightly cool. They also found that the other category (nonverbal/symbolic) was performed most accurately at neutral and less accurately at lower temperatures, while the speed was fastest at neutral and slowest at higher temperatures. They also classified the tests according to their difficulty, by the self-rated effort assessment, and found that more difficult tasks were stronger associated regarding their accuracy while the simpler ones had stronger association regarding their speed (when the temperature deviated from thermally neutral). The mood was significantly associated with the temperatures concerning the feeling of tension and anger and the total mood disturbance (significantly different between 28 °C and 21 °C). These results are interesting, as they show the complexity in measuring productivity by performance tests because the results of these tests may depend considerably upon the nature of the tasks and their difficulty levels. Another problem with performance tests that is mentioned in this study is the problem of motivation. They refer to their previous work, Lan et.al (2008), that showed that tests subjects can perform well even in adverse environmental conditions if they are highly motivated. The high motivation of the previous study is believed to be caused by the fact that the subjects were allowed to leave the room once the performance test was complete, and that uncomfortably high temperatures would increase the incentives of completing the tests fast. The study does not support the hypothesis that productivity is associated with subjective evaluations, because it failed to show many considerable productivity impacts.

Another similar study was conducted by Lan et.al (2010), where the impact of the same three temperature conditions (17, 21 and 28 °C) were evaluated based on similar evaluations. It was found that the total mood and the feelings of anger and the tension were significantly associated with high temperatures, and that the subjects perceived higher well-being at neutral and cool temperatures compared to the high one. The motivation of the subjects was significantly higher at the neutral condition (21°C) than at the hot one, and the workload was perceived as significantly higher at 17 and 28 °C. However regarding the performance of the neurobehavioral tests, no significant associations were observed between the performance and the perception of emotion, wellbeing, and motivation. The performance was significantly associated with the perception of effort, although the correlation was positive for some tests and negative for others, so it is difficult to conclude something from this. No significant association between the temperature and the performance could be observed. The

study does not support the hypothesis that productivity is associated with subjective evaluation of emotion, wellbeing and motivation.

Zhang et.al (2009) have investigated the impact of personal task- ambient conditioning systems on the productivity and the subjective perception of air quality and thermal comfort. The system works by allowing the building users to control a few important parameters of their local office environment (palm warmer, feet warmer and ventilation towards head). The impact on productivity and environmental perception was evaluated in a climate chamber where 18 subjects were exposed to a variety of different temperatures, either with the system present or absent. The perception of the air quality and thermal climate was evaluated by a survey, in which the subjects were asked to evaluate their thermal sensation, comfort and acceptability of thermal climate and air quality, among a few other parameters. The performance test comprised a sudoku test to assess logical thinking, math problems to assess mental performance and a typing exercise to assess dexterity. These three tests are designed to represent what the authors consider to be typical office work. The results showed that the presence of task- ambient conditioning system that could be controlled by the occupants improved the thermal comfort significantly for all temperatures, causing the thermal sensation to approach neutral. Even for temperatures as hot as 28 °C and as cold as 20 °C the system managed to create thermal neutrality. The perceived air quality was also significantly improved by the system, both through the heating and the ventilation functions. The scores of the performance tests were in general better in the sudoku and the math exercises, and significant differences between the conditions (system present or not present) was observed at 28 °C for the sudoku test and 18 °C for the math test. No significant association could be observed in the text typing task. This study shows the potential in allowing the building users to have more control of their personal office environment, both in achieving higher satisfaction and higher productivity. The fact that both were influenced positively by the increased ability to control the environment indicates that there is an association between them which support the hypothesis.

Zhang et.al have investigated the impact of CO<sub>2</sub>- concentration and bioeffluents on subjects, by either reducing the ventilation rate or by adding pure CO<sub>2</sub>. The subjective evaluations of the subjects and their cognitive performance is presented by Zhang et.al (2017a), and the findings from several physiological measurements are presented Zhang et.al (2017b). No significant difference could be observed regarding the perception of air quality, acute health symptoms or cognitive performance when pure CO<sub>2</sub> was added up to a concentration of 3000 ppm, compared to the reference condition of 550 ppm. However, when the same CO<sub>2</sub>- concentration was created by reduced ventilation rate, the results showed that the perception of air quality was significantly degraded. This condition was also associated with significantly higher symptoms of headache, fatigue, sleepiness and difficulty in thinking clearly. The latter condition was also associated with decreased performance in two of the cognitive performance tests. Regarding the physiological measurements it was found that end- tidal CO<sub>2</sub> and heart rate decreased more in both high CO<sub>2</sub> concentration condition, in comparison to the reference condition. In the condition with low ventilation rate there were significant increases in diastolic blood pressure and salivary alpha- amylase which is believed to indicate higher stress and arousal. One of the tests that were used was the Tsai- Partington test, which is a test believed to indicate stress and arousal levels. The results from that test also indicate that the high levels of bioeffluents are associated with increased arousal and stress. The response time in a "redirection test" was improved in the high bioeffluents condition, which is believed to be a result of increased arousal and stress. These findings indicate that bioeffluents are the main pollutant associated with low ventilation rates. The study found that low ventilation rates are associated with significantly lower performance in a few performance tests, and it was also associated with a number of acute health symptoms. This support the hypothesis that productivity is associated with subjective evaluations, although it must be maintained that one of



the performance tests actually received higher scores in the low ventilation condition. The physiological measurements are consistent with the productivity assessments.

Park & Yoon, (2010) have conducted laboratory experiments to evaluate the impact of different ventilation rates on simulated office work. The ventilation rates were 5, 10 and 20 l/s-person, and the performance tests were designed to resemble typical office work. The perception of the indoor air was evaluated as “acceptability” of the air quality. The results indicated significant differences in dissatisfaction of the indoor air between the different ventilation rates, and the dissatisfaction ratio was less than 17% at the ventilation rate of 20l/s-person, in comparison to approximately 25% for 5 and 10l/s-person. They also found significant improvements of between 2,5% to 5% in three out of the seven tests conducted. These findings correspond well with previous findings from similar laboratory experiments, but an imperative difference was that the authors in this experiment also found significant learning effects throughout the experiments. The learning effect was estimated to surpass the impact of the ventilation rate, and this is considered to be a major uncertainty in laboratory experiments. The authors also discuss the uncertainty in laboratory experiments due to their short duration in comparison to field experiments, and the uncertainty in the selection of tasks to represent typical office work. In the current study, the authors attempted to address the issue of short test duration that they find by conducting the study for 8 hours that corresponds to a typical work day. Despite the learning effects that were observed, the study shows a consistency between the productivity outcomes and subjective perception of air quality that support the hypothesis.

Clausen & Wyon, (2008), have investigated the impact of changing several indoor environmental parameters simultaneously on productivity, perceived productivity, acute health symptoms and perception of the environment. Perceived productivity was evaluated by asking the subjects to rate their performance on a scale from 0= zero performance and 100= full performance. The quantitatively measured performance was evaluated by simulated office work, but no significant difference was observed, although the test scores were on average 7% higher when all indoor environmental parameters were improved. The perceived productivity on the other hand was changed as much as 25% when all possible improvements were incorporated, and significant associations were observed with the thermal sensation, perceived air stuffiness, perceived sound level, mood and ability to concentrate. This shows the combined impact of a wide range of environmental improvements on both quantitatively and subjectively measured productivity. The considerable difference between perceived productivity and the measured productivity shows how difficult it is to measure productivity, and that the subjective evaluation don't necessarily correspond to the quantitatively measured one. The authors recognise the limitations of conducting a relatively short experiment to represent long-term impacts of the indoor environment. Although the difference between the perceived productivity and the measured productivity was quite large, they are indeed consistent in a sense that if the perceived productivity is high, the real productivity should be relatively high as well. This is interpreted as a support for the hypothesis that there is an association between subjective evaluations and real productivity

In a laboratory experiment, Tanabe et.al (2015) have created 5 different thermal conditions by combining different temperatures, clothing and cooling devices. The 11 subjects were performing three different simulated office work tasks and answered questions regarding their perception of the indoor environment. Each session lasted for a total time of 6 hours, and they were free to adjust their clothing and their personal cooling devices (during the conditions in which the devices were available). The performance tests consisted of three-digit multiplication, proof-reading and creative thinking. It was found that the satisfaction with the thermal environment was significantly correlated with the

performance in the multiplication task ( $R^2 = 0,403$ ) and for proof reading ( $R^2 = 0,464$ ) based on linear regression, however the performance was not significantly correlated with the different thermal conditions directly. Higher satisfaction was in turn associated with increased ability to control the thermal conditions. This shows the importance of personal control of the thermal environment to create a satisfying work environment which in turn is associated with higher performance. This study also found a direct association between productivity and a subjective evaluation (thermal comfort) which support the hypothesis that subjective evaluations of the indoor environment may be used as indicators of productivity.

## 2.4 OTHER INTERESTING QUANTITATIVE PRODUCTIVITY EVALUATIONS

*This chapter will review studies that have measured productivity quantitatively through different methodologies that are deemed interesting. Most of the following studies do not contain any subjective evaluations of the occupants, but they do nevertheless provide further insight into how productivity can be evaluated quantitatively.*

### 2.4.1 Educational achievements

*School buildings are unique in a sense that the occupants, the students, often have a grading system which is a quantifiable work output. Since the Educational Building is a university building for university students, it may be interesting to investigate if there are any associations between educational achievements and the quality of the indoor environment. Studies that have investigated the performance of students has been covered in previous sections as well, but neither of them has used educational achievements as the work output.*

Haverinen- Shaughnessy et.al (2011) have analysed the results of standardised tests of fifth graders to investigate if any correlation between test scores and ventilation rate in the children's classroom could be observed. The ventilation rate was estimated based on CO<sub>2</sub>- concentration measurements and assumptions of the children's activity level, masses and ages. The test scores of standardised tests and the CO<sub>2</sub>- concentration measurements in 100 schools were analysed. All the classrooms had mechanical ventilation and the windows and doors were instructed to be closed during occupational hours. It was found that 87 of them had lower ventilation rate than the 7,1 l/s-person (with mean and median ventilation values close to half of what is recommended). The results from the whole sample did not show significant correlation between ventilation rate and test scores, but by only analysing the 87 schools with substandard ventilation the authors were able to identify significant linear correlations between ventilation rate and test outcomes. According to the correlation, an increase of 1l/s-person (below 7,1l/s-person) is associated with 2,7% more student passing the math test and 2,9% more student passing the reading test. The data does not provide a valid estimation of how the test outcomes is influenced by ventilation rates above the recommendations, but the authors recognise that excessive ventilation may even have negative influences.

Another similar study was later conducted by Haverinen-Shaughnessy & Shaughnessy (2015), in which temperatures and ventilation rate were measured in 140 fifth grade classrooms housing 3109 students. The associations between the indoor environmental conditions and the education achievements were smaller in this study than the previous one; a higher ventilation rate of 1l/s-person was associated with an improvement of 0,5% of the mean math score, and a similarly large difference was observed by a 1 °C lower temperature (lower temperatures are considered positive in this instance).

Issa et.al (2011) have investigated if they could observe any association between test scores, absenteeism and subjective evaluations of the indoor environment in 33 schools in Toronto. Reading

and calculation test data and absenteeism data from students of the 3<sup>rd</sup> and 6<sup>th</sup> grades were evaluated. The environmental perception of the teachers was also evaluated. Among the schools, 3 were certified according to LEED NC, 10 were energy retrofitted and 20 were considered to be conventional. No significant differences were observed concerning the test scores between the three building categories, although the average score was highest in the green buildings in every test. However, there were a great number of differences concerning the subjective evaluations of the teachers, among them significant associations between building category and satisfaction with the overall physical conditions, classrooms, every indoor environmental quality parameter included (including thermal comfort). There were also many more significant differences observed between the categories. There were also significant association between the school category and the absenteeism among the teachers, but not among the students. So, concerning the teachers, the building category is associated with how the building and indoor environment is perceived and with the absenteeism. Assuming that absenteeism is a valid metric of productivity, these findings support the hypothesis that subjective evaluation and productivity is associated with each other. Concerning the students, the building category had no significant association with the test scores or with the absenteeism. It should be mentioned that the lack of significant results concerning the children does not necessarily mean that children are not influenced by the indoor environment, and it could instead be explained by the fact that certified buildings don't necessarily have better indoor environment than conventional ones. This matter will be discussed more in depth in section 3.5.2.

#### 2.4.2 Sickness absenteeism

*This section will deal with sickness absenteeism as a productivity metric. It will investigate whether the quality of the indoor environment may influence the number of absent days due to sickness. Sickness absenteeism is considered an indicator of productivity, because a higher absenteeism should correspond to lower work output. The symptoms that are associated with sickness absenteeism might also influence the productivity negatively. Fisk (2000) reviews several studies that have shown that cleanliness, maintenance, ventilation rate, temperature and humidity in a building are associated with the prevalence of communicable respiratory illnesses. He also present evidence that allergies and asthma is associated with the prevalence of dust mites, pets, fungi, insects, pollen, moisture, and insufficient cleaning. The quality of the indoor environment may also influence the sleep of the building occupants. Wargoocki & Wyon (2017) reviews a couple of studies that show that the ventilation in a bedroom may affect the quality of sleep, and MacNaughton et.al (2016) show some evidence that indicate that improved lighting conditions during the day is associated with better sleep. Based on these evidence, it is reasonable to assume that the prevalence of communicable respiratory illnesses, allergies, asthma and sleep problems may be influenced by the quality of the indoor environment. It has been shown by Smith (1990) that even subclinical respiratory illnesses can influence the performance of simulated work tests. This chapter will not go into the details about how these symptoms may influence the productivity, but it will review a few articles that have investigated if the quality of the indoor environment may influence the sickness absenteeism.*

The approach of analysing sickness absenteeism has been undertaken by Milton et.al (2000). They investigated if any association could be observed between the ventilation rate, the absenteeism data, and data of the number of occupant complaints in a large company in Massachusetts. The ventilation rate was altered between 24 l/s-person and 12l/s-person. The focus was on clerical office workers and their data was analysed by both total sickness absenteeism as well as short term sickness absenteeism (by removing subjects who were absent for more than 50% of the year as well as the ones that receive short-term disability payment). This was done to better represent typical workers that are relatively healthy and not suffering from long term health issues. The lower ventilation rate was associated with higher absenteeism, and it was estimated that 57% of the total sickness absenteeism, and 35 % of the

short-term sickness absenteeism was attributed to the lower ventilation rate. It was also found that the number of complaints were significantly associated with the short-term absenteeism. The number of complaints was not shown to be significantly correlated with ventilation rate. However, the presence of humidifiers was significantly and positively associated with both total and short-term sickness absenteeism, although the humidifiers were not shown to have elevated levels of fungi or endotoxins. So, the study has shown that the ventilation rate is associated with the sickness absenteeism and between sickness absenteeism and complaints. The numbers of complaints could be considered to be an indicator of how the occupants perceive the indoor environment. The fact that the buildings that have higher absenteeism (lower productivity) have more complaints (perceived worse) support the hypothesis that productivity and subjective evaluations are associated.

After the findings of Milton et.al (2000), Myatt et.al (2002) conducted a study to further explore the relationship between ventilation rate (CO<sub>2</sub> -concentration) and sickness absenteeism that was observed. Field experiments were conducted in the same office buildings, but this time the ventilation rate was controlled for by having different damper settings in the mechanical ventilation system for 3-month periods in two buildings. Tracer gas measurements were used to determine the air exchange rate, and CO<sub>2</sub>- concentration measurements were taken every 10 minutes, and the average CO<sub>2</sub> differential was calculated daily. Hourly attendance was collected from the corporate database, including sickness absenteeism data of 292 hourly workers for a total of approximately 50 000 scheduled workdays. The desired CO<sub>2</sub>- concentrations were 350 to 500 ppm above the background condition in the low ventilation condition, and 100-250 for the high ventilation condition. However, they had difficulties in controlling the dampers, and the CO<sub>2</sub> concentrations that were achieved were between 37 and 250 ppm above the background concentration which corresponds to very high ventilation rates. They did not observe any association between CO<sub>2</sub>- concentration and sickness absenteeism, possibly because they were unable to achieve a ventilation rates closer to that of a typical building.

Another attempt to explore the association between ventilation rate and absenteeism has been conducted Shendell et.al (2004). They analysed the absenteeism records of students in 409 traditional and 25 portable classrooms in Washington and Idaho, as well as conducted measurements of CO<sub>2</sub>-concentration in the classrooms. All of the classrooms had individual (not central) mechanical HVAC systems (except two that relied on natural ventilation only). It was found that 45% of the classrooms had CO<sub>2</sub> concentrations above 1000 ppm, and it was estimated based on this that more than 50% had ventilation rates below 7,5 l/s-person which is a commonly recommended value. They also found significant associations between ventilation rates and absenteeism records. The absenteeism was analysed as the average absenteeism for the whole year, but also for the part of the year before the measurements. The results showed that a 1000 ppm higher CO<sub>2</sub>- concentration was associated with a significant decrease of attendance of 0,5 % for the while year, and 0,9% for the pre-visit analysis. The mean absence values were 5%, which means that the lower attendance corresponds to approximately 10 and 20% higher absenteeism. The authors emphasise the uncertainty of these findings because the CO<sub>2</sub> -concentration measurement were conducted during very short periods. (approximately 5 minutes in each classroom at a single occasion, at different times of the day). The values that were obtained are therefore not regarded as valid representations of the air conditions in the classrooms on long term. However, due to the large sample size, these findings may nevertheless indicate that ventilation rate can have a considerable impact on the absenteeism of children which may in turn influence their productivity.

The uncertainty regarding the limited physical measurements in the previously mentioned study is recognised by Mendell et.al (2013). Another uncertainty that is mentioned concerning that study is

that absenteeism was not evaluated solemnly on sickness absenteeism, but on total absenteeism. Total absenteeism is also be influenced by other factors that may have little to do with sickness and the indoor environment. Therefore, a similar study was conducted, but their measurements were conducted during a two-year period in 162 classrooms that was housing children of the grades 3, 4 and 5. Among the buildings, 61 relied on natural ventilation and the remaining 101 used mechanical ventilation, and the ventilation rate was estimated based on the measurements of the CO<sub>2</sub>-concentration. It was found that for each increase of 1l/s-person the absence due to illness was significantly reduced by 1,6%. This change is smaller than what was previously shown by Shendell (2004), but it is statistically significant. By increasing the ventilation rate from the average value of California to the state standard would, according to these results, correspond to a decrease in absence due to illness by 3,4%. It is also stated that the mean daily absence due to sickness was between 2,25 and 2,54 % in the grades 3 to 5. A 3,4% decrease of such low values corresponds to a very small improvement of the total attendance, and thus very low productivity and health gains. However, it is calculated that such an improvement nevertheless is very economically beneficial.

Simons et.al (2010) have also investigated the relationship between sickness absenteeism of school children and the quality of the indoor environment. However, instead of taking measurements of the air quality or the thermal climate, they analysed the data from buildings inspections of 2751 schools by professional certified inspectors in upstate New York. The inspections concerned a variety of different building conditions that was evaluated based on their presence or their severity. The conditions included problems with mold, moisture, ventilation problems, vermin, and evaluation of the condition of HVAC and plumbing systems. All these conditions may significant influence on the indoor environment negatively. Approximately 62% of the buildings had problem with either mold, moisture or vermin, 83% had problems with either the structure or the air handling system and 45% had problems with either the HVAC system or the plumbing system. They found significant associations between absenteeism and a variety of conditions. The magnitude of impact of the association is presented as odd ratios. The conditions that were significantly associated were presence of cockroaches (5,19 odd ratio), overall humidity rating (3,07), mold in common areas (2,94), plumbing leaks in classrooms (2,29), plumbing leaks in other areas (2,08), condensation (2,35), air intake near garbage storage (2,90), fresh air intake blockage (2,23), damper malfunction (2,50), inadequate outside air flow (2,89) and presence of rodents (2,22). There were a few conditions that were not associated with absenteeism, for instance filter condition, but they were fewer than the ones that were significantly associated. These findings indicate that the condition of the building can have considerable influence on the health and productivity of children. It is also shown that the evaluation of certified building inspectors can predict the quality of the indoor environment by examining these aspects, without any objective physical measurements conducted.

The studies above have provided evidence that absenteeism indeed is influenced by the quality of the indoor environment. Ferrie et.al (2005) have shown that that self- reported sickness absenteeism corresponds relatively well with recorded data from employers. 67 % of the men and 63% of the women in the study reported that their total number of absenteeism days during a whole year was within two days from the real absenteeism. This means that a question in a questionnaire concerning the self-estimated absenteeism of the subjects could be helpful in the investigation of how the indoor environment in the *Educational Building* influence the productivity of the occupants.

#### 2.4.3 Meta- studies of quantitative productivity assessments

*There are a few interesting meta- studies where the data from several other studies are combined in a statistical analysis. This chapter will review a few meta studies that are considered relevant, to show*

*the combined impact of different indoor environmental parameters on the productivity of the building users and to provide further insight into how meta- studies could be used for future analyses.*

Seppänen et.al (2006) have conducted a meta- analysis to investigate the correlation between ventilation rate and quantitatively measured performance. The studies that were included were chosen based on their objectivity in assessing the performance of the subjects, and all of them have been reviewed in the previous chapters. The equation is created by weighting the studies by sample size and by the authors subjective assessment of how relevant they deem that the performance metric is for reflecting real work. The results indicate that performance is indeed improved by higher rates. The improvement is approximately 1 to 3% for each 10 l/s-person increased ventilation rate, and that the margin effect is higher at lower ventilation rates than at high ones.

The same authors have also conducted another similar meta- analysis regarding the association between productivity and room temperature. (Seppanen, et al., 2006). By only including studies that use quantitative metrics of productivity that is relevant for office work, they selected 24 studies from both laboratory and field studies. The studies were weighted by sample size and according to the authors subjective judgement of how relevant they perceived the performance metric to be as an indicator of real office work. It was found that increased temperatures up to 21 °C was associated with significant improvements of productivity, as significant decreases of productivity were found above 24 °C. For example, at the temperature of 25 °C, the productivity was approximately 2% lower than at thermally neutral, and the corresponding difference at 28 °C was approximately 6%. At the temperature of 20°C, the productivity was approximately 1% lower, and the corresponding number for 18 °C was approximately 3%. Most of the studies included in this meta- analysis have not been included in the current review, because many of them were either relatively old (written before 1990) or difficult to obtain.

By reviewing papers in journals about psychology and ergonomics about the impact of temperature on performance, Pilcher et.al (2002) have summarized the findings in a meta- analysis. 22 papers were included in the analysis, comprising a total number of 317 participants and 7044 data points. Air temperatures were classified in different groups, such as “hot 1” and “hot 2” that corresponded to specific intervals of temperatures. Only quantitative measurements of productivity were included, such as reaction time tasks and memory tasks. The impact of the thermal conditions on productivity was evaluated by comparing the scores on the tests in a neutral thermal condition with the scores of a hot or cold condition. The temperature category that was closest to be associated with optimal performance was between 21.11 and 26.62 °C. Temperatures between 26.62 and 32.17 °C were associated with 7.5% lower performance, and temperatures between 10 and 18.28 °C were associated with 7.81% lower performance. The study also analysed the association between experimental session length and performance outcome. It was found that shorter experimental sessions and task duration was associated with lower scores compared to longer sessions and task durations. However, it was also found that longer exposure to the temperature condition before the start of the test was associated with lower performance. They also found differences in outcomes between different types of performance tasks. This meta- study indicate that productivity is influenced by the thermal climate in the room. It also shows the importance of the design of the performance evaluations on the test outcomes.

#### **2.4.4 More quantitative productivity assessments**

*This chapter will review a few studies that have investigated whether the quality indoor environment is associated with productivity in offices. These studies do not include any subjective evaluations at all, but they are nevertheless interesting because they provide additional information about how*

*productivity can be evaluated and how great the impact of different adverse environmental conditions is.*

Myhrvold et.al (1996) have investigated the association between classroom ventilation and the performance in reaction time tests. 35 Norwegian classrooms were evaluated, and it was found that higher concentrations of CO<sub>2</sub> were associated with reduced performance of reaction time tests. The study is reviewed by Fisk et.al (2002).

Federspiel et.al (2004) have conducted a field experiment in call centres, where the ventilation rate was altered between 0,26 l/s-m<sup>2</sup> and 10 l/s-m<sup>2</sup> to see the impact on the operators talk time and wrap up time. They did not observe a clear dose- response relationship between ventilation rate and work performance (the performance was better at low ventilation rate than at intermediate ventilation, and the difference in performance at low and high ventilation rates were not significantly different). However, it was observed that room temperatures above 25,4 °C were significantly associated with lower performance.

Another field experiment in call centres has been conducted by Niemelä et.al (2002). The study intended to investigate the association between indoor temperature and labour productivity, evaluated by the number of calls divided by working time. One of their approaches was to observe the differences of productivity between different months of different indoor temperature in two different zones in an office. In one of the zones there was a difference in mean indoor temperature between the months; approximately 25 °C during the warmest month and 23,5 °C during the other months. There was a statistically significant difference in productivity of approximately 5% between the two conditions. In the other zone the temperature difference was smaller and no significant difference in productivity was observed. The second approach of the study was to alter the temperature in another call centre through mechanical cooling. Before the intervention, the mean indoor temperature was 25,1 °C and afterwards it was 22,6 °C. The intervention was significantly associated with a 7% higher productivity. The study also included a questionnaire where the call-centre operators answered questions regarding the indoor environment, but the questionnaire was answered before the intervention and not after so there are no conclusions to draw regarding how the change impacted the subjective perception of the indoor environment. These findings indicate that the thermal climate impact the productivity significantly, although nothing can be concluded regarding the consistency between the subjective and objective evaluations.

Tanabe et.al (2009) have conducted another call centre study on productivity. Instead of making any intervention of the indoor environment they conducted the performance measurement and physical measurement throughout a whole year, which allowed them to be able to observe differences of the thermal climate as a result of the change of seasons. The study was conducted in Japan and the productivity of the 70 to 120 female operators was evaluated based on their number of calls per hour. The building was equipped with a central HVAC system with setpoints of 23 and 25 °C for heating and cooling respectively. The indoor temperature varied depending on the outdoor temperature, and in the summer the indoor temperature was sometimes as high as 27 °C and in the winter how to approximately 23 °C. The data from the whole year was used to create a linear regression model, which had the correlation coefficient of -0,69. A 1 °C higher temperature was associated with a 1,9% lower performance (with 25 °C as reference point). The authors interpret the association between temperature and productivity as a causal relationship.

Satish et.al (2012) have investigated the association between CO<sub>2</sub>- concentration level and cognitive performance. They found that moderately high levels of pure CO<sub>2</sub> (1000 ppm) was significantly associated with lower performance in six out of nine decision making performance tests, compared to

the reference condition of 600 ppm. However, one of the tests did receive significantly higher scores in the high CO<sub>2</sub>-condition. That test was evaluating “focussed activity”, and the improvement is believed to be caused by “overconcentration”, at the expense of “the big picture”.

A similar study was conducted by Allen et.al (2016). They injected pure CO<sub>2</sub> into a test chamber and observed if any association could be observed between the CO<sub>2</sub>- concentration and the subjects’ cognitive abilities. Significant declines in the cognitive test scores were observed when CO<sub>2</sub> concentrations was increased from the reference condition of approximately 550 ppm to approximately 950 ppm, and even greater declines was observed when the levels were increased to 1400 ppm.

Allen et.al (2016) have investigated the association between air quality and cognitive performance. They found significant improvements on many aspects of decision making cognitive performance by changing TVOC concentrations between approximately 500 and 50 µg/m<sup>3</sup>. Those two levels would correspond to the ones in a certified building and in a conventional one. The difference in performance was as high as 61% between the two TVOC conditions when the ventilation rate was approximately 9,5 l/s-person (corresponding to a CO<sub>2</sub> concentration of approximately 750 ppm). The difference in performance between the two TVOC- conditions was a high as 101% when the ventilation rate was 19 l/s-person (corresponding to a CO<sub>2</sub> concentration of approximately 550 ppm). It was also found that an increase of ventilation rate from 9,5 to 19 l/s-person corresponded to an improvement of cognitive test score by 18%. These findings provide evidence of how the indoor air quality may influence the cognition of office workers, especially that low polluting materials may have a considerable impact.

## 2.5 SUBJECTIVE PRODUCTIVITY ASSESSMENTS

*Many researchers within the field consider it very difficult to measure productivity by quantitative means. In the recent sections, we have observed some of the issues that are associated with the methods. The following chapter will only address subjective evaluations of the indoor environment, with special emphasis on perceived productivity. Leaman & Bordass (1999) have stated several advantages and disadvantages with evaluating productivity subjectively. A summary of the advantages are:*

- *A single question can cover the whole topic, which enables it to be included in surveys about the indoor environment*
- *The responses can easily be compared with those of other buildings, for instance via databases which contain the data from a large number of buildings*
- *Large samples can easily be achieved*
- *Data analysis and verification is easily conducted for large samples*

*The disadvantages presented are:*

- *That the question remains whether perceived productivity is truly a valid indicator of real life productivity.*
- *The problem of formulating good questions to receive answers that can be used to conclude something about the real-life productivity*
- *Possible contextual circumstances that can influence the responses*

*The studies that are reviewed in the following section do all include perceived productivity in some sense. It should be stated that there are a great number of studies that have included perceived productivity in some way. This section has not attempt to review all of them, but focussed on those that*



*have investigated the association between perceived productivity and other subjective perceptions (for instance satisfaction, dissatisfaction, acute health symptoms and environmental control).*

Leaman (1995) has investigated the relationship between environmental dissatisfaction and perceived productivity. It was found that the more dissatisfied people are with the temperature, air quality, lighting and noise the more likely they are to report that their productivity is negatively influenced. The data that was analysed was adopted from the Building Use Studies Survey (BUS- survey) that included responses from more than 7500 subjects in 80 buildings regarding environmental comfort, health, satisfaction, productivity, and control. The individual questions regarding the environmental conditions had between 1500 and 6300 answers. It was found that environmental dissatisfaction was between 23 and 55%, based on answers from a 7-point scale from 1= very dissatisfied and 7= very satisfied. Perceived productivity was evaluated by a question about how much the office environment influence the productivity at work. The scale used was a nine-point scale between -40% to +40%. The mean productivity loss for each of the environmental parameters was between 7% and 12%, and the aspects with the greatest dissatisfaction were also the ones with the lowest perceived productivity. The correlation between dissatisfaction and perceived productivity was strong and significant ( $r^2 = 0.84$ ,  $p=0,0034$ ). Air quality and temperature received the lowest satisfaction and productivity in the buildings that were included. The subjects were also asked to rate their ability to control each parameter on a three-point scale, from low to high control, and it was found that the perception of control was significantly correlated with perceived productivity. For instance, the productivity of a subject who perceived that they had high control of the ventilation in the building was on average 5,63% higher than for the ones that perceived that they had low control. The corresponding number was 8,83% for heating and 9,35% for cooling. It was also found that environmental dissatisfaction was associated with what the authors call "forgiveness". Forgiveness is defined as the willingness of occupants to forgive the shortcomings of the building, and it is calculated by dividing the overall comfort with the mean value of satisfaction of the environmental parameters (temperature, air quality, noise and lighting). If the score is above 1, the occupants are considered willing to forgive the shortcomings. High forgiveness could be achieved if the occupants know that every effort is made to amend the problems. The data shows us that 26% of the buildings are "unforgiving" and that the buildings with the highest satisfaction are also the ones with that are ranked as "best" from a variety of aspects.

The conclusion that perceived control is correlated with perceived productivity is supported by Oseland and Bartlett (1999) who evaluated the subjective perception of 10 office buildings. Their findings are reviewed by Haynes (2008). By asking questions about how satisfied the subjects were with the indoor environment, considering the effect on their performance, and about how much control they perceived that they have. They found a strong correlation ( $0,93 < r < 0,99$ ) between environmental satisfaction and perceived productivity, as well as a correlation between perceived productivity and control ( $r=0,49$ ).

Leaman & Bordass (1999) have attempted to find out what parameters that most significantly impact the productivity of office workers. By analysed the results of 11 office buildings in the UK by the data from the BUS- survey, they identified four variables that they believe have the greatest impact on perceived productivity. The four variables are personal control, responsiveness, building depth and workgroups. The total perception of personal control is measured as an average of the perception of control of the individual parameters heating, cooling, lighting and noise. The perception of control is significantly associated with perceived productivity in 7 out of the 11 buildings. It was also shown that the association is weaker for buildings with higher satisfaction. The Spearman's rho for the 7 buildings varies between 0,16 and 0,49. These findings indicate that personal control is a crucial parameter in

the subjective perception of a building, especially for buildings that perform less good. The second variable is responsiveness, which is defined as how fast and how well the facility managers respond to responds to complaints or proposed changes of the facility. The subjects are asked to answer if they have made a request to the facility manager to change an indoor environmental parameter, and if they have they are subsequently asked to rate their satisfaction with the speed of response and the effectiveness of response. The results show that there was a significant association between satisfaction with responsiveness and perceived productivity in 8 out of 11 buildings, and that the association is weaker for buildings with higher satisfaction. This indicates that a good facility management system is a crucial parameter in the subjective perception of a building, especially for buildings that perform less good. It was also found that a good facility management system can compensate for lack of control, but also that a high level of control requires high levels of facility management. The two last variables do not concern thermal climate or air quality and will therefore not be reviewed.

By analysing data from a survey in 23 conventional and 22 “green” buildings in Australia Leaman et.al (2007) have investigated how well the green buildings perform regarding the indoor environment and if productivity is associated with environmental satisfaction. The thermal climate, air quality, lighting noise and perceived productivity was evaluated by the BUS- survey. Perceived productivity was found to be significantly associated with the thermal comfort ( $r=0.74$  and  $P>F<0,001$ ). It was also found that the performance in green buildings was inferior than that of conventional ones concerning thermal comfort in both summer and winter, while the air quality was approximately equally good. The “forgiveness” is calculated as previously described by Leaman (1995) and it was found that about one third of the buildings were not “forgiving”, which corresponds quite well with the previous findings. It was also found that forgiveness is correlated with perceived productivity ( $r=0.74$ ,  $P>F<0,001$ ).

A similar study was conducted by Leaman & Bordass (2007), who investigated 177 buildings in the UK with the BUS survey with the purpose to investigate whether “green” buildings are perceived as more comfortable and productive than conventional ones. They found a strong correlation between overall comfort and perceived productivity ( $r$ -values between 0,82 and 0,87 depending on ventilation type). Regarding the “forgiveness”, they found that naturally ventilated buildings typically had higher forgiveness scores, and that forgiveness was higher when likeable features are present, such as view out, more natural light and more environmental control. Building users are generally more tolerant of green buildings than conventional ones. Tolerance is also improved by increased understanding of how the system is supposed to work and by knowing that actions are taken to correct any faults that are reported.

Thomas (2010) has also used the BUS- survey to investigate the differences between a certified and a conventional building. The study intended to find out how the employees of a company perceived the indoor environment in a newly renovated office according to *Green Star*, in comparison with their previous non-certified accommodation. The BUS- database was used as benchmark to compare the results with both international and Australian buildings. The international benchmark database consisted of data from 65 buildings, however the authors mention that approximately 50% of the buildings in the database comprise newly renovated buildings with “green” intent. This could mean that the data is not representative of the whole building stock. The survey was conducted both before and after the relocation to the new office, and it was found that almost all main study parameters were improved. The only one of them that was not improved was the satisfaction with the overall acoustical quality, while significant improvements were observed concerning temperature (both in summer and winter), air quality (both in summer and winter), lighting, comfort, design, needs, image to visitors and perceived productivity. By summarizing the scores, the office scored significantly better than the

previous one, as well as better than most buildings in the BUS- database. The results from the productivity evaluation showed that the occupants perceived that the indoor environment to cause an improved productivity of 7,21%. The results support the previously observed correlation ( $r=0,80$ ) between overall comfort and perceived productivity. The study also observed significant improvements regarding perceived health, believed to be caused by the improved environmental conditions. The responsiveness of the building management system was deemed satisfactory, although the controllability of the indoor environmental parameters was considered poor. The low perception of control and the high levels of perceived productivity and satisfaction is consistent with the previous findings of Leaman & Bordass (1999) who found that the correlation between perceived productivity and control was weaker for buildings with higher satisfaction. The findings are also consistent with their findings regarding that responsiveness can compensate for lack of controllability.

Another comparison between certified buildings with non- certified was conducted by Thatcher & Milner (2014). They analysed the environmental satisfaction, prevalence of acute health symptoms, perceived productivity and other subjective factors before and after a relocation to a Green Star rated building. A group of employees that stayed in the old, non- certified building, was used a reference group. It was found that the satisfaction with the air quality was significantly higher in the certified building, while the satisfaction with the lighting was lower. It was also found that the perceived productivity was significantly higher, and the prevalence of acute health symptoms was lower in the certified building. The consistency between perceived productivity, prevalence of acute health symptoms and satisfaction with air quality indicate that low environmental satisfaction and health symptoms influence the productivity of building users.

The Office Productivity Network has developed a survey called OPN- survey, which is a tool to evaluate how well buildings support the productivity and activities of the building users (Oseland, 2004). The survey evaluates both the indoor environmental parameters, but also the facilities (such as office layout and available computer and IT systems) and their impact on productivity. The OPN survey is a POE tool that has been used in more than 60 buildings and with more than 6500 respondents at the time of the study (2004). The responses can be found on a database that can be used to benchmark a specific building to find out how it performs in relation to other buildings. The survey consists of 86 questions regarding the office environment along with some background information. Several questions concern how the users perceive that the office environment support their work activities. There are also questions regarding perceived productivity, in which the subjects are asked to rate how many percent that the indoor environment impact their productivity on a 9-point scale from -40% to +40%. This is the same scale as used in the BUS- survey. Each point in the scale represents a 10% difference, which is recognised by the authors to be quite large intervals. The subjects are also asked to rate how much they perceive that the facility influence their productivity. It was found that perceived productivity is highly correlated to overall satisfaction with the indoor environment ( $r= 0,91$ ) but it is also correlated with the satisfaction with the facilities ( $r=0,94$ ). Satisfaction is evaluated by the fraction of respondents that are not dissatisfied with the overall environment or the facilities. The subjects are asked to answer how they perceive a specific environmental or facility parameter on a 5-point scale (1= very dissatisfied, 2= satisfied, 3= indifferent, 4= satisfied, 5= very satisfied). The benchmarking data shows that temperature, air quality and air movement are among the parameters that most occupants are dissatisfied with. The dissatisfaction reaches as high as 55- 60% on those three parameters. Another method of evaluating how productivity is influenced by the indoor environment (and the facilities) is to evaluate the "downtime". Downtime is defined as time lost per week due to poor design and operation of the building. The downtime is evaluated by asking the subjects to estimate the time "wasted" due to 18 listed issues. Most of these issues are related to the facility, but a few of them are also concerning the indoor environment such as feeling to warm, feeling to cold and

distractions from glare. The upper and lower quartiles regarding the downtime of the environmental factors are approximately 11 and 4 minutes regarding “too cold” and 14 and 4 minutes for “too warm”. This means that the estimated time lost due to thermal discomfort is between 4 and 14 minutes per week. There is also a negative correlation between downtime and overall environmental satisfaction ( $r=0,78$ ). These findings support the previous findings that indicate that environmental satisfaction is correlated with perceived productivity, and a similar correlation between environmental satisfaction and downtime. Downtime appears to be a promising way of indicating productivity, especially concerning how productivity is influenced by facility issues, but also by poor environmental condition.

The Center for the Built Environment have developed another standard survey (the CBE IEQ- survey) that has been used to assess indoor environmental quality and productivity. The core survey includes questions regarding office features like office layout, furnishings, cleanliness and maintenance. It also includes questions regarding indoor environmental parameters such as thermal comfort, air quality, acoustical quality and lighting. There are also optional modules that assesses the presence of features like shading systems, operable windows and washrooms. The survey is web- based and the answers of all buildings is included in a database that can be used to systematically compare the performance of a particular building to that of others. The survey can also be used to compare several particular buildings to one another and to analyse patterns within a set of buildings. The questions are structured according to a branching system, which means that if the subjects are dissatisfied with a specific parameter, more detailed questions concerning that parameter is asked. (Zagreus, et al., 2004)

The CBE IEQ- survey has been used by Lee & Guerin (2009) to evaluate the indoor environment of 15 LEED certified buildings regarding how satisfied the building users are with their workplaces and how they perceive their work performance. The aim was to evaluate which environmental parameters and facility features that have the highest impact on overall workplace satisfaction and work performance. The environmental and facility parameters included were those of the core module: thermal climate, air quality, lighting acoustics, office layout, furnishings, maintenance and cleanliness. The data originates from the CBE IEQ survey database which at that time included 200 office buildings and responses from 3769 occupants. The questionnaire uses a scale that ranges from “very dissatisfied” (-3) to “very satisfied” (+3) to assess satisfaction with the individual facility features and IEQ parameters. Perceived productivity was evaluated by asking the subjects to assess how much the ability to get work done was influenced by the individual facility features and IEQ parameters, from “enhances” (+3) to “interferes” (-3). The number of questions for each of the four IEQ parameters were quite few. Air quality and thermal climate was only assessed by one overall question each, while lighting and acoustic quality was assessed by who questions each. The results from the 15 LEED certified buildings showed that the satisfaction with the individual parameters were similar to the performance impact of the same parameter. Overall workplace satisfaction was calculated as the average satisfaction level of the individual parameters, and overall productivity was calculated similarly. The overall satisfaction was found to be significantly associated only with office furnishings, but overall performance was significantly associated with both office furnishings and air quality. It is also found that furnishings and air quality was the parameters that had strongest association with overall satisfaction and perceived productivity, while other parameters like thermal comfort, lighting quality and acoustics had no significant association.

The CBE IEQ- survey has also been used to compare two conventional buildings with two buildings that are certified according to the Korean green building certification criteria (Sediso & Lee, 2016). A total of 222 occupants answered the core module of the survey, and the results were used to see which environmental parameters that most significantly influences the overall satisfaction and performance of the office workers. They also wanted to investigate whether the certified buildings are perceived to

have better indoor environment than conventional ones. The conventional buildings were matched with a certified one, according to similarity of size, age, climate and of work type. The building pairs were compared separately. Perceived productivity was significantly influenced by the satisfaction with lighting, thermal climate, indoor air and acoustics in one of the comparisons, but only significantly concerning thermal comfort and lighting satisfaction in the second pair. Perceived productivity was also significantly influenced by several building features. The environmental parameters that had the most considerable influence on overall satisfaction and overall productivity was thermal comfort, air quality and lighting. The result show that the same environmental parameters are significantly associated with overall satisfaction and overall productivity. This indicates that there is an association between environmental satisfaction and perceived productivity.

The CBE- IEQ survey has also been used by Zagreus et.al (2004). In that paper, three different ways of using the survey is deployed in three case studies, to show how the survey can be used in different ways. The first case was conducted to evaluate if there were any differences between a new and an old office, especially considering that the new one had a special type of ventilation system installed. The findings indicated that the new ventilation system worked better, because it received higher satisfaction scores concerning air quality and air movement. The second case study was conducted to evaluate how operable windows may influence the indoor environmental preferences of the building users. It was found that the increased possibility to control the windows was associated with higher perceived productivity, and that the users were more tolerant of environmental variations. The third case study was conducted to evaluate how a particular building performed in relation to the other building in the database. It was found that the building performed well below average in most individual environmental parameters such as thermal comfort, air quality and acoustics. Despite the low environmental satisfaction, the overall building satisfaction was significantly above average. This could be explained by the high satisfaction with the building management, and by the fact that the occupants found the building to be visually appealing. The findings of this paper support several previous findings. First, it indicates that higher controllability is associated with higher environmental tolerance and higher perceived productivity. The study also supports the previous findings that satisfaction with the building management is associated with higher "forgiveness" (that the overall satisfaction is better than the satisfaction with the individual components).

The CBE IEQ- survey database has also been used by Huizenga et.al (2006) to analyse the responses regarding air quality and the thermal climate, and to investigate if they are associated with perceived productivity. Air quality and thermal comfort was among the parameters that had the lowest scores of satisfactions in the survey; only 11% of the buildings had more than 80% of the occupants satisfied with the thermal climate, and the corresponding figure for air quality was 26%. The most common reasons to the dissatisfaction with the thermal condition was associated with lack of control (thermostats, operable widows and portable heaters and fans) and the most common reason to the dissatisfaction with air quality was stuffy/stale air and air cleanliness. Increased control was associated with increased satisfaction with both the thermal conditions and the air quality, although the statistical significance is not stated in the article. Very high correlations were observed between perceived productivity and satisfaction with the thermal environment and the air quality. The coefficient of determination between perceived productivity and thermal satisfaction was  $R^2 = 0,99$  and the correlation between perceived productivity and satisfaction with air quality is claimed to be similar. This study shows that few buildings achieve the satisfaction levels that is recommended in the standards, and it support the previous findings that have found associations between environmental satisfaction and perceived productivity, and between satisfaction and perception of control.

Humphreys & Nicol (2007) have analysed data from the SCATs project, where 26 office buildings in 6 European countries were evaluated through surveys about the indoor environment combined with physical measurements of thermal climate, CO<sub>2</sub>- concentrations, illuminance, noise and relative humidity. The aim was also to study the relationship between perceived productivity and the physical measurements, as well as investigate whether there are any association between perceived productivity and environmental satisfaction. Perceived productivity was evaluated by asking the subjects to assess how much the environmental conditions either helped or hindered their ability to work, on a scale from -2 to +2. The scale is similar to the one in the CBE IEQ- survey, although in this case the productivity was assessed in relation to the indoor environment as a whole, instead of assessing the impact of each and every environmental factor separately. The findings concerning the objective measurements showed that perceived productivity was significantly associated with the temperature and the illuminance, although the association with illuminance was not as consistent as concerning the other parameters. There were no significant associations between perceived productivity and any other of the environmental parameters. Interestingly, the association between perceived productivity was stronger with the temperature than with the PMV- value and the standard effective temperature (SEP). This is interesting, because the PMV model and SEP are designed to give a more realistic assessment of how the thermal environment influence a subject. The association between perceived productivity and the subjective perception of the indoor environmental parameters were stronger. All of the parameters that were assessed subjectively, except perception of humidity, was significantly associated with perceived productivity. Many of the environmental parameters were assessed on a 5-point scale where the middle value (3) was optimal, meaning that the subject desired no change of the parameter in question. Air quality was assessed on a 7- point scale ranging from "very bad" to "excellent". Among the environmental parameters that were significantly associated with perceived productivity, thermal climate, noise and air quality had the strongest associations. There was a generally good association between the environmental satisfaction and perceived productivity. 79% of the occupants answered that they were neither hindered or helped by the environmental conditions, but among the remaining 21% there were twice as many who answered that they were negatively influenced than who answered that they were positively influenced. It was also found that the overall comfort was significantly associated with perceived productivity ( $r^2 = 0,19$ ). The association was stronger than that of any of the individual environmental parameters association with perceived productivity. These results indicate that subjective evaluations of the indoor environment are more closely associated with perceived productivity than physical measurements of the indoor environment. The authors claim that the lack of association between the data from air quality, noise and relative humidity and perceived productivity does not necessarily indicate that there is no association between them, but rather that the levels of those parameters that were encountered was not enough to induce any greater variations of subjective evaluations.

By analysing the data from the SCATs project, McCarney & Humphreys (2002) have found that perceived productivity has greater association with the thermal sensation than with the actual indoor temperature. The analysis was aimed to explore the relationship between thermal comfort and perceived productivity. It was found that the highest average productivity was associated with the thermal preference of "neutral". Interestingly, the productivity was on the contrary not associated with indoor temperature.

The HOPE- project (health optimisation protocol for energy-efficient buildings) was an EU project aimed to improve the energy- and indoor environmental performance of office and apartment buildings. They wanted to develop a uniform approach to assess buildings with both quantitative and qualitative criteria. The criteria were developed based on available knowledge about indoor environment and energy systems, and the assessment included inspections of the building, interview

with the building manager, surveys of the building users and more detailed inspection in some of the buildings. One aim is to develop knowledge of how to solve the conflict between strategies to increase energy efficiency and strategies to create buildings that are healthy for the occupants. Another aim is to identify agreed parameters and strategies to describe health status of occupants, and energy efficiency of buildings. Approximately 75% of the buildings included in the study were designed to be energy-efficient. The project allowed non- participants to get access to recommendations about how to make their buildings healthier and more energy efficient as well as benchmarking their own building to those in the study (Bluyssen, 2002). The survey in the HOPE- project consisted of questions regarding health symptoms, environmental comfort and productivity. 5732 occupants in 69 office buildings and 59 apartment buildings responded to it (Bluyssen, et al., 2011).

Cox (2005) has analysed the data from the HOPE- project, regarding acute health symptoms, absenteeism, perceived productivity and physical measurements. Acute building related health symptoms are evaluated by their frequency of occurrence. It was found that higher frequencies were associated with higher absenteeism in offices. Perceived productivity was evaluated by asking the subjects to estimate how much the indoor environment affects their ability to work between -30% and + 30 %. It was found that overall comfort in the summer was positively associated with perceived productivity. A health hazard assessment was also made in the project, by conducting measurements and making observations in the building. Interestingly, the occurrence of substances that cause illness (such as ozone, nitrogen oxides, particulate matter, fungi, allergens, VOCs and CO) was not associated with the prevalence of acute health symptoms. The presence of highly hazardous substances, such as radon or asbestos, was also evaluated and was likewise not associated with the occurrence of health symptoms.

The association between overall comfort and perceived productivity that was observed in the HOPE- project is further explained in Roulet et.al (2006). It was found that the thermal comfort is associated with perceived productivity, but that the correlation is less apparent in the winter. The paper displays a graph where the correlation between thermal comfort and perceived productivity is marked, although the exact strength of the correlation is not presented. The graph shows a perceived productivity of approximately +3% at thermal neutrality (0), and at +1 (slightly warm) the productivity is approximately -2% and at +2 (warm) the productivity is approximately -6%. The paper also presents some other interesting correlations, for instance that the average number of building- related symptoms per occupant was significantly correlated with the perception of air quality, thermal comfort, acoustics and lighting in office buildings. A more precise definition of how the symptoms was evaluated is presented in the next section. The prevalence of allergies is also significantly correlated with perceived air quality.

By reanalysing the database from the office buildings in the HOPE- study, Boerstra et.al (2004) have investigated the correlation between perception of control and perceived productivity. The perception of control was analysed through the combined index of the perception of control of the individual environmental parameters. A significant and positive correlation was observed between amount of control and perceived productivity (Spearman's  $\rho = 0,183$ ;  $p = 0,001$ ). The correlation is of similar magnitude as that of Leaman & Bordass (1999). Each point on the 7- point scale (from *no control* to *full control*) was associated with an increase in perceived productivity by approximately 1%. As mentioned above, frequency of occurrence acute health symptoms was also evaluated by the HOPE- study. The frequency was evaluated by asking the subjects whether they have had any of the listed symptoms more than on two occasions during the last 12 months (dryness of eyes, itchy or watery eyes, blocked or stuffy nose, runny nose, dry throat, lethargy, tiredness, headaches, dry or irritated skin). The reanalysis of the data also showed a significant and negative correlation between the

frequency and the control index (Spearman's rho = -0,208; p= 0,001), indicating that increased control is associated with fewer health symptoms. Lastly, also the overall comfort (combined summer and winter comfort) was shown to be significantly and positively correlated with the perception of control (Spearman's rho =0,268; p= 0,001). As a complement to the reanalysis of the HOPE study regarding control, the current paper also conducted a field study. 236 occupants in 9 buildings were asked to rate their environmental control, perceived productivity, comfort and prevalence of acute health symptoms. The questions were formulated similarly as in the corresponding questions in the HOPE-project. The results were also similar to their previous reanalysis. The correlation between perceived control and perceived productivity was significant and positive (Spearman's rho of 0,200, p= 0,001), and the correlation between perceived control and overall comfort was also significant and positive (Spearman's rho of 0,222. p= 0,001). Perceived control was not significantly associated with the prevalence of acute health symptoms. This study supports the previous findings that have suggested that perceived control is associated with productivity, health and comfort.

Bluyssen et.al (2011) have also analysed the findings from the HOPE- project concerning environmental control and the facility management responsiveness (satisfaction with speed and efficiency of the responses). It was found that the overall perception of control was significantly associated with perceived comfort, and that the more satisfied the building users are with the responsiveness the more satisfied they are with the comfort.

Tanabe et.al (2015) conducted a field survey in an office building of 355 office workers. The indoor temperature was approximately 28 °C, causing 70% of the subjects feeling dissatisfied with the thermal climate. Perceived productivity was evaluated by a scale from 0 to 100, where 100 corresponded to the productivity that could be achieved in optimal environmental conditions. The average perceived productivity was approximately 65, and there was a strong correlation observed between the thermal satisfaction and perceived productivity ( $R^2 = 0,944$ ). The indoor temperature itself was not as strongly associated with perceived productivity as the thermal satisfaction was. This shows the importance of achieving a high thermal satisfaction to be able to achieve a productive workplace.

## 2.6 THE INDOOR ENVIRONMENT IN CERTIFIED BUILDINGS

*A green building is described by USGBC as one that has significantly reduced the negative impacts on the environment and the occupants, which is reviewed by Abbaszadeh et.al (2006). It is clear from this definition that "greenness" not only comprise environmental aspects, but also the health and comfort of the humans living in it. However, it has been stated that there is a conflict between strategies to reduce energy and strategies to create healthy buildings (Cox, 2005). It has also been stated that green buildings can be more difficult to manage and operate due to their more complex systems. They may also include features that are not thoroughly tested or understood and that they may put too much focus on token gestures instead of focussing on basic decent design, and this might increase the risk of not achieving the indoor environmental that was intended. (Leaman, et al., 2007). After reviewing a few certification systems, among them LEED and BREEAM, Tu & Kim (2011) have concluded that the certification systems should put more emphasis on the maintenance of ventilation and HVAC systems. According to Leaman & Bordass (2007), the performance of green buildings is more fragile and that makes it more vital that every component work well together. Malfunctioning building systems is a common problem in buildings, which may cause severe degradation of the indoor environment (Fanger, et al., 1988).*

*The previous chapters have already showed a few examples of when "green" buildings have been compared to "conventional" ones, such as Leaman et.al (2007), Leaman & Bordass (2007), Thomas (2010) and Sediso & Lee (2016). From these few studies, it has been observed that the indoor*



*environment in green buildings are not necessarily perceived as superior than conventional ones. This matter will be further investigated in the following chapter, although it was not possible to review all studies that have conducted such a comparison. A more thorough review is presented by Thatcher & Milner (2016), who also analyse research flaws that they have identified in the existing literature. This is an interesting topic in this context because The Educational Building is a certified building that will be elevated based on its indoor environment.*

By analysing data from 21 “green” buildings and 145 non- green buildings, Abbaszadeh et.al (2006) have investigated if the satisfaction with the thermal climate, air quality, lighting and acoustics are different between the groups. The green buildings are either LEED certified or identified as similarly designed and constructed. It was found that the occupants in the certified buildings are significantly more satisfied with the thermal climate and with the air quality, while no significant difference could be observed concerning lighting and acoustics, and these aspects actually received lower ratings in the green buildings. Since all 21 of the green buildings were relatively new, the authors also adjusted the analysis for building age. When only buildings that were newer than 15 years old were included in the comparison, the only significant difference was regarding the satisfaction with air quality.

Singh et.al (2010) have analysed the perception of the occupants before and after a relocation from a conventional building to a LEED certified one. The study relied on self-reporting concerning the perceived number hours absent from work due to asthma and allergy, hours absent from work due to depression or stress related conditions, and perceived productivity (enhanced or decreased due to the IEQ- conditions). It was found that all of the questions received significantly better scores in the certified building.

Newsham et.al (2013) have compared 12 LEED certified buildings with 12 conventional ones in Canada and USA by conducting physical measurements of the indoor environment and conducting a survey among the building users. It was found that relatively few of the physical parameters were superior in the certified buildings. Only air velocities and airborne particulates was better in the certified one, while there was no difference concerning thermal climate, CO<sub>2</sub> – concentration, lighting, or acoustics. However, the subjective evaluation showed that the certified buildings was perceived as significantly better regarding the overall environment, ventilation, temperature, noise from HVAC- systems and health symptoms.

Gou et.al (2012) have compared two buildings with LEED interior certification with satisfaction data from a number of non- certified buildings in Hong Kong. The certified offices were using low VOC materials and had were equipped with individual lighting control, a thermal environmental monitor and a CO<sub>2</sub> sensor that controlled the ventilation system. It was found that both the LEED certified offices had higher satisfaction concerning lighting than the conventional buildings, while the acoustical satisfaction was lower in the certified office. No other significant differences were observed.

Lee (2011) have compared the occupant’s satisfaction and perceived productivity between different LEED- certified buildings to investigate if higher rating is associated with higher satisfaction and productivity. Data from 15 buildings and more than 3000 respondents was analysed concerning their perception of thermal comfort, indoor air quality and general building quality. Some general associations could be observed between the four certification levels and how the users perceived the building. A higher rating was often associated with improvements of perceived productivity and higher satisfaction with the indoor air quality and the thermal climate, but the differences were only significant in about half of the comparisons where each certification levels was compared to all the other levels. In approximately one third of the comparisons, the higher rated building received lower satisfaction scores.

Tham et.al (2015) have investigated if the perception of the occupants is different between a certified and a non-certified building in Singapore. The building certification is the Singaporean Green Mark Scheme. 33 occupants from each building were surveyed about their perception of the indoor environment and about their acute health symptoms. They also made physical measurements of the following parameters: air velocity, relative humidity, sound pressure level, illuminance, air exchange and concentration of CO<sub>2</sub>, CO, formaldehyde, TVOC, ozone, PM10 and measured the presence of fungi and bacteria. The only considerable differences regarding the measurements were that the non-certified building had several times more air leakage, was one degree cooler (cooler is assumed to be positive in the context) and slightly lower illuminance. The perception of the indoor environment had more significant differences although. The air was perceived as cooler (assumed positive in this context) and the air was perceived as more satisfactory, less smelly, fresher and cleaner in the certified building. There were no significant differences between the prevalence of acute health symptoms.

Altomonte et.al (2017a) have analysed the data from 93 LEED buildings and 11 243 survey responses to investigate if the LEED rating and LEED scores earned is associated with the satisfaction level of the occupants. Different LEED versions and LEED products were analysed, and the combined results were indicating that the overall rating level of the building did not have a substantial influence on the satisfaction rate. There was even a tendency that the satisfaction was lower in buildings with many IEQ credits. It was investigated whether the number of credits earned in a specific category was associated with higher occupant satisfaction in the corresponding IEQ parameter, but there was little evidence that indicated so.

Altomonte et.al (2017b) have distributed questionnaire about the indoor environment and conducting physical measurements in four BREEAM certified buildings (rated *outstanding* and *excellent*) and in non- BREEAM certified buildings. It was found that the overall satisfaction with the building was approximately the same between the two groups, while the satisfaction of the individual IEQ-parameters were equal or slightly lower in the certified buildings. The satisfaction in the certified buildings was significantly lower regarding air quality, visual privacy and noise privacy. The data from the physical measurements was not significantly different except that the relative humidity was a few percent higher in the non- certified building.

Leder et.al (2015) have investigated whether green buildings achieve higher satisfaction with the indoor environment by analysing data from two field studies. It was found that the occupants in the green buildings perceived higher satisfaction regarding every environmental aspect: acoustics and privacy, lighting, ventilation, temperature, and overall environmental satisfaction.

Liang et.al (2014) have also investigate if certified buildings have better indoor environment than non-certified ones. By conducting questionnaire and in three certified and two non-certified buildings in Taiwan, they concluded that the environmental satisfaction was indeed higher in the certified one. The difference was significant concerning acoustics, thermal conditions, indoor air quality and for overall environmental satisfaction.

Hedge et.al (2014) have compared survey results regarding the indoor environment between two LEED certified buildings and one non-certified building on a university campus in Canada. They found that the certified buildings received higher rating in many aspects, but not in all, and that there were considerable differences between the two certified ones. The buildings were evaluated based on the occupant's environmental satisfaction and how they perceived that the building impact their health and productivity. The environmental aspects that were evaluated were the thermal parameters, air quality, noise and light. In comparison between the conventional building, the air temperature was in general perceived better in one of the certified buildings and worse in the other, the air quality was

better in the certified ones, air movement was better in one of the certified ones and similar in the other, noise was better in one of the certified ones and similar in the other, the daylight was better in both the certified ones and the office lighting received similar scores in all buildings.

These examples show us that a building certification not necessarily mean that the indoor environment is better than in a conventional one, and in some cases, it is rather the opposite. However, the papers reviewed are only a few examples of studies that have investigated the question. We have observed a variety of different methodologies to compare indoor environmental performance. A critical analysis of the methods is presented by Thatcher & Milner (2016).

The certified buildings in the studies above are mainly LEED- certified, which is quite different than the Miljöbyggnad system that the Educational Building is certified according to. There are indeed considerable differences between the systems, but the underlying purpose of promoting energy efficiency and good indoor environment remains similar. One of the substantial differences between Miljöbyggnad and LEED and BREEAM is that the two latter ones are considered more extensive and complex. There are also differences between which aspects are included and how they are weighted (Jakubova & Millander, 2012).

The fact that certified buildings don't necessarily have better indoor environment than conventional ones makes it interesting to evaluate how the certified university building *The Educational Building* is performing regarding its indoor environment. It would be interesting to investigate whether it performs as good as it is intended or if the indoor environment has been compromised by energy savings and complicated features. We have previously seen evidence that suggest that the quality of the indoor environment influence the productivity of the occupants. It would therefore be interesting to evaluate how productivity, satisfied and healthy the occupants in the *Educational Building* feel.

An issue that has been mentioned concerning evaluations of green buildings in comparison with conventional ones is that the "greenness" itself is believed to influence the occupants, for instance that a green building is perceived differently than an identical conventional one, possibly because some of the occupants are aware of the green intent and or if the building is certified. This should be regarded as a form of bias in this context, which could explain why some certified buildings receive lower environmental satisfaction ratings while still obtain higher overall satisfaction votes, for instance in Leaman & Bordass (1999). The possible bias issue has been investigated by Monfared & Sharples (2011) who found that occupants who sympathise with the green intent are more satisfied with the building, and that people who are less satisfied are more likely to believe that their comfort is sacrificed to achieve greenness. Among the occupants that were surveyed in the study, more believed that the greenness was associated with lower environmental comfort than those who though the opposite. Newsham et.al (2013) found that there were only a few physical parameters that were significantly better in the green buildings, while the subjective evaluations showed that the perception was better in more aspects. The issues concerning bias in certified building is certainly a matter of high relevance, especially when comparing the subjective perception (for instance perceived productivity) of occupants in green buildings in relation to conventional ones. The current study will not make such a comparison, but for future studies this is a matter that deserved more attention.

### 3 METHOD

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The purpose of the study is to evaluate how the indoor environment influence productivity in the *Educational Building*, a university building in Stockholm. The study has so far reviewed numerous papers that have included both quantitative measurements of productivity and subjective evaluations

of the indoor environment with the purpose of investigating if there is a consistency between the two. Although no clear consensus has been found, it seems like there is a tendency showing that a person who is negatively influenced by the indoor environment is also more likely to feel unwell and unproductive and perceive that the indoor environment is substandard. There is no doubt however that the relationship is very complex and not very well understood, but the method of using the subjective evaluations as indicators of productivity will be used nevertheless. The previously established method of conducting surveys to reflect the opinions of the subjects will be used, because that has the potential to reach out to a large group of subjects with standardised questions. Physical measurements will be conducted while the subjects are in the room, to find out how different physical conditions are perceived and to evaluate the specific conditions in the *Educational Building*.

### 3.1 CREATING THE SURVEY

*With the purpose of evaluating how the indoor environment influences the productivity of the building users, a survey with special emphasis on productivity will be designed. This is done by combining the relevant findings from the literature review above. The first sections will cover general design matters, for instance what response scales that should be used, how the questions should be structured and how the survey should be conducted. The subsequent sections will present all the included questions and why they were included. The discussion chapter will ultimately discuss a few questions that were not included in the current study, but that may be of interest for future ones. The complete survey is presented in Appendix A.*

#### 3.1.1 General survey design

*The layout of the survey is a fundamental part of achieving its purpose. The following sections is about how the survey design was created based on previous surveys and the findings from the literature review.*

The survey was designed to have three parts. The parts were answered at different times during the lecture, to be able to observe how the perception developed over time and to increase the sensitivity to air pollutants. The first part was answered in the beginning of the break, after approximately 45 minutes into the lecture. The second part was answered at the end of the break, approximately 60 minutes into the lecture. The third and final part was answered after 105 minutes, which in most instances corresponded to the end of the lecture.

The survey uses circles that are marked to indicate how the subject feel about a specific environmental parameter or symptom. Which scale is used depend on the type of question. For some parameters the level of satisfaction is highest when the level of the parameter is neither too high or too low. For instance, temperatures in a room should not be too high nor to low, and similarly the air should not be to dry nor to humid. Other parameters that are related to the indoor environment have their optimum level of satisfaction on one side of the scale, for instance it is always desired to have as little headache as possible, and the odour intensity in a room should preferably be as low as possible. A third type of question occurs for the parameters that has no obvious preference. These types of questions are common in the sections about acoustical and lighting comfort. For instance, the optimum level of echo/reverberation depends very much upon the type of room and upon context. In a crowded public space, the reverberation should be low to reduce the noise, but in an auditory it should be high to be able to hear the lecturer. The first type of scale (A scale) has a neutral and optimal value in the middle box, and different types of dissatisfaction at the two ends of the scale ends (for instance too hot and too cold). The second type of scale (B- scale) has a high value at the end of the scale, and a low at the other. For instance, 'low motivation' at the left end and 'high motivation' at the right. The third type of scale (C-scale) ranges between 'very dissatisfied' on the left end to 'very

satisfied' on the right, which is a similar scale as has been used in the BUS- survey and in the CBE IEQ- survey for instance. The type of scale used will influence the subsequent statistical analysis, for instance that the B and C scales may not receive responses that are normally distributed.

It was decided that paper-based surveys would be used in the study. Paper based surveys have been shown to have higher response rates than computer based surveys, which is deemed important. The response rate is typically 75-85% for paper-based ones, while it is only 25-55% for computer based (Oseland, 2004). It was found by Zagreus et.al (2004) that no significant association between response rate and responses regarding occupancy satisfaction exists (occupants with a particular opinion regarding their satisfaction with the indoor environment were not more likely to respond to the survey). This is supported by Peterson & Wilson (1992) who investigated the association between response rate and satisfaction rate by analysing the results of a number of studies within another research field. No significant correlation was found, which indicates that people who are particularly satisfied or dissatisfied are not more likely to respond to a satisfaction survey. It is nevertheless desirable to achieve a high response rate because that would increase the statistical power of the subsequent analysis. The disadvantage of paper-based surveys is the additional work of printing, handing out and collecting the papers, and to transfer the responses to a digital format that needs to be done manually. Within the relatively small scope of this study, it was deemed beneficial to use paper-based ones, but for future studies of larger populations it would certainly be useful to use a computer-based method.

The time that it takes to complete the survey is an important matter. On one hand, the survey needs to include as many questions as possible to be able to draw as many conclusions as possible. On the other hand, if it takes too long to complete there might be a risk that the subjects become frustrated which could impact their answers and the response rate. The negative aspects of too long surveys are recognised by Huizenga et.al (2003), who designed the CBE IEQ- survey's core module to take 5 to 12 minutes to complete. The time in the current study is limited by the break time that is 15 minutes, which is the maximum time that is available for the main parts of the survey. It would be desirable if the students also had time to take a break so that they are able to concentrate after the break as well. Sufficient time for a break is also desirable so be able to "reset" the students olfactory senses to become more sensible to the odours in the room. Considering all this, it is thus desirable that the first part of the survey takes no more than 8 minutes to complete, to allow the students a short break before they finish the second part (about air quality) upon re-entering the room (which should take no more than 1 minute to complete). The third and last part of the survey is to be answered at the end of the lecture, and therefore it needs to be very short (maximum 2 minutes) to maintain a high response rate, because the students might be short of time until their following lectures.

The current survey type is a so called "right- now evaluation", which in contrast to "long-term evaluation" means that the subjects are asked to answer the questions based on their perception *right now*. Long term evaluations are, on the contrary, including the perception during some time in the past (for instance the previous month). Right- now evaluations are often accompanying physical measurements, which is the case in this study as well (Peretti & Schiavon, 2011). The format enables a direct comparison between the physical measurements and the student's environmental perception. There exist studies that include both "right now" and "long term" questions, such as Toftum et.al (2005) and Kekäläinen et.al (2010). Thatcher & Milner (2016) are critically analysing the use of surveys that ask respondents to remember environmental conditions of the past. They state that such questions are open to memory bias and that they are regarded as weak forms of comparisons. To conduct long term evaluations with a "right now"- survey, one would have to conduct repeated survey sessions, preferably of the same study population.

An important question concerns how detailed the questions should be. Leaman et.al (2007) have found that more general questions about satisfaction of a specific environmental condition receive more positive answers than more specific ones. Leaman & Bordass (2007) have found that more detailed questions tend to show larger varieties between two conditions, for instance when comparing “green” and conventional buildings the differences are of greater magnitude with detailed questions than with more general ones. By using both detailed and specific questions Leaman et.al (2007) hopes to receive responses that reflect reality accurately. By including both general and detailed questions will also enable an analysis of the “forgiveness” of a building, which has been shown to be associated with perceived productivity (Leaman & Bordass 1999).

The scales and the formulation of the questions have been inspired by various different surveys, but the exact formulations have been rephrased to make them more comprehensible as possible. The risk of formulating the questions in a way that may cause the subjects to interpret it slightly different has been considered, but it was deemed to be more important to formulate them as comprehensive as possible given the context. Another reason why there was a need to rephrase many of the questions before adopting them from the literature was because of the fact that our survey is a “right now evaluation”, in contrast to most other surveys that are “long term evaluations”. (Peretti & Schiavon, 2011). There are surveys that are utilizing comparisons with other buildings as a way of evaluating a particular building, for instance Hedge et.al (2013). One such questions has been used in the current survey, but in general that way of evaluation is deemed as perilous because the individual reference condition may vary substantially between different subjects. Another risk with such questions that has been considered is that the subjects might consider past experiences in their evaluation, while we want them to evaluate their perceptions only now.

7- point scales have mainly been used in the survey, due to several reasons. One reason is that 7- point scaled are very commonly used by the surveys in the literature. It was also believed that 7- point scales provide sufficient amount of resolution, even for the questions where the middle value is the optimal one. The fact that 7 is an uneven number also provides the scale with a box in the middle of the scale, which is a useful feature. For one of the productivity questions a 9- point scale has been deployed instead, to allow high resolution and a wide range of options simultaneously. There is also one question with a 3-point scale for a question that require very low resolution. By using a similar scale for all questions is believed to make the survey easier to answer as well as faster to transfer the data into a digital format.

There are surveys in the literature that have been using branching questions. For instance, in the CBE IEQ survey the subjects were asked to answer more questions if dissatisfaction with a specific aspect is indicated. This method has not been used in the current study. Instead, all subjects are asked to answer all the questions, because it was deemed as interesting to evaluate the discrepancies between the more general questions and the more detailed ones. For instance, that can be used to evaluate the “forgiveness”. By asking every subject to answer every question also allows higher flexibility in the subsequent data analysis.

An important part of the design process of the survey was to let test subjects fill in the survey and give their feedback on the formulation of the questions. A “think aloud” method was used for this purpose, as has previously been used by Zagreus et.al (2004) in the creation process of the CBE IEQ- survey. In the method, the test subjects are asked to fill in the questionnaire and told to comment or ask anything that come across their mind when approaching the questions. The first version of the survey was tested on one participant only, while the second version was tested on 6 participants by using this method. The feedback from the subjects was used to improve the survey, for instance by rephrasing the questions or adjusting a scale to make the questions more understandable. The time to complete the



How do you **feel** at the moment?

Cold      Cool      Slightly Cool      Neutral      Slightly Warm      Warm      Hot

Would you prefer the room temperature to be?

Warmer      No change      Cooler

How satisfied you are with the **temperature** in the room at the moment?

Very Dissatisfied      Very Satisfied

How do you perceive the **air movement** at the moment?

Still      High draft

How do you perceive the level of **humidity** at the moment?

Too dry      Too humid

### 3.1.5 Acoustical comfort

The acoustical comfort is evaluated by an overall question first, and then by three more detailed question regarding the sound disturbance of more specific sources. The overall question appears in part 1 and part 3, while the more detailed one only appear in part 1. The questions are presented below.

How satisfied are you with the **level of sound/noise** at the moment?

Very Dissatisfied      Very Satisfied

How satisfied are you with the **following sound/noise** aspects at the moment?

	Very Dissatisfied					Very Satisfied
➤ Sound from Phones, Printers, Computers	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
➤ Sound from Building Systems	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
➤ Sound from Speech	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

### 3.1.6 Visual comfort

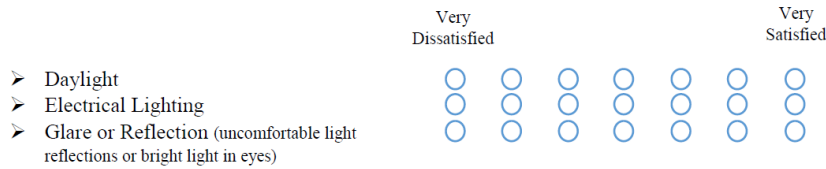
Visual comfort is evaluated through an overall question, as well as by a few more detailed ones concerning the satisfaction with a few light sources or light phenomena. The overall question appears in part 1 and 3, while the detailed ones only appear in part 1. The questions are presented below.



How satisfied you are with the **lighting conditions** (daylight and electrical lighting) at the moment?



How **satisfied** are you with the following?



### 3.1.7 Perception of health

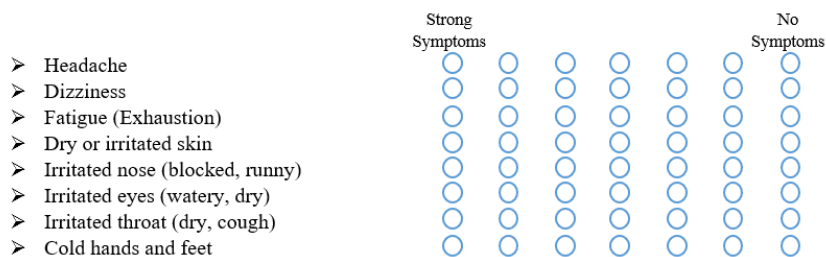
It has been found in several studies that the occurrence or severity of several different acute health symptoms is associated with quality of the indoor environment. Increased intensities or prevalence of acute health symptoms have also been shown to occur simultaneously as decreases of productivity.

The questions deal with how intense the subjects perceive a number of symptoms, such as headache, dizziness or symptoms of the nose, eyes and throat. There are other symptoms that have been included in various papers reviewed above, but these are some of the ones that are deemed to be have the closest association with productivity. Symptoms of poor concentration and low motivation have been included as well, but in another section. The section starts with the general question, which is about how the subjects feel in general. The specific symptoms are evaluated by intensity and not of prevalence, because this is a “right now” evaluation. The questions concerning acute health symptoms are only present in part 1.

How do you **feel** at the moment?



How **strong** do you feel the following **symptoms** at the moment?



### 3.1.8 Productivity

The perceived productivity is evaluated based on two main questions, and two questions that are closely associated to productivity. Productivity is considered to be a very complex concept, and therefore it may not be entirely covered by merely one question. With those four question, one may be able to analyse productivity from a broader and more diversified perspective.

The first of the two main productivity questions are about the subjects ability to work, which is a similar question to the ones that has been used by Witterseh et.al (2004). It is evaluated on a scale between 0 and 100%, where 100% is supposed to represent ideal environmental conditions. The second main question is about how much the productivity is increased or decreased by the environmental conditions (+20% to -20%). This kind of question has been used in the BUS- survey (Leaman 1995) but with a slightly different scale. The two questions may appear very similar, but an important difference

is that the distribution of the responses may be different. The second question is likely to be normally distributed, which may enable the use of other statistical methods in the data analysis.

An important question that should be regarded when designing questions for a survey about productivity is whether or not the indoor environment should be used as a reference condition of the evaluation. A fictive and simplified question will be used as an example. Either one can formulate the question “how productive are you”. Another alternative could be “how productive are you, considering the quality of the indoor environment”. The first question could provide useful information if the responses are correlated with the responses of other questions. For instance, if associations can be observed between thermal satisfaction and perceived productivity one may suspect that thermal satisfaction *causes* the higher perceived productivity. The other way of formulating the question is directly providing the casual relationship between how the indoor environment influence the perceived productivity. The problem is that the second question may be much more difficult to answer for the subjects, and a more difficult question should yield less reliable results. However, the responses of the first question may be more influenced by aspects that are quite unrelated to the building, for instance how well a subject slept the last night or if he or she is having a cold at the moment. It was decided that both ways would be used in different questions (question 15 and 16) because that would allow us to investigate if any difference occur as a result of this matter. The question about “ability to work” does not use the indoor environment as a reference, while the question about “perceived productivity” will do so.

The two other questions that are closely associated with productivity are concerning concentration and motivation. The perception of not being able to concentrate and the feeling of low motivation has often occurred simultaneously as poor performance or low perceived productivity. The questions about motivation and concentration does not explicitly state that the subjects are to evaluate the influence of the indoor environment on them. Because of this, the responses to these questions may of course be influenced by other factors, such as how interested the subject are about the topic of the lecture. Given that the statistical samples are large enough, such differences in the background conditions may be evened out. In a more advanced experiment it would be desired if background conditions were controlled better, like the lecture content and time of the day. This topic will be discussed in the *discussion chapter*.

To be able to investigate which parameters that the subjects *perceive* themselves that they are influenced the most by, another productivity question was included. That question lists a number of environmental issues, as well as a few issues related to the facility. The subjects are asked to evaluate how much their productivity is influenced by each of them. The facility issues are included only as a reference, to be able to compare the impact of the indoor environment with typical facility faults. The approach of asking the subjects directly about how they perceive that each parameter influence their productivity is quite different than having one overall productivity question, and correlating its responses to the responses of the environmental satisfaction questions. Both ways were included to investigate if they yield similar results.

There are other questions and other scales used in the literature, but these are some of the ones that are deemed to be most relevant. The questions regarding productivity are presented below. The questions concerning productivity are included in part 1 and part 3.

To what extent are you **able to concentrate** at the moment?



How **motivated** are you to **work hard** at the moment?



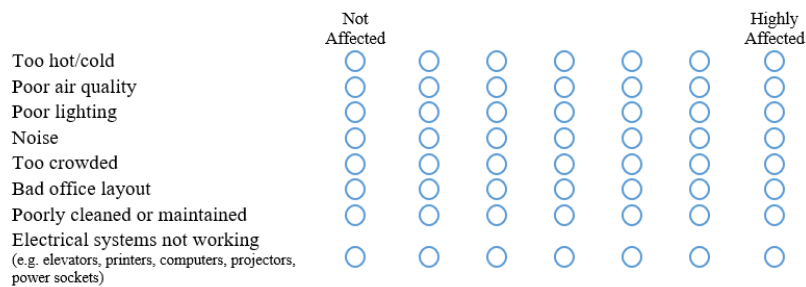
To what extent are you **able to work** in this room at the moment, considering the **environmental conditions**?



How much is your **productivity** increased or decreased by the **general environmental conditions** in the building? (0% represents a “normal” building).



How much is your **productivity affected** by the following conditions?



### 3.1.9 Perceived Air quality

The survey has also included several questions concerning the perceived air quality. The perception of poor air quality, for instance bad smell and stuffiness is associated with decreased productivity, both from quantitative and subjective evaluations.

The questions about air quality are included in part two only. This means that the subjects are free to exit the room before they answer the questions about air quality. This will increase their olfactory sensitivity which will allow them to better sense if the air quality is poor. This is a method that has been used by several previous studies in the literature review. However, the subjects of this study will not be forced to exit and re-enter the room, so it is not expected that everybody will do so, although it is desirable if as many as possible do so.

The first question about air quality is a general one. There are three more specific ones concerning smell, dryness and stuffiness. Air quality has been associated with productivity in the literature. All of the questions regarding air quality have individual scales to make the questions clearer. It was deemed that this was more feasible than using the ordinary satisfaction scales, because it is never desirable to have dry, stuffy or smelly air. The questions regarding the air quality is presented below and they are included in part 2 only.

How do you feel about the **air quality** at the moment?

Unacceptable        Acceptable

How much **smell** do you sense at the moment?

Too smelly        No smell

How **dry** is the air at the moment?

Very dry        Not dry

How **stuffy** (closed in/ unrefresh) is the air at the moment?

Stuffy        Fresh

### 3.1.10 Environmental control

The ability to control the indoor environment has been found to be associated with perceived and measured productivity. A few questions have therefore been added to be able to investigate whether the occupants in the building are feeling that they have control over the indoor environmental conditions or not. Similar questions and scales has been used by Boerstra et.al (2004). Examples of control possibilities within each parameter is given in the parenthesis, because the subjects of the test survey often found it unclear what the concept of *environmental control* included. The questions regarding perceived control are presented below and are only included in part 1.

How much **control** do you have over the following parameters at the moment?

	No Control	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Control
Temperature (Change setpoints, radiators)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Air quality (Window, Ventilation)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Noise (Noise barriers)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Lighting (Shading, adjust electrical light)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

## 3.2 PHYSICAL MEASUREMENTS

*This section will briefly present the measurement equipment that was used for the physical measurements of the indoor environment in the classrooms.*

The thermal parameters of the indoor environment were measured by a Comfort Sense equipment from Dante Dynamics that fulfils the standards of EN 13182, ISO 7726, ISO 7730, ASHRAE standard 55 and ASHRAE standard 113. It measures the dry bulb air temperature, air velocity, relative humidity, and radiant temperature. The sensors were placed in a relatively central location in the classrooms at the height of approximately 1,2 meters. The locations of the sensors were also adjusted based on the available space in each classroom. Locations were also chosen that would cause as little disturbance to the occupants. The inclination of the radiant temperature probe was approximately 30 degrees. The thermal properties were used to calculate the PMV and PPD- values of the indoor environment through the software *Comfort Sense*, by assuming an activity level of 1,2 met and a clothing level depending on the mean clothing values of each session, based on the responses from the survey. The sampling rate

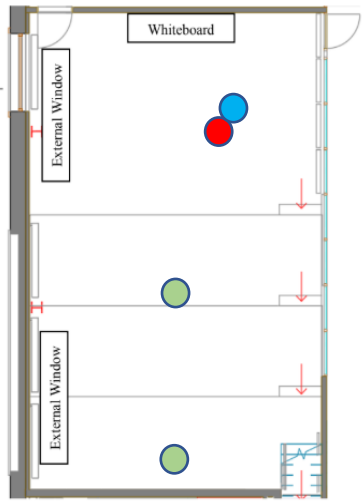
was 2,5 seconds and the resolution of more than 4 decimals for each parameter. The equipment was calibrated within a few months prior to the measurements. The air velocity probe has an accuracy of  $\pm 2\%$  or 0,02 m/s. The humidity probe has an accuracy of  $\pm 1,5\%$  RH (within the current temperature range), and the operative temperature probe has an accuracy of  $\pm 0,2\text{K}$  (within the current temperature range).

CO<sub>2</sub> – concentration was measured by Rotonix CP211 units. In one classroom there were two CO<sub>2</sub>-sensors used because the floor had different levels. One of the two sensors in that classroom was placed at a central location, while the other was placed approximately 1 metre from the back wall. The CO<sub>2</sub>-sensors in the other two classrooms were placed approximately 1 metre from the back wall to cause as little disturbance as possible. The CO<sub>2</sub>-concentration sensor was found to be sensitive to people being close to it (due to higher CO<sub>2</sub>-concentration in the breath) so it was prioritized that the sensors were placed on locations that were not within 1 metre from the nearest seat, which was also the reason why the locations in the back was selected. The sampling rate was 2 seconds and the precision 1ppm and the accuracy of 30 ppm ( $\pm 5\%$ ). The sensor was calibrated approximately 1 year before the measurements according to the ISO standard ISO9001-2998, so the validity is regarded as relatively high.

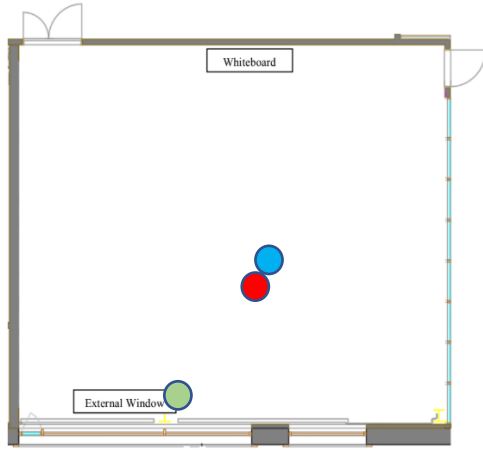
Sound pressure level was measured by a sensor of unknown name and manufacturer, but that applies to the standards IEC651 type 2 and ANSI S1.4 type2. The location of the sound pressure sensor was on top of the stand of the thermal sensors, in a relatively central location. The sampling rate was 1 second and the resolution 1 dBA, at the accuracy of  $\pm 1,5$  dB. The time weighting was set to 125 ms. No data concerning the most recent calibration could be obtained for the instrument, so the validity is not regarded as high.

The probes were placed on locations in the rooms that were as central as possible without obstructing the view of the students. It was believed that if the equipment caused too high disturbance the students would be less willing to participate in the survey, so the decision of where to place the probes was based on a trade-off between response rate and validity of the physical measurements. The locations of the measurement probes are presented in the pictures below.

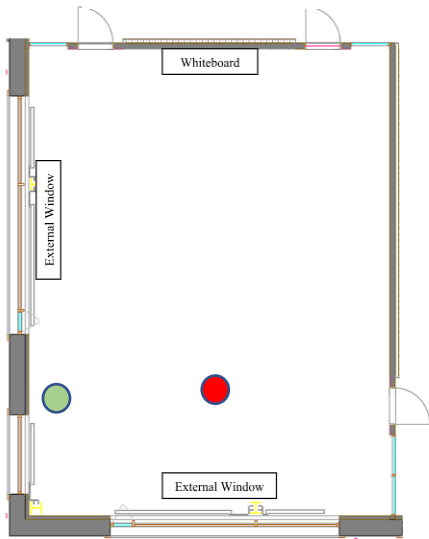
A total number of 5 rooms were visited 2 to 4 times each. Each of the five rooms correspond to one course, so the students in a particular room are approximately the same between each session. The room that was visited the most times was classroom U61, which was occupied a master's course in chemical catalysis. The room U1 was visited three times and was occupied by a bachelor's course in chemical dynamics. The rooms U21, U31 and U41 was visited 4, 2 and 3 times each, and they were occupied by a bachelor's course in civil engineering structures. The students in that course were free to choose which of the three classrooms that they would visit, so it is reasonable to assume that the variation of students was higher in U21, U31 and U41. The number of visits to each classroom was not predetermined but was decided during the progressions of the project based on how well the schedules of the courses and the classrooms did fit with the available time that was required for the measurements. The lectures in the classrooms that were visited took place at different times during the day (between 8.15 am and 6.00 pm). The drawings of the classrooms are presented below, where the red dot represent the approximate location of the thermal measurement equipment. The blue dot represents the location of the sound pressure level meter, and the green dots the CO<sub>2</sub>-concentration sensors.



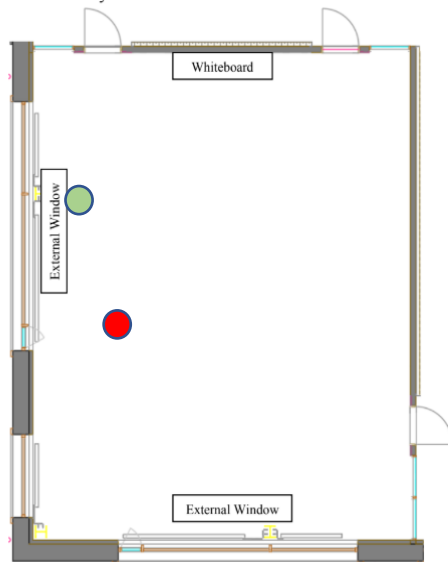
Classroom U1



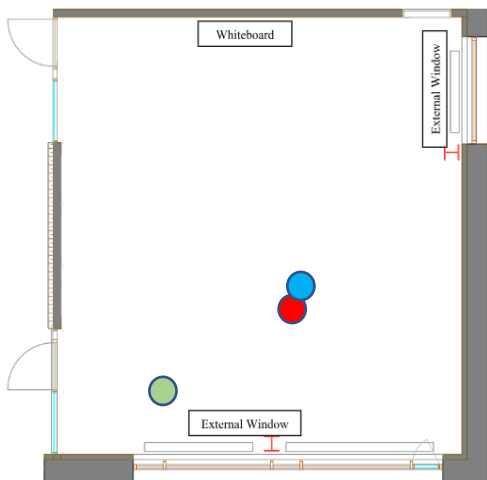
Classroom U21



Classroom U31



Classroom U41



Classroom U61

### 3.3 STUDY PROCEDURE

*The current study is a part of a group of studies that aim to investigate the indoor environmental conditions in the Educational Building. This section will mainly address the survey procedure. The survey and measurement investigations were divided into two phases. Preliminary analyses of the data collected were carried out between the two periods and one minor adjustments of the study were conducted based on the preliminary analysis and a few minor adjustments were made in the measurement routines.*

The first study phase took place in *The Educational Building* between 2018-03-20 and 2018-03-29, and the second study phase between 2018- 04- 26 and 2018-05-08. Physical measurements of the indoor environment were conducted during lectures and exercises that were parts of the ordinary schedules of bachelor and masters student of different engineering programmes at KTH- Royal Institute of Technology. The lectures lasted for 2 hours, and the exercises for three hours but the measurements were terminated after 2 hours in those instances. During the lecture and exercises, students filled in the survey.

The study was conducted partly as a longitudinal study; the lectures of three courses were visited several times each. It has been shown that longitudinal survey studies are affected by a considerable drop off in the response rate; that fewer and fewer subjects are willing to participate in the survey for each occasion. The drop off effect is lower for studies using paper- based surveys, which was an additional reason why paper based surveys were used (Sax, et al., 2003). The drop off was considered and therefore only two visits were made to every course during the first study phase, and maximum 2 times each in the second one. In an attempt to maintain a high response rate, the same lecture was only visited once per week and it was ensured that at least one other lecture in each course had taken place between each study session. This is believed to make the subjects less annoyed by the presence of the measurement equipment and by the time that it takes to fill in the survey and may therefore be more willing to participate.

The lectures that were visited took place both during the morning and the afternoon depending on the course schedules. The three courses took place in the same room each lecture and the three courses used different rooms. So, three rooms, corresponding to three courses were evaluated twice each. During the second study phase, two more rooms were visited for one of the courses. The data from those two rooms may not be enough to analyse the rooms individually, for instance how the HVAC systems function in them. However, the data can nevertheless be included in the data analyses that include the complete dataset and may be used to understand the associations between satisfaction, productivity and the physical conditions of the indoor environment.

The courses were selected based on their schedules; that they had frequent lectures in the *Eduational Building* and in classrooms that were deemed interesting to investigate. The first course was a bachelors course in chemical dynamics, the second one was a masters course in environmental catalysis, and the third course was a bachelors course in buildings and civil engineering structures. So, the courses were not selected randomly, and the difference in the composition of the students in the three courses may influence the results from the survey. For instance, the age and gender distribution may vary between the different courses and the personal interest of the topic of indoor environment may vary between the subjects of different engineering programmes.

As mentioned previously, the survey was divided into three parts that were to be answered at different times throughout the lectures. Before the lecture began the experimental leaders introduced themselves and informed the student about the measurement and the survey. The students were informed that the participation was voluntary and that they may quit the survey at any time if they so

wished. They were also informed that the results from the survey would only be used for educational and research purpose and that their answers are anonymous. The physical measurement equipment was set up approximately 45 minutes prior the start of the lecture, and the surveys were placed on the tables. No intervention of the indoor environment was made by the study leaders; the windows and the window shadings remained as they were before, and the students and the teachers were free to adjust them. The measurements were started 15 to 30 minutes prior the start of the lecture, which enabled measurements of the indoor environment before the students entered, and the measurements were terminated 5 to 15 minutes after the end of part three of the survey.

After the introduction the lecture started as usual and lasted for approximately 45 minutes, until the first break. At the break, the students who wished to participate were asked to fill in the first part of the survey. The break lasted for approximately 15 minutes, and at the end of the break the students were asked to fill in the second part of the survey. The second part was about air quality which, according to the literature review, is perceived stronger when a person enters a room. By introducing a short break in between part 1 and 2, the students could choose to exit the room during the break. The students were informed that they could do so if they wished, but not the reason why. At the end of the lecture, the subjects were asked to answer the last part of the survey.

The subjects were free to open the windows, fold down the window shading, adjust their clothing or by any other means adapt to the environment. This approach was chosen to make the conditions as similar to reality as possible. The main measurement station (thermal parameters and sound pressure level) was placed to create as little distraction as possible, although it had to be placed on a relatively central location in the room to be able to provide reliable average values of the physical parameters. The study leaders were attempting to intervene as little as possible, but the subjects were allowed to ask questions while they filled in the survey (but no subject asked any question). If any question would have arisen, the study leaders would have attempted to clarify the question as neutrally as possible to avoid influencing the subject.

It was decided that no interventions were to be made to the indoor environment, and the different values of the indoor environmental parameters should be caused naturally by for instance variance in occupancy, weather and season. The notion of not making any intervention to the environment has been used previously by for instance Tanabe et.al (2009) who let the conditions in a building change naturally, and they were nevertheless able to observe interesting associations between different environmental parameters and productivity. By merely observing and monitoring the indoor environment it is also possible to evaluate how good the quality of the indoor environment is in the *Educational Building*, which was deemed to be valuable information. However, by actively intervene with the indoor environment it may be possible to observe larger varieties in the parameters which may result in larger varieties of perceived comfort, satisfaction and productivity. By dividing the study into two periods with the possibility to make preliminary analysis between, it may be possible to find out whether the naturally occurred differences were large enough to cause any noticeable difference in the subjective perception and enable changes in the study design, if needed. After the first study phase, it was found that the environmental differences between the different lectures were large enough to be able to observe interesting correlations between different parameters and the approach of not intervening was reassumed.

### 3.4 DATA ANALYSIS

*The following section will present how the collected data was handled and how it was analysed through different statistical methods.*



The surveys were collected at the end of the class, or after two hours if the class was longer than two hours. The data was transcribed into an excel sheet, where the different answer options were represented by numbers. The alternative to the left on the sheet was always coded as 1, and the second from the left as 2 and so on. The responses were sorted based on the lecture, so be able to compare the responses with the physical measurements of each session. It was not possible to track the subjects throughout the different lectures. However, it was possible to do so between the two sessions of each lecture because the three parts of the surveys were collected together. For instance, it is possible to analyse how the thermal comfort has changed for a specific subject between the first and the second sessions of a specific lecture.

Incomplete surveys are dealt differently depending on how large part that was missing. If more than 60 % of the survey was incomplete the entire survey was removed from the data set, and otherwise the data is included nevertheless. This means that if a subject had answered fewer than 10 questions, the survey was removed for the sample.

The main statistical method that has been used to determine correlation between two variables is Spearman's rank correlation. This method has been used mainly because few, or none, of the questions received responses that seemed to be normally distributed. Most responses are skewed to one side (often to the side that corresponds to higher satisfaction, because the satisfaction was generally high). Spearman's rank correlation is a non-parametric statistical method, and it does not assume that one or both variables are normally distributed. Spearman's rank correlation also does not assume that the relationship between the two parameters is linear, which a linear Pearson correlation does. However, but the relationship between the two variables need to be monotonic. Spearman's rank correlation tests the correlation between the ranks of the independent observations, and not the correlation between the observed results themselves (McDonald, 2014). However, McDonald (2004) claims that numerous evidence suggest that linear regression is not sensitive to non- normality, and that a linear regression may be used even when the data is not normally distributed. Several of the studies in the literature have used the Pearson correlation for similar analyses, which is another reason why both Spearman's rank correlation and the Pearson's linear regression will be used in the statistical analyses.

It should be mentioned that since this is a longitudinal study (the opinions of the same subjects are investigated at different occasions), the independency between the different observations may not be entirely fulfilled. For instance, a subject who has headache during one session may have a slightly higher probability to have a headache the next week, simply because some people have headache more often than others. Some of the question have approximately 460 responses, but the data originates from considerably fewer subjects (the exact number is uncertain because the survey was anonymous). Future studies would benefit from considering other statistical methods that are more applicable in longitudinal studies. The current statistical analysis should merely be considered to be a preliminary one.

To investigate if any correlation could be observed between any of the physical measurements and the subjective responses from the questionnaire, the mean values of every session was used. Each 105 minute lecture was divided into two 45 minutes sessions (before and after the 15 minutes break). The mean values of the physical parameters were calculated for each 45 minute session, along with the mean value of the corresponding subjective responses. Questions that were only included in part 1 could not be evaluated by this method, because part 1 corresponds to the first 45 minutes, and part 2 the last 45 minutes. Questions that were only included in part 1 or 2 could therefore only be evaluated for correlation with the physical measurements of the first 45 minutes.

The correlation analyses between the responses of different questions did also depend on which question that appear in part 3. For instance, a regression analysis between thermal satisfaction and perceived productivity had twice as many data sets compared to a regression analysis between perceived environmental control and perceived productivity. This is because thermal satisfaction and perceived productivity appears in both part 1 and 3, while perceived environmental control only does so in part 1.

The graphs and the linear correlation formulas are created based on the numbers from the responses and not on corresponding values on the scales in the survey. For instance, in question 16, the response "4" correspond to 0% higher productivity than a typical building, and the response "5" corresponds to 5% higher productivity. The correlation analyses that are performed uses the responses (1 to 7) and not the actual values (-20% to +20%). All the scales used are linear, so the translation between the response scale and the scale of the question can be done easily.

Some of the correlations that have been found will be visualised in the result section as graphs. This has been done by using the mean values for each value of a specific parameters. For instance, among the ones who have replied "3" on question 16/ 32 the mean response of question 14/32 is 3,625. By doing this for the responses of all the alternatives on question 16/32, the correlation is visualised in a simplified way. However, it should be mentioned that this is not a statistically accurate visualisation of the correlation, but it does provide a picture of the trend that can be overviewed more easily than if the complete dataset would have been included. The most apparent drawback of this method is that some of the mean values are based on very few observations, so the corresponding datapoints are therefore not as statistically valid as the datapoints that are based on mean values from many observations. Especially the end of the scales in the graphs are subjects to high uncertainty, because there are typically much fewer subjects who reply 1 on a question (very dissatisfied) than who reply 4 (neutral), on a 7- point scale.

## 4 RESULTS

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*This section presents the results from the survey and the physical measurements. The first section will present a summary of the sessions, while the other sections will use statistical methods to investigate if any association can be observed between productivity, satisfaction, acute health symptoms and physical measurements.*

### 4.1 SUMMARY OF THE SESSIONS

#### 4.1.1 Attendance and response rate

The three courses were visited three to four times each. The three different classes had quite different number of attendants, and it varied between different dates and there were also some drop off between the first and the second half of the class. The response rate is calculated based on the number of students attending the lecture initially, even though there often were slightly fewer when it was time to answer part 1, and even fewer when it was time to answer part 3.

The course in chemical dynamics had between 65 and 36 students attending. Among the student attending, 44 participated in the survey during the first week and 33 the second one, which corresponds to a response rate of 68% and 72%. The course was only visited once during the second study phase, and among the 36 students participating, 17 answered the survey which corresponds to

a response rate of 47 %. The lectures during this course had considerably higher occupancy density than the other two, and the room is designed for 60 occupants.

The masters course in environmental catalysis had between 14 and 19 students attending the classes, and among them between 4 and 12 answered the survey. This corresponds to a response rate between 29 % and 71%. The room is designed for 36 occupants.

The exercises in the course in buildings and civil engineering structures had a quite different structure than the other two courses. The students were completing exercises by themselves and they had a “course assistant” present that they could ask questions to whenever they wanted to. This resulted in a more dynamic lecture, with the number of students varying more throughout the lectures and the student were more moving around more. The number of student attending the lecture were between 14 and 46, and the response rate was between 16% and 63%. Only the students that had been in the classroom for at least 30 successive minutes were asked to fill in the questionnaire, because the subjects need to be exposed to the environmental conditions for some time to be able to give a reliable opinion about it. The three rooms used in this course are designed for 70 occupants, so the occupancy density in relation to the ventilation system should have considerably between the sessions in this course considering the difference in attendance.

During all the lectures, one professor or assistant and one or two experimental leaders were present. The response rate is deemed to be satisfactory, but the drop off rates between the sessions was beginning to get problematic towards the end of the second study phase. The matter will be discussed in the discussion chapter. A major difference between the three courses was the occupancy density in the classrooms (number of occupants in relation to the designed number of occupants in the room). Those differences gave rise to interesting differences in the physical properties of the room, for instance temperature and CO<sub>2</sub>- concentrations that were reflected in the responses of the survey. The mean values of the physical measurements will be presented in the next section.

#### 4.1.2 Summary of the physical measurements

*This section will briefly present the outcomes of the physical measurements. The table below present the mean values of each session. There were two sessions for each lecture (before and after the break).*

Date	Session	PMV-value	CO <sub>2</sub> - conc.**	Sound pressure level ***
20/3-2018	1	0,015	1004	52
20/3-2018	2	0,035	954	55
21/3-2018	3	0,182	969	50
21/3-2018	4	0,160	869	50
22/3-2018	5	-0,358	769	56
22/3-2018	6	-0,311	878	52
27/3-2018	7	0,140*	923	49
27/3-2018	8	0,140*	**	**
28/3-2018	9	-0,050*	796	51
28/3-2018	10	-0,050*	803	50
29/3-2018	11	-0,440*	741	48
29/3-2018	12	-0,440*	812	48
24/4-2018	13	0,106	733	48
24/4-2018	14	0,126	679	49
26/4- 2018 (classroom 1)	15	-0,309	**	58
26/4- 2018 (classroom 1)	16	-0,260	819	58

26/4- 2018 (classroom 2)	17	-0,476	631	**
26/4- 2018 (classroom 2)	18	-0,410	671	**
26/4- 2018 (classroom 3)	19	-0,318	822	**
26/4- 2018 (classroom 3)	20	-0,168	844	**
2/5-2018 (classroom 3)	21	-0,117	886	**
2/5-2018 (classroom 3)	22	-0,118	800	**
2/5-2018 (classroom 2)	23	-0,111	777	**
2/5-2018 (classroom 2)	24	-0,085	741	**
2/5-2018 (classroom 1)	25	-0,436	933	59
2/5-2018 (classroom 1)	26	-0,386	884	**
4/5-2018	27	-0,202	762	**
4/5-2018	28	-0,173	744	**
7/5-2018	29	-0,322	669	54
7/5-2018	30	-0,336	587	53
8/5-2018	31	-0,117	685	49
8/5-2018	32	-0,177	625	48

\* The PMV- value for those calculations could had to be calculated manually (because of lost data) based on the physical measurements and the responses from the clothing questions in the survey. The calculations are based on the mean value of the entire lecture (both sessions) so the two sessions of each lecture have the same PMV- value. This is believed to be a acceptable assumption, because the PMV- value that was calculated based on the constant clo value of 0,7 differed very little between the first and the second sessions during those lectures (between 0,01 and 0,03).

\*\*Both sessions at the 20/3, the first session the 28/3, and both session at the 7/5 used two CO<sub>2</sub>- concentration sensors (at different locations in the classroom). The analyses in this report will use the mean value of the two.

\*\*\*Due to technical problems, measurement data from a number of sessions could not be collected, and those boxes in the table have been left blank, and the data will not be included in the subsequent data analysis.

From the table, it is possible to make a few simple conclusions:

- The mean PMV- value were either close to zero or negative
- The mean CO<sub>2</sub>- concentration is below 1000 ppm for almost all sessions, which should fulfil the maximum level prescribed in ASHRAE standard 62 (by assuming an outdoor concentration between 300 and 400 ppm)
- The sound pressure level is between 48 and 56 dB(A)

#### 4.1.3 Summary of the subjective responses

*This section will briefly present the mean values of the responses to a few questions for each session. The questions include here are mainly the overall questions concerning each topic.*

Date	Session	Thermal satisfaction (question 4 and 26)	Acoustical satisfaction (question 7 and 29)	Lighting satisfaction (question 9 and 30)	Air quality acceptability (question 19)*	General wellbeing (question 11)*	Perceived productivity (question 16 and 34)
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20/3-2018	1	5,00	4,65	5,23	4,61	5,09	5,00
20/3-2018	2	5,00	5,21	5,38			4,68
21/3-2018	3	5,75	5,19	5,94	6,00	5,375	6,19
21/3-2018	4	5,62	5,63	5,69			5,86
22/3-2018	5	5,89	5,78	6,33	6,38	6,00	7,33
22/3-2018	6	5,78	6,33	5,89			7,00
27/3-2018	7	4,67	5,00	4,83	5,67	5,50	5,17
27/3-2018	8	4,75		5,00			5,25
28/3-2018	9	5,15	5,00	5,67	4,78	4,84	4,64
28/3-2018	10	5,27	5,00	5,29			4,41
29/3-2018	11	5,5	6,10	6,50	6,10	6,00	6,80
29/3-2018	12	5,75	5,88	6,25			6,25
24/4-2018	13	5,375	4,5	4,125	5,625	4,375	5,125
24/4-2018	14	4,75	4,75	4,75			4,875

26/4- 2018 (classroom 1)	15	5,364	3,500	6,000	4,750	6,083	5,917
26/4- 2018 (classroom 1)	16	4,667	3,909	4,750			5,273
26/4- 2018 (classroom 2)	17	5,48	4,10	6,00	6,20	6,14	6,05
26/4- 2018 (classroom 2)	18	5,50	3,95	5,63			5,80
26/4- 2018 (classroom 3)	19	5,88	3,88	6,13	5,63	5,50	6,75
26/4- 2018 (classroom 3)	20	4,93	4,53	5,60			6,33
2/5-2018 (classroom 3)	21	5,80	5,35	5,68	6,00	5,05	6,25
2/5-2018 (classroom 3)	22	5,71	5,47	5,82			6,00
2/5-2018 (classroom 2)	23	5,43	4,43	5,71	6,29	5,86	4,86
2/5-2018 (classroom 2)	24	5,67	4,33	4,83			4,33
2/5-2018 (classroom 1)	25	4,33	2,50	5,83	5,67	6,00	5,00
2/5-2018 (classroom 1)	26	4,50	3,17	6,17			4,83
4/5-2018	27	6,75	6,25	4,75	6,5	6,5	5,25
4/5-2018	28	5,75	4,75	4,5			6

7/5-2018	29	5,86	5,88	6,38	6,00	5,50	7,13
7/5-2018	30	6,00	6,33	6,33			6,67
8/5-2018	31	5,56	4,75	3,81	5,64	5,00	4,75
8/5-2018	32	5,36	4,91	4,18			5,27

\*The questions about air quality and wellbeing were not included in the third part, so air quality was only evaluated after the first session of each lecture

Based on the numbers in the table, it appears like the subjects are relatively satisfied with their indoor environment, and that they feel relatively well and productive. These are just the mean value of a few questions, but they provide a quite good picture of how the indoor environment is perceived. The general positive perceptions indicate that the building is relatively well functioning concerning thermal comfort, air quality, acoustic climate and lighting and that the occupants perceive themselves as productive. Having concluded this, the subsequent analysis will investigate the relationships between the different subjective and objective parameters.

## 4.2 STATISTICAL ANALYSIS

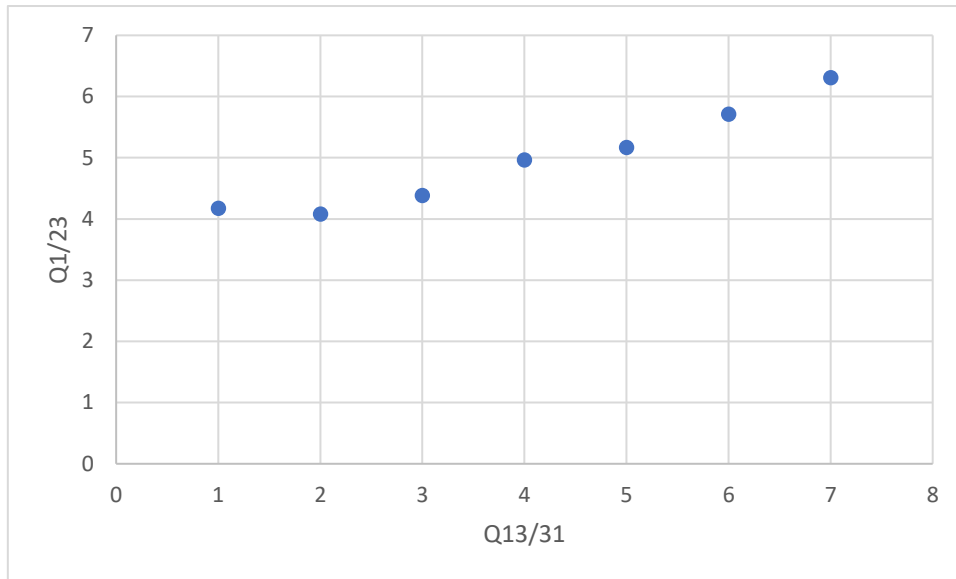
### 4.2.1 General satisfaction and productivity

*The correlation between the general environmental satisfaction and the four productivity metrics was investigated. Each correlation test was based on approximately 460 datapoints.*

The correlation analysis between general satisfaction (question 1 and 23) and the question regarding whether the subjects could concentrate (question 13 and 31) received a Spearman's correlation coefficient of 0,497. The linear regression received a R- value of 0,460 at the significance level of 3,6E-25.

$$Q1/23 = 3,277 + 0,405 * Q16/34$$

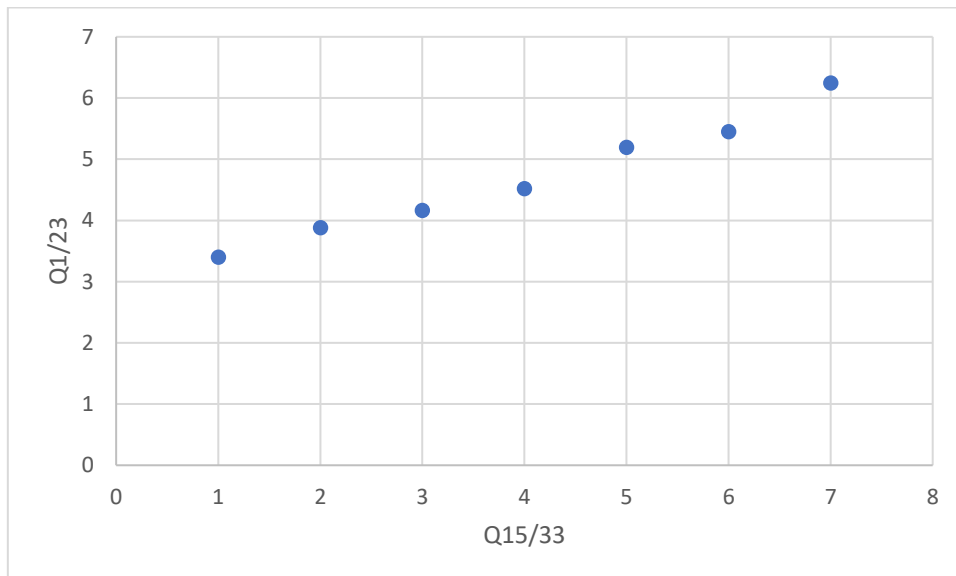
Where Q1/23 represent the response on question 1 and question 23, and Q16/34 represent the response of question 16 and 34. To illustrate the correlation in a simplified way, for each value of question 13/31 the corresponding mean value of question 1/23 are plotted in the graph below.



The correlation between general environmental satisfaction (question 1 and 23) and perceived ability to work (question 15 and 33) received a Spearman's correlation of 0,518 and a R- value of 0,494 at the significance level of 1,95E-29. From the linear regression, the following relationship between the responses was created.

$$Q1/23 = 2,70 + 0,484 * Q15/33$$

To illustrate the correlation in a simplified way, for each value of question 15/33 the corresponding mean value of question 1/23 are plotted in the graph below.

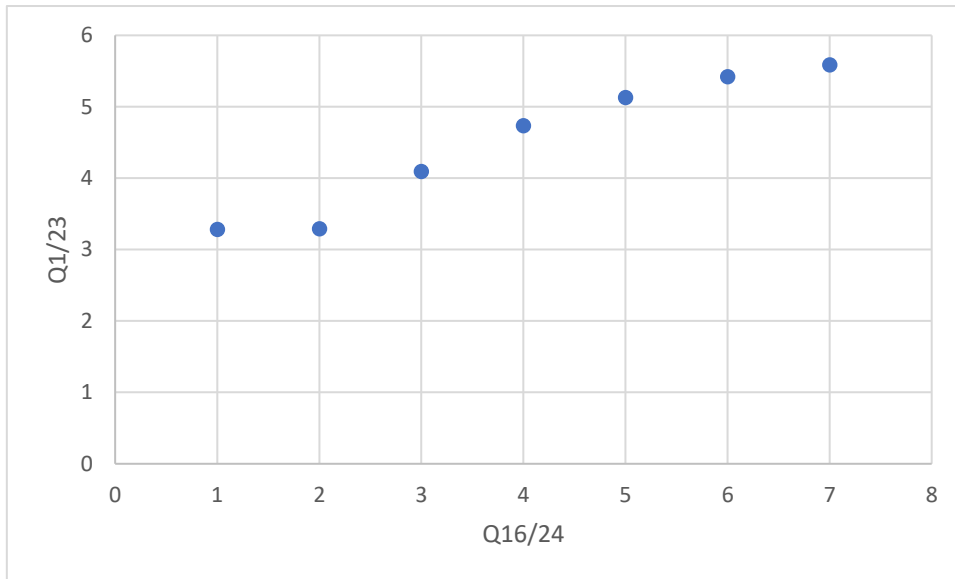


The correlation between general satisfaction (question 1 and 23) and perceived productivity (question 16 and 34) was approximately similarly strong, with a Spearman's correlation of 0,446 and a R-value of 0,443 at the significance level of 2,69E-23. From the linear regression, the following relationship between the responses was created.

$$Q1/23 = 3,06 + 0,383 * Q16/34$$

To illustrate the correlation in a simplified way, for each value of question 16/34 the corresponding mean value of question 1/23 are plotted in the graph below.

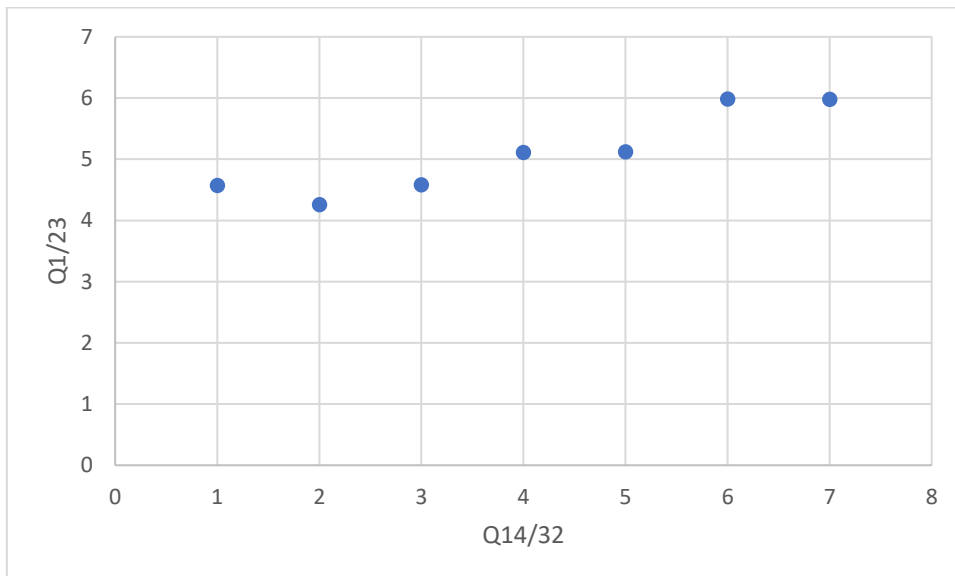




And lastly, the correlation between general satisfaction (question 1 and 23) and motivation (question 14 and 32) was also similarly strong with a Spearman's correlation of 0,432 and a R -value of 0,387 at the significance level of 9,34E-18. From the linear regression, the following relationship between the responses was created.

$$Q1/23 = 3,80 + 0,315 * Q14/32$$

To illustrate the correlation in a simplified way, for each value of question 14/32 the corresponding mean value of question 1/23 are plotted in the graph below.

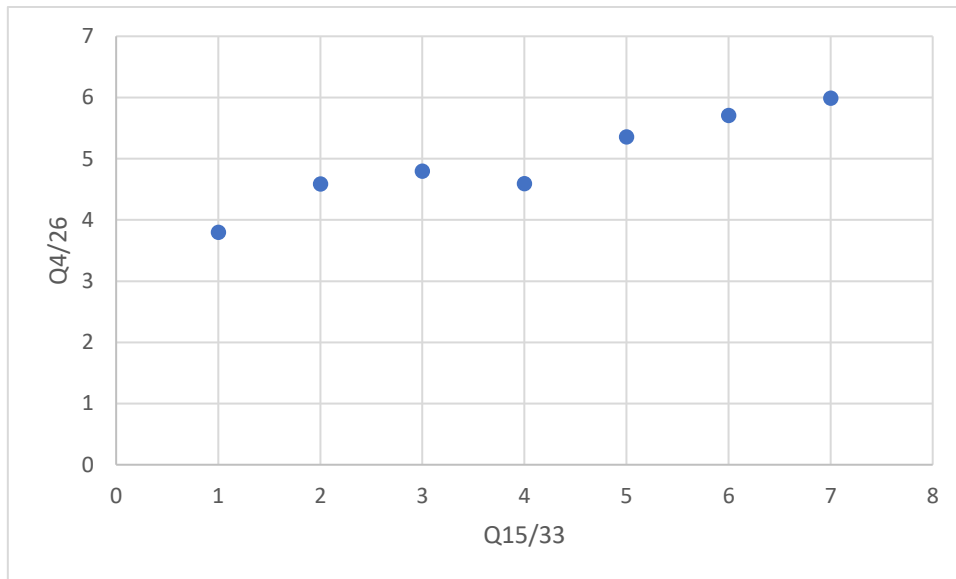


Based from these correlations it is evident that overall satisfaction is approximately equally strongly correlated with the four productivity metrics. The correlation is moderately strong.

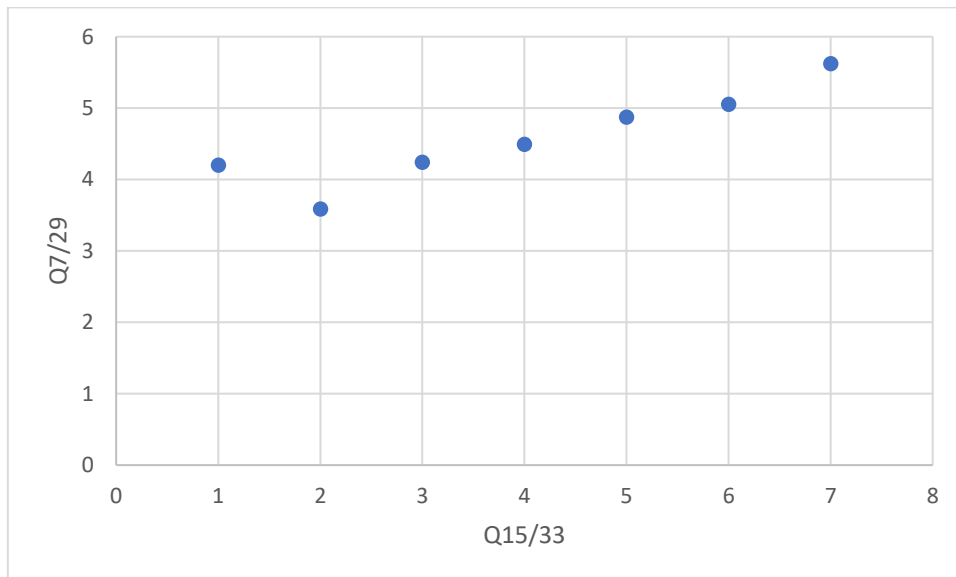
#### 4.2.2 Ability to work and environmental satisfaction

*The satisfaction with the four overall environmental parameters were analysed concerning their correlation with the question regarding how the subjects perceive their ability to work. Each test had approximately 460 datapoints, except concerning air quality that had 233 (since air quality did not appear in part 3).*

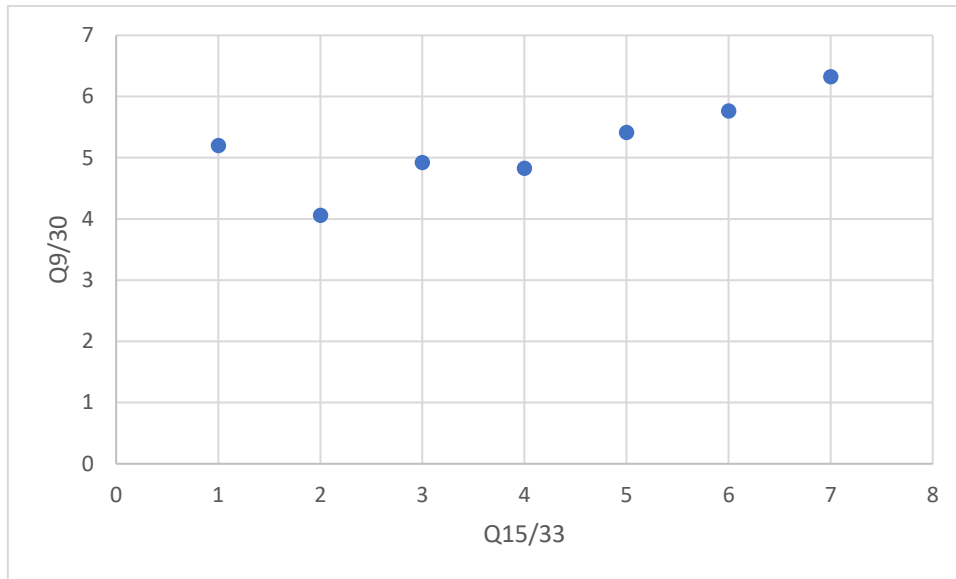
The correlation between thermal satisfaction (question 4 and 26) and ability to work (question 15 and 33) received a Spearman's rank correlation coefficient of 0,404, and a linear correlation of 0,321,  $p < 5,66E-16$ . To illustrate the correlation in a simplified way, a graph of the mean values is presented below.



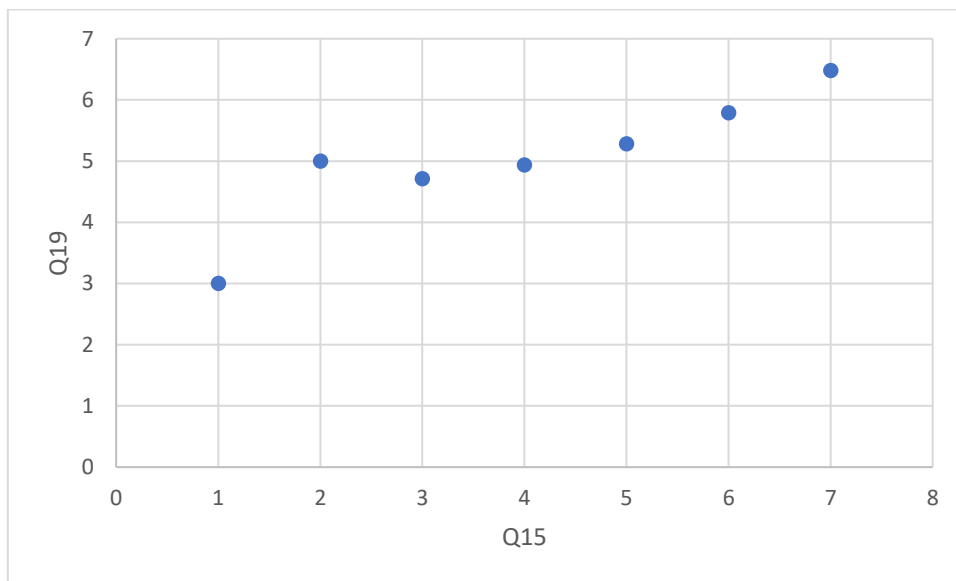
The correlation between acoustical satisfaction (question 7 and 29) and ability to work (question 15 and 33) received a Spearman's rank correlation coefficient of 0,332 and a linear correlation of  $R = 0,301$ ,  $p < 0,5,31E-11$ . To illustrate the correlation in a simplified way, a graph of the mean values is presented below.



The correlation between satisfaction with lighting (question 9 and 30) and ability to work (question 15 and 33) received a Spearman's rank correlation coefficient of 0,409, while the linear correlation received a correlation of  $R = 0,346$ ,  $p < 2,63E-14$ . To illustrate the correlation in a simplified way, a graph of the mean values is presented below.



The correlation between air quality satisfaction (question 19) and ability to work (question 15) received a Spearman's rank correlation coefficient of 0,407 while the R- value was 0,386 with a significance level of 1,11E-9. To illustrate the correlation in a simplified way, a graph of the mean values is presented below.

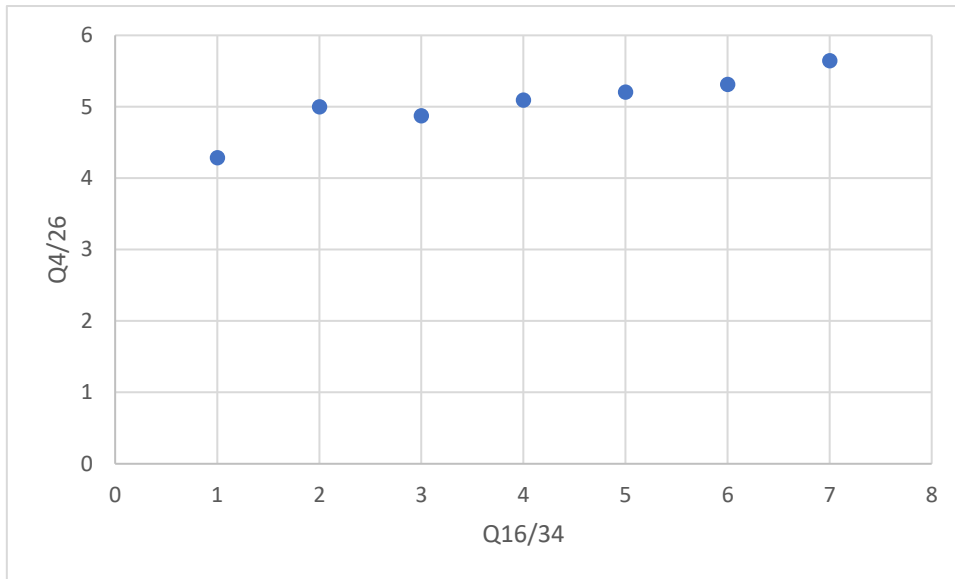


#### 4.2.3 Perceived productivity and environmental satisfaction

The correlation between thermal satisfaction (question 4 and 26) and perceived productivity (question 16 and 34) received a Spearman's rank correlation coefficient of 0,264 , while the linear correlation coefficient was 0,232 at the significance level of 5,25E-7. From the linear regression, the following relationship between the responses was created:

$$Q4/26 = 4,29 + 0,190 * Q16/34$$

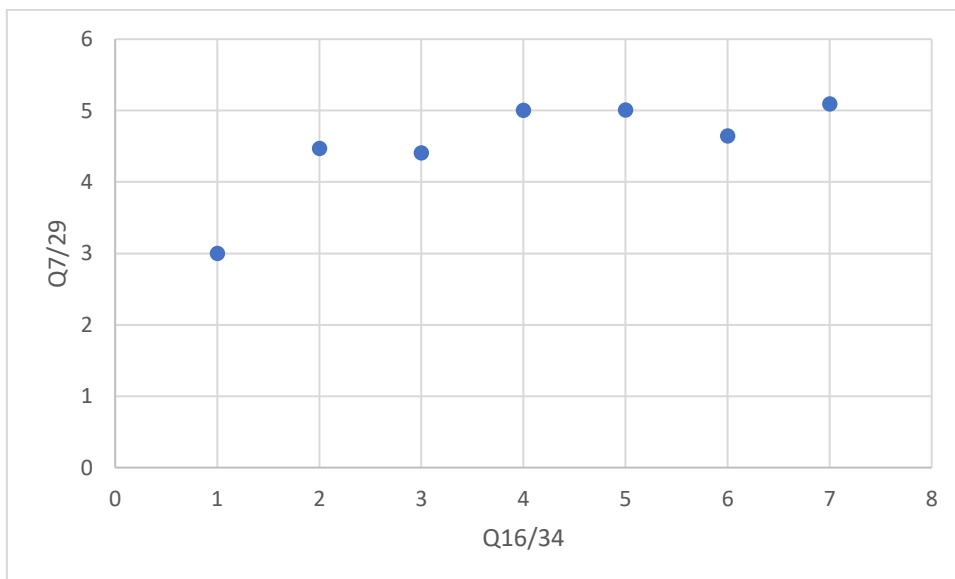
To illustrate the correlation in a simplified way, a graph of the mean values is presented below.



The correlation between acoustical satisfaction (question 7 and 29) and perceived productivity (question 16 and 34) received a Spearman's rank correlation coefficient of 0,117, while the linear correlation was equally weak ( $R= 0,119$  ,  $p<0,0111$ ). From the linear regression, the following relationship between the responses was created:

$$Q7/29 = 4,23 + 0,115 * Q16/34$$

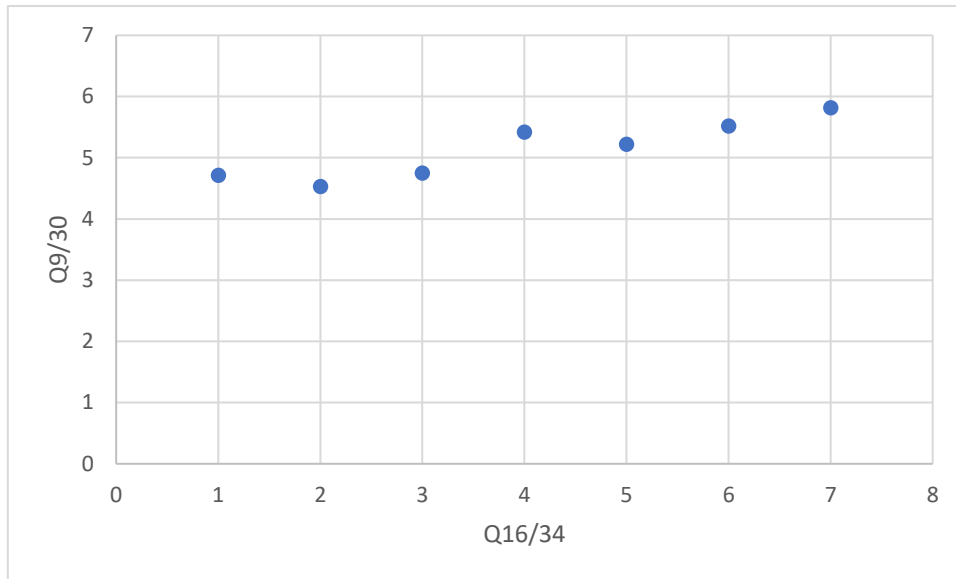
To illustrate the correlation in a simplified way, a graph of the mean values is presented below.



The correlation between the satisfaction with lighting (question 9 and 30) and perceived productivity (question 16 and 34) received a Spearman's rank correlation coefficient of 0,310 and the linear correlation coefficient was 0,280 at the significance level of 1,18E-9. From the linear regression, the following relationship between the responses was created:

$$Q9/30 = 4,03 + 0,262 * Q16/34$$

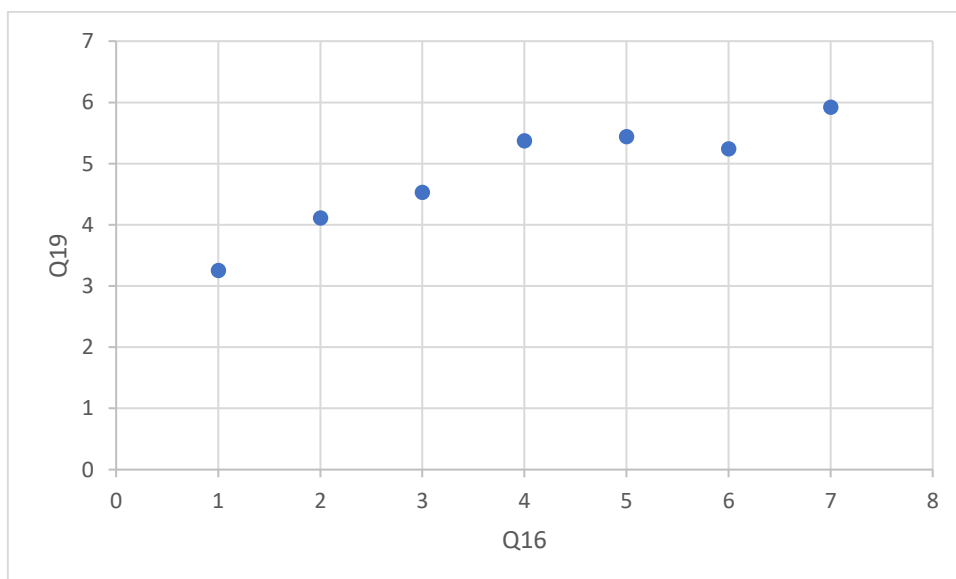
To illustrate the correlation in a simplified way, a graph of the mean values is presented below.



Lastly, the correlation between air quality acceptability (question 19) and perceived productivity (question 16) received a Spearman's rank correlation coefficient of 0,342, while the R-value was 0,348 at the significance level of 5,11E-8. From the linear regression, the following relationship between the responses was created:

$$Q19 = 3,68 + 0,319 * Q16$$

To illustrate the correlation in a simplified way, a graph of the mean values is presented below.



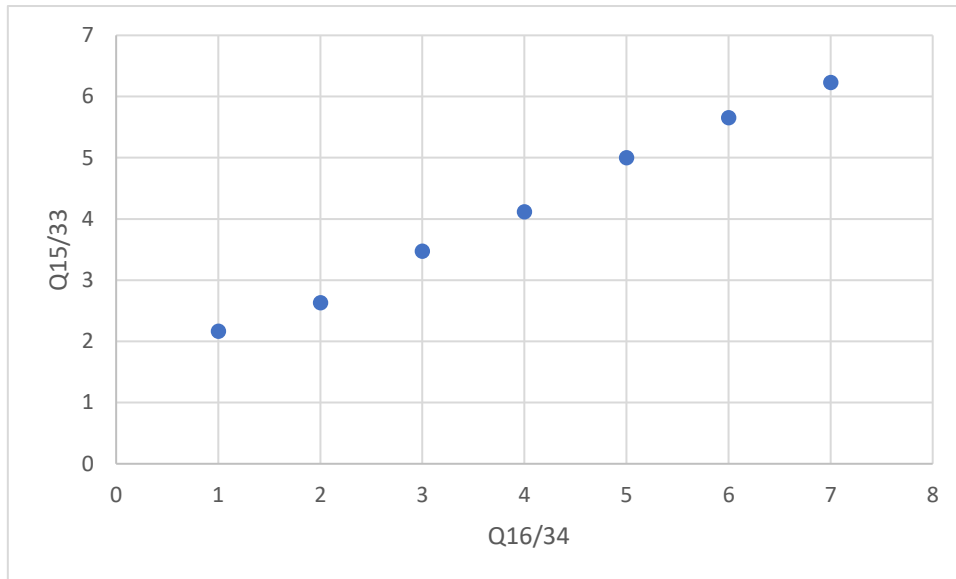
#### 4.2.4 Correlations between different productivity metrics

The correlation between the four productivity questions (question 13 to 16 and 31 to 34) was investigated based on approximately 460 datapoints each.

The correlation between ability to work (question 15 and 33) and perceived productivity (question 16 and 34) received a Spearman's rank correlation of 0,705 and R value of 0,702 at the significance level of 2,24E-69. From the linear regression, the following relationship between the responses was created.

$$Q15/33 = 1,72 + 0,628 * Q16/34$$

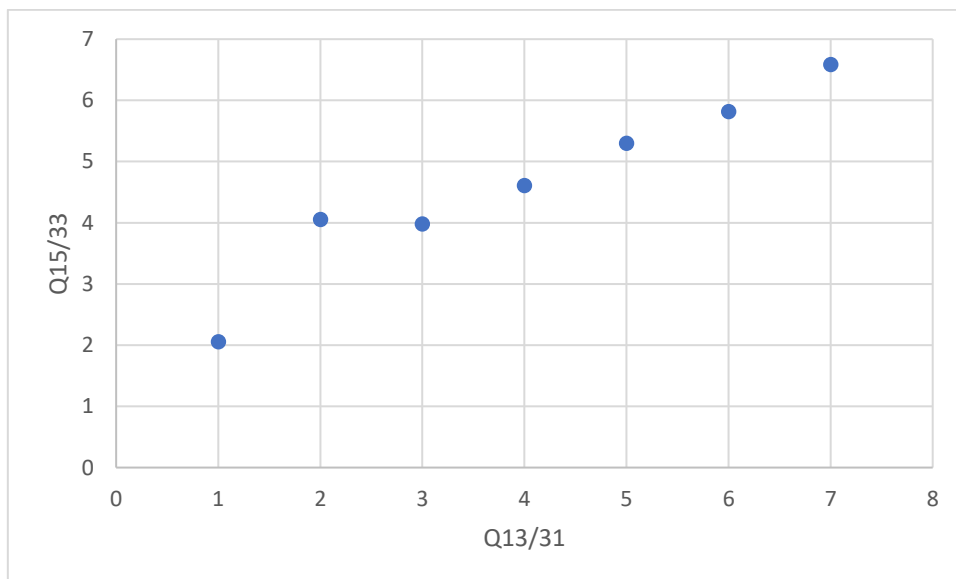
To illustrate the correlation in a simplified way, a graph of the mean values is presented below.



The correlation between ability to work (question 15 and 34) and concentration (question 13 and 31) received a Spearman's rank correlation of 0,663 and a R- value of 0,678 at the significance level of 9,94E-63. From the linear regression, the following relationship between the responses was created:

$$Q15/33 = 2,22 + 0,612 * Q16/34$$

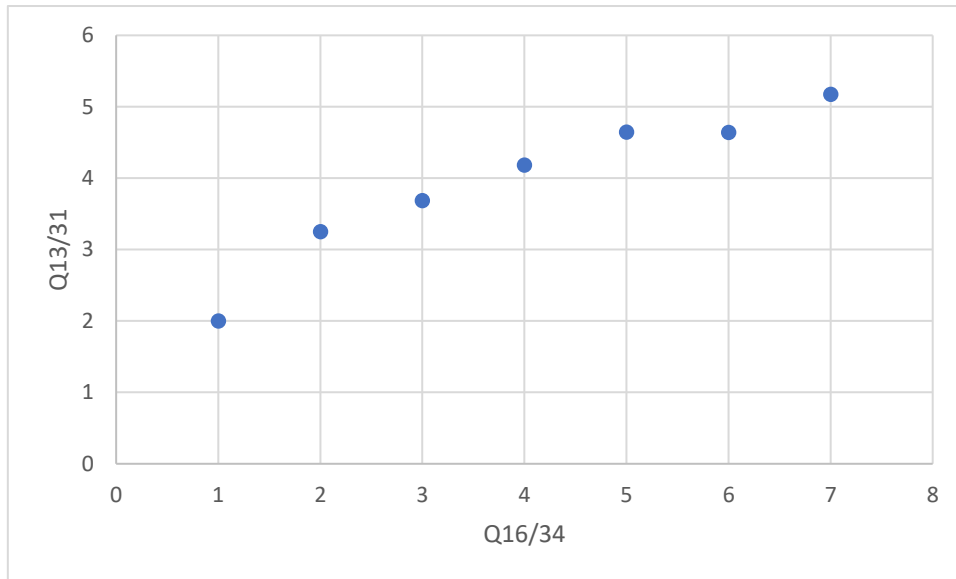
To illustrate the correlation in a simplified way, a graph of the mean values is presented below.



The correlation between concentration (question 13 and 31) and perceived productivity (question 16 and 34) received a Spearman's rank correlation of 0,391 and a R- value of 0,398 with a significance level of 1,004E-18. From the linear regression, the following relationship between the responses was created:

$$Q13/31 = 2,53 + 0,388 * Q16/34$$

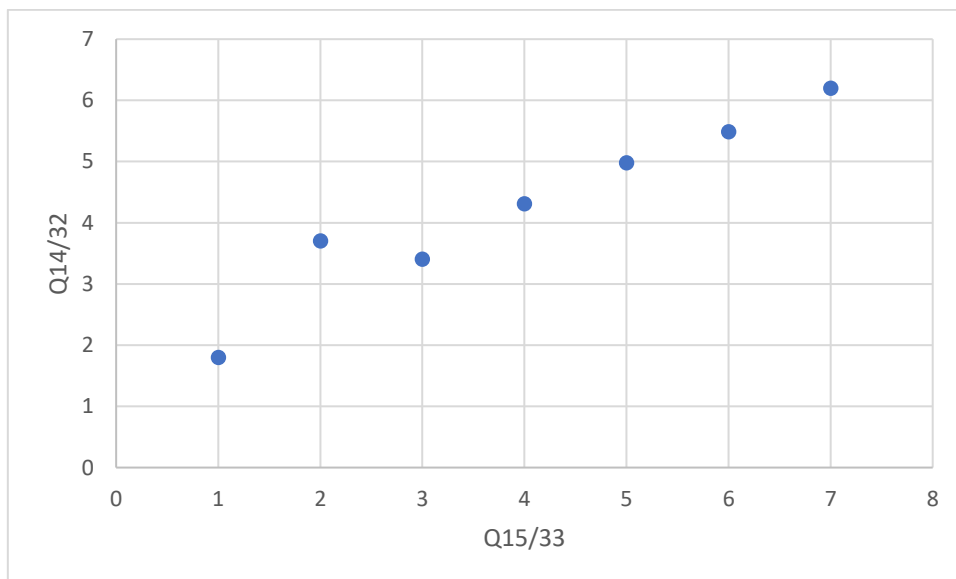
To illustrate the correlation in a simplified way, a graph of the mean values is presented below.



The correlation between motivation (question 14 and 32) and ability to work (question 15 and 33) received a Spearman's rank correlation of 0,548 and a R- value of 0,545 at the significance level of 1,17E-36. From the linear regression, the following relationship between the responses was created:

$$Q14/32 = 1,76 + 0,631 * Q15/33$$

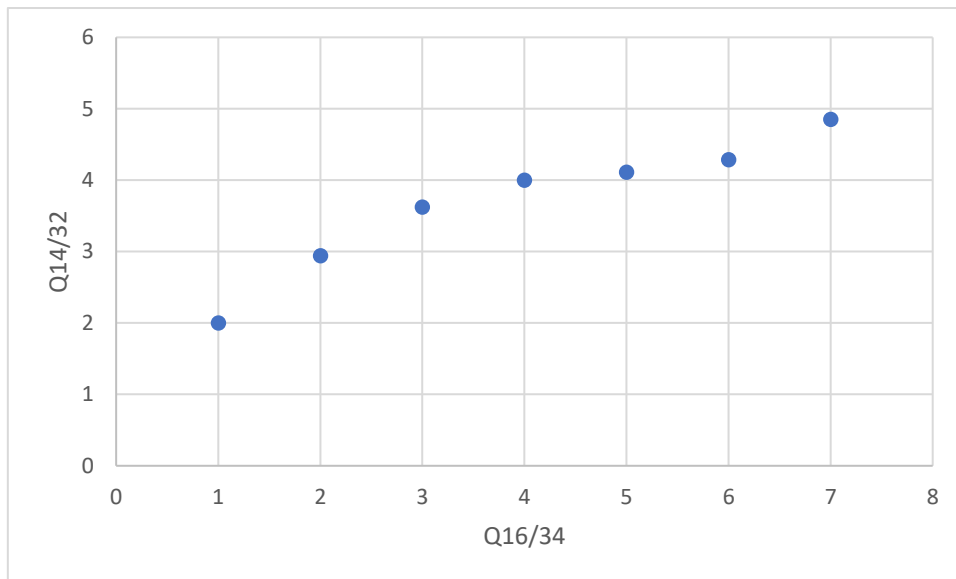
To illustrate the correlation in a simplified way, a graph of the mean values is presented below.



The correlation between motivation (question 14 and 32) and perceived productivity (question 16 and 34) received a Spearman's rank correlation of 0,367 and a R- value of 0,360 at the significance level of 1,75E-15. From the linear regression, the following relationship between the responses was created:

$$Q14/32 = 2,23 + 0,382 * Q16/34$$

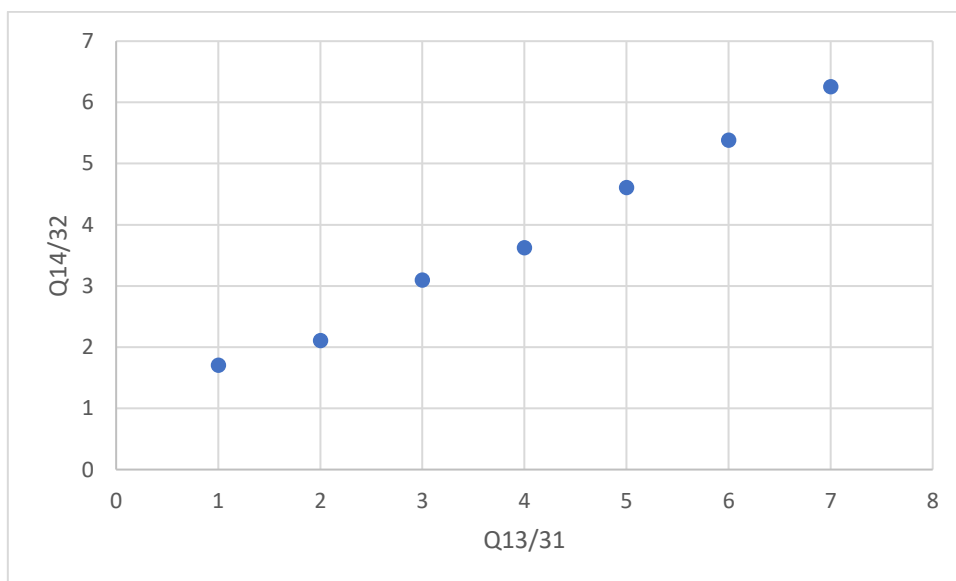
To illustrate the correlation in a simplified way, a graph of the mean values is presented below.



The correlation between motivation (question 14 and 32) and concentration (question 13 and 31) received a Spearman's rank correlation of 0,734 and a R- value of 0,729 at the significance level of 5,17E-77. From the linear regression, the following relationship between the responses was created:

$$Q14/32 = 0,629 + 0,794 * Q13/31$$

To illustrate the correlation in a simplified way, a graph of the mean values is presented below.



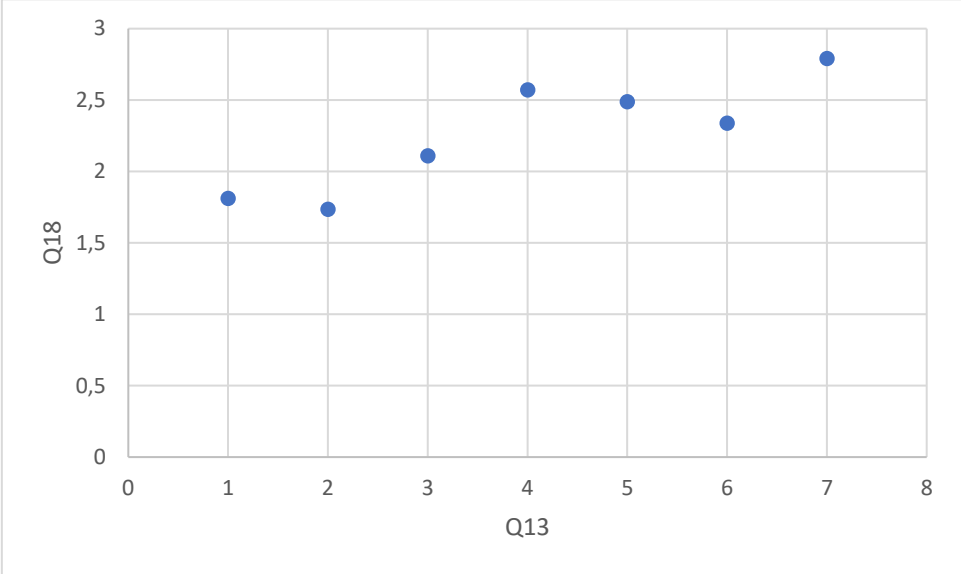
The responses from all of the four productivity questions were moderately strongly correlated with each other, and but the strongest correlations were between ability to work and ability to concentrate, and between motivation and ability to concentrate. The moderate correlation indicate that they work as supplements to one another.

#### 4.2.5 Overall control and productivity

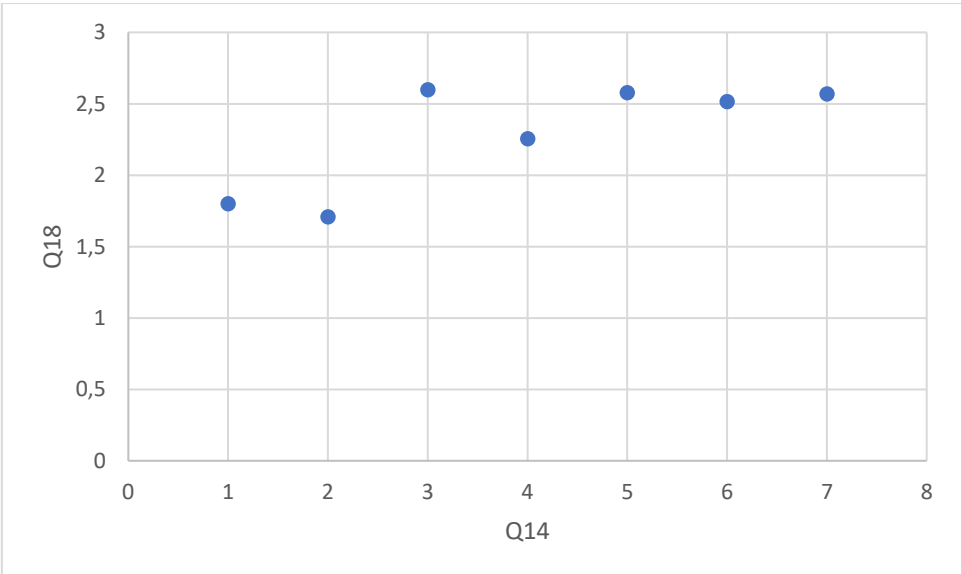
*The amount of overall control is evaluated by the mean value of the four control aspects (temperature, air quality, acoustics and lighting), similarly as it was evaluated by Leaman & Bordass (1999). The correlation between environmental control and the four different productivity metrics were investigated based on approximately 230 datapoints.*



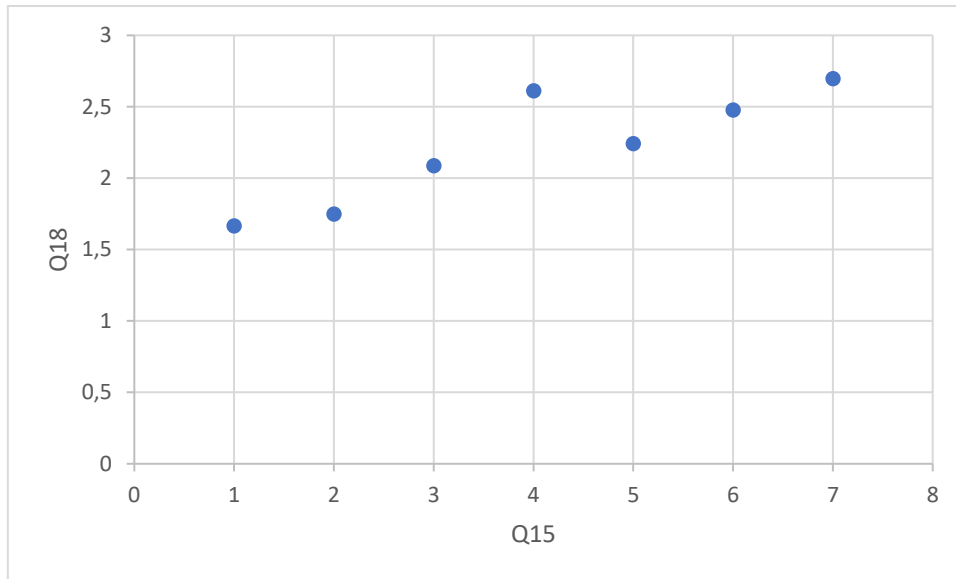
The correlation between overall control (question 18) and ability to concentrate (question 13) was relatively weak and insignificant (Spearman’s rank correlation= 0,145 , R=0,167, p<0,00698). To illustrate the correlation in a simplified way, a graph of the mean values is presented below.



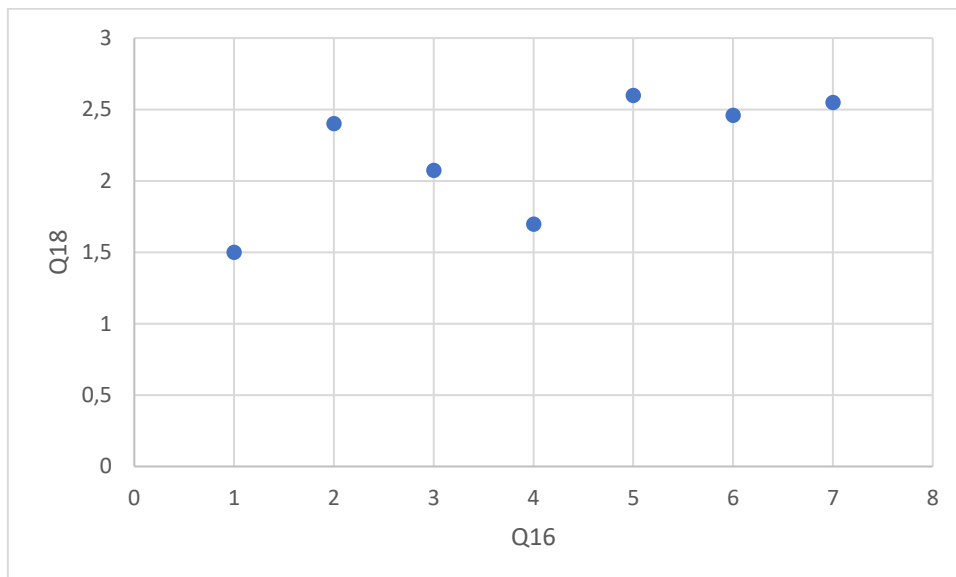
The correlation between overall control (question 18) and motivation (question 14) had similar magnitude (Spearman’s rank correlation = 0,150, R= 0,151 , p<0,0193). To illustrate the correlation in a simplified way, a graph of the mean values is presented below.



The correlation between control (question 18) and ability to work (question 15) received a Spearman’s rank correlation of 0,160 and a R- value of 0,142 at the significance level of 0,0282. To illustrate the correlation in a simplified way, a graph of the mean values is presented below.



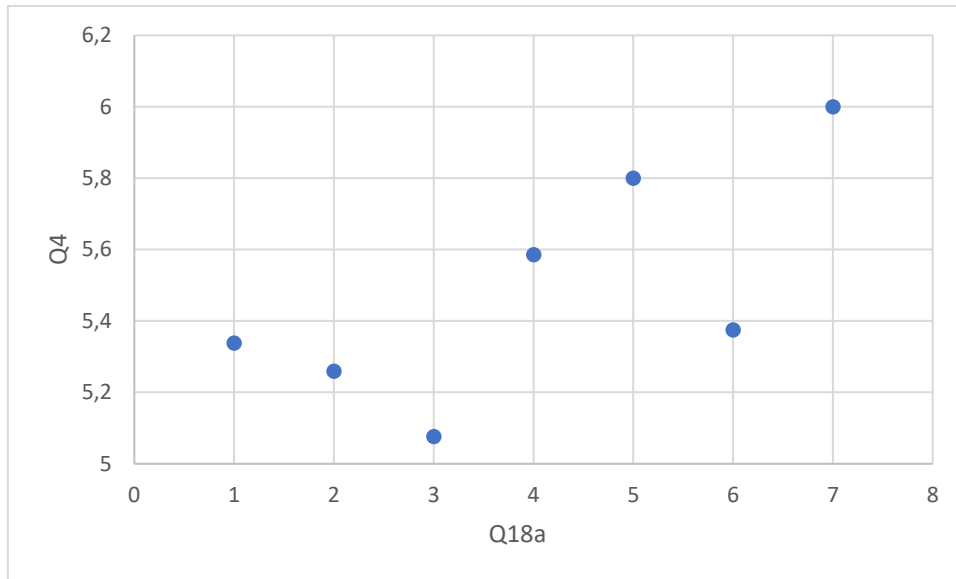
The correlation between control (question 18) and perceived productivity (question 16) received a Spearman's rank correlation of 0,112 and a R-value of 0,088 at the significance level of 0,173. To illustrate the correlation in a simplified way, a graph of the mean values is presented below.



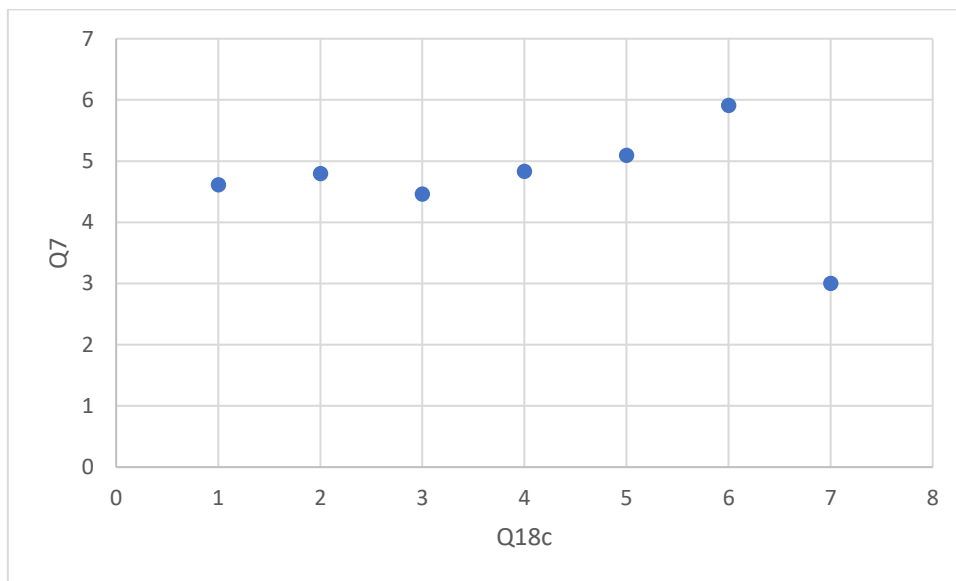
#### 4.2.6 Control and satisfaction

*This section will analyse if there are any significant correlations between the satisfaction of a particular environmental parameter and how the subjects perceive that the parameter influence productivity. The correlations are based on approximately 230 datapoints.*

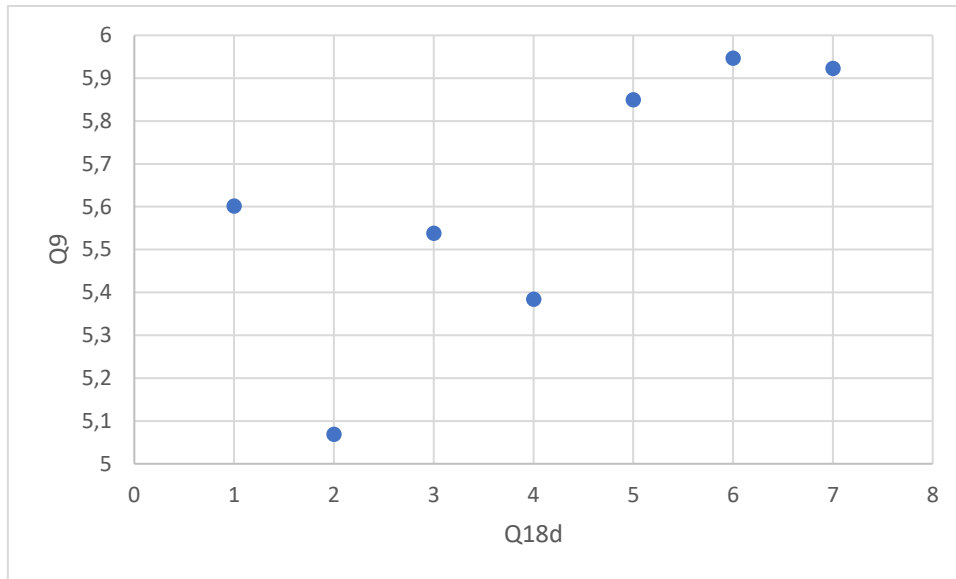
The correlation between thermal satisfaction (question 4) and perceived control of the temperature (question 18a) received a Spearman's rank correlation of 0,199, while the R-value was considerably lower and insignificant ( $R=0,101$ ,  $p < 0,118$ ). To illustrate the correlation in a simplified way, a graph of the mean values is presented below.



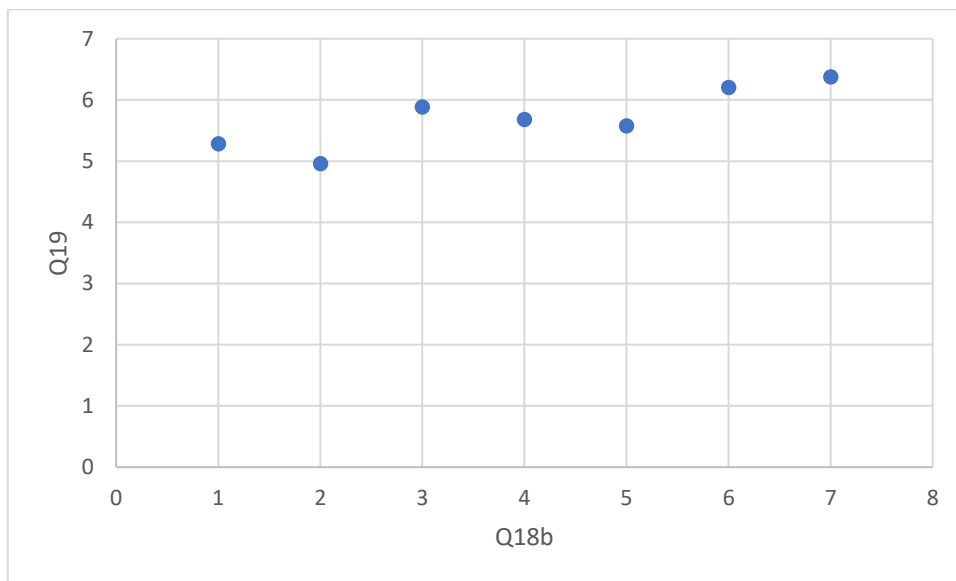
The correlation between acoustical satisfaction (question 7) and ability to control the noise (question 18c) received a Spearman's rank correlation of 0,182, while the R- value was lower an insignificant ( $R=0,118$  ,  $p < 0,07$ ). To illustrate the correlation in a simplified way, a graph of the mean values is presented below.



The correlation between the satisfaction with lighting (question 9) and ability to control the light (question 18d) received a Spearman's rank correlation of 0,098, while the R-value was lower and insignificant ( $R=0,073$  ,  $p < 0,259$ ). To illustrate the correlation in a simplified way, a graph of the mean values is presented below.



The correlation between air quality acceptability (question 19) and ability to control the air quality (question 18b) received a moderately strong Spearman’s rank correlation of 0,234, and a significant but weaker R- value of 0,180 ( $p < 0,0062$ ). To illustrate the correlation in a simplified way, a graph of the mean values is presented below.



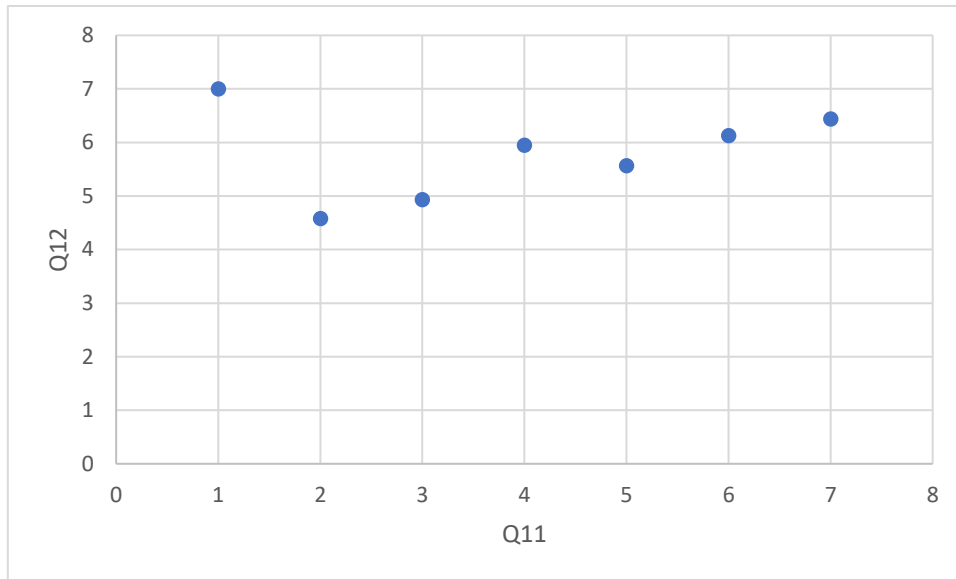
#### 4.2.7 General questions and specific ones

*This section will investigate if the general questions concerning the four environmental parameters receive similar responses as the mean values of the more detailed ones. The analyses are based on approximately 230 datapoints.*

To begin with, the correlation between the acute health symptoms (mean value of question 12) and general wellbeing (question 11) received a Spearman’s rank correlation coefficient of 0,458, while the R-value was 0,371 at the significance level of 3,39E-9. From the linear regression, the following relationship between the responses was created:

$$Q12_{avg} = 4,16 + 0,322 * Q11$$

To illustrate the correlation in a simplified way, a graph of the mean values is presented below.

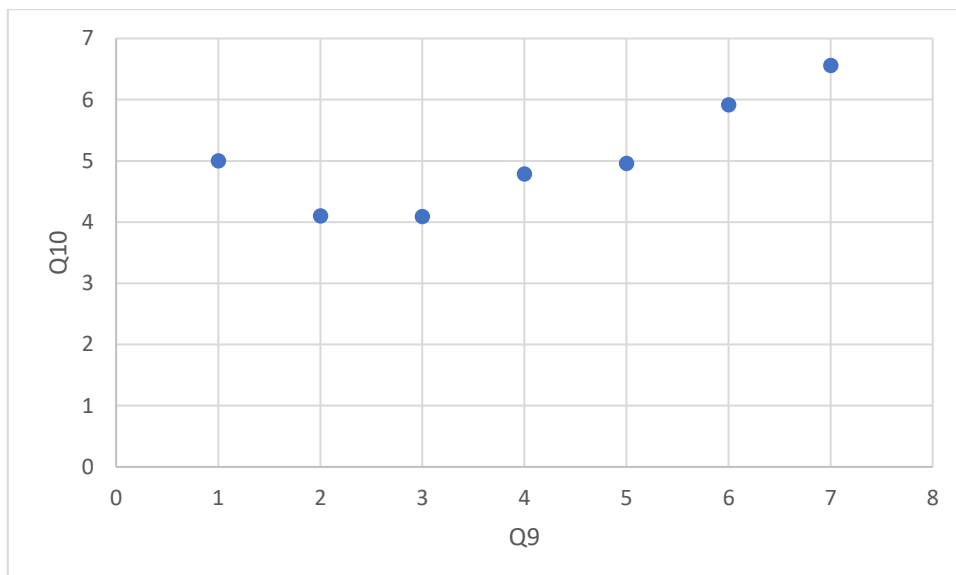


The mean value of question 12 was 5,91 (mean standard deviation of 1,96) compared to a mean value of 5,44 for question 11 (standard deviation of 1,38), which means that the subjects were more negative in their overall wellbeing assessment than in the more detailed evaluations. However, it must be pointed out that the scales are slightly different (the general one is between *unwell* and *very well*, while the specific ones are between *strong symptoms* and *no symptoms*) although all were 7- pointed.

The correlation between the mean values of the individual lighting questions (question 10) and the general lighting satisfaction (question 9) received a Spearman's rank correlation coefficient of 0,738 and an R-value of 0,696 at the significance level of 5,70E-36. From the linear regression, the following relationship between the responses was created:

$$Q10_{avg} = 2,69 + 0,533 * Q9$$

To illustrate the correlation in a simplified way, a graph of the mean values is presented below.

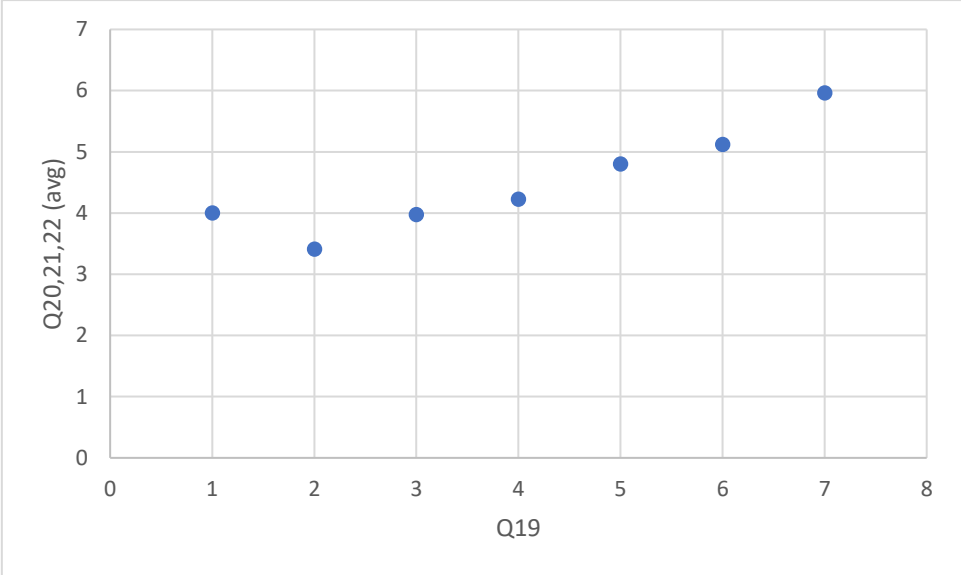


The mean satisfaction in the specific question was slightly higher than the overall question (5,65 compared to 5,54, with the standard deviations of 1,50 and 1,55).

The correlation between the mean value of the following three specific questions regarding air quality (question 20, 21 and 22) and overall air acceptability (question 19) received a Spearman’s rank correlation coefficient of 0,678 and a R- value of 0,667 at the significance level of 6,78E-31. From the linear regression, the following relationship between the responses was created:

$$Q_{20/21/22_{avg}} = 2,35 + 0,496 * Q_{19}$$

To illustrate the correlation in a simplified way, a graph of the mean values is presented below.

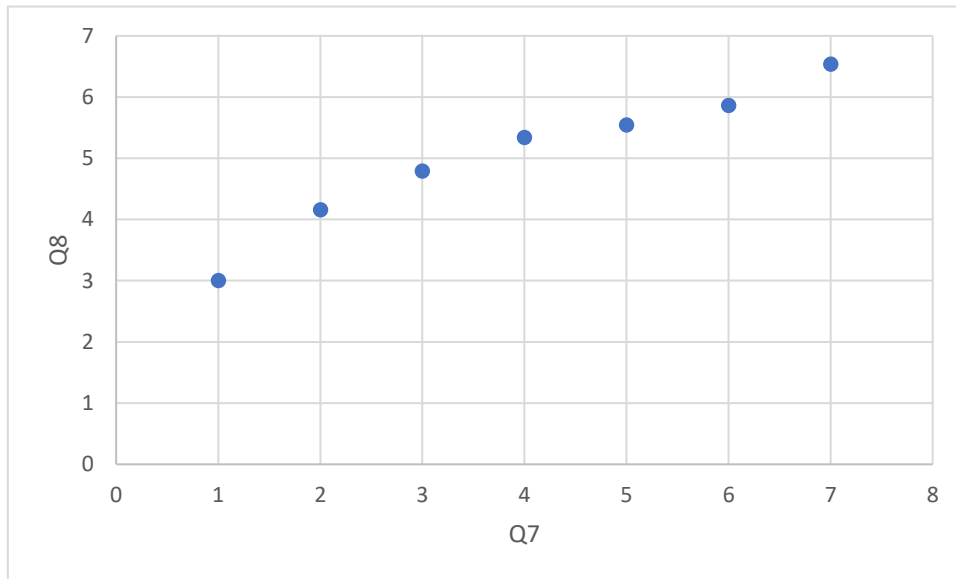


The mean satisfaction was lower concerning the more specific questions compared to the general acceptability question (5,08 compared to 5,47, with the standard deviations of 1,51 and 1,58). It must be mentioned again that scales were slightly different between all of the questions regarding air quality, although all were 7 pointed with poor air quality to the left and good air quality to the right.

The correlation between the mean values of the specific parameters regarding acoustics (question 8) and overall acoustic (question 7) received a Spearman’s rank correlation coefficient of 0,591, while the R- value was 0,570 at the significance level of 4,64E-22. From the linear regression, the following relationship between the responses was created:

$$Q_{8_{avg}} = 3,43 + 0,431 * Q_7$$

To illustrate the correlation in a simplified way, a graph of the mean values is presented below.



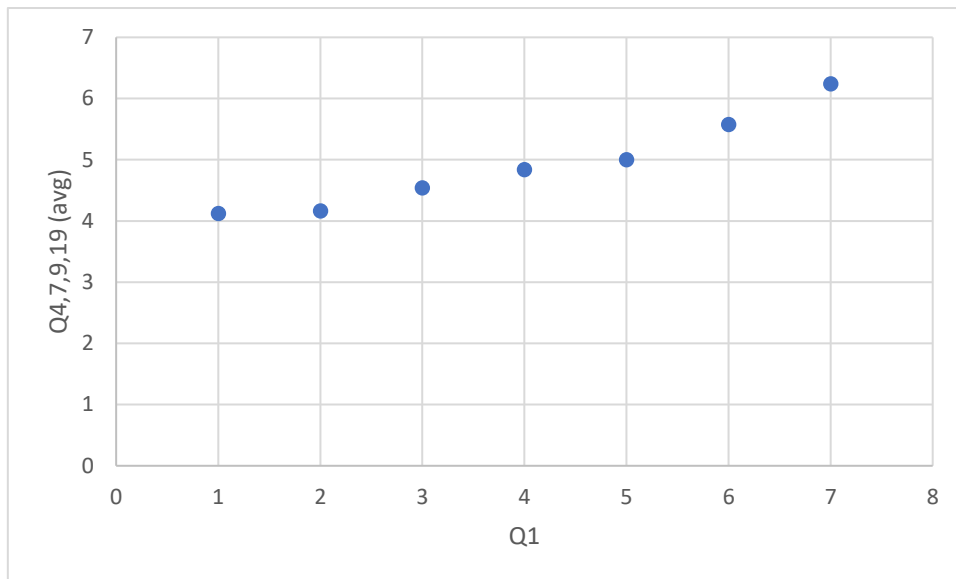
The mean value of the individual parameters received higher satisfaction than the overall acoustic question (in average 5,48 compared to 4,76, with the standard deviations of 1,63 and 1,62).

The questions concerning thermal comfort was not structured the same way which made it more difficult to compare the overall thermal satisfaction with the more specific aspects of thermal satisfaction.

#### 4.2.8 Forgiveness

*The “forgiveness” has been defined by Leaman (1995) as the ratio between the overall satisfaction and the satisfaction with the four individual environmental parameters (thermal climate, air quality, lighting and acoustics). However, the overall air quality has not been evaluated by the exact same scale as the others, but it is nevertheless deemed meaningful to do the analysis. The forgiveness evaluation is based on approximately 230 datapoints. Leaman et.al (2007) have found a strong correlation between forgiveness and perceived productivity, which is why this topic might be of some interest.*

The correlation between the mean values of the four environmental parameters (question 4, 7, 9 and 19) and the overall satisfaction overall satisfaction (question 1) received a Spearman rank correlation coefficient of 0,578, while the R- value was 0,555 at the significance level of 8,95E-21. To illustrate the correlation in a simplified way, a graph of the mean values is presented below.



The mean value of the general environmental satisfaction was lower than the mean value of the individual ones (5,15 compared to 5,29, with the standard deviations of 1,46 and 1,54) which would indicate that the occupants are not forgiving of the building.

#### 4.2.9 The perceived productivity impact of different environmental parameters

*Question 17 concerned how the subjects perceived that the different environmental parameters influenced their productivity. The approach of directly asking the subjects how each parameter influence productivity is quite different than asking how productive the subjects feel and correlate that with how satisfied they are with different environmental parameters. It has previously been found that the correlation between productivity (perceived productivity and ability to work) and thermal comfort, air quality acceptability and lighting satisfaction is approximately equally strong, while it is weaker with acoustical satisfaction. The previous findings would thus indicate that acoustics would be the parameter with the lowest impact on productivity. The following analysis is based on approximately 120 responses.*

The responses from question 17 do not support the previous findings. Instead, the responses indicate that thermal comfort is the parameter with the lowest influence on productivity while acoustics is the one with the greatest impact. So, there is a crucial inconsistency between the two ways of measuring how productivity, but the question remains which one is most valid. A higher number corresponds to the perception of stronger influence on productivity. The question was slightly modified between phase 1 and 2 of the study, and it was decided that only the data from the second part was to be used. The mean values that were obtained were 3.0 for thermal comfort, 3.28 for air quality, 3.11 for lighting and 3.97 for acoustics. These values are considerably lower than for the entire dataset, but the “order” remained the same. The standard deviation was 2.19, 2.19, 2.15 and 2.22 for the responses of the second phase, which yields coefficients of variation (standard deviation divided by the mean value) between 0,73 and 0,55. These coefficients of variation are relatively high (the mean coefficient of variation for all the questions were 0,39) which means that the responses were relatively scattered.

Question 17 also included evaluations of how much productivity is influenced by crowdedness, office layout, cleaning & maintenance, or building systems that do not function properly. They received mean values of 3,29 for crowdedness, 3.71 for office layout, 3.20 for cleaning & maintenance and 3.37 for building systems. The coefficients of variation were also very high concerning those four aspects (between 0,68 and 0,77) which means that the responses are scattered. Out of those parameters, the layout is clearly perceived as the most important parameter in creating a productive building.



#### 4.2.10 Satisfaction with the individual environmental parameters and perception of their influence on productivity

*This section will analyse if any correlation can be observed between the overall satisfaction questions regarding temperature, noise/acoustics, lighting and air quality and how they are perceived to influence the productivity. Each correlation is based on approximately 230 datapoints.*

The correlation between satisfaction of the temperature (question 4) and how much the subject perceived that he/she was influenced by too hot or too cold temperatures (question 17a) was low (Spearman's rank correlation of -0,143,  $R = -0,216$  at  $p < 0,0008$ ). So, a subject who is more satisfied with the temperature may perceive that their productivity is slightly less affected by poor temperature conditions. Again, it must be mentioned that the formulation of question 17 was slightly changed before the second phase of the study. By only analysing the data from phase two, the corresponding correlations were -0,176 and -0,270.

The correlation between satisfaction with the acoustics (question 7) and how much the subject perceived that he/she was influenced by noise (question 17d) was low (Spearman's rank correlation of -0,164,  $R = -0,216$  at  $p < 0,0008$ ). So, a subject who is more satisfied with the acoustics may perceive that their productivity is slightly less affected by noise. By only analysing the data from phase two, the corresponding correlations were -0,393 and -0,431, which is considerably higher than for the whole dataset.

The correlation between satisfaction of the lighting (question 9) and how much the subject perceived that he/she was influenced by poor lighting (question 17c) was low (Spearman's rank correlation of -0,120,  $R = -0,190$  at  $p < 0,0032$ ). So, a subject who is more satisfied with the lighting may perceive that their productivity is slightly less affected by poor lighting quality. By only analysing the data from phase two, the corresponding correlations were -0,293 and -0,312.

The correlation between air quality acceptability (question 19) and how much the subject perceived that he/she was influenced by poor air quality (question 17b) was slightly stronger (Spearman's rank correlation of -0,237,  $R = -0,304$  at  $p < 2,71E-6$ ). So, a subject who is more satisfied with the air quality should perceive that their productivity is less influenced by poor air quality. By only analysing the data from phase two, the corresponding correlations were -0,286 and -0,344.

#### 4.2.11 Productivity/crowdedness and the individual parameters

*As shown in the previous section, crowdedness was perceived to be moderately strongly associated with productivity. It may not be surprising that a high occupancy density influence productivity negatively, because humans are associated with the emittance of bioeffluents, sound, heat, moisture for instance. This section will investigate if any strong correlations can be observed between how productivity is influenced by the crowdedness and how satisfied the occupants are with the thermal climate, acoustic climate, and air quality.*

The correlation between crowdedness/productivity (question 17e) and thermal satisfaction received a Spearman's rank correlation coefficient of -0,110, while the linear correlation was -0,178 at the significance level of 0,0062. When only including the data from the second study phase (after the rephrasing of question 17) the correlation was approximately equally strong (Spearman's rank correlation coefficient of -0,104 and a  $R$ -value of -0,214).

The correlation between crowdedness/productivity (question 17e) and acoustical satisfaction (question 7) received a Spearman's rank correlation coefficient of -0,103 while the linear correlation was -0,153 at the significance level of 0,018. However, when only including the data from the second

phase the correlations were considerably stronger (Spearman's rank correlation of -0,264 and R value of -0,313 at the significance level of 0,000155).

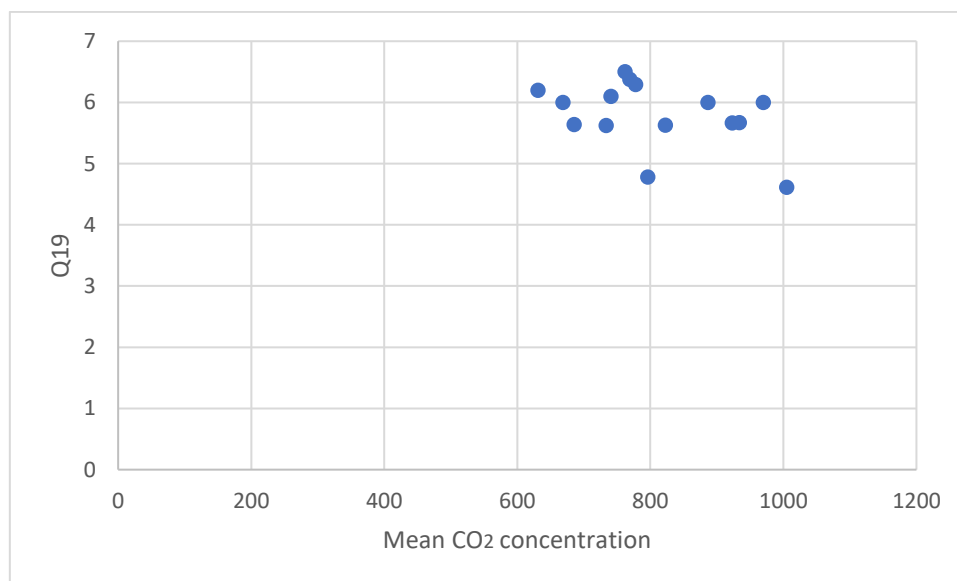
The correlation between crowdedness/productivity (question 17e) and air quality acceptability (question 19) received a Spearman's rank correlation coefficient of - 0,233 and a linear correlation of - 0,293 at the significance level of 6,59E-6. When only including the data from the second phase the correlations approximately similarly strong (Spearman's rank correlation of -0,246 and R value of - 0,340 at the significance level of 0,00036).

These findings indicate that disturbance caused by crowdedness is more strongly associated with poor air quality than with the thermal climate and with acoustics.

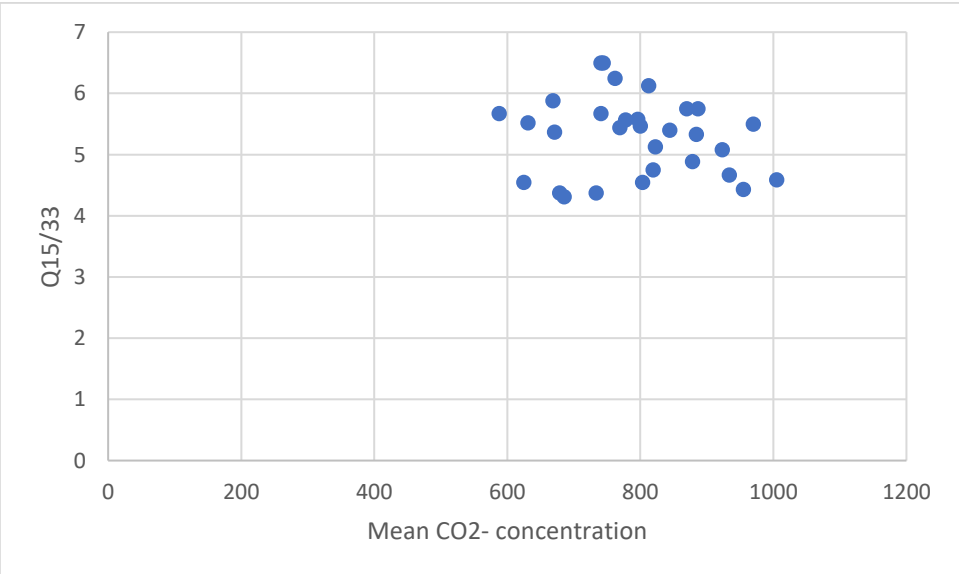
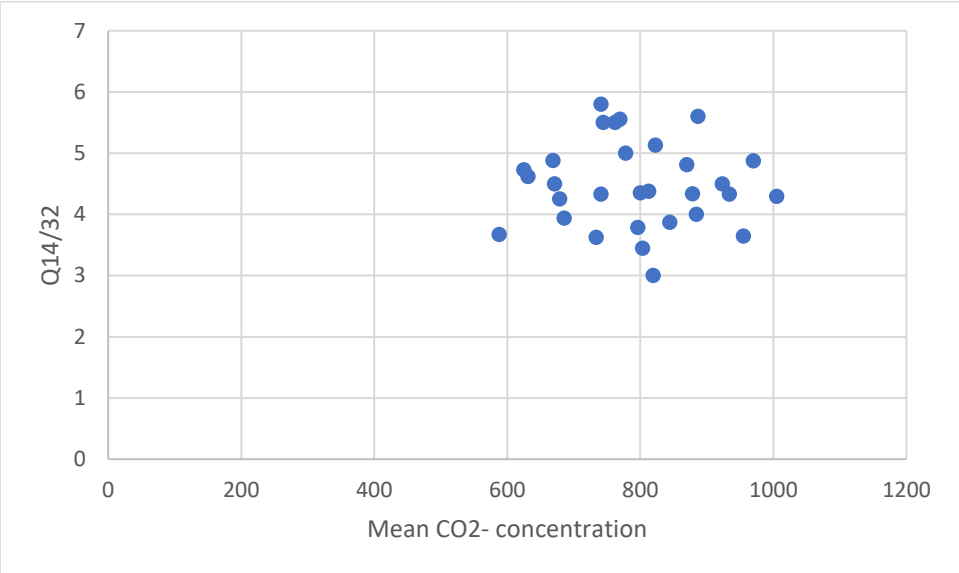
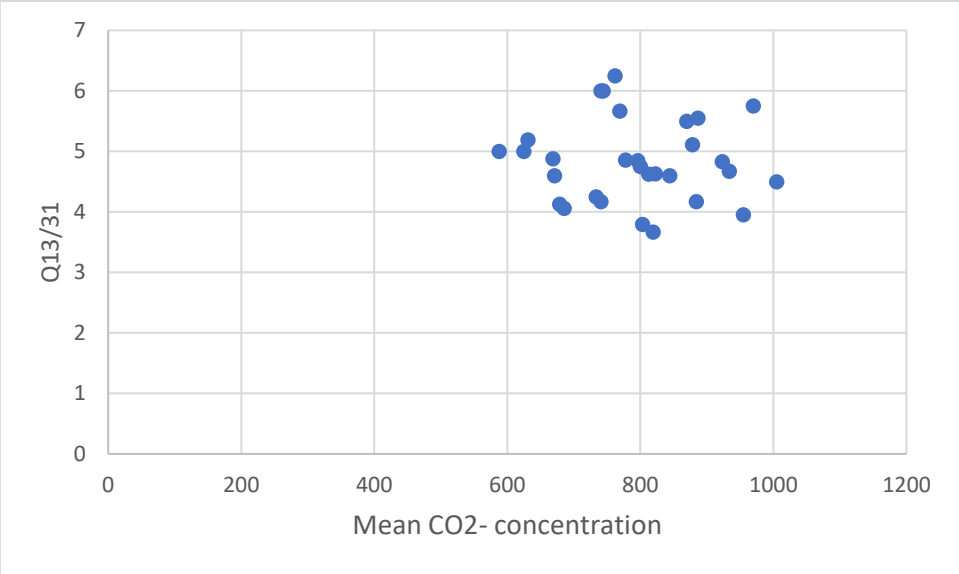
#### 4.2.12 CO<sub>2</sub>- concentration

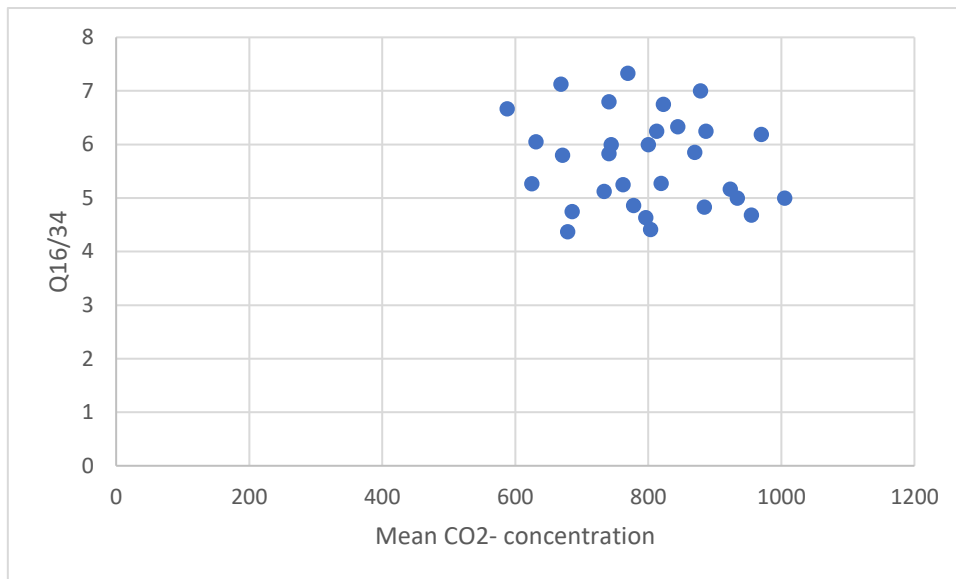
*The correlations between mean CO<sub>2</sub>- concentration during a session and the responses of the corresponding survey concerning the questions about air quality acceptability (question 19), concentration (question 13 and 31), motivation (question 14 and 32), ability to work (question 15 and 33) and perceived productivity (question 16 and 34) were investigated.*

The Spearman's rank correlation between CO<sub>2</sub>-concentration and air quality acceptability was -0,336, while the linear correlation was -0,427 but not statistically significant ( $p < 0,112$ ). Only 15 datapoints was available for this investigation, which would explain the relatively high correlation coefficients but the low statistical significance. The datapoints are presented in the following graph.



The Spearman's rank correlation between CO<sub>2</sub>- concentration and the four productivity questions was weak (between -0,073 and -0,146) for all of them. None of the linear correlations was statistically significant. All of these correlations tests were based on 30 datapoints. The graphs are presented below.



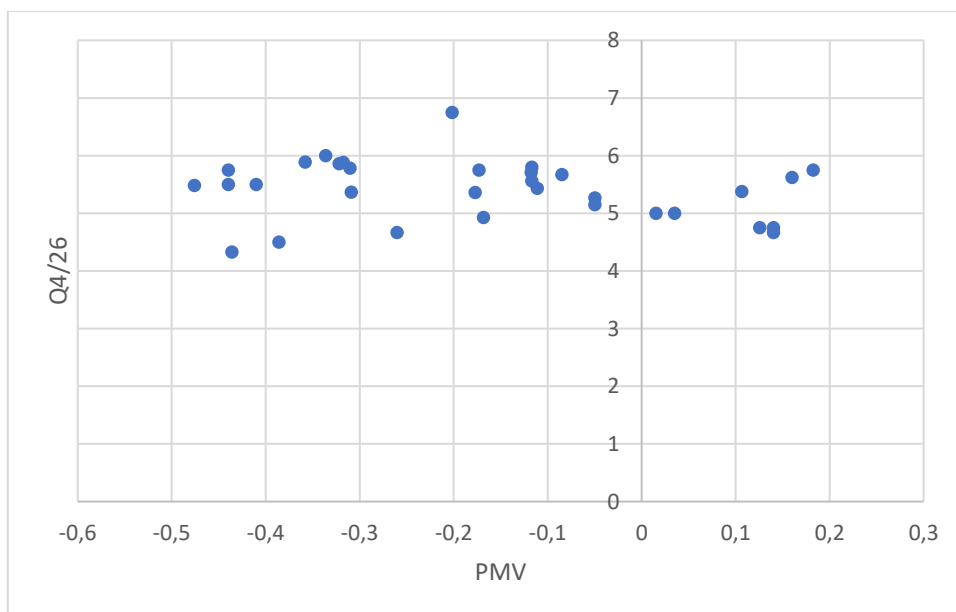


#### 4.2.13 PMV- value

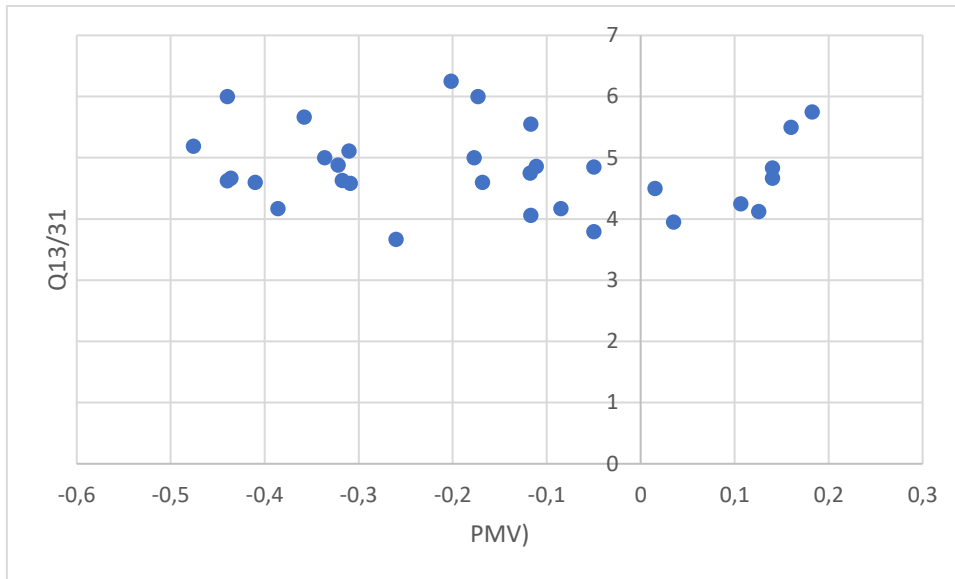
The correlations between the calculated PMV- value and the responses of the questions about thermal satisfaction (question 4), concentration (question 13 and 31), motivation (question 14 and 32), ability to work (question 15 and 33) and perceived productivity (question 16 and 34) were investigated. All these correlation tests are based on 32 datapoints.

The mean PMV- value of each session was calculated based on the physical measurements and the responses from the clothing question in the survey. The metabolic rate of 1,2 met was assumed to be applicable for all sessions.

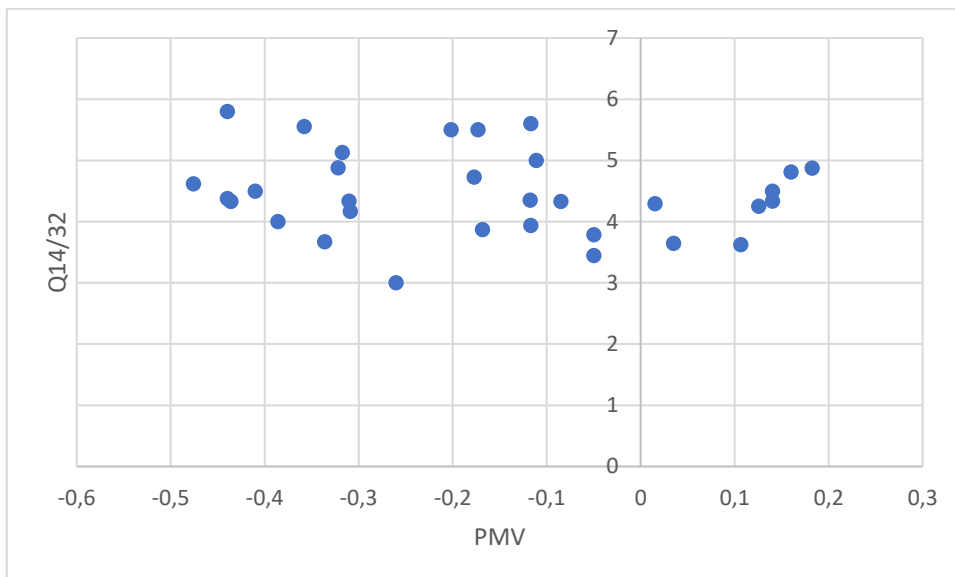
The correlation between PMV- value and thermal satisfaction (question 4/26) was low (Spearman's rank correlation coefficient of -0,256 and a R- value of 0,188 that was not statistically significant. The inclination of the trend appears to be relatively weak in the graph below.



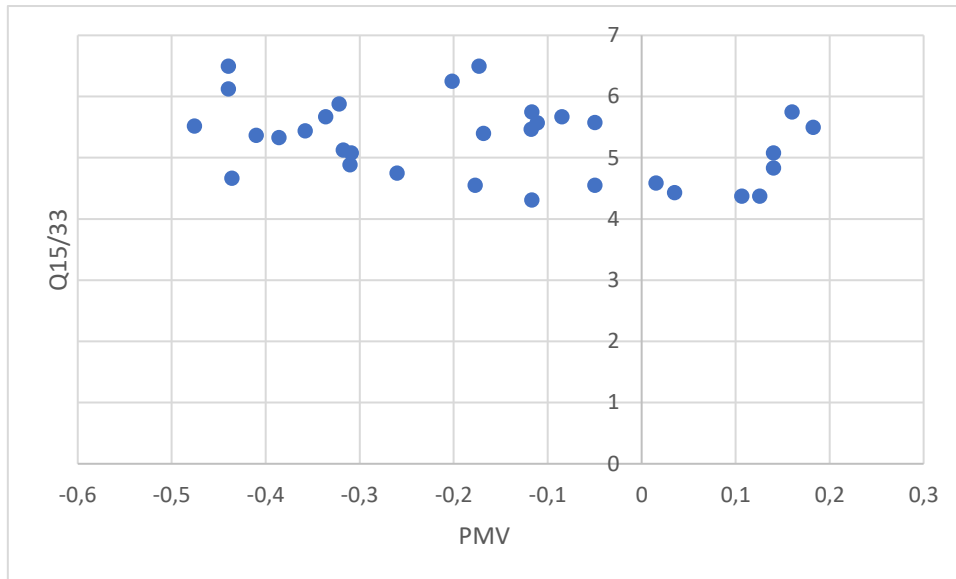
The Spearman's rank correlation between PMV- value and ability to concentrate (question 13/31) was -0,192 and the R- value -0,130 but not statistically significant. The graph is presented below.



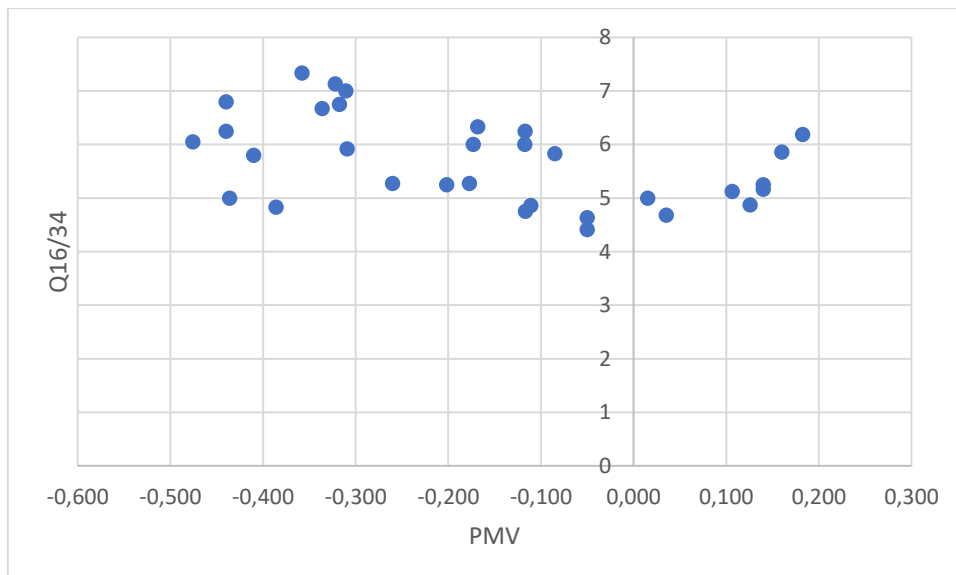
The Spearman's rank correlation between PMV- value and how motivated the subjects were to work hard (question 14) was -0,228 and the R- value -0,176, but not statistically significant. The graph is presented below.



The Spearman's rank correlation between PMV- value and ability to work was -0,312 and the R- value -0,348 and not quite statistically significant. The graph is presented below.



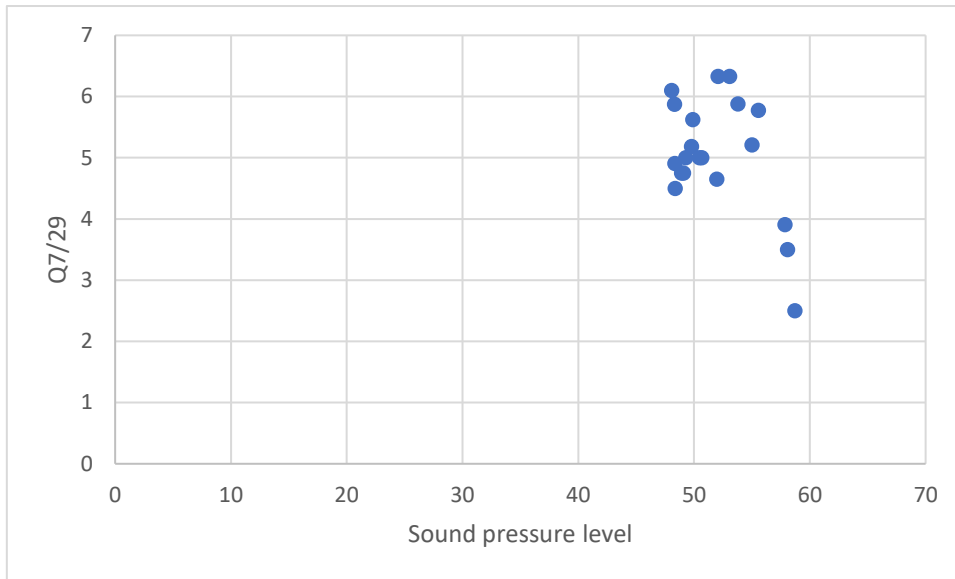
The Spearman's rank correlation between PMV- value and perceived productivity was -0,467 and the R- value -0,458 at a significance level of 0,0085. The graph is presented below.



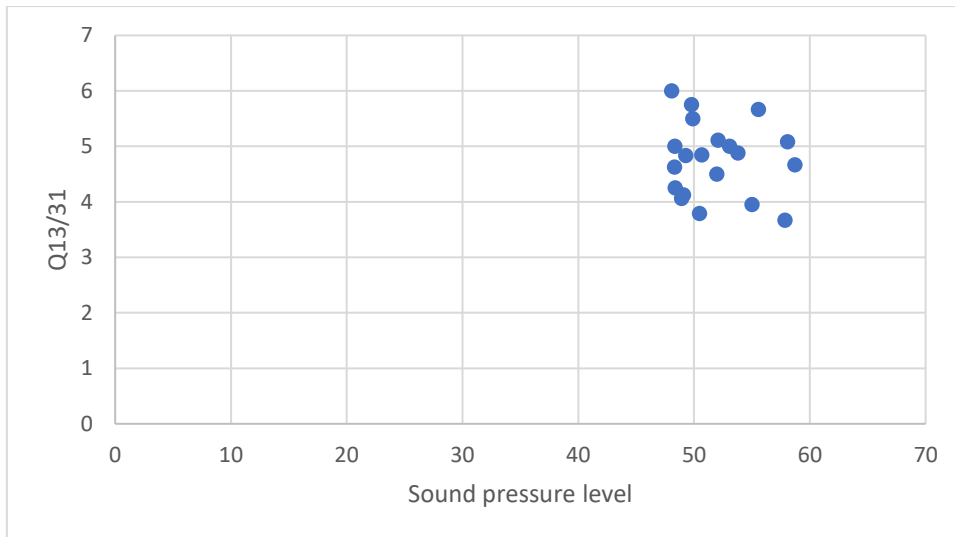
#### 4.2.14 Sound pressure level

*The correlations between the measured sound pressure level and the responses of the questions about acoustical satisfaction (question 7 and 29), concentration (question 13 and 31), motivation (question 14 and 32), ability to work (question 15 and 33) and perceived productivity (question 16 and 34) were investigated. The analyses are based on 20 datapoints.*

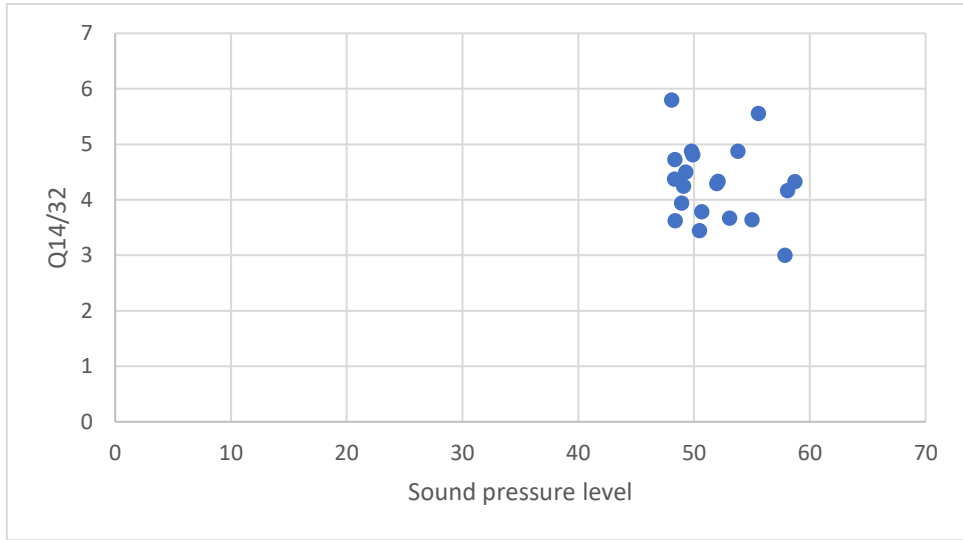
The Spearman's rank correlation between mean sound pressure level and acoustical satisfaction was relatively weak (-0,186) but the R- value was much stronger (-0,486) and statistically significant ( $p < 0,030$ ).



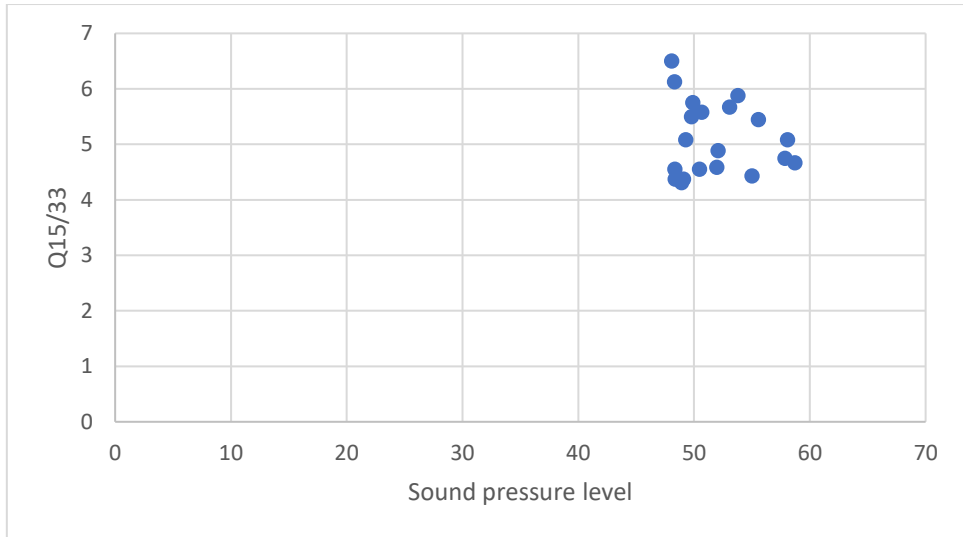
The Spearman's rank correlation between mean sound pressure level and ability to concentrate was weak (-0,061), and the R- value was -0,129 and not statistically significant.



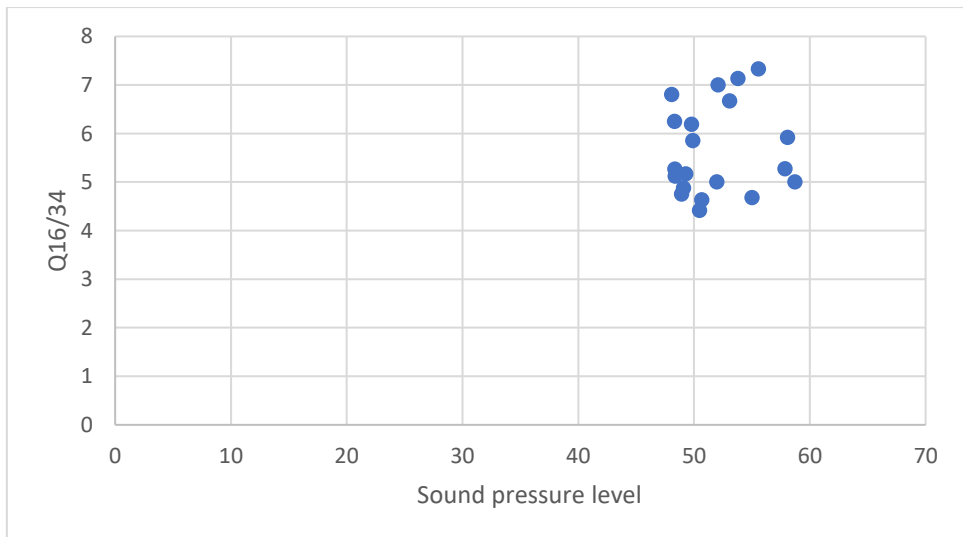
The Spearman's rank correlation between mean sound pressure level and motivation to work hard was relatively weak (-0,235) and the R- value was -0,223 but not statistically significant.



The Spearman's rank correlation between mean sound pressure level and ability to work was weak (-0,011) and the R- value was -0,133 and not statistically significant.



The Spearman's rank correlation between mean sound pressure level and perceived productivity was weak (-0,080) and the R- value was -0,105 and not statistically significant.





## 5 DISCUSSION

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*This chapter will discuss the findings of the report. The first section will discuss the literature review, especially concerning the methodologies used and the results that have been obtained in the papers that have been reviewed. The second section will discuss the outcomes of the statistical analyses, sometimes through comparisons with the literature. The third and final part of the discussion will discuss how future studies should be conducted based on the findings from the current one, as well as discuss the shortcomings and weaknesses of the current study.*

### 5.1 DISCUSSION OF THE LITERATURE REVIEW

The evidence from the literature indicate that the connection between quantitative measurements of productivity and subjective evaluations is complex. Several studies have found a clear consistency between the two, while other have failed to show any consistency at all. Numerous studies have found that quantitative improvements of productivity occur simultaneously as a few subjective improvements. Other have found that different environmental conditions are associated with several subjective feelings and with a few quantitative ones. Based on this, it is found likely that if poor environmental conditions give rise to feeling of low environmental satisfaction, intense health symptoms, bad mood or low perceived productivity, then real productivity should also be low. Similar thoughts have been discussed previously, for instance by Fang et.al (2004) who consider acute health symptoms as indicators of productivity, especially on long term. Just like the reasoning of Fang et.al (2004), it may be reasonable to believe that environmental dissatisfaction after a while may cause disturbance that in turn may influence productivity negatively. The time aspect may be critical in some instances, both in a sense that it may take time for symptoms and other subjective feelings to appear, but also that it is often problematic to conduct long term measurements.

The connection between quantitatively measured productivity and subjective evaluations may not be strong for every individual aspect/question. However, it is believed that by combining the findings from several questions it may be possible to conclude something about how the indoor environment influence real productivity. If the occupants in a particular building has low environmental satisfaction, high prevalence or intensity of acute health symptoms and if they also perceive that their productivity is low, it is found likely that the real productivity has potential to be increased by improving the indoor environmental conditions.

However, there are several studies that do not show any consistency between the subjective and quantitative evaluations. The inconsistency and ambiguity between the studies has resulted in confusion among researchers and attempts to explain this has been undertaken. It has been speculated that motivation, fatigue and arousal may have some influence on the outcomes of the quantitative productivity tests. Failing to observe a productivity change may also be due to inappropriate productivity evaluation. It has been mentioned repeatedly how difficult it is to measure productivity for most office works, and it is possible that a change in the indoor environment influence simulated office tasks and real work differently. The evaluation design, test composition and other factors such as the complexity of the simulated tasks are also parameters that may influence the outcomes of the tests. As discussed above, it is believed by a number of researchers that the test durations may influence the outcomes considerably, for instance that the impact of adverse indoor environment may appear only after longer time than what is typically used in the productivity tests. Another possible issue that has been brought up is that subjects may experience a learning effect if they perform similar tests at different occasions. This effect could certainly be very problematic in

simulated office evaluations where the same subjects are exposed to different environmental conditions.

A few of the above reviewed studies have found significantly *lower* satisfaction or higher symptom intensities in environmental conditions that was, as opposed to what one may expect, significantly associated with *higher* productivity. Such inconsistencies are of special interest in this study, because they contradict the hypothesis that subjective evaluations are valid indicators of productivity. Tham et.al (2003) found that quantitatively measured productivity was higher in a condition where the thermal satisfaction was lower. Petersen et.al (2016) found that the indoor environment was perceived worse in a ventilation condition that was associated with higher quantitatively measured productivity. These studies emphasise the complexity in measuring productivity, as well as highlighting the complexity in creating good indoor environment. They have shown that *attempts* to create better indoor environment may actually have the opposite effect. This complexity demonstrates how important it is to include proficient designers, contractors and managers in the design, construction and operation phases of a building. This should be particularly important for developers that aim to surpass the requirements in the existing building codes, as they need to be extra conscious of the side effects that may appear from, for instance, increasing the ventilation flow.

It is possible that there are no generalisable optimum levels of the indoor environmental parameters because the perception of the indoor environment depends on so many contextual factors that interact with each other in complex ways. What is perceived as too low temperature in one context might be too high in another. The same should apply for air quality, lighting and acoustics as well. Too high values of a variable may be just as distracting or uncomfortable as a too low one. This emphasises the importance of individual control, to provide the occupants the possibility to adjust the environment according to his or her preferences in every context. It is also crucial that the professionals in the industry have a deep understanding of the indoor environment and how it influence the occupants. We need designers and engineers who are aware of the potential negative aspects that may arise from suboptimal solutions, and that they do care about how the occupants perceive the building.

It is likewise vital that the occupants possess an understanding about the building and its systems, especially if the occupants would receive higher environmental control. In that way, they can make more rational decisions when operating the building. They should for instance be aware of the potential trade-offs that may arise from different operations, for instance by adjusting the thermostats, opening the windows, or let down the window blinds. As an example, by opening the windows one may reduce the CO<sub>2</sub>- concentration in the room, but it may also influence the air temperature and the concentration of other air pollutants. By letting down the window blinds one may reduce the glare, but simultaneously reduce the temperature and increasing the need for electrical lighting (electrical lighting may be perceived as less satisfactory than natural). These are a few trade-offs that the building users need to be aware off if the strategy to increase the environmental control is to be successful. Environmental control is indeed associated with both perceived productivity and quantitatively measured productivity, but it is not enough to simply increase the possibility to control the indoor environment. To be able to achieve a higher productivity from the higher environmental control, the occupants need to know that they possess the control and how to use it. The perceived environmental control in the *Educational Building* was indeed relatively low in general. The mean value of question 18 was between 2,11 and 2,88 for the four environmental parameters (on a 7-point scale, where a low value corresponded to low control). Based on my own personal experience, I would say that the environmental control is relatively high in the building and I believe that the low mean values of the perceived control may be because the students are not aware of their possibilities.

There are a few studies that have observed decreased productivity from environmental changes that were intended as improvements. Wargocki et.al (2004) have found that the productivity was lower in a condition with higher ventilation rate, when the air filters were old. Zhang et.al (2017a) have found that the performance of one performance test was higher when the air quality was considerably degraded. This is believed to be caused by higher stress and arousal that may come as a result of poor indoor environment. Satish et.al (2012) found that one out of nine cognitive performance tests received higher scores in a condition with higher CO<sub>2</sub>- concentration than in a lower one. This is believed to be caused by “overconcentration”, at the expense of “the big picture”. These findings further indicate how complex it is to achieve a good indoor environment that enhance productivity, and also how complex it is to measure productivity reliably. Some productivity tests may be influenced differently than one might expect from a changed environmental condition. However, it must be maintained that most productivity tests are either positively, or not at all, influenced by environmental modifications that are intended as positive.

A few of the studies reviewed have investigating what impact the indoor environment has on the educational achievements of children. It should be mentioned that children in schools might be influenced differently by substandard indoor environmental conditions than adults do. For instance, children are more sensitive to high levels of air pollution because they inhale more air in relation to their body (Faustman, et al., 2000). Learning in school and office work may also be influenced differently by the environmental conditions. Evidence has been shown that poor indoor environment may influence the educational achievements of children, and it is thus not unreasonable to assume that young adults in a university building should be influenced much differently. The methods of using data of educational achievement seems promising, as it provides a real and quantifiable output of the work performed at the school. Educational achievements such as grades or test scores may therefore be a relatively valid indicator of how much the students have learned and thus of their productivity at school. The strength in this productivity metric is that it measures the real output of the student’s time at school and that there are no disturbing or complex measurements required. The method may also give a long-term picture of how the indoor environment influence the productivity because it may not only be the indoor environment at the time of the exam that influence the test scores, but the indoor environment throughout the entire course. Two of the three studies reviewed concerning educational achievements have found that the indoor environment in the school buildings may influence the educational achievements.

A few of the papers reviewed have also studied the physiological responses that may arise due to inferior indoor environment. The physiological responses are for instance changes in the haemoglobin in the brain, heart rate, respiratory ventilation, metabolism, end- tidal partial pressure of CO<sub>2</sub>, increased arterial oxygen saturation, tear film mucous quality, diastolic blood pressure, saliva biomarkers, sweating, and finger skin temperature. Responses of these parameters may arise from poor indoor environment, which could be a part of the explanation why poor indoor environment may influence productivity negatively. Such physical responses may even be reflected in the subjective evaluation, for instance as acute health symptoms. Symptoms like fatigue, headache, and difficulty in thinking clearly have occurred simultaneously as those physical responses, which support the hypothesis that subjective evaluations of the indoor environment are valid indicators of how the indoor environment influence the building users. However, several studies have found physiological responses without quantitative productivity impacts. This is yet another indication of how complex the task of measuring productivity is. If physiological responses can be observed after relatively short measurement periods, it is not deemed as unreasonable to assume that some form of productivity impact should be observed after extended periods. This suggest that productivity should either be measured subjectively, or through long term measurements, preferably of real work output if it

somehow can be quantifiable. Physiological measurements can be useful tools to understand the mechanisms behind the impact that the indoor environment has on productivity. Those mechanisms have not been studied in detail in this study, but there are a number of different papers concerning this immensely important topic. It seems like the mechanisms behind how the indoor environment influence the occupants is not very well understood, and it is possible that the topic deserves more attention and more research.

Perceived productivity has been evaluated through a variety of different methods. The perhaps most common way has been to ask the subjects to rate their ability work, given the environmental conditions. However, the interpretation of the question may be considered quite unclear. For instance, does a 5% lower ability to work mean that the productivity is 5% lower? A 5% difference between 50% and 55% is in fact a 10% difference. How the subjects interpret this question remains unknown, but the question has been used frequently in the literature and interesting correlations have been observed between its responses and the responses of other questions. Another way of measuring perceived productivity, that has been used by Murakami et.al (2006) and Ito et.al (2006) is to let the subjects rate the impact that the environmental conditions have had on their test scores and on their speed. This method is deemed as easier to “translate” into real productivity. However, the method tended to overestimate the impact of the environment (in a comparison with their actual test outcomes). The approach of using two different productivity metrics is deemed as promising and would later be incorporated into the survey of the current study. Productivity seems like a too complex concept to be covered in merely one question.

Other scales that have been used does not have a clear connection to a realistic output, such as the scale between “clearly below my average efficiency” and “clearly above my average efficiency”. Such scales may be useful for studying possible associations between productivity and the quality of the indoor environment, although the translation into “reality” is difficult. Another common productivity question is to ask, “how much is your productivity enhanced or decreased by the environmental conditions?”. The responses from such question is easy to translate into reality, if a percentage scale is used, but the question may be perceived to be indeed very difficult to answer for the subjects. The question also remains how valid such responses are, as a more difficult question should yield less accurate responses. It is possible that a simpler response such as “clearly below my average” is much more valid than “10% lower productivity than average”, but what can the information be used for if it does not have a connection to reality? As stated in the introduction, one of the main reasons it is so important to study the topic of productivity in buildings is to create incentives for stakeholders to improve the indoor environment in existing and in future buildings. To be able to achieve this, it is not enough to establish that there is a relationship between productivity and the indoor environment. Additionally, we need to quantify that relationship in real terms so that stakeholders can make rational investment decisions. For instance, we need relationships in terms like “for every l/s-person ventilation airflow above the standards the productivity can be expected to increase between x and y %, given that the ventilation system is installed and maintained according to best practice”. The problem remains that the qualitative output of most office tasks is impossible to quantify, which is the reason why subjective estimations of productivity may be the only viable solution. Therefore, we need to establish a standardised way of evaluating productivity subjectively. That is why we need more research on how productivity can be evaluated subjectively.

A vital parameter that should be considered when uniting around a specific method of evaluating productivity subjectively is its connection to quantitatively measured productivity. We need a subjective method that is relatively closely associated with quantitative ways of measuring productivity, for instance by using real work output or long-term productivity tests. The current study

has reviewed articles that have included both quantitative productivity measurements and subjective evaluations of the indoor environment. It has been found that relatively few have made direct comparisons between perceived productivity and quantitatively measured productivity. Only four such articles have been found (Murakami et.al 2006; Ito et.al 2006; de Visme 2006; Clausen & Wyon 2008). All four are showing a consistency between the two metrics (higher perceived productivity occurs simultaneously as higher measured productivity). However, perceived productivity is clearly overestimating the real productivity considerably in the studies by Ito et.al (2006) and Clausen & Wyon (2008). If it can be assumed that the productivity test that that were used were relatively strong indicators of real productivity, this would indicate that perceived productivity is an indicator of real productivity (although the precision of the subjective evaluation may remain quite uncertain). This emphasise the need for more research within the field, especially research that aim to explore the relationship between perceived productivity and quantitatively measured productivity, and between productivity and other subjective evaluations of the indoor environment (for instance environmental satisfaction and perceived health).

Out of those four papers, three have used methods that relatively easily could be applied in a university context. The evaluations in Murakami et.al and Ito et.al were all conducted as tests of how much the subjects had learned during a lecture, and the productivity evaluation in de Visme it was conducted as a mathematics test. Either of these methods could relatively easily be incorporated in the courses at a university, and they have the advantage of measuring a real productivity output (the output of schoolwork is how much a student has learned). The methodology described above could be applied for future studies by introducing short diagnostic test at the end of standardised lectures. The lecture could for instance be from a basic course in engineering mathematics, as such courses are highly standardised and given to a great number of first and second year students at technological universities. The scores from such tests should be complemented with physical measurements of the indoor environment as well as surveys about how the student perceive the indoor environment, their health and how productive they feel. To investigate the correlation between perceived productivity and quantitatively measured productivity would be the main topic of such study, but it would also be interesting to investigate the correlation between acute health symptoms and measured productivity, and between environmental satisfaction and measured productivity for instance. Any connection between the subjective perceptions of the subjects and their productivity is of great interest.

A problem with this method would be that there would have to be different students for the same lecture, which could result in differences in the study population. As an example, students of a particular engineering programmes might be more interested in learning mathematics than others based on their interests and their other ongoing courses. Another approach could be to evaluate the test scores of the exams at the end of the courses and correlate them with the different building that the different subgroups had their lectures in. The problem with this method would be that the students at The Royal Institute of Technology typically don't spend much of their time in one specific building. Even if they would have all of the lectures of one course in one building, they would probably spend a lot of their time in other buildings while studying on their free time. This makes it complicated to assign any observed differences in the educational achievements to the indoor environmental conditions of a specific building.

Although several studies have observed that improved environmental conditions are associated with both subjective and quantitative improvements, it is difficult to conclude how large the impact is. The perhaps most promising method to decide the productivity impact of, for instance, 1°C or 1l/s-person is to conduct a meta-analysis that include a variety of different productivity metrics. However, it is important to remember that even quantitative methods of measuring productivity don't necessarily

correspond to real productivity. Humphreys & Nicol (2007) have stated that typical office work requires a wide range of skills such as creativity, social skills, analytical skills, intellectual skills and skills of routine work. It could be further claimed that most work contain all of these components to some degree, but the relationship between these “components” can vary quite considerably between different work tasks. This should also be true for the different quantitative methods of assessing productivity that has been used in the reviewed studies above. For instance, the work of a call centre operator at an insurance company might consist largely of routine skills, and undertaking a cognitive decision-making test mainly comprises analytical and creativity skills. Neither of these includes much of social and creative skills for instance, which should be essential component in most office jobs. It is deemed likely that real productivity lies somewhere in between the quantitatively measurements and the qualitative ones, which suggest that we need to use both methods until we understand the relationship between them.

As stated several times before, we need to develop a uniform and unifying way of measuring productivity. To be able to agree upon one method we need much more research within the field. The connection between perceived productivity and quantitatively measured productivity is of great importance, but so is also the connection between environmental satisfaction, health symptoms, physiological responses, and other feelings. The future research need to adapt a multidisciplinary approach because the topic is so complex and comprehensive. The engineering and building perspectives are certainly of importance, but there is also a great need for the behavioural and physiological perspectives to be able to understand how the human body and mind is influenced by the indoor environment. There may also be a need to involve a discipline that can evaluate how different formulations of the productivity questions are perceived by the users, for instance what parameters are typically included in the concept of productivity (for instance concentration, motivation, speed, accuracy, creativity, social skills, ability to learn etc.). There is also a need to involve the industry in the progress of developing an understanding of productivity in buildings. This is necessary to be able to create solutions that may be implemented in reality. For instance, the productivity evaluation should be possible to conduct relatively easily (subjectively and/or quantitatively) which, for instance, would enable it to be implemented in the building certification systems. It is of great importance that the topic of healthy and productive buildings receives more attention in the industry, and by implementing a productivity evaluation as a mandatory procedure in the certification systems would probably be an important step in spreading the knowledge of how productivity is influenced by the quality of the indoor environment.

## 5.2 DISCUSSION OF THE FINDINGS FROM THE SURVEYS AND THE MEASUREMENTS

The correlations that was observed between general satisfaction and the four productivity metrics were moderately strong (Spearman’s rank correlation coefficient between 0,518 and 0,432). The strongest correlation was found regarding ability to work. The correlation concerning perceived productivity was similarly strong as the correlation that was previously found by Humphreys & Nicol 2007, but weaker than the one found by Oseland and Bartlett (1999) (who found  $r$ - values between 0,93 and 0,99). Approximately equally strong  $r$ - values have been found by Leaman & Bordass 2007 and by Oseland (2004) as the ones observed in the current study. However, it appears like most studies that have been reviewed in the literature have observed stronger correlations than observed in the current study.

The correlation between ability to work and the four indoor environmental parameters were similarly strong concerning thermal comfort, lighting satisfaction and air quality acceptability (Spearman’s rank correlation of approximately 0,4) which would indicate that those three parameters influence the

ability to work approximately equally much. The correlation between ability to work and acoustic was slightly lower.

The correlation between perceived productivity and the four environmental parameters support the previous findings that have indicate that acoustical satisfaction is the parameter with the lowest impact in productivity (Spearman's rank correlation of 0,177) while it is approximately equally strongly influenced by the other three (between 0,264 and 0,342). Interestingly, the correlations were considerably weaker than between ability to work and the environmental aspects. This indicates that the question concerning ability to work is more sensitive to the environmental perception than the question regarding perceived productivity. However, it must be mentioned that higher sensitivity does not mean that it is more reliable and more closely associated with real productivity. This brings up the most fundamental question that remains unanswered: how closely connected are subjective evaluations of productivity with real productivity. There are only a few articles in the literature review that shed light on the topic (through a direct comparison) and unfortunately the current study don't contribute to this essential question. However, these findings indicate that there is a considerable difference between the two very common ways of evaluating productivity subjectively (*perceived productivity* and *ability to work*). At first glance, they may appear to be very similar, but they have quite different scales (0 to 100% and -20% to +20%), different formulations and choice of words. One specific difference that is interesting is that fact that the *ability to work* question is not formulated in relation to the indoor environment, while the *perceived productivity* question is. It is found rather surprising that the responses from the *ability to work* question nevertheless is stronger associated with the environmental satisfaction. A question that is easier to answer (and to understand) is believed to yield responses that are more reliable, and it is therefore deemed preferable to use a question like "how productive do you feel?" in comparison with "how productive do you feel in relation to the quality of the indoor environment?". The results from this study indicate that the correlation with the indoor environment is not stronger because the indoor environment is used as a reference (in fact, it appears to be the opposite) and it is therefore preferable not to mention the indoor environment in the formulation of the question.

However, it should be mentioned that the correlations between perceived productivity and environmental satisfaction was lower than expected based on the literature review. Huizenga et.al (2006) found a much stronger linear correlation between perceived productivity and thermal comfort ( $R^2= 0,99$ ) and Tanabe et.al (2015) observed a similarly strong one. Leaman et.al (2007) have also found a much stronger correlation between perceived productivity and the thermal comfort, with  $r$ - values of 0,74. It remains uncertain why the correlations in the current study obtained considerably weaker associations than previously found in the literature. One possible explanation could be that the indoor environment is perceived to be relatively satisfactory in the *Educational Building* (mean value of 5,15 on a 7 point scale) and the subjects may therefore not perceive that they are influenced very negatively by the indoor environment. In a building with greater variations of the indoor environment, the users may perceive that the indoor environment has a stronger influence on their productivity.

The correlations between the four different productivity metrics were moderate to strong. The strongest correlations were observed between perceived productivity and ability to work (Spearman's rank correlation of 0,702) and between motivation and concentration (Spearman's rank correlation of 0,729). The correlation was weaker between perceived productivity and concentration and between perceived productivity and motivation. Interestingly, the correlation between ability to work and concentration and motivation was much stronger which indicates that the question about ability to work may more successfully cover concentration and motivation aspects than the perceived productivity question does. The fact that the correlations were only moderately strong at best, and

relatively weak between some aspects (for instance between concentration and perceived productivity, and between motivation and perceived productivity) indicate that the questions are covering different aspects of productivity like they were intended to do. Most studies that have been reviewed above only include one question about productivity, and Humphreys & Nicol (2007) have even claimed that productivity can be evaluated subjectively by one single question. These findings suggest that one question may not be sufficient to cover the complex concept of productivity. These results would also indicate that the questions concerning *perceived productivity* and *ability to work* are quite different in a sense that *ability to work* seem to cover productivity aspects like *ability to concentrate* and *motivation to work hard* better. *Ability to work* may therefore be a more holistic question and therefore preferable if only one productivity question should be used in future studies.

This report has shown that there are numerous ways of evaluating productivity, but the concept of productivity itself is very vaguely defined for most office works. Productivity has often been defined as the work output divided by the work input. The question that should arise from this definition is what should be included in the definition of input and in the definition of output. The input may be defined as the time spent working, but it could also be the effort (physical and mental effort). Feeling of tiredness, motivation and perception of concentration are all aspects of the work input, but there are more feelings that may be included in the concept. The work output is equally complex to define. Most jobs have some degree of quantitative output and that is often easy to evaluate. It is the qualitative output that is difficult to evaluate, as it comprises numerous aspects like creativity, social interactions, individual learning, artistry and creativity. The current study has attempted to cover all those aspects through four simple questions (ability to concentrate, motivation to work hard, ability to work and perceived productivity in relation to the indoor environment). These four aspects of productivity have been found to be associated with quantitatively measured productivity in the literature, but there are certainly many more aspects that may be included in the concept of productivity. The definition of these four aspects remains quite vague, and different subjects may interpret them differently. For future studies, it would be interesting to study how subjects interpret words like “productivity” “ability to work” and what aspects of their jobs that they regard when they answer a question concerning their productivity. This may be of interest for future studies that are aiming to develop our understanding of how productivity should be evaluated subjectively. The notion of evaluating productivity through more than one question has been presented previously by Murakami et.al (2006) and Ito et.al (2006). Both these studies used *speed* and *accuracy* as separate questions, which made sense in the context of the studies (short diagnostic tests at the end of recorded lectures). However, *speed* and *accuracy* fail to include all those qualitative aspects of productivity that have been discussed above, and I see it as a risk to explicitly emphasise only those two aspects of productivity as the subjects may interpret this as that only quantitative aspects should be regarded.

The correlation between perceived control and the four productivity metrics was relatively weak. The correlations are slightly weaker than previously found by Boerstra et.al (2004), and much weaker than previously found by Oseland & Bartlett (1999). Leaman & Bordass (1999) found a variety of different correlation coefficients between control and perceived productivity in different buildings. The lowest values that they observed were of similar strength as the ones observed in the current one. However, the correlation was much stronger in other buildings. They also found that the association between environmental control and perceived productivity was weaker for buildings with higher satisfaction, which could explain why the correlations were low in the *Educational Building* (with an overall mean environmental satisfaction of 5,16 on a 7 point scale). It is also possible that the weak correlations in this building could be caused by the fact that students of the university typically spend their time in several different buildings, which could mean that they don't investigate what options they have to control the indoor environment in each and every building that they visit. A typical office worker that



spend all of their work time in a single building and may thus be more aware of their options to control the indoor environment.

The correlation between control and satisfaction is relatively weak for most environmental parameters. The strongest correlation was between control and air quality satisfaction, which indicate that air quality is the environmental parameter that should be most vital to let the occupants control in order to create a satisfactory building. The correlation between the satisfaction with the lighting and ability to control the lighting was very weak. This could be explained by a generally high satisfaction with the lighting, but it could also be that the subjects may expect to have a high degree of control of the electrical lighting in most buildings, so they take lighting control for granted. The weak correlation between lighting control and lighting satisfaction could also be because the subjects may simply perceive that lighting control is not particularly important. The correlation between environmental control and environmental satisfaction was indeed weak for all of the four aspects, which may be found surprising. My own personal belief is that somebody who has a large degree of control of the temperature should be much more satisfied with the temperature in the room. The low correlation could indeed be explained by a generally high satisfaction in the building, or that the students chose to maintain thermal neutrality by adjusting their clothing instead. That is of course an alternative to some, but to others it is not possible to adjust the clothing and the environmental control should be an important aspect for them.

There was a generally quite good consistency between the more general questions and the more specific ones. The correlation was moderate concerning all aspects. Part 3 of the survey was designed to be a shorter version of part 1, and several of the detailed questions were removed based on the assumption that the general questions could would reflect the average value of the more detailed ones. This assumption builds upon the guess that the correlation would be strong between the overall questions and the detailed ones. These results indicate that the assumption may not be entirely true, which indicate that the detailed questions are necessary supplements to the general ones. The more specific question received higher satisfaction than the general ones, except concerning air quality. This is inconsistent with the findings of Leaman et.al (2007), who found that the more general questions received more positive responses.

The correlation between the overall environmental satisfaction and the satisfaction with the four environmental parameters were moderately strong. The mean satisfaction values of the individual parameters were higher than the overall satisfaction, which according to Leaman's definition would indicate that the occupants are *unforgiving* of the building. The reason why the occupants are not as satisfied with the environment as a whole as with the individual environmental parameters is difficult to know, but the literature has suggested that forgiveness is associated with satisfactory facility management, high environmental control, appealing views, natural ventilation, natural lighting and "greenness". Based on this, it is found surprising that the occupants in the building are rated as unforgiving. The previous findings, that the detailed questions concerning an environmental parameter received higher satisfaction than the more general questions, support the findings that the occupants are *unforgiving* of the building. Could this be caused by some underlying dissatisfaction towards the building or by any other unknown factor? The literature has suggested that a great majority of all buildings are classified as *forgiving*, and considering how well the building function and its green image and modern design it is found surprising that this one is not.

The formulation of question 17 was slightly modified during the study to clarify that it is the current environmental conditions that is referred to. Based on some responses from the first study phase, it was found likely that some subjects interpreted the question as "if the temperature is too hot or too cold, how much do you feel that your productivity is influenced by that" instead of "how much do you

feel that you are influenced by the temperature being either too hot or too cold at the moment". Based on that, the phrase "at the moment" was added at the end of the question to clarify the issue. This means that approximately half of the responses are based on a slightly modified question which apparently had some impact on some of the results.

The study has used two different ways of evaluating how important each of the four environmental parameters are in creating a productive building. The first way is to ask how productive the subjects feel in general, and to correlate the responses to that question with how satisfied they are with the different environmental parameters. The second way of evaluating the question is to ask directly how much each environmental parameter influence productivity. The two methods have found quite different results, for instance that acoustics is the environmental parameter that has the highest and the lowest influence on productivity. Also, when question 17 was analysed only based on the data from both phases, the order of the parameters remained the same (for instance that acoustics was the parameter that was perceived to influence productivity the most). This would indicate that the subjects interpreted the question similarly before and after the adjustment of the formulation.

Which of the two methods that is most reliable, and the best indicator of real productivity is difficult to conclude based on this study. The topic deserved more attention in future studies of productivity in buildings. However, based on my own subjective estimation, the first way seems more reliable because it is deemed easier to answer the following two questions "how satisfied you with the thermal environment?" and "how productive do you feel?", rather than to answer the more complex question "how much do you feel that the thermal environment influence your productivity". A simpler question should yield more reliable results, and that is why I believe that the first method is more reliable. The relatively high coefficient of variation of question 17 could indicate that many subjects interpreted the question differently. That is also the reason why the question was formulated differently between phase 1 and phase 2. The high coefficient of variation could also be caused by the fact that the question is perceived to be very difficult to answer, especially by the fact that the subjects are asked to estimate the productivity impact of one single parameter. In reality, it is difficult to isolate the impact of one single parameter because they are all interconnected with each other. The literature review above has shown examples of how poor air quality is associated with the perception of poor lighting quality, and similarly that thermal comfort is associated with the perception of air freshness. Based on the issues that have been mentioned concerning the approach of question 17 (asking directly how much productivity is influenced by each of the parameters) I would, until the matter has been researched more thoroughly, recommend using the approach of analysing the correlation between environmental satisfaction and one or several overall productivity questions. It should be mentioned that the findings presented above concerning question 17 should be interpreted with caution. To evaluate such a complex concept such as productivity by mean values and standard deviation alone does not provide the complete picture of the matter. For a better understanding of the question, the responses should be analysed with more sophisticated statistical analyses. It should also be mentioned again that these findings are based on only approximately 120 responses since the responses from phase one was removed. This decreases statistical power of those findings, and should the topic be investigated in detail one would probably need to collect more data.

Based on the discrepancy in the results between the two ways of evaluating how the indoor environment influence productivity, the correlation between the satisfaction with the four indoor environmental parameters and how much the subjects perceive that the same parameter influences their productivity was investigated. For instance, how close is the association between a low thermal satisfaction and the feeling that the thermal environment causes decreased productivity. The correlation was found to be relatively low concerning all four environmental parameters (Spearman's

rank correlation between -0,143 and 0,237). However, when only analysing the results from the second study phase the correlations became considerably stronger concerning acoustics and lighting but remained approximately equally strong concerning thermal comfort and air quality. Either way, the correlation between the two is surprisingly weak. This is another indication that the two ways of measuring the productivity impact from an environmental parameter give quite different results. Based on my own estimation, someone who is dissatisfied with the air quality *should* be very inclined to report that their productivity is negatively influenced by poor air quality. The topic is of high relevance, because both approaches has been used in the literature and we need to know which approach should be used for future studies.

The results have also shown that the students in the *Educational Building* perceive that their productivity is influenced less by the maintenance and cleanliness of the building and by dysfunctional building systems, compared with the environmental conditions. However, we cannot conclude anything about whether those results appear because the students perceive that the building is particularly well maintained and cleaned or because those parameters are perceived as less important in the creation of a productive building.

The correlation between CO<sub>2</sub>-concentration and air quality acceptability was moderately strong (Spearman's rank correlation of -0,427). This would indicate that a higher mean CO<sub>2</sub>- concentration during a session should correspond to a lower satisfaction. Many of the subjects did however not exit the classrooms during the break, and it is possible that the correlation would have been stronger if more would have done so. The correlation between CO<sub>2</sub>-concentration and the four productivity metrics was weak (Spearman's rank correlation between -0,073 and -0,146). This weak correlation may be found surprising, because the Spearman's rank correlation between air quality acceptability and ability to work and perceived productivity was 0,407 and 0,342. It is evident that the correlation between the subjective perception of air quality and productivity is stronger than with the physical measurements. This emphasise the importance of listening to the occupants when conducting a post occupancy evaluation of a building, and not only conducting physical measurements.

The correlations between PMV- values and the perception of thermal comfort was relatively weak, although often considerably stronger than between the other physical measurements and the subjective evaluations. The only one that appears to be moderately strong is between PMV and perceived productivity. That correlation is actually stronger than the corresponding correlation between thermal satisfaction and perceived productivity. Concerning the other parameters, the correlation seemed to be stronger between the different subjective parameters than between a subjective parameter and a measured one. The stronger correlation concerning PMV- value than for sound pressure level and CO<sub>2</sub>- concentration indicate could indicate that the thermal properties of the indoor environment are among the most important ones in the creation of a productive building. It could also mean that the thermal parameters varied more in this particular building, which gave rise to larger variations of thermal perception.

Based on the graphs above, a PMV- value of 0 should correspond to slightly higher productivity than in a typical office building (5%) while a PMV- value of -0,4 should correspond to an approximate 10% increase. This is a drastic change from a relatively little difference in the physical properties. Based on the question about *ability to work*, the same difference in PMV should correspond to approximately 16% higher productivity. However, it should be remembered that it is difficult to know how close to real productivity these results are. The preference towards a lower PMV- value could be explained by the fact that most participants in the study are from Sweden, that typically may prefer slightly colder temperatures than inhabitants of other countries. The difference could also be caused by errors in the responses of the survey. It is possible that the subjects find the question about their clothing as long

and difficult to answer, which may result in careless answers and they may fail to fill in all the boxes that represent their clothing. That could result in a lower calculated clo- value than in reality, which would offset the PMV- scale.

The correlation between sound pressure levels and the four productivity metrics was relatively weak (Spearman's rank correlation between -0,011 and - 0,235). Again, the correlation between the measured values and the productivity metrics are weaker than the correlation between the measured values and the productivity metrics, indicating how important it is to ask for the opinions of the occupants when evaluating a building.

### 5.3 FUTURE STUDIES AND WEAKNESSES IN THE CURRENT ONE

#### 5.3.1 Making physical interventions

Relatively few and weak association were observed between the physical measurements and the subjective responses. For future studies it may be of some interest to actively change indoor environmental parameters to provoke larger sensational differences. The indoor environment was quite stable at relatively adequate levels in the building. That should give rise to relatively small subjective differences between the sessions. By, for instance, changing the temperature setpoints or the ventilation flow, a possible correlation may be more apparent.

A relatively easy intervention that can be used in future studies would be to open the windows. The method has previously been used by Coley et.al (2007), and they found significantly higher productivity in the condition with the open window. However, it must be mentioned that the CO<sub>2</sub>- concentrations were considerably higher in the condition with the closed windows than they are in the *Educational Building*, so the impact of such intervention may therefore be much lower in this instance. It should also be mentioned that opening the windows might cause lower concentration of CO<sub>2</sub> and bioeffluents, but it may increase the levels of other pollutants such as allergens, particulate matter or combustion products. It may also be difficult to conclude anything about a specific parameter, because an open window will probably influence the air temperature, air velocity, relative humidity and sound pressure level as well. For some building it may be difficult to make any physical intervention by adjusting the HVAC- systems. For future studies in such buildings it may be preferable to install a portable ventilation, heating or cooling unit instead, which for instance has been used by Petersen et.al (2016).

#### 5.3.2 Comparisons with other buildings

An alternative to making interventions to the indoor environment is to conduct the study in different buildings that are found likely to have considerable differences concerning their indoor environment. The method has been used in numerous studies, but it may be accompanied by a few issues. One of the issues that has been discussed previously is the bias that some believe exist toward "green" buildings. That would make a comparison between the *Educational building* and another university less valid. Even buildings without any special green intent may similarly be influenced by bias, for instance that newer buildings and buildings with better architectural design may be perceived to have better indoor environment. Another bias that has been discussed in the literature, for instance by Singh et.al (2010), is the bias that may arise from when an organisation move from their "old" building to a new one and the workers are asked to evaluate the indoor environment before and after the relocation. The bias would mean that the subjects are more likely to report higher satisfaction and productivity in the new building, independent of the actual productivity and indoor environment. Comparisons between different buildings is indeed a complex method of evaluating the impact of different indoor environmental conditions on the users, and should be used with caution.

### 5.3.3 Maintenance, monitoring and inspections

As a supplement to asking the subjects about how they perceive the indoor environment, there are studies that have conducted professional inspections of buildings. This approach is considered promising, as they have the possibility to detect defects that may cause degradations of the indoor environment on long term and give rise to long term health impacts. The inspections might include visual inspections of the HVAC systems and critical construction elements, as well as physical measurements of hazardous substances.

It has been found that the number of building defects observed in school buildings in a visual inspection is positively associated with sickness absenteeism among children. As has been discussed previously, absenteeism is considered an indicator of productivity. Some of the aspects that were evaluated were the presence of mold, moisture and vermin, and they also evaluated the condition of the ventilation, plumbing and heating systems (Simons et.al 2010).

In the HOPE- project, hazardous substances in the indoor air were identified as a part of a building evaluation. However, it was found that the presence of highly hazardous substances such as cancerogenic radon or asbestos was not associated with higher occurrence of acute health symptoms. Neither was the less hazardous substances such as ozone, nitrogen oxide, particulate matter, fungi, allergens, VOCs and CO at low concentrations associated with acute health symptoms. However, those substances are believed to have the potential to cause long term health impacts. The subjects' inability to detect the presence of those substances indicate that the occupants' subjective evaluation does not provide the complete picture of the quality of the indoor environment, and that professional inspections and measurements may be necessary supplements. (Cox, 2005).

In another paper concerning the HOPE-project, the authors recommend that one should include physical, chemical, biological and environmental measurements as complement to the questionnaire of the occupants. It would also be beneficial to examine the cleaning and maintenance routines. They recognise that there is a discrepancy between what people answer that they need (for instance in a survey) and what they really need (Bluyssen, et al., 2011). An example of a maintenance routine that has been found to be vital in creating a productive building is the air filter condition. Poor air filter condition is associated with decreased productivity in call centres and with higher prevalence of a few acute health symptoms and with the perception of lower air freshness and lower cleanliness.

The findings that indicate that the occupants are unable to sense all environmental parameters is supported by Wargocki & Wyon (2013). They found no association between particulate matter concentration and productivity, environmental perception or acute health symptoms. They also found that even inadequate ventilation was difficult to perceive by the subjects when they were in the room (but easier to detect upon entering).

These are a few examples that show the importance of frequent and systematic building maintenance, environmental monitoring and building inspections to be able to achieve a healthy indoor environment that promote productivity. It would be interesting to evaluate the *Educational Building* from these perspectives as well. The information from such evaluations could be useful in combination from the findings from the surveys and the physical measurements to be able to provide a more complete picture of the indoor environment in the building.

### 5.3.4 Computerised survey system and long-term evaluations

The current study was conducted through paper-based surveys because that has been found to be associated with higher response rate. In this study, high response rate was deemed as very important because physical measurements were conducted simultaneously. A higher response rate would enable

us to make fewer measurement sessions to achieve an adequate statistical basis from the responses. I would recommend conducting physical measurements simultaneously as the subjective perception of the subjects are surveyed, but for studies that don't intend to do that would probably benefit from conducting the survey through a computerised system. That could also be an alternative for future studies that can monitor the indoor environment through built in sensors in the building. That would save considerable amounts of time and provide the possibility to reach out to a larger group of subjects. Such a survey could be distributed via email for instance, but that would make it difficult to know the precise location of the subjects at a specific time. It would probably make more sense to conduct such a survey as a *long term evaluation*, which means that the subjects are not evaluating the indoor environment *at the moment*, but of a certain period in the past. *Long term evaluations* are useful for comparing different building with each other and has been used by a number of standardised surveys. For studies that aim to compare the performance of a specific building to that of a larger number of other buildings, it would probably be beneficial to use one of the already well-established surveys, because that would allow direct comparisons with the rest of the database.

The RPM- tool seems like a promising method of measuring productivity quantitatively as well as evaluating the indoor environment subjectively. The standardised and computerised approach makes it more accessible and enables comparisons between different buildings. The productivity measurements may not be an ideal reflection of real productivity, but one could argue that this is something that will never be found, especially not that applies to a variety of different office jobs. One may therefore one just as well agree upon a model that is relatively simple and measurable that somewhat resemble typical office work. The RPM tool may be a good prototype for such a standardised method, as it comprises both a quantitative productivity test and subjective evaluations. However, the tool does not contain any measurements of the physical properties of the room, which would be useful to be able to obtain a more complete picture of the indoor environment and how it influences the occupants.

### 5.3.5 Sample size and participants

A major weakness concerning the current study is the relatively limited sample size. Databases of similar surveys, such as the BUS- survey or the CBE IEQ survey, contain thousands of responses which or course will provide much stronger statistical power. The current study should be considered as a preliminary one that may be developed further for those who believe that the question of *how* productivity should be measured is a topic that deserves more attention.

Another related weakness in the current study is that it is only carried out in one building. The correlations that are observed may not be applicable in other buildings that have different systems, layouts and materials. To be able to generalise the correlations and associations that has been observed, it would be necessary to conduct the measurements and surveys in other buildings as well. For instance, in future studies it would be interesting to evaluate other buildings on the university campus to obtain a broader picture of how the indoor environment influence the health, wellbeing and productivity of the users.

As mentioned earlier, some of the questions have approximately 460 responses (for the questions that are included in part 1 or 2 and 3), while other have approximately 230 (the question that are only included in part 1 or 2). However, it should be emphasised that the same group of subjects were answering the questions repeated times (up to 4 times each) which means that the 460 or 230 responses are not entirely independent of each other. A person that have answered that he or she has a headache during one session is probably slightly more likely to report that he/she has a headache during the next session simply because some people have headache more often than others. So those 460 datapoints are in fact derived from a group of a little more than 100 subjects. It is also likely that

it is the same subjects who choose to answer the survey repeated times, but since the survey is completely anonymous there is no data about the exact number of different participants. This would mean that the number of subjects answering the survey may be well below 100. For future studies, it could be beneficial to track the individual subjects through a coding system (for instance that each subject is assigned a code that only they are aware of) that maintain the anonymity towards the researchers but that will allow us to see how an individual subject change their perception from time to time. For further analyses of the current data or from other longitudinal studies, one may benefit from considering using other statistical methods that are more applicable for longitudinal studies. One should consider these statistical findings as no more than preliminary ones.

The response rate varied considerably between the sessions. The question has been discussed previously and it was concluded, based on a few articles, that the response rate was not a matter of bias. So, subjects who choose to answer the survey are not more or less likely to be of a specific opinion. This would mean that even the responses from a relatively low response rate can be considered as valid although with high statistical uncertainty. For the correlation tests between the different subjective responses, a low response rate for a few sessions does not oppose a vast problem because all the responses from the different sessions are merged together regardless of which session they originated from. However, in the statistical analyses between the physical measurements and the responses from the surveys, a very low response rate (or low number of responses in particular) could oppose a statistical issue. The mean values of some question of each session was paired with the mean value of the physical parameters. So, for instance, the mean air quality acceptability was 6,29 during session number 12, and the corresponding CO<sub>2</sub>- concentration was 777 ppm. If the responses that constitute the mean value of 6,29 was very few, it is of high probability that it is not representative of what a larger group of subjects would perceive. The lowest number of responses that was obtained for an individual session was four, which may be deemed as unsatisfactory. It was decided that the data would be used nevertheless, but for future studies this would be worth reconsidering.

A related issue is the difference in attendance and number of responses for each session. The number of responses from U1 are for instance more than twice as many than the ones from U61. Except that the mean values from the sessions in U61 are more uncertain (as discussed above), the statistical analysis where all the samples are added together makes the environmental conditions and the students perception in U1 more prominent in the data analysis. For instance, let us assume that the students who are studying chemical engineering may be more aware of the chemical pollutants in the air and thus more sensitive to their presence, in comparison with civil engineering students. Let us also assume that the classroom U1 has a different paint that emit more VOC than the paint in the other 4 classrooms. Out of the total number of responses, almost 40% derives from classroom U1, and specific conditions like the ones described may thus influence the results quite substantially. However, those conditions may not be representative of the student population and of the building as a whole. For future studies, it would be beneficial if the subjects were more evenly distributed between different groups of students (possibly not only engineering students either). It would also be beneficial if all the subjects were allowed to visit each classroom equally many times.

Another issue with bias concerns the drop off rate between the first and the second session of each lecture. During some lectures, the drop off rate was quite substantial, which resulted in many more responses during the first and second part of the survey and the third part. The issue with low response rate and few responses has already been discussed, but this problem arises a potential other issue: that the drop off may be influenced by the quality of the indoor environment. If that is so, which I don't find unreasonable, the responses in part 3 may be highly influenced by bias. For instance, if the temperature is relatively hot during the first hour of the lecture, some students may feel hot, tired,

and unproductive. Those students may be more likely to leave the lecture during the break, which may result in that the students who are more satisfied are, to a larger extent, the ones answering the third and final part of the survey. The issue may be resolved by excluding all the data from the third part of the survey, but that would also mean that the number of datapoints would decrease substantially. It is likewise possible that the students that are least satisfied with the indoor environment did not participate in the lectures in the first place, but that is difficult to know and control for.

For future studies, I would like to highlight the concerns that have been discussed above concerning longitudinal studies. The drop off rate and the fact that other statistical methods may be more suitable are indeed critical issues, and it is vital that one consider the use of a cross-sectional study design as well.

#### 5.3.6 Publication bias

The validity of the current literature review could be influenced by publication bias, which means that the outcomes of the study influence the decision whether or not the findings should be published. It is possible that articles that show that productivity is influenced by the indoor environment are more likely to be published than those that don't. It is found likely that publication bias is additionally prominent in literature reviews (that the studies that show the strongest correlations and most prominent findings receive more attention) and that is a reason why it was deemed important to search for literature via keywords in literature search tools, and not merely search for literature via literature reviews.

#### 5.3.7 Duration, time and date of the study

One weakness with the current study is that the surveys and measurements were carried out at different times during the days. The time of the day may have some influence of how the indoor environment is perceived, how strong acute health symptoms appear or how much someone is able to concentrate. It is recommended that future experiments are carried out at the same time during every day to be able to eliminate this possible effect.

Another uncertainty that might have influenced the outcomes of the experiments is the different seasons in phase one and two. The season will naturally influence the indoor environment, for instance, it is darker and colder in the spring than in the summer. Those differences gave rise to interesting differences in the physical properties of the indoor environment. However, the season may also influence the occupants more than what may be explained by the differences in the physical parameters. Based on my own estimations, I find it likely that people in general feel slightly more tired during the winter and early spring, and that the occurrence of the common flu may be higher. The literature review has shown evidence that the prevalence of the common cold is influenced by the quality of the indoor environment, but the difference between the seasons may also have a vast impact. Another difference may be that students at the university may feel more stressed in the early summer because of exams that often occur at the end of the semester. Another example that could be mentioned is that pollen allergens in the outdoor air is higher in the spring and early summer. These are just a few examples that I can think of that may influence the outcomes of the surveys when they are conducted throughout different seasons. The difference between the seasons is difficult to control, unless one is able to allocate all the experiment sessions during a relatively short time span. In the current study, this was not possible, especially considering the longitudinal study design. It may have been possible to conduct the 32 measurement sessions (16 lectures) during only one week (by visiting several classes each day, but that would be extremely intense, and one would need to visit many different courses and classrooms to make it work). It should also be mentioned again that the fact that



the study was conducted during a relatively extended period helped in creating interesting differences of the indoor environment that may have caused differences in subjective responses.

The duration of each session is a matter of relevance as well. The first part of the survey was filled in after approximately 45 minutes of presence in the room, and the last part after 105 minutes. It is possible that most acute health symptoms may appear mainly after extended periods of inadequate indoor environment and that the time frames in this study is too short. This may make it difficult to observe the association between the quality of the indoor environment and, for instance, productivity. Future studies should be conducted during longer sessions, preferably as long as 8 hours because that is the duration of a typical workday. Another issue that may arise from the relatively short test durations is that the subjects may still be influenced by the quality of the indoor environment of the previous building that they occupied. For instance, a headache may not vanish within 45 minutes from leaving a building that may have caused the headache.

#### 5.3.8 Reliance on subjective evaluations

The perhaps most considerable weakness in the current study would be that the study has relied entirely on perceived productivity. The literature review was not able to conclude anything conclusive regarding the most fundamental question of this report: whether any connections exist between real productivity, perceived productivity, and measured productivity. There are only a few studies that have studied the connection between perceived productivity and measured productivity explicitly, but there are a number of studies that have *included* both subjective and quantitative evaluations simultaneously. Many of them have found that an environmental difference that is associated with a difference in measured productivity is also associated with a difference in perceived productivity. If the productivity is increased, the subjective perception is in many instances improved. The connection between the two ways of evaluating productivity is in that case quite indirect, but it provides some indication of their relationship nevertheless. However, another question remains, which is whether quantitatively measured productivity is a valid and reliable indicator of real productivity. Considering the difficulty in measuring *real* productivity objectively and the benefits of measuring it subjectively, it was decided that the subjective approach would be used in the current study. The subjective evaluations of productivity are not only based on one question, as in many other surveys, but on several questions that are designed to cover different aspects of productivity. Also, the questions about environmental satisfaction, acute health symptoms and control were deemed as useful indicators of productivity, although the correlations that were observed between them were weaker than expected in some instances. Despite the various approaches of measuring productivity subjectively, the great uncertainty remains whether subjective evaluations reflect reality in a reliable way. Based on the literature review, it is considered that they do, but that the size of the impact is impossible to quantify based on the current knowledge. There is a need for more research within the topic to develop a deeper understanding of the connection between perceived and quantitatively measured productivity. Quantitatively measured productivity should, when possible, be based on existing productivity metrics (such as educational achievements) to give the correlation a solid foundation in reality.

#### 5.3.9 Existing productivity metrics

A quite different approach to evaluate productivity has been conducted by Newsham et.al (2017). The method may not be applicable in a university building, but for future studies of office buildings the method contains several interesting approaches that could be utilised. The method uses available data from the HR group (such as employee demographics, manager assessed performance and salary) as well as data from the facility management about complaints regarding the HVAC systems. They also use data from the annual employee survey about job satisfaction and organisational commitment. The

analysis was conducted for a Canadian company to compare green buildings with conventional ones. The results showed that the green buildings received higher ratings in the survey (more work engagement, better perceived work management and higher work satisfaction). and the occupants in the green buildings performed better according to the manager assessed performance. This is deemed as an interesting and promising method, because I find it preferable to use existing metrics of productivity, rather than perceived productivity or attempt to measure it quantitatively. If data of manager assessed performance is available for different buildings with similar work characteristics, it may be used to study the impact of the indoor environment on productivity. It must be mentioned that manager assessed performance is not an objective productivity metric, but it may be more objective than self-assessed productivity, and it has the potential to capture even the qualitative aspects of a work output. It must also be mentioned that the employee survey did not contain any questions about the indoor environment, but only about the workplace. It would have been interesting to compare the manager assessed performance with the environmental satisfaction, perceived productivity, and prevalence of acute health symptoms.

Another example of where existing metrics is used to indicate productivity is in the numerous studies that have used educational achievements as output metric. This is also deemed as a promising method, because it is a quantifiable output that is designed to reflect the quality and quantity of knowledge that the student has obtained during a course. It is likely that the ability to absorb knowledge is similarly influenced by the quality of the indoor environment as typical office work is. The practical problems that may arise from this method, that has already been discussed, is that university students typically don't spend all of their study time in a particular building. There is also the problem that the quality of the lectures may vary between different teachers even if the course content is identical between different groups. So, to make this method scientifically robust one would need to give identical lectures to two, or more, different groups that are exposed to different environmental conditions. A similar approach has been conducted by Murakami et.al (2006) who found significant test score differences between the groups in different environmental conditions.

Another existing metric that has been utilised in the literature is sickness absenteeism. That is not really a direct productivity metric, but an indirect indicator of productivity. Significant associations have been observed between the quality of the indoor environment and sickness absenteeism. It has also been shown that productivity is influenced by sickness symptoms. This makes it reasonable to assume that a poor indoor environment that cause high sickness absenteeism should also make the occupants less productive (not to mention the time lost during the absence). By analysing the sickness absenteeism and the number of facility complaints that were reported in a corporation, Milton et.al found that buildings that have higher absenteeism (lower productivity) have more complaints (perceived worse), which support the hypothesis that productivity and subjective evaluations are associated. That is a good example of how existing productivity metrics can be utilised to conclude something about the subjective perceptions of the occupants and of their productivity.

#### 5.3.10 Additional questions in the survey

*This is a short section about a few questions that was decided not to include in the current survey. Although the questions are considered interesting, they are either prioritized away or deemed as not relevant in the specific context of this study. They may however be highly useful in future studies.*

#### **Sickness absence**

The literature review has found that the indoor environment at work or at school has significant associations with absenteeism. Interestingly, it has also been shown by Ferrie et.al (2005) that self-reported sickness absence corresponds well with recorded data from employers. If it is assumed that

the indoor environment of the workplace or school has an influence on absenteeism, and that the building users are relatively accurate in their estimations of their absenteeism, this could imply that the subject's own estimations of the number of days that they have been absent during a specific period could indicate something about the quality of the indoor environment. By asking the occupants to estimate their own sickness absence could provide another indicator of how the productivity is influenced by the indoor environment at the workplace.

Another related question that has been used by Thatcher & Milner (2014) is to ask the subjects to assess how many days that they had attended work despite feeling ill, as a result of feeling obliged to. It is reasonable to assume that the productivity of a sick person is severely degraded, and this question could thus be highly relevant although the productivity impact of an illness may vary substantially and be difficult to evaluate.

In this study, the aim is to evaluate the productivity in a university building. Many students at the particular university don't have a clear "home building" that they spend most of their time in. It is therefore considered impossible to deduce how much of the absenteeism that is caused by the indoor environment in the *Educational Building*. Therefore, it was decided that questions regarding absenteeism should not be included in this survey. For future studies of other buildings, a question regarding sickness absenteeism could be highly relevant.

### **Mood**

By including a few questions regarding the mood of the subjects a few studies have investigated whether the subjects feel for "off", unmotivated, unhappy, angry, frustrated, calm or if they perceive the workload as exhausting. Several of those feelings have been shown to be associated with the environmental conditions in a building, simultaneously as the environmental condition have been shown to be associated with the productivity. This indicates that the mood of the subject has a connection to their productivity.

In order to keep the questionnaire reasonably short, it was not deemed possible to include any more questions about the mood except the ones that have already been included (motivation and concentration). These two feelings are considered to give a relatively fair picture of the mood of the subjects and they are closely connected with productivity, but for future studies it may be beneficial to include more questions about the mood of the subjects.

### **Facility management**

The user's perception of how responsive the facility management is has been found to be associated with perceived productivity. There are surveys that include explicit questions regarding how responsive and effective the facility management is. However, this survey is mainly focussing on the indoor environmental quality rather than satisfaction with the facilities, so no such question has been included therefore. A good facility management is nevertheless considered vital to be able to maintain a healthy and productive building, and questions regarding this would be interesting to include in future studies.

### **Downtime**

Downtime is another way of measuring how much productivity is influenced by the building (Oseland, 2004). Downtime could be considered an indicator of productivity as it quantifies time lost due to certain building related problems. Those issues are mainly regarding facility issues, but may also be used for problems concerning the indoor environment. For air quality and thermal climate under

normal indoor environmental conditions it is deemed that such questions would not add so much. It is quite intuitive that poor thermal climate impacts productivity negatively, but it could be questioned whether these parameters really cause any considerable downtime (for instance the time that it takes to adjust the thermostat). For a relatively well functioning building the time to make such adjustments should be relatively small, and that time may anyway be included in the other productivity metrics.

### **Fatigue and exhaustion**

There are a few studies that have argued that poor indoor environment may not influence productivity on short term, but that it will influence how tired the occupants become after a while. A motivated subject may “overcome” the physical parameters for a while, but it will increase his or her fatigue. Such exhaustion and fatigue is believed to influence productivity negatively on long term, and it could thus be interesting to investigate how tired or alert the subjects are after a few hours in the classroom. To keep the questionnaire relatively short, it was decided that the already included question about motivation and ability to concentrate could represent this aspect of productivity, but it would certainly be highly interesting to learn more about this phenomenon in future studies.

### **Adaptive behaviour**

An interesting question related to environmental control would be to ask a series of questions regarding the user’s adaptive behaviours. It would be interesting to know what measures they take if they feel uncomfortable, and how often the building “forces” them do so. The literature has shown that environmental control is closely associated with productivity, although the correlation was quite weak in the current study. This could be because the students prefer to adapt their clothing instead of adjusting the building, and that is why this would be of interest to study.

## **6 CONCLUSIONS**

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The study has reviewed numerous papers that have included both quantitative measurements of productivity and subjective evaluations of the indoor environment, with the purpose to investigate if there is a consistency between the two. Although no clear consensus has been reached, my personal opinion based on the literature review, is that there is a tendency showing that a person who is negatively influenced by the indoor environment is also more likely to feel unwell and unproductive and perceive that the indoor environment is substandard. There is no doubt however that the relationship is very complex and not very well understood.

The literature has provided many examples of how productivity can be evaluated quantitatively. Simulated office work, diagnostic tests and measurements of real work output are just a few examples. The different methods are subject to a variety of different concerns, for instance issues concerning motivation, learning effects, task complexity and too short test durations. The most prominent problem concerning quantitative productivity evaluations is that it has difficulties to cover the qualitative aspects that should be an important part of most modern office jobs.

The literature has also provided a number of examples of different ways of evaluating productivity subjectively. The questions in the survey have been formulated with a variety of different formulations and response scales, and different buildings have been compared through different methods. The main underlying issue with this approach is bias; that self-assessment may not be accurate in reflecting real productivity and that the responses may be influenced by unrelated parameters, such as the image of the building.

The outcomes of the physical measurements and the surveys align relatively well with the previous findings concerning productivity. There were moderately strong correlations between environmental satisfaction and productivity, but there were considerable differences between the different productivity metrics. The correlation between productivity and environmental satisfaction was weakest concerning acoustics, which indicate that acoustics is the environmental parameter with the lowest impact on productivity. Productivity was also evaluated by asking how much each of the four environmental aspects was perceived to influence the productivity. The two methods provided quite different outcomes, as the latter one indicated that acoustics was the parameter with the strongest. Both approaches have been used in the literature, but the ambiguity is certainly very problematic and a topic that deserves more attention and more research.

The correlation between the different productivity questions were moderate to weak. That could indicate that the different questions cover different aspects of productivity, and that one question alone cannot cover the complex question. This shows the need for more research concerning what questions should be included in a subjective productivity evaluation.

From the results, it can also be concluded that the building occupants are *unforgiving* of the building, i.e. that they rate their overall impression lower than they rate the four environmental parameters. This is found surprising, because the literature has provided evidence that suggest that the *Educational Building* is a typical *forgiving* building. This is of special interest for future studies that aim to use subjective evaluations to compare buildings to each other, because *building forgiveness* should be closely associated with bias.

The correlations between the physical measurements and the subjective evaluations were in general considerably weaker than between the different subjective ones. The correlations between CO<sub>2</sub>-concentration and the productivity metrics were weak. Similar findings were obtained concerning sound pressure level. This emphasise the importance in listening to the opinions of the subjects while performing a post occupancy evaluation of the performance of a building, because physical measurements alone may not reflect the users' perspective very well. The correlation between the PMV- value and the subjective evaluations were however considerably stronger. This would indicate that the thermal parameters are the most influential ones in creating a productive workplace.

Methods and approaches for future studies are discussed. Productivity in buildings is indeed a complex but important topic that deserve more research. The link between subjective evaluations and measurements of productivity is of special interest in the endeavour to develop a deeper understanding of how the indoor environment influence productivity.

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## APPENDIX A

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*This appendix will present the indoor environmental survey that was used in the study. Each classroom had an individual drawing on page 2, and this survey corresponds to classroom U1. Question 17 was slightly rephrased after the first phase of the study, and the words “at the moment” were added.*



## Indoor Environmental Quality Questionnaire

Thermal, Visual and Acoustic Comfort in the Educational Building at KTH, Stockholm

This study is a part of our **master's degree project**, with the purpose of increasing our understanding of how the indoor environment is perceived by building users.

This questionnaire survey is **anonymous** and intended for **educational purposes** only. **Your participation is completely voluntary and you are free to terminate your participation at any time.**

The **time** to complete the survey is approximately **8 minutes in total**. Please go through every question and give an answer based on how you feel **at the moment**.

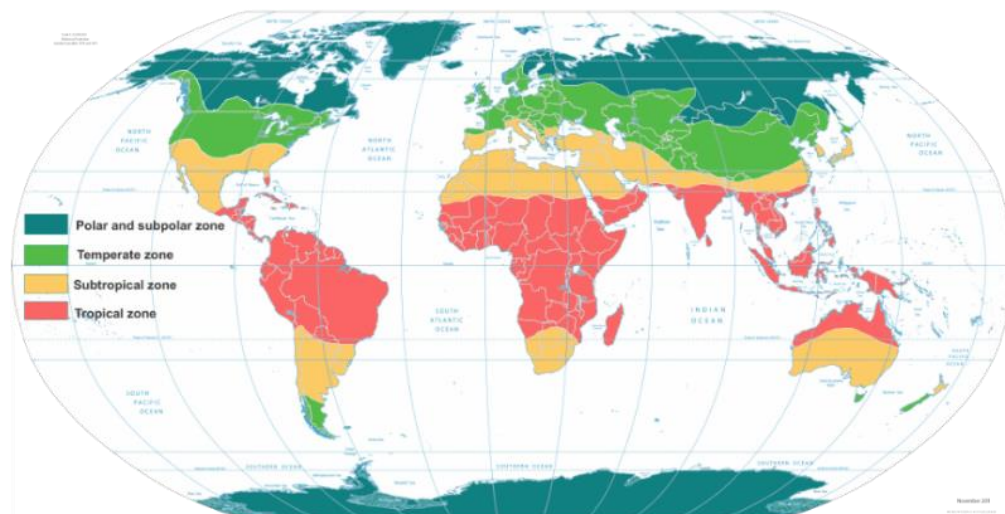
### Part 1 (To be filled in before the break)

#### BACKGROUND INFORMATION

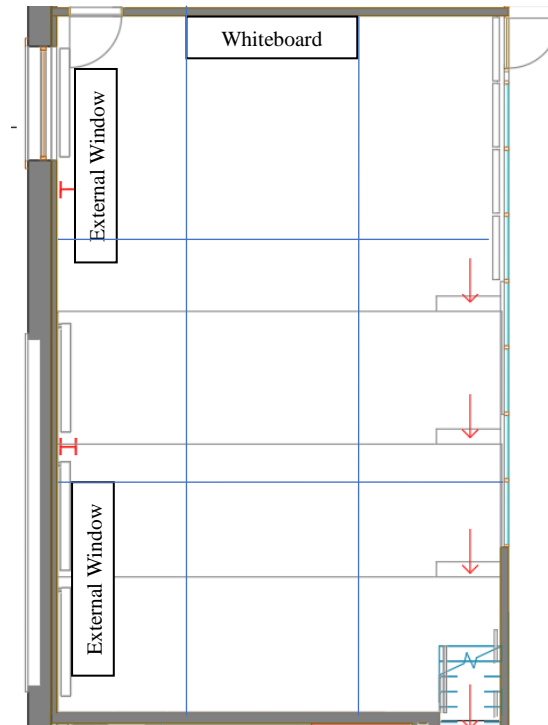
- **Year of birth** \_\_\_\_\_ **Gender:**  Female  Male  Other
- In the list below check the type of **Clothing** you are currently wearing
 

<b>Undershirt</b>	<input type="radio"/>	Light	<input type="radio"/>	Heavy		
<b>Socks</b>	<input type="radio"/>	Light	<input type="radio"/>	Heavy		
<b>Footwear</b>	<input type="radio"/>	Shoes	<input type="radio"/>	Boots		
<b>Shirt</b>	<input type="radio"/>	Light Short Sleeve	<input type="radio"/>	Light Long Sleeve	<input type="radio"/>	Heavy Short Sleeve
<b>Sweater</b>	<input type="radio"/>	Light	<input type="radio"/>	Heavy		
<b>Jacket</b>	<input type="radio"/>	Light	<input type="radio"/>	Heavy		
<b>Trousers</b>	<input type="radio"/>	Light	<input type="radio"/>	Medium	<input type="radio"/>	Heavy
<b>Skirt</b>	<input type="radio"/>	Thin	<input type="radio"/>	Thick		
<b>Dress</b>	<input type="radio"/>	Short Sleeve Thin	<input type="radio"/>	Long Sleeve Thin	<input type="radio"/>	Long Sleeve Thick
- Check the **Climate Zone** you originate from
 

<input type="radio"/> Polar/Subpolar	<input type="radio"/> Temperate	<input type="radio"/> Subtropical	<input type="radio"/> Tropical
--------------------------------------	---------------------------------	-----------------------------------	--------------------------------



- In the picture below mark your **Location** in the room



- What has been the **main activity** of the lecture (previous 45 minutes). Mark **what is applicable** (at least one alternative)

Listening, Taking notes	Making calculations	Writing reports	Group discussion	Work in computer program	Listening to presentations	Making presentation
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

## GENERAL SATISFACTION

---

1. How **satisfied** are you with the indoor environment in general at the moment?

Very Dissatisfied							Very Satisfied
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

## THERMAL COMFORT

---

2. How do you **feel** at the moment?

Cold    
  Cool    
  Slightly Cool    
  Neutral    
  Slightly Warm    
  Warm    
  Hot

3. Would you prefer the room temperature to be?

Warmer    
  No change    
  Cooler

4. How satisfied you are with the **temperature** in the room at the moment?

Very Dissatisfied    
     
     
     
     
     
  Very Satisfied

5. How do you perceive the **air movement** at the moment?

Still    
     
     
     
     
     
  High draft

6. How do you perceive the level of **humidity** at the moment?

Too dry    
     
     
     
     
     
  Too humid

## ACOUSTIC COMFORT

---

7. How satisfied are you with the **level of sound/noise** at the moment?

Very Dissatisfied    
     
     
     
     
     
  Very Satisfied

8. How satisfied are you with the **following sound/noise** aspects at the moment?

	Very Dissatisfied						Very Satisfied
➤ Sound from Phones, Printers, Computers	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
➤ Sound from Building Systems	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
➤ Sound from Speech	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

## VISUAL COMFORT

9. How satisfied you are with the **lighting conditions** (daylight and electrical lighting) at the moment?

Very Dissatisfied        Very Satisfied

10. How **satisfied** are you with the following?

	Very Dissatisfied						Very Satisfied
➤ Daylight	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
➤ Electrical Lighting	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
➤ Glare or Reflection (uncomfortable light reflections or bright light in eyes)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

## HEALTH SYMPTOMS

11. How do you **feel** at the moment?

Very unwell        Very well

12. How **strong** do you feel the following **symptoms** at the moment?

	Strong Symptoms						No Symptoms
➤ Headache	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
➤ Dizziness	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
➤ Fatigue (Exhaustion)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
➤ Dry or irritated skin	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
➤ Irritated nose (blocked, runny)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
➤ Irritated eyes (watery, dry)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
➤ Irritated throat (dry, cough)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
➤ Cold hands and feet	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

## GENERAL QUESTIONS

13. To what extent are you **able to concentrate** at the moment?

Not able to concentrate        Fully able to concentrate

14. How **motivated** are you to **work hard** at the moment?

Low motivation       High motivation

15. How much are you **able to work** in this room at the moment in relation to your optimum performance?

0% (not able to work)       100% (fully able to work)

16. How much is your **productivity** increased or decreased by the **general environmental conditions** in the building? (0% represents a “normal” building).

-20%  -15%  -10%  -5%  0%  +5%  +10%  +15%  +20%

17. How much is your **productivity affected** by the following conditions?

	Not Affected	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Highly Affected
Too hot/cold	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Poor air quality	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Poor lighting	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Noise	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Too crowded	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Bad office layout	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Poorly cleaned or maintained	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Electrical systems not working (e.g. elevators, printers, computers, projectors, power sockets)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

18. How much **control** do you have over the following parameters?

	No Control	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	High Control
Temperature (Change setpoints, radiators)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Air quality (Window, Ventilation)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Noise (Noise barriers)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Lighting (Shading, adjust electrical light)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

## Part 2 (To be filled in after the break)

### AIR QUALITY

---

19. How do you feel about the **air quality** at the moment?

Unacceptable

Acceptable

20. How much **smell** do you sense at the moment?

Too smelly

No smell

21. How **dry** is the air at the moment?

Very dry

Not dry

22. How **stuffy** (closed in/ unrefresh) is the air at the moment?

Stuffy

Fresh

# Part 3 (To be filled in at the end of the lecture)

## GENERAL SATISFACTION

---

23. How **satisfied** are you with the indoor environment in general at the moment?

Very Dissatisfied      ○      ○      ○      ○      ○      ○      Very Satisfied

## THERMAL COMFORT

---

24. How do you **feel** at the moment?

Cold      Cool      Slightly Cool      Neutral      Slightly Warm      Warm      Hot

25. Would you prefer the room temperature to be?

Warmer      No change      Cooler

26. How satisfied you are with the **temperature** in the room at the moment?

Very Dissatisfied      ○      ○      ○      ○      ○      Very Satisfied

27. How do you perceive the **air movement** at the moment?

Still      ○      ○      ○      ○      ○      High draft

28. How do you perceive the level of **humidity** at the moment?

Too dry      ○      ○      ○      ○      ○      Too humid

## ACOUSTIC COMFORT

---

29. How satisfied are you with the **level of sound/noise** at the moment?

Very Dissatisfied      ○      ○      ○      ○      ○      Very Satisfied

## VISUAL COMFORT

---

30. How satisfied you are with the **lighting conditions** (daylight and electrical lighting) at the moment?

Very Dissatisfied        Very Satisfied

## GENERAL QUESTIONS

---

31. To what extent are you **able to concentrate** at the moment?

Not able to concentrate       Fully able to concentrate

32. How **motivated** are you to **work hard** at the moment?

Low motivation       High motivation

33. To what extent are you **able to work** in this room at the moment, considering the **environmental conditions**?

0% (not able to work)       100% (fully able to work)

34. How much is your **productivity** increased or decreased by the **general environmental conditions** in the building? (0% represents a “normal” building).

-20%  -15%  -10%  -5%  0%  +5%  +10%  +15%  +20%

**Thank you for your participation!**



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