Indoor Climate Design in a Preschool Building:

Balancing health, comfort, work performance and environmental impact of the ventilation system

Master's thesis in the Master's Programme Structural Engineering and Building Technology

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CHALMERS UNIVERSITY OF TECHNOLOGY

Master's Thesis ACEX30-19-37
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Illustration of a room in the Hoppet preschool. Author: Liljewall Arkitekter, 2017.

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ABSTRACT

Indoor environment has significant influence on users' well-being, understood as comfort, health and performance. These three aspects are determined by factors such as air temperature, relative humidity or gaseous pollutants and particles concentration, which values are controlled by air exchange with outdoors. However, one ventilation setting is not able to provide optimal levels for all parameters simultaneously and some of them are strictly defined by legal regulations. Moreover, adjustments of HVAC system can always be translated to change of environmental impact, which is of interest in fossil-free construction.

A literature study has been conducted in order to identify the functional requirements for an indoor environment with focus on preschool buildings according to Swedish law, available methods to assess an environmental impact, components of indoor climate and their effect on health, comfort and performance, and ventilation solutions for a case study preschool building. Furthermore, 18 sets of indoor conditions for winter and summer cases were tested in order to establish what supply air temperature and air flow in the ventilation system would be required to maintain them. Cases most supporting for health, comfort or performance have been identified. The obtained results were taken further to simplified assessment of environmental impact of materials and energy use in FTX and hybrid ventilation systems.

Finally, based on findings from theoretical study and simulations, the discussion has been raised to identify how different aspects of indoor climate should be prioritized and weighed against each other to enable design of ventilation in preschool spaces considering users and environment in optimal way. The attempt to obtain a universal model for such an assessment has been made. The most important conclusion is that functional requirements for health, comfort and performance are to some extent contradictory, therefore prioritized aspect should be decided upon prior to space design process. Ventilation should be able to fulfil requirements for the selected aspect and once that is secured, a discussion about different solutions' environmental impact can lead to the final choice of the system.

Key words: preschool, indoor climate, indoor air quality, thermal comfort, health, ventilation system, environmental impact, fossil-free construction.

Utformning av förskolas inomhusklimat:

Balans mellan hälsa, komfort, prestation och ventilationssystems miljöpåverkan

Examensarbete inom masterprogrammet Structural Engineering and Building Technology

INGA SIERPINSKA

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SAMMANFATTNING

Inomhusklimat har betydande påverkan på användares välmående i form av komfort, hälsa och prestation. De tre aspekterna är bestämda av faktorer såsom lufttemperatur, relativ fuktighet, gasformiga föroreningar och partiklar, vilka i sin tur styrs av luftutbyte med utomhusmiljön. Ett driftläge för ventilationssystemet kan dock inte säkerställa optimala nivåer för alla parametrar samtidigt och några av dem är rigoröst definierade i lagar. Inställning och utformning av ventilationssystem kan dessutom alltid bli omsatt i ändring av miljöpåverkan vilket är av stort intresse i fossilfritt byggande.

En litteraturstudie har utförts för att kartlägga funktionskrav för inomhusmiljö enligt den svenska lagen med fokus på förskolebyggnader, tillgängliga metoder att bedöma miljöpåverkan, komponenter av inomhusklimat och deras komfort-, prestation- och hälsoeffekter samt ventilationslösningar för en fallstudies förskola. Vidare har 18 uppsättningar av inomhusluftsparametrar för vinter- och sommarfall testats för att identifiera vilken tilluftstemperatur och vilket luftflöde i ventilationssystem som krävs för att uppnå och behålla dem. Fallen som är mest gynnsamma för hälsa, komfort eller prestation har identifierats. Resultaten har använts i en förenklad bedömning av miljöpåverkan för material och energi i FTX och hybrid ventilationssystem.

Slutligen har, med utgångspunkt i resultaten från den teoretiska undersökningen och simuleringarna, en fråga tagits upp om hur olika aspekter av inomhusklimat ska prioriteras och vägas mot varandra för att möjliggöra utformning av ventilationssystem i förskolor som tar hänsyn till användare och miljön på optimalt sätt. Ett försök till att skaffa en universell modell för sådan bedömning har gjorts. Den viktigaste slutsatsen är att funktionskrav för hälsa, komfort och prestation är delvis motsägelsefulla, därför bör den prioriterade aspekten bestämmas innan inomhusklimats utformning påbörjas. När det är säkerställt kan diskussion om olika tekniska lösningars miljöpåverkan leda till ett slutligt val av ett system.

Nyckelord: förskola, inomhusklimat, luftkvalitet inomhus, termisk komfort, hälsa, ventilationssystem, miljöpåverkan, fossilfritt byggande.

Contents

Preface

In this study, the balance between health, comfort and performance provided by indoor environment in a preschool and ventilation system's environmental impact has been studied. The thesis project was carried out from January to June 2019 at the Division of Building Services Engineering, Department of Architecture and Civil Engineering of Chalmers University of Technology and at Bengt Dahlgren AB in Gothenburg, Sweden.

This thesis project would not be possible to finish if it was not for the huge amount of help I received from kind people around me.

Firstly, I would like to thank my supervisors: Jan Gustén at Chalmers for valuable references and keeping an eye on my work's academic quality; Andreas Karlsson at Bengt Dahlgren for all advice, guidance and encouragement that gave me new energy every time I was feeling lost in my own ideas.

Secondly, I owe thanks to a big group of people from Göteborg Stads Lokalförvaltningen – Hanna Ljungstedt, Anders Hall, Jan-Erik Andersson, Mikael Rosén and Jörgen Bruce – for their engagement, trust, sharing knowledge and experience, and all invitations to inspiring meetings.

Moreover, I would like to thank my opponent group, Tor Lundberg and Henric Erntoft, for interesting discussions and useful comments on my project as well as for motivation to speed up my work.

Last but not least, I would like to thank my dearest family and friends for all the support I received from them and their faith in me and my success. Among them I would like to particularly mention Nabil – for standing me all these months when I used word "thesis" in every other sentence, Agnieszka – for Oxford comma, proofreading half of my report and making fun of all my long, complicated, compound-complex sentences (even if I usually did not divide them in accordance with her suggestions), and Abed – for motivating me when I needed motivation and distracting when I needed distraction.

Göteborg, June 2019

Inga Sierpinska

Notations

Roman upper-case letters

AHU	Air handling unit
A_{temp}	Total heated floor area [m^2]
BBR	Boverkets byggrelger
CO_2e	Carbon dioxide equivalent
FTX	Mechanical ventilation system with heat recovery
GWP	Global Warming Potential
IAQ	Indoor air quality
IEQ	Indoor environment quality
I_{cl}	Clothing insulation [m^2K/W]
LCA	Life Cycle Assessment
LF	Göteborgs Stad Lokalförvaltningen
M	Metabolic rate [W/m^2]
MB	Miljöbyggnad
PM	Particulate matter
PMV	Predicted Mean Vote
PPD	Predicted Percentage Dissatisfied
RH	Relative humidity [%]
RMR	Resting Metabolic Rate [W/m^2]
SBS	Sick Building Syndrome
SFP	Specific Fan Power [$kW/m^3/s$]
SGBC	Sweden Green Building Council
TKA	Tekniska krav och anvisningar
VOC	Volatile Organic Compound
W	Effective mechanical power [W/m^2]

Roman lower-case letters

clo	Clothing insulation unit [1 clo = 0,155 m^2K/W]
f_{cl}	Clothing surface area factor [-]
h_{cl}	Convective heat transfer coefficient [W/m^2K]
met	Metabolic rate unit [1 met = 58,15 W/m^2]

t_a	Air temperature [°C]
t_{cl}	Clothing surface temperature [°C]
t_{dp}	Dew point temperature [°C]
t_o	Operative temperature [°C]
$\overline{t_r}$	Mean radiant temperature [°C]
t_{supply}	Supply air temperature [°C]
p_v	Water vapour partial pressure [Pa]
p_{vs}	Saturation pressure of water vapour [Pa]
v	Absolute humidity [kg/m^3]
v_{ar}	Relative air velocity [m/s]
v_s	Absolute humidity at saturation [kg/m^3]
x	Humidity ratio [g/kg]

1 Introduction

In this chapter the background of the project is presented, followed by the description of the thesis's aim, applied methods, assumptions and delimitations.

1.1 Background

The Lokalförvaltningen of the City of Gothenburg, an organisation responsible for building and administration of, among others, schools and preschools, together with Bengt Dahlgren AB as external project manager, is carrying out the project of Hoppet – a fossil-free construction. The aim of this innovative project is to investigate the prerequisites and conditions for fossil-free construction in general in order to facilitate reaching Gothenburg's goal of becoming a climate-neutral city with a sustainable level of greenhouse gases emissions by 2050 – which is a part of its wide climate strategy. Finding sustainable solutions for building sector is crucial, as it is responsible, according to Boverket's data, for around 31% of total energy use and 18% of greenhouse gas emissions in Sweden (Göteborgs Stad Lokalförvaltningen, 2019). The first milestone within Hoppet's framework is a fossil-free preschool which is a pilot project realised with a purpose of testing different materials and processes and thus finding the optimal ones to obtain fossil-free methods for resources extraction, production and transport of materials, actual construction and operation phase. Where fully fossil-free solutions cannot be achieved, the alternative ways to compensate for negative impact should be investigated. The results and conclusions from the project should eventually be implemented into the city's climate strategy.

Project Hoppet is being carried out in three areas. The first one comprises a variety of innovation projects which goal is to research and develop new fossil-free materials with lowest possible environmental footprint, preferably also using reclaimed waste. Some examples of such materials are fossil-free glues and paints, foundation slab constructed in timber or recycled glass, organic insulation and, most interesting from installations perspective, pipes produced from old, dismantled ones (Re:pipe), parts of electrical system made of recycled plastic coming from other industries (GreenPipe) or duct system consisting only of aluminium foil and insulation, which allows for efficient transport and eliminates environmental impact of metal sheets (Climate Recovery). Moreover, even possible use of clay obtained during ground works on Västlänken is investigated.

The second area concerns spreading the information and remaining in continuous contact with all possible actors who may be interested in contributing to the project. The communication channels include presentations during building sector related events, seminars, study trips, workshops, conferences, contact with press and up-to-date website.

The third and the main area within project Hoppet one is focusing on the actual construction and can be further divided into pre-study phase and production phase. The aim of the pre-study is to investigate and improve the current situation in the subject of fossil-free building by, among others, analysing the amount of fossil materials built-in in the typical preschool and their environmental impact, looking for similar projects worldwide, researching on alternative fossil-free materials and identifying the fields in which their lack is most problematic, establishing contacts with actors in the industry in order to support and initiate development of new solutions, cooperation with scientific environment and co-supervising bachelor and master theses.

Seen from the angle of the following report, some of the activities within pre-study phase should be described in a more detailed way. One of the first actions taken was to map the way how the environmental footprint of construction is currently defined, monitored, controlled and limited by European, national and local law and directives, industry standards, praxis-based guidelines, environmental certifications' instructions and other tools developed to calculate the impact. The result of this research will be discussed further in Chapter 3.

Another interesting study has been conducted on one of Lokalförvaltningen's existing buildings – Byvädersgångens förskola – in order to quantify the share of fossil materials built-in in a typical new preschool. This case was also used to carry out a simplified life cycle assessment using a tool developed by IVL – Swedish Environmental Research Institute – which is based on Environmental Product Declaration index (EPD). One important finding of the study is that the amount of HVAC system components may be small in a scale of a whole building, but they are among these with the highest content of fossil materials, which makes it even more urgent to investigate possibilities of reducing systems' size or finding alternative technical solutions. Another interesting result is the value of 223 kg CO_2e per 1 m^2 heated floor area found out to be the measure of the preschool's environmental impact in phases A1-A5 of its life cycle, as it gives a reference point for further improvements.

Furthermore, Lokalförvaltningen has developed a project of model preschool called Grönskan. The design process put most focus on flexibility, functionality and creating optimal environment to support kids learning and playing, creating therefore a good base for future improvements in terms of more specific, technical solutions. At the time of this report being written, the preschool is being built in Lillhagsparken in Gothenburg. Grönskan, since Hoppet is supposed to be built using same architectonic assumptions, is used as a reference case in several ongoing research projects. One of them, setting in a way a starting point for the following report, was a bachelor thesis investigating the environmental impact of alternative ventilation system solutions. The conclusion drawn from this project was that an efficient way to minimize the CO_2 footprint may be to adjust parameters such as flow or requirements on filters, as long as it is done with consideration of other functions, indoor climate and users' well-being. The description of how this thesis will try to answer these questions can be found further in the chapter.

The actual production of the Hoppet preschool is planned to start in the first quarter of 2019 on a plot near Backaskolan in Hisingen, it is thus obvious that all mentioned research projects will not be finished by that time and all conclusions will not be applied. Nevertheless, the most important outcome of the pilot project is the initiation of the discussion, raising awareness and encouraging further actions in order to eventually reach the ambitious goal of fully fossil-free construction.

1.2 Aim

The aim of the following thesis is to evaluate and study the relation between legal regulations, functional requirements for good indoor climate, users' comfort and health, and the environmental impact of technical installations in the building. It will attempt to identify which requirements are the most decisive and have the biggest potential to increase environmental friendliness of ventilation and at the same time discuss how this influences the building's users and applied technical solutions. Based on the findings, the project should suggest guidelines for setting the functional requirements and discuss how these can be related to technical systems in order to decrease the environmental impact and help in the future design of fossil-free constructions.

1.3 Objectives

In order to reach the intended aim, the thesis investigates the following questions:

- What are the current requirements on indoor air quality and ventilation parameters and what is the theoretical base behind these values? To what extent these limits could be changed without risking with unsatisfying indoor environment?
- What is the influence of indoor air temperature, CO_2 concentration and relative humidity on users' comfort (perceived air quality), direct health effects (e.g. physical discomfort, eye irritation, mucous membranes drying) and indirect health effects (e.g. incidence of allergies and respiratory diseases, concentration of chemicals, emissions rates)?
- What are the main characteristics of FTX and hybrid ventilation systems? What are the advantages and disadvantages of both systems in terms of fulfilling requirements for above-mentioned comfort and health issues?
- What is the influence of requirements set for indoor space on flow and supply air temperature in the ventilation system? How are these parameters translated to its design in terms of size, materials and energy use? How are these aspects translated to environmental impact of ventilation?
- How would the possible change of requirements and following ventilation system's parameters influence indoor air characteristics? What are the optimal requirements regarding indoor conditions, balancing the interest in users' well-being and environmental issues?

1.4 Methodology

The thesis is divided in a theoretical and practical part.

1.4.1 Theory

The theoretical part puts focus on several questions. A review of legal documents defining limits for functional requirements in the preschool buildings is done in an attempt to identify the hierarchy of regulations and check if the reasoning behind given values has a source in the same scientific knowledge. The other goal of this review is to find out if existing guidelines give a clear idea about how the design process should be initiated, if they are not confusing, misleading or even contradictory. The results are compared with requirements concerning environmental impact, set both by law and commercial certification systems, to establish in which ways indoor air quality can be translated to influence on the climate.

The next step is a literature study investigating the relation between IAQ and buildings' users' well-being and health. An emphasis is put on school and preschool environment in order to decide which parameters are critical for providing an optimal learning climate, allowing for best possible concentration and intellectual performance, minimizing the risk of allergies and diseases.

The last step in theoretical part is a study on the design principles of some types of ventilation systems. The FTX system in the model preschool Grönskan as a reference and the hybrid system planned in preschool Hoppet are described and compared based on the technical documentation and the findings from the previous thesis in this field, mentioned in Section 1.1. Advantages and disadvantages of both solutions are presented as well as some possible modifications which can be introduced, it is discussed which system may be preferred under different circumstances and how do they perform in terms of environmental impact.

1.4.2 Calculations

The practical part of the work includes two types of calculations. Firstly, it has been checked how different sets of functional requirements will be translated to design parameters of ventilation system. From demand on CO_2 concentration minimum air flow per person has been obtained, then it was checked what supply air temperature would be required to handle internal heat gains and provide air flow as close to minimal as possible. For every case resulting RH has been examined as well as PMV and PPD for adults and children at two different activity level. In addition, it has been checked which temperatures indoors would provide RH and PMV/PPD in desirable range and to what extent thermal inertia of the room may help maintaining desired indoor climate.

Secondly, using CO_2 equivalents, a simplified environmental impact was calculated for different solutions for ventilation system, based on energy needed for fans and pumps, production of district heat and materials use.

1.4.3 Evaluation model

The evaluation of results throughout the thesis follows the order presented in Figure 1.1 below:

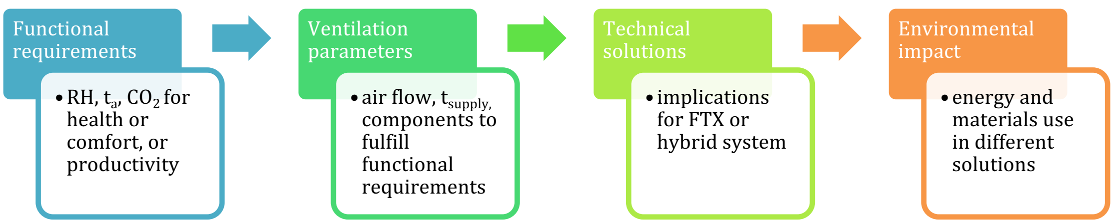


Figure 1.1 Model for evaluation of project's results.

Based on findings from literature study in the subject of indoor climate characteristics' effects on health, comfort and work performance, sets of functional requirements aiming for providing fulfillment of each of these aspects are obtained.

Then, basic parameters of ventilation – air flow and supply air temperature – are calculated so that the functional requirements are met. In the next step it is analyzed what such design parameters would imply for specific technical solutions and as examples FTX and hybrid system are used. Finally, it is evaluated what is the potential of considered solutions to decrease environmental impact.

1.5 Assumptions and delimitations

The following assumptions and delimitations apply throughout the thesis:

- environmental impact is limited to climate impact; aspects such as acidification potential, eutrophication potential or ozone depletion potential are not considered;
- environmental impact assessment focuses mostly on energy for fans and pumps, and heating demand; only limited analysis is carried out for materials and life cycle;
- economical aspects are not included – cost is not a criterium for any of discussed issues;
- the project is carried out in Sweden; all legal aspects and environmental data apply to the local conditions;
- term "hybrid ventilation" always concerns a system with preheating in the ground, other solutions that can be qualified as hybrid are not considered.

2 Current Functional Requirements

The following chapter aims to outline the framework for defining functional requirements in terms of indoor climate in newly built preschool buildings given by a variety of legal regulations, standards and guidelines applying in Sweden. The term “indoor climate” includes many factors but here focus has been put on air quality and thermal climate, leaving out questions of, for instance, lighting or acoustics.

2.1 Regulations applying in Sweden

In this section Swedish law, directives, general advices, industry standards, guidelines and other legal documents describing requirements for good indoor climate and air quality are presented. Its aim is to clarify the hierarchy of rules, show how they refer to each other, explain which ones are prior to the others, compare limit values of indicators they give and investigate if they are based on the same theoretical base.

Regulations followed in Sweden are quite unique in terms of the way they set their demands – giving them in form of functional requirements means that a designer can freely choose a method to fulfil them and none specific theoretical calculation model is imposed in order to prove that expected conditions will be maintained. However, to ensure that functional requirements will be fulfilled in reality, there must exist relatively simple tools allowing for ensuring it in advance. Three most common, used separately or simultaneously, are theoretical calculations of certain indicators, following commonly accepted practice and assuming big safety margins (Tillberg, 2015). As the first one is the most specific, easiest to control and supports a cost-efficient design, it is referred to by the majority of legal documents.

2.1.1 Government authorities’ requirements

In general, there are three government authorities which make demands on the indoor climate: Boverket (The National Board of Housing, Building and Planning) – responsible for urban planning, city development and construction, ensuring high quality of buildings and publishing to some extent legally binding manuals and handbooks; Arbetsmiljöverket (The Swedish Work Environment Authority) – which goal is to provide safe work environment, free from risk of harm or sicknesses; Folkhälsomyndigheten (Public Health Agency of Sweden) – responsible for questions of the public health and working with prevention of diseases, injuries and other health hazards. It means that in some cases there are three sets of rules putting requirements on the same characteristic of air quality in indoor environment.

2.1.1.1 Boverket

A superior document regulating the building industry in Sweden is Swedish building law – Plan- och bygglag (2010:900). However, in terms of indoor climate the law is quite vague as it states only that “a building must have the technical properties which are essential for the protection in terms of hygiene, health and environment”. This rule is developed to some extent in Plan- och byggförordning (2011:338) where 3 kap. 9 § specifies that “a building must be designed and constructed in a way which will not result in unacceptable risks for users’ or neighbors’ hygiene or health, especially as a consequence of poisonous gas emission, occurrence of dangerous particles or gases in the air, dangerous radiation, pollution of water or ground, insufficient handling of sewage, smoke, solid and fluid waste or occurrence of moisture in building components". Moreover, 3 kap. 14 § defines a part of fulfilling the requirements on energy use and thermal insulation as "equipping the building with components consisting of one or a few layers which insulates the inside of the building from the outside in a way that allows only a low amount of heat to pass through".

Boverket, in Boverkets byggregel (BBR), a publication containing further directives and guidelines, gives more details about how requirements should or could be satisfied. In terms of ventilation it states, among others, that:

- ventilation should be designed so that a sufficient outside air flow is supplied to the building; it should be able to carry away harmful compounds, moisture, odours, discharge products from people and materials, and pollutants generated by activities taking place;
- ventilation should be designed in a way that provides the outside air flow of at least 0.35 l/s per 1 m^2 floor area;
- it should be taken into consideration that the designed air flow can decrease in reality due to pressure drops in filters or dirt in the ducts;
- the local ventilation index must be at least 90% or air exchange efficiency must be at least 40%;
- in buildings other than residential there should be a possibility of reducing the supply air flow in case no one stays inside;
- such a reduction should, however, not cause risks for health or damages to the building and its installations; a whole air volume in the room should be exchanged before it goes back to normal use.

From the thermal climate perspective, some of the most important points are:

- building should be designed in a way that allows to maintain satisfying thermal climate;
- satisfying thermal climate should be maintained in zones or rooms where people stay longer than temporary;
- a building and its installations should be designed in such a way that thermal comfort adjusted to expected use of a space can be maintained during normal operation;
- a building should be designed so that at DVUT (design value for outdoor winter temperature):
    - the lowest directed operative temperature (see Section 4.1.1.3) in an occupied zone is 20ºC in rooms for children in preschools;
    - the difference in directional operative temperature at different points in the occupied zone of the room is calculated at a maximum of 5 K;
    - the surface temperature of the floor beneath the occupied zone is calculated at a minimum of 20°C in premises utilized by children and can be restricted to a maximum of 26°C.
- calculated air velocity in the occupied zone of a room should not exceed 0.15 m/s during the heating season and air velocity in the occupied zone from the ventilation systems should not exceed 0.25 m/s at other times of the year.

There are no rules regarding thermal comfort in the summer period defined by BBR.

BBR refers to regulations given by Arbetsmiljöverket and Folkhälsomyndigheten.

2.1.1.2 Arbetsmiljöverket

Arbetsmiljöverket has drawn up a document called *Arbetsplatsens utformning (AFS 2009:2) Arbetsmiljöverkets föreskrifter om arbetsplatsens utformning samt allmänna råd om tillämpningen av föreskrifterna* – a set of regulations for workplace design and advice on how these regulations can be applied in practice. It is worth to point out that within the meaning of this document school pupils are considered in a same way as employees.

In terms of air quality AFS 2009:2 gives a few valuable remarks. Firstly, it states that premises containing workplaces should have ventilation system for air exchange and removal of pollution sufficient to provide satisfying indoor air quality in occupancy zone. It mentions some symptoms which may indicate problems with IAQ, such as irritated eyes, nose and throat, dry mucous membranes and skin, rash, tiredness, headache and dizziness. It also draws attention to the complexity behind achieving the proper air quality as the problems may be caused by a combination of physical, chemical, medical, biological and psychosocial factors; even questions such as ventilation system maintenance or cleaning methods can influence the final performance of a space. Apart from general remarks, the document gives some more specific numbers:

- air exchange efficiency should be at least 40%;
- exhaust air flow should be at least:
    - in toilets 15 l/s per toilet;
    - in cleaning rooms 3 l/s per 1 m^2 floor, but at least 15 l/s;
    - in showers 15 l/s per shower; when a room lacks openable windows, this can be increased to 30 l/s per shower.

The section concerning air quality suggests also that in premises where people are the main source of air pollution, CO_2 concentration can be used as an indicator of air quality as it is easy to measure; carbon dioxide concentration should be generally lower than 1000 ppm, but it is acceptable if this limit value is exceeded during short periods over the day. A low CO_2 level is however not a guarantee of sufficient IAQ because temperature or cleanness can as well affect how it is perceived.

In terms of ventilation AFS 2009:2 gives mostly general recommendations about what should be taken into account while designing supply air and exhaust air devices as well as air circulation system in the building in order to avoid insufficient ventilation, draught or pollution spreading. The document states explicitly that air flow per person will not be strictly defined but it should be chosen appropriately to occurring pollution and requirements for sufficient and draught-free ventilation.

However, further in the document some advised values can be found:

- in premises occupied more than temporary outside air flow may be set to 7 l/s per person in case of sedentary work, more intense physical work may require higher flow; other sources of pollution require an addition of 0.35 l/s per 1 m^2 floor area;
- air velocity should be kept around 0.15-0.20 m/s as experience shows that it is perceived as draught-free for most people, however at higher air temperature higher velocities may be accepted.

There are also some recommendations about filters given. Outside air needs to be let through a filter in order to remove dirt that may harm installation and decrease IAQ.

Exhaust air, if it is supposed to be utilized as return air, also needs filtration from particles.

Another statement worth noticing is that in most cases it is not people's need for oxygen or CO_2 emission which is determining the need for ventilation, but need to remove odours, regulate temperature and keep proper level of moisture.

Concerning thermal climate, it is mentioned that a workplace must have suitable thermal climate considering the type of work and level of physical activity. A source of heating should in principle be located in all premises where work is carried out all year round. The document states that perception of thermal climate is determined by a number of factors: air temperature, mean radiant temperature, air velocity, relative humidity, physical activity and clothing (which is coherent with PMV model). Thermal climate is divided into three zones, where temperatures between 10 and 30°C set the boundaries for so called neutral climate in which stress for a human body is minimal, it is however also mentioned, that even small deviation from ideal temperature can result in decreased concentration, attention and assessment.

For measurements of thermal climate, it is recommended to use standard *ISO 7730:2005 Ergonomics of the thermal environment -- Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria* and the limit value for PPD is set to at most 10% (more about calculation of PMV and PPD can be found in Section 4.1.1). As limits for indoor air temperature above or below which a more detailed investigation of thermal climate should be performed are 20-24°C in winter and 20-26°C in summer. Also, vertical and horizontal temperature differences should be restricted according to ISO 7730.

At the time of writing this report, Arbetsmiljöverket is working on an update to the regulations. Proposed changes have been published for comments and remarks to public until 15th March 2019. The new version introduced significant simplifications. From the section concerning air quality all specific requirements, for instance for exhaust air flows or CO_2, are removed and only general information about need of providing satisfying air quality, for example in terms of temperature and humidity is left. The part concerning thermal climate does no longer contain a PPD requirement of 10%, even though ISO 7730 is still used as a reference for measurement methods. These changes highlight the tendency to set only functional requirements and leave up to the designer in which way they will be fulfilled.

2.1.1.3 Folkhälsomyndigheten

Folkhälsomyndigheten has published a document called FoHMFS 2014:17 Folkhälsomyndighetens allmänna råd om temperatur inomhus, which can be translated as general advice on indoor temperatures. This regulation has its sources in Miljöbalken (1998:808) – a general, comprehensive, environmental law – as it defines a term "inconvenience for human health", meaning disturbance which from medical or hygienic perspective can negatively affect health and which are neither negligible nor fully temporary. FoHMFS 2014:17 provides a table with temperature limits and air velocity to prevent occurrence of such inconveniences, considering also presence of people with higher sensitivity due to age or physical condition.

Table 2.1 Limit values and recommended values for indoor climate given by FoHMFS 2014:17.

	Limit value for estimation of inconveniences	Recommended value
Operative temperature	Below 18°C; for sensitive groups below 20°C	20-23°C; for sensitive groups 22-24°C
Operative temperature, permanent	Above 24°C; in summer above 26°C	
Operative temperature, temporary	Above 26°C; in summer above 28°C	
Difference in operative temperature measured vertically 0.1 and 1.1 m above the floor		Not above 3°C
Radiant temperature difference between a window and an opposite wall		Not above 10°C
Radiant temperature difference between a floor and a ceiling		Not above 5°C
Mean air velocity		Not above 0.15 m/s; at indoor air temperature above 24°C can higher velocity be accepted
Surface temperature of the floor	Below 16°C; for sensitive groups below 18°C	20-26°C

2.1.2 Lokalförvaltningen's tekniska krav och anvisningar (TKA)

TKA are Lokalförvaltningen's specific complement of government regulations, standards and common practice. Their aim is to secure energy efficiency, moisture safety, good indoor climate, poison-free environment and create technical solutions and systems easy to administrate and operate in an effective way. TKA concern the branches that are in LF's interest, i.e. schools, elderly housing and offices and are divided into several technical areas.

In the framework program for preschool and school buildings a wide scope of questions has been mentioned, but some of them are directly or indirectly related to the indoor environment. For instance, the document states that design of interior must be flexible enough to accommodate potential future change of age structure and number of pupils. Flexibility is also striven in use of building's areas which are supposed to be multifunction. It implies that, among others, ventilation system must be able to be adjusted to different demands. More specific directives which can be found in the program include:

- ventilation should be steered by demand based on CO_2 concentration and indoor air temperature; air exchange rate should be chosen according to Arbetsmiljöverket's recommendations so that CO_2 concentration does not exceed 1000 ppm;
- a reference made to SOSFS 1999:25 – Socialstyrelsen's advise in terms of ventilation in accordance with Miljöbalken, this regulation states the following:
  - in schools and other premises for child care, air flow should not be lower than 7 l/s per person and addition of 0.35 l/s per 1 m^2 floor area should be made;
  - CO_2 concentration should normally not exceed 1000 ppm;
  - the difference between indoor and outdoor absolute moisture content in the air should not exceed 3 g/m^3 in winter;
  - it is important to take into consideration number of people in the room, way of use, possibility and routines for airing and occupancy time when assessing ventilation's sufficiency;
- yearly mean value of NO_2 concentration should not exceed 20 µg/m^3.

Furthermore, TKA for air handling system gives much more detailed numbers regarding the ventilation design assumptions:

- the total pressure drop in supply air and exhaust air system should not exceed 200 Pa (at the time of writing the following report the value is being updated to 250 Pa);
- SFP should not exceed 1.5 kW/m^3/s at mean air flow for VAV and maximum air flow for CAV systems;
- maximum pressure drops and air velocities in system's different components should meet criteria presented in table below:

Table 2.2 Dimensioning air velocities and pressure in ducts and components according to TKA.

	Maximum air velocity	Maximum pressure drop
Air intake	2.0 m/s	20.0 Pa
Exhaust air cowls		40.0 Pa
Air filter	2.5 m/s	
Air heating coil	3.0 m/s	
Air cooling coil	2.5 m/s	
Dampers		30.0 Pa
Main ducts, rectangular		0.8 Pa/m
Main ducts, circular		0.8 Pa/m
Branch ducts		0.8 Pa/m

- in rooms occupied longer than temporarily the maximal air velocity in the heating season should not exceed 0.15 m/s;

- kitchen and dining area should be equipped with separate air handling unit;
- in CAV systems rooms with dimensioning flow exceeding 50 l/s should be provided with demand-controlled ventilation;
- in preschools the whole ventilation system should be designed as CAV system;
- air handling unit in a preschool should have outdoor temperature compensation for pressure- and temperature regulation according to specification ("Driftkort FTX – CAV", provided in TKA);
- Heat recovery efficiency should be at least 94% for rotary heat exchanger and 72% for plate heat exchanger (in the upcoming update of the document this is changed to 80% temperature efficiency for both types).

Specifications for CAV system in preschool give another important data – supply air temperature should be constantly 14°C.

Despite the above-mentioned demand on CAV systems in preschools, reference building in this thesis is designed with VAV. Such a system is, analogically to CAV, described in details in its specification. One important difference is that specification for VAV system uses 1500 ppm CO_2 instead of 1000 ppm as upper limit value. It has been established in personal communication with LF (29.03.2019) that the reason for this is to avoid situations when carbon dioxide concentration steers demand-controlled ventilation rather than indoor temperatures.

A part of TKA are templates which should be used to prepare environmental plan when designing new buildings or expansion of the existing ones. In these templates recommendations for thermal climate indoors can be found. For preschool they are as follows:

- temperature in winter:
  - in general 20°C;
  - in corridors and cloak room 17°C;
  - in vestibule above frost temperature;
- in summer:
  - no specific temperature value;
  - PPD at most 10% without airing;
  - comfort cooling is not allowed;
  - at least one openable window per room where people stay longer than temporarily;
  - other TKA and governmental regulations apply.

2.1.3 Energi- och Miljötekniska Föreningens riktlinjer R1

Energi- och Miljötekniska Föreningen – Society of Energy and Environmental Technology – issued guidelines called R1, describing specification for indoor climate. The first edition was published in the beginning of '90s and second, containing important updates regarding new experience, recommendations and rules, in 2000. These guidelines are not a legally binding document, but they were commonly used as a reference for HVAC designers while setting requirements and quality levels for indoor environment.

In 2006 third and in 2013 fourth edition was published. In these publications R1 changed significantly: the idea with the guidelines is now to use them as a framework when defining functional requirements, but it is not possible anymore to refer to them directly – design values must be chosen outside from R1. In the newest version some of thermal quality classes are removed and the remaining ones are no longer described with measurable indicators but in general words. For that reason, it does not happen as often as before that R1's requirements are referred to and, if so, it is mostly aimed at the second edition. (Tillberg, 2015). Therefore, in the following section, more specific demands from the older version of R1 are presented.

For the thermal climate quality classification PPD index is used as an indicator and its limit values are in accordance with either ISO 7730 or ASHRAE 62-1989 standards. The limits are shown in Table 2.3.

Table 2.3 Thermal comfort (TQ) – PPD for different quality classes and indoor climate factors.

Indoor climate factor	Quality class			
	TQ1	TQ2	TQ3	TQX
Operative temperature	<10%	10%	20%	acc. to spec.
Air velocity	10%	10%	20%	-
Vertical temperature difference	<10%	10%	20%	-
Radiant asymmetry	<10%	10%	20%	-
Floor temperature	<10%	10%	20%	-

Further in the documents more detailed recommendations for how to fulfil PPD requirement are given. These are presented in Table 2.4.

Table 2.4 Thermal comfort – acceptable values for different factors in different quality classes.

No.	Indoor climate factor	TQ1	TQ2	TQ3
1.	Operative temperature			
1.1.	In winter			
	- highest, °C	23	24	25
	- mean, °C	22	22	22
	- lowest, °C	21	20	19
1.2.	In summer			
	- highest, °C	25	26*	-
	- mean, °C	24.5	24.5	24.5
	- lowest, °C	24	23	22
2.	Air velocity in occupied zone, m/s			
	- winter	0.15	0.18	0.21
	- summer	0.18	0.22	0.25
3.	Vertical temperature difference, K/m	2.0	2.5	3.0
4.	Radiant asymmetry			
	- towards warm ceiling, K	4	5	7
	- towards cold wall (window), K	8	10	12
5.	Floor temperature			
	- highest, °C	26	26	-
	- lowest, °C	22	19	16
	Acc. to BFS 1998:38			
	- highest, °C	27	27	27
	- lowest, °C	16	16	16
	- optimal, °C	24	24	24

* it can be exceeded maximum 30 hours per year

Operative temperature in winter is given with assumption of clothing factor of 1 clo and in summer 0.5 clo. In case of different clothing level, temperatures need to be recalculated.

Relative humidity is not limited as it is not affecting perception of indoor climate in a significant way, however, considering construction's moisture safety, it is recommended to keep absolute humidity below 7 g/m^3, which normally corresponds to around 50% RH.

For operative temperature deviations up to 1.2 K are acceptable. For air velocity maximum allowable deviation is 0.05 m/s.

R1 defines also requirements for air quality classes, AQ. In this case, the classification is based upon a frequency of people's reaction for a number of factors, which is presented in Table 2.5.

Table 2.5 Air quality (AQ) – frequency value for different quality classes and indoor climate factors.

Indoor climate factor	Quality class			
	AQ1	AQ2	AQX	Remarks
According to toxicologic assessment	-	-	acc. to spec.	Concerns reactions causing health-related hazards; regardless of the class, government authorities' requirements should be accounted for
Inconvenience reactions	0-1%	5%	-	Aims at reactions giving measurable inconvenience
Mucous membranes' irritation	0-1%	10%	-	Includes even barely perceptible irritation such as eyes irritation
Dissatisfaction with perceived air quality	10%	20%	-	Aims at climate perception by means of senses
Odour detection	10%	50%	-	Even hardly perceptible odour at the moment of entering the room

Same as in case of TQ, the document gives more detailed limits to reach goals within quality classes, for AQ expressed in content of pollutants per 1 m^3 of air. These limits are presented in Table 2.6.

Table 2.6 Air quality– acceptable content of pollutants in the air in different quality classes.

Compound	Higher content in mg/m^3	
	AQ1	AQ2
Carbon monoxide - mean 1 h - mean 8 h	 40 10 / 6	 40 10 / 6
Carbon dioxide - if given in ppm	1000 / 1500 600 / 800 ppm	1800 1000 ppm
Ozon, mean 1 h	0.05	0.07
Nitrogen dioxides - mean 1 h - mean 24 h	 0.1 0.075	 0.1 0.075
VOC - total, mean 0.5 h - formaldehyde, mean 0.5 h	 0.2 0.05	 0.5 0.01
Dust	0.06	0.15
Soot, mean 24 h	0.04	0.09
Mould, cfu/m^3	50	150
Bacteria, cfu/m^3	4500	4500
Radon - mean 1 year, Bq/m^3 - gamma ray, Sv/h	 200 0.5	 200 0.5

For some of the indicators two values are given, which is caused by referring to different standards.

Specific demands in terms of ventilation system are not a part of the guidelines. However, in order to meet air quality requirements from Table 2.6, minimum air flow calculation methods are suggested. Air flow can be found through a use of template method, or, if exact emissions and pollutant generation is known, through individual dimensioning. The template includes factors such as number of people per square meter, percentage of smokers and material emissions. For preschool, this calculation method would result in 0.35 l/s per 1 m^2 floor area for AQ2 and 0.8 l/s per 1 m^2 floor area for AQ1. Further in the document it can also be found that air flow cannot in any case be lower than 5 l/s per person.

Moreover, in AQ1 use of return air in ventilation is not accepted and in AQ2 it is accepted only if the air comes from premises with no other pollution sources than human metabolism products or emissions from low- or medium-emission materials' surfaces. Ventilation system in TQ1 and AQ1 must be equipped with control devices allowing for individual adjustments of indoor climate. In classes AQ1 and AQ2 it has to be possible for the air flow to decrease down to 40% when the building is not used.

2.1.4 SS-EN 15251:2007

SS-EN 15251:2007 is a standard entitled *Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics*. Its main purpose is to propose how to establish design criteria for dimensioning of systems in a building, performing energy calculations and long-term evaluation of IAQ. It does not specify exact criteria for thermal comfort but as it gives a few categories of them to choose from in the design process, it also gives general information about reasonable limits for several parameters.

SS-EN 15251 defines four categories of criteria, where category I is addressed to spaces with high level of expectations, such as facilities occupied by very fragile people with special needs, for example handicapped, sick, very young children and the elderly. Category II is for new buildings with normal level of expectations.

The standard recommends use of PPD and PMV indices for thermal comfort rather than temperatures, as in this case also air velocity is taken into consideration. For category I it is desirable to keep PPD below 6%, which corresponds to PMV between -0.2 and 0.2, while category II is associated with PPD below 10% and PMV between -0.5 and 0.5. It can be seen that despite including young children in the group of users with special needs, other regulations usually aim for fulfilling the requirements for category II.

With additional assumptions of typical winter or summer clothing insulation and activity level connected to the type of space, further recommendations on operative temperatures are given. For a preschool it should be: in category I min. 19°C in winter and max. 24.5°C in summer, in category II min. 17.5°C in winter and max. 25.5°C in summer.

For ventilation, the required rates for diluting emissions are 10 l/s per person in category I and 7 l/s per person in category II, which proves again that other regulations use values for the latter. Same can be noticed in requirements for ventilation due to material emissions: 0.5 l/s per $1m^2$ for category I and 0.35 l/s per $1m^2$ for category II (in very low polluting buildings, which applies to most of these in Sweden).

CO_2 levels are recommended to not exceed 350 ppm above outdoors concentration in category I and 500 ppm in category II. Assuming average outdoor concentration 350-400 ppm, these levels are lower than in other regulations for both categories.

In spaces where humidity requirements are determined by human occupancy it is recommended to keep RH between 30 and 50% in category I and 25 and 60% in category II. Moreover, specific humidity should never exceed 12 g/kg air.

2.2 A comparison of functional requirements

As can be seen, indoor environment in a preschool building can be described by demands of a number of regulations. Some of them are equally important from legal perspective and thus all must be fulfilled. The table below summarizes limit values of indicators which can be compared between different documents. For R1 limits for TQ2 are presented as they are corresponding with PPD requirement of 10% occurring in most of the remaining regulations. SS-EN 15251 is not included in the comparison as it is not supposed to be used for setting the requirements as long as other national regulations apply. The value which is decisive for a given indicator is written in bold font.

Table 2.7 Summary of regulations in force for indoor environment in a preschool in Sweden.

Indicator	BBR	AFS 2009:2	FoHMFS 2014:17	TKA	R1 (for TQ2 and AQ2)
Mean indoor air temperature, winter	-	-	-	**20°C**	22°C
Mean indoor air temperature, summer	-	-	-	-	24.5°C
Directed operative temperature, winter	**20°C**	-	-	-	-
Operative temperature, winter	-	-	**≥20°C*** **≤24°C**	-	-
Operative temperature, summer	-	-	**≥20°C*** **≤26°C**	-	-
Air velocity in heating season	**0.15 m/s**	0.15-0.20 m/s	0.15 m/s**	-	0.18 m/s
Air velocity outside heating season	0.25 m/s	0.15-0.20 m/s	**0.15 m/s****	-	0.22 m/s
CO_2 concentration	-	**1000 ppm**	**1000 ppm**	1500 ppm	-
PPD	-	**≤10%**	-	≤10% in summer	10%
Air flow	0.35 l/s per m^2	**7 l/s person + 0.35 l/s m^2**	**-**	**7 l/s person + 0.35 l/s m^2**	5 l/s person + 0.35 l/s m^2

* recommended 22-24°C; ** unless air temperature is at least 24°C

Recommendations given by R1 are not considered as governing, even if they set the strictest requirements, as they function as guidelines, not law.

The table shows clearly that regulations give very coherent and consequent framework for setting functional requirements. It can be, after minor simplifications, concluded that a preschool building should provide indoor environment with operative temperature between 20 and 24°C in winter and 20 and 26°C in summer, with PPD always at most 10%, air velocity at most 0.15 m/s, CO_2 concentration not exceeding 1000 ppm longer than temporarily and air flow of 7 l/s per person and 0.35 l/s per 1 m^2 floor area (for occupied zones). Such a conclusion is on one hand beneficial as it proves that requirements are not contradictory to each other and thus not confusing for a designer. On the second hand though, it results in lack of flexibility in the design of indoor spaces. Even if one of the regulations leaves some space for adjustment of limits to individual case, the next one sets strict demands again. Law created by the government is applied to a wide scope of activities - in certain cases it treats residential, commercial and public indoor spaces equally – and in this kind of general approach some vital differences between desired building characteristics are inevitably lost in the process. The optimal indoor climate can vary in function of the way in which the space is used and these differences can concern even seemingly same rooms – for instance in school there may be a significant mismatch between air flow demand in classes dependent on the age of kids who occupy them.

Another issue that needs to be raised is whether the current way to set requirements is the best possible. There are differences between documents in terms of choosing air temperature, operative temperature and directed operative temperature, but among these three indicators only operative temperature has a strong connection to perception of thermal comfort (Tillberg, 2015). There is also a number of research proving that PPD/PMV model does not work sufficiently for children, which leads to overestimation of desired temperatures (Teli, 2012). Current requirements do not consider adaptive model of thermal comfort, where users can adjust to certain conditions depending on their expectations and possibility to make changes in the indoor environment, for example by controlling the air flow and temperature personally.

A conclusion is that there is an apparent space for improvement in legal regulations on indoor climate and future changes should have in focus increased flexibility in general documents with wide scope. More detailed demands should be perhaps defined in specifications aiming at particular types of buildings. Some of suggested changes are briefly discussed in Section 4.7 further in the report.

3 Construction's Environmental Impact

In the following chapter, focus is being put on the ways to evaluate construction's environmental impact. The idea of Life Cycle Assessment is introduced and a few calculation methods and models are described with emphasis on CO_2 equivalents. Finally, a brief review of commercial environmental certification systems and legal regulations mentioning environmental footprint is carried out in order to define existing framework for work with environmental questions in Sweden.

3.1 Existing methods to measure environmental impact

3.1.1 Life Cycle Assessment

Life Cycle Assessment (LCA) is a calculation method to estimate environmental impact of the whole life cycle of a product, from the extraction of natural resources, through production, to end-of-life (and in the case of a building – demolition) and recycling. It allows to identify which phase of a construction process implies the biggest burden on the environment and helps taking measures to reduce it. LCA is recommended to be carried out already in the early stage of the project, as it maximizes the possibility of making conscious choices in terms of materials and structural systems, minimizing the risk of neglecting important factors, such as for instance long transports, required machinery or complicated maintenance. Nevertheless, LCA can bring benefits also later in the construction process, for example when contractor is chosen (to motivate involved actors to improved environmental work), during follow-up (to verify previous calculations and obtain an underlay for environmental certification) or refurbishment (as it may imply significant changes in the amount of materials built-in or energy use, it is considered as a new life cycle, starting from stage A) (Boverket, 2019).

For calculations on the general level, the international standard ISO 14044 is a base for LCA (Göteborgs Stad Lokalförvaltningen, 2019). For buildings, there is a standardized calculation method given in the European standard *EN 15978 Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method.* It divides building's life cycle into the following phases:

- A 1-3 Product stage
    - A1 Raw material supply
    - A2 Transport
    - A3 Manufacturing
- A 4-5 Construction process stage
    - A4 Transport
    - A5 Construction – installation process
- B 1-7 Use stage
    - B1 Use
    - B2 Maintenance

B3 Repair

B4 Replacement

B5 Refurbishment

B6 Operational energy use

B7 Operational water use

C 1-4 End-of-life stage

C1 Deconstruction, demolition

C2 Transport

C3 Waste processing

C4 Disposal

An additional phase D, benefits and loads beyond the system boundary, can be added to the analysis to include gains and drawback from reusing and recycling, but as it is scenario-based, it must be considered and reported separately (Trafik- og Byggestyrelsen, 2016). All stages are indicated in the Figure 3.1 below:

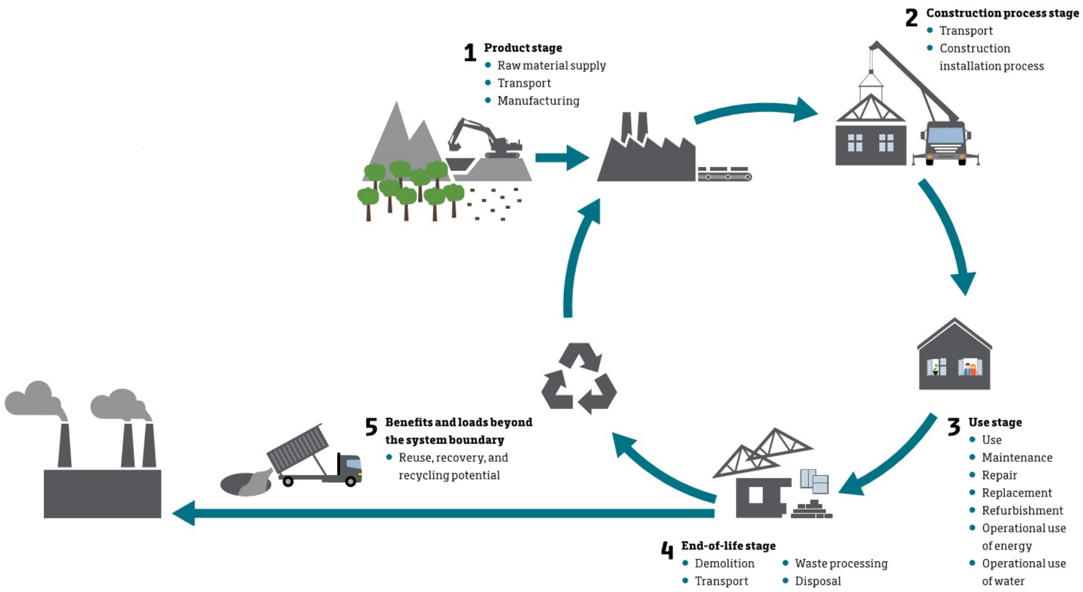


Figure 3.1 The stages of building's life cycle (Trafik- og Byggestyrelsen, 2016).

Nowadays the biggest environmental impact is associated usually with construction and operational energy use, but as buildings are becoming more energy-efficient and energy sources more sustainable, it can be expected that in the future the meaning of the former will increase and of the latter – become less significant.

LCA described in EN 15978 is so called attributional LCA, which means that it examines environmental impact associated with a certain building product. This type of LCA gives detailed data about a building but demands very precise boundary conditions in the applied methodology, which may lead to necessary consensuses. The second type of LCA is consequential one and its goal is to study what impact is implied by different choices or changes in the project. In that way it investigates a wider system, including various products, but due to its scenario-based nature and assumptions made, it brings also bigger uncertainties (IVL, 2014).

LCA uses different categories to assess the total environmental impact. Each of them works as an indicator, measurable with a given unit and associated to a specific problem. The most important and therefore also characterized by best developed calculation methods, are:

- Global Warming Potential (GWP) – described in CO_2 equivalents – associated with climate change due to increase of greenhouse gases in the atmosphere;
- Acidification Potential (AP) – described in SO_2 equivalents – associated with acid rains harmful primarily for plants;
- Eutrophication Potential (EP) – described in PO_4 equivalents – associated with excessive supply of nutrients generating unwanted plant growth;
- Depletion Potential of the Stratospheric Ozone Layer (ODP) – described in R11 (refrigerant CCl_3F, trichloromonofluoromethane) equivalents – associated with decreasing protection for flora and fauna from UV-A and UV-B sun radiation;
- Formation Potential of Tropospheric Ozone Photochemical Oxidants (POCP) – described in ethylene equivalents – associated with formation of harmful ozone in the lower atmosphere;
- Abiotic Depletion Potential for Non-fossil Resources (ADPe) – described in Sb (antimony) equivalents and Abiotic Depletion Potential for Fossil Resources (ADPf) – described in MJ – associated with depletion of available elements and fossil energy sources due to heavy consumption.

Other categories are, for instance, total use of primary energy, ecotoxicity, human toxicity, land use, loss of biodiversity or noise (Trafik- og Byggestyrelsen, 2016). Categories of environmental impact which are not included in LCA can be investigated separately with different methods. It may regard for instance site-specific aspects, such as biodiversity or water conditions (Boverket, 2019).

For the time being, Global Warming Potential is considered often to be the most severe danger for the environment and therefore it is common to limit LCA for buildings to this category.

3.1.2 CO_2 equivalents

CO_2 equivalents (further referred to as CO_2e) are used to calculate and describe climate impact since it is the most common greenhouse gas. The influence of other chemical compounds, such as methane, water vapour or nitrogen dioxide, is obtained as well, but it is translated to CO_2's effect with an appropriate factor, based on GWP – Global Warming Potential (SGBC, 2017). It indicates how much heat a weight unit of a certain gas can trap in the atmosphere compared to CO_2.

3.1.3 Environmental Product Declaration

Environmental Product Declaration (henceforth referred to as EPD) is a method of presenting environmental impact of a product or a group of products. EPD is obtained from ISO 14025 *Environmental labels and declarations - Type III environmental declarations - Principles and procedures* and specific rules for building products from

EN 15804 *Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products*. Thanks to standardized calculation method, it can be guaranteed that EPDs are derived from same LCA methodology and reviewed by third party before registering. Comparability is further increased by PCR – Product Category Rules, setting additional limiting criteria for specific groups of products (Boverket, 2019).

EPD consists of three parts: product data sheet, method choice and results from environmental impact assessment (Boverket, 2019). A part of results is climate impact expressed in kilograms of CO_2 (or CO_2e) per unit, for instance m^2, m^3 or kg.

EPD for groups of products is based on generic data which is usually assumed with big safety margins, therefore it is beneficial for manufacturers to develop EPDs for their particular wares. Specific values enable also convenient comparison of two products. Nevertheless, generic EPDs facilitate discussion about environmental impact of different solutions in terms of materials and construction methods in general. On the other hand, all comparisons must be carried out carefully as even though standards give guidance on obtaining EPDs, there is a lot of space for interpretation, which may lead to incoherence in assumptions and delimitations. Furthermore, if EPD is supposed to work efficiently as an underlay for strategic decisions, the database must be continuously developed and customers must be encouraged to demand EPDs from producers in order to accelerate their introduction to the industry (Göteborgs Stad Lokalförvaltningen, 2019).

In Sweden EPD has been since 2014 administrated by IVL Swedish Environmental Research Institute. This organisation provides an LCA methodology-based tool called Byggsektorns Miljöberäkningsverktyg. It contains generic data for materials and products used on Swedish market and allows for adding specific data if it is available. It is also possible to run climate calculations directly in the tool (IVL, 2019).

3.1.4 Environmental impact of energy production

Apart from materials or products, CO_2e can of course also be calculated for energy production.

In terms of electricity, environmental impact depends on emissions generated in production of energy from primary sources, of which a given energy mix consists. Swedish energy mix that has been assumed for all calculations in this report, based on data from Energimyndigheten (2018) has a share of different primary sources as shown in Figure 3.2.

For windpower, the biggest emission generation is associated with ground preparation for wind turbines and construction phase. Important factors are local wind conditions, chosen building materials, turbine’s power, operation time and life span. For hydropower, environmental footprint is the result of extensive construction works required to establish facilities such as dams, tunnels, turbines etc., but the biggest impact is caused if flooding occurs due to dam operation, as it changes among others condition of standing biomass and coal deposits in the ground. For nuclear power, resources use is mostly determined by construction of power plants and emissions to air and water by extracting and enriching uranium. For CHP (combined heat and power) the biggest environmental impact is caused by combustion (Gode et al., 2011).

For Swedish energy mix emission factor of 36.4 g CO_2e/kWh has been assumed, according to Gode et al. (2011). However, their results were obtained for slightly different share of primary energy sources, so the actual emission factor may be lower.

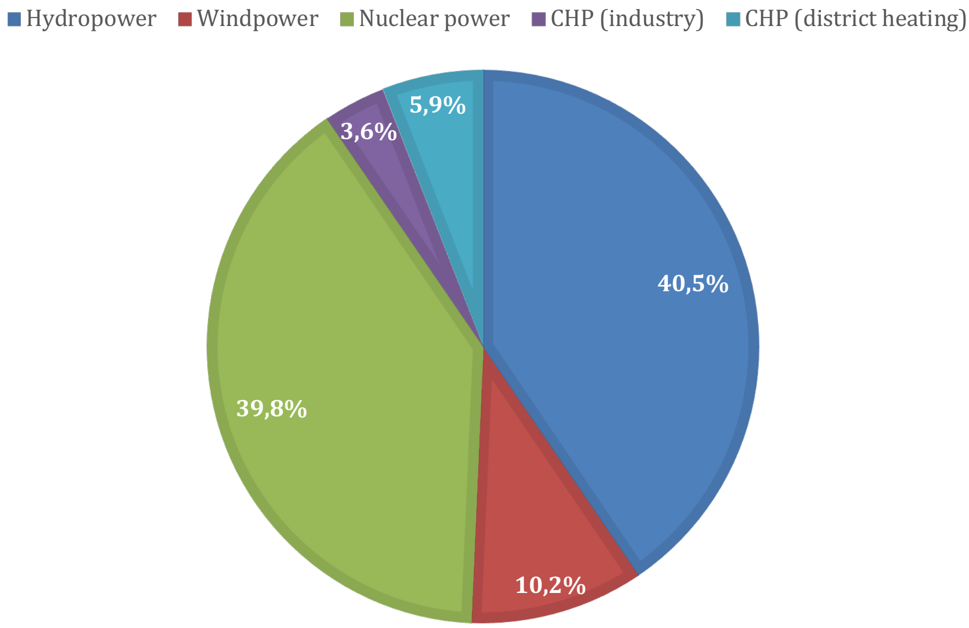
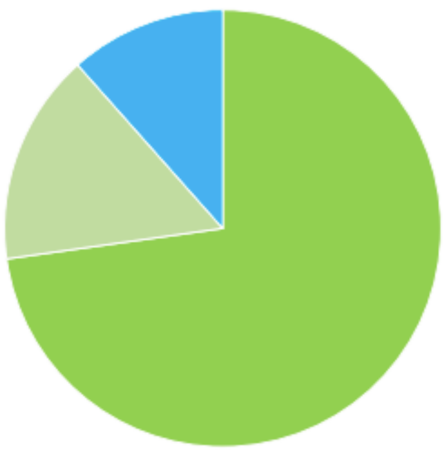


Figure 3.2 Net electricity production in Sweden, 2016 – share of primary energy sources.

In terms of district heating, Göteborg Energi provides yearly reports on environmental impact associated with its production. In the report from 2018 total greenhouse gases emission is divided into three aspects: combustion (65.0 g CO_2e/kWh), transport and production of fuel (8.0 g CO_2e/kWh), and electricity use (5.0 g CO_2e/kWh). The share of fossil fuels is 12%.



Återvunnen energi		73%
* Kraftvärme (avfall)	23%	
* Industriell spillvärme (raffinaderier mm)	32%	
* Avloppsvatten	8%	
* Rökgaskondensering	10%	
Förnyelsebar energi		16%
* Kraftvärme (biobränsle)	3%	
* Värmepanna (biobränsle)	5%	
* Köpt värme (biobränsle)	3%	
* El till värmepump (avlopp)	3%	
* Hjälpel (pumpar mm)	1%	
Fossil energi		12%
* Kraftvärme (naturgas)	12%	
* Värmepanna (naturgas, olja)	0%	

Figure 3.3 Energy sources for district heat production in Sweden, 2018 (Göteborg Energi, 2018).

3.2 Applying regulations and guidelines on construction's environmental impact

3.2.1 Legal regulations

Environmental impact of construction is currently defined rather vaguely in legal documents in force in Sweden. In 2016 Boverket published a pre-study called *Miljö- och klimatanpassade byggregler* aiming to analyze and assess if new administrative measures are needed to adjust building sector from environment's and climate's perspective. The general conclusion from this report is that even though there are some regulations concerning environment, they are limited to the one in closest surroundings of a building, neglecting the general and global environmental issues (Boverket, 2016). For instance, Miljöbalken states that all who have an intention of running an activity, should have knowledge and apply measures in order to protect human health and environment. Plan- och bygglag refers to Miljöbalken's environmental quality standards and environmental impact assessment methodology and requires following them in all cases covered by this law. Furthermore, PBL in 2 kap. 3 § states that all planning should, considering nature and cultural value, environmental and climate aspects and local circumstances, support long-term conservation of land, water, energy and resources as well as other environmental conditions. Moreover, in 8 kap. 4 § it is stated that a building must have technical properties which are essential in terms of protection for hygiene, health and environment. However, in Plan- och byggförordingen it is further specified that this is limited to risks for users or neighbors and does not concern general questions. None of the laws contain specific demands on emission of greenhouse gases.

Furthermore, there are no requirements in public-law regulations, such as for instance building law, for carrying out Life Cycle Assessment (Boverket, 2019). However, Boverket recently published a report called *Vägledning om LCA för byggnader* (Sw. Guidelines for LCA for buildings), based in civil law, addressed to everybody willing to order or carry out LCA. It has been proposed in this document to, latest in 2020, start using LCA as starting point in all new- and rebuilding investments as well as in buildings administration, in order to reach the goal of environment- and climate-adjusted construction. The goal of the guidelines is to increase demand for LCA in the industry. Calculation method described here is in accordance with EN 15978.

Another idea, also brought up by Boverket, is to demand climate declaration for every building; it has been reported to the government for further work.

3.2.2 Commercial certification systems

There is a number of commercial certification systems on the construction market, which purpose is to provide a universal tool to assess and compare buildings, promote these with better performance and thus create an incentive for developers to improve quality in their investments. In this section a few of them, most popular or applying only in Sweden, are briefly described. In contrast to legal regulations, all of them include some aspects of environmental impact of buildings or their parts.

3.2.2.1 Miljöbyggnad

Miljöbyggnad is a certification system which is used in Sweden. It is owned and developed by the country's biggest organization working with sustainable construction, Sweden Green Building Council (SGBC). In Miljöbyggnad fifteen different indicators, divided into three groups: energy, indoor climate and building materials, are measured in order to compare obtained values to given limits for three grades – Bronze, Silver and Gold, describing building's performance (SGBC, 2017a). Admittedly, the biggest focus of MB is on indoor climate, but in version 3.0 there is an indicator called "environmental impact of the building's structural system and foundations". It is focusing on examining influence of products and their transportation to construction site, neglecting though the operation phase. There is also a requirement to present detailed climate data in form of EPDs when applying for certification, as the impact is expressed in grams CO_2e per 1 m^2 heated floor area, which is supposed to promote the use of this method in the industry (Göteborgs Stad Lokalförvaltningen, 2019). However, Miljöbyggnad does not set specific demands on emissions – grades Bronze and Silver can be obtained just by calculating climate impact with a given method, while Gold is defined in reference to Silver by impact decreased by 10% while using the same load-bearing structure and foundation. It means that the indicator is relative, not objective.

3.2.2.2 BREEAM and LEED

BREEAM is an environmental certification developed in Great Britain in 1990. It is nowadays the most commonly used system in Europe and it has been used for over 500 000 buildings worldwide. Since 2013 the Swedish version, BREEAM-SE is managed by SGBC. It is adjusted to local regulations but at the same time can still be compared on the international level. BREEAM is covering a wider scope of questions than Miljöbyggnad – for instance energy use, indoor climate, water use, waste management, project management, access to public transport or choice of materials are evaluated, a building can also get extra points for innovative technical solutions (SGBC, 2017b). A point about LCA is included in BREEAM and it concerns impact of ceilings, external walls, windows and roof. Moreover, not only climate, but also at least two other environmental impact categories must be considered in the assessment. LCA is recommended early in the project so that it can be a base for further choices (Göteborgs Stad Lokalförvaltningen, 2019). However, in terms of CO_2 emissions, BREEAM does not give any specific limits except for one case which is connected to refrigerants.

LEED is a system similar to BREEAM, but with slightly more narrow scope (it does not include waste, economy and construction phase in the assessment), coming from the United States and more popular in a global scale. In LEED a point about LCA for load-bearing structure, foundation and building envelope can be found. At least six different environmental impact categories must be analyzed and one of them has to be climate. The climate impact needs to be at least 10% lower than for a standard project (Göteborgs Stad Lokalförvaltningen, 2019). Again, as in case of BREEAM, there is no detailed limit values, it is enough to prove that reduction was made.

The difference between Miljöbyggnad, BREEAM and LEED in terms of considered aspects and their weights can be seen in the Figure 3.1 below, adapted from Olsson (2013).

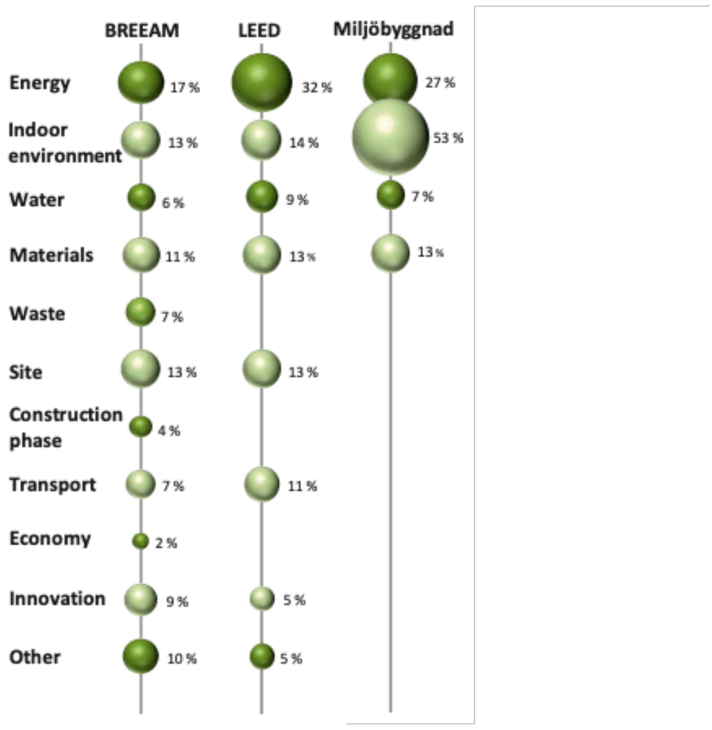


Figure 3.4 The proportions of the different categories in environmental certification systems (Olsson, 2013).

3.2.2.3 NollCO_2

NollCO_2 is a new certification system being currently developed by SGBC. The pilot version is undergoing tests to be published as version 1.0 later in 2019. Its aim is to contribute to construction of climate-neutral buildings by minimizing the emission of greenhouse gases through supporting energy- and resources-efficiency and renewable energy production. The ultimate goal is zero-emission throughout the whole life cycle of a building and therefore this system is wider than the others mentioned before (SGBC, 2019). It includes more than just finished building and its operation – products and production phase are considered as well. Possible reparations, alterations maintenance or demolition are, however, not accounted for. The certification assumes that a building should compensate for its environmental footprint by producing renewable energy (Göteborgs Stad Lokalförvaltningen, 2019).

3.3 Environmental impact in Hoppet

There is a big number of definitions, terms and concepts which can be connected to the idea of climate-neutral construction. Therefore, it is important to know and understand differences between them in terms of main assumptions and delimitations in order to be able to choose the one best matching one's intended priorities.

Figure 3.2 below collects the ways in which environmental impact is included in construction industry:

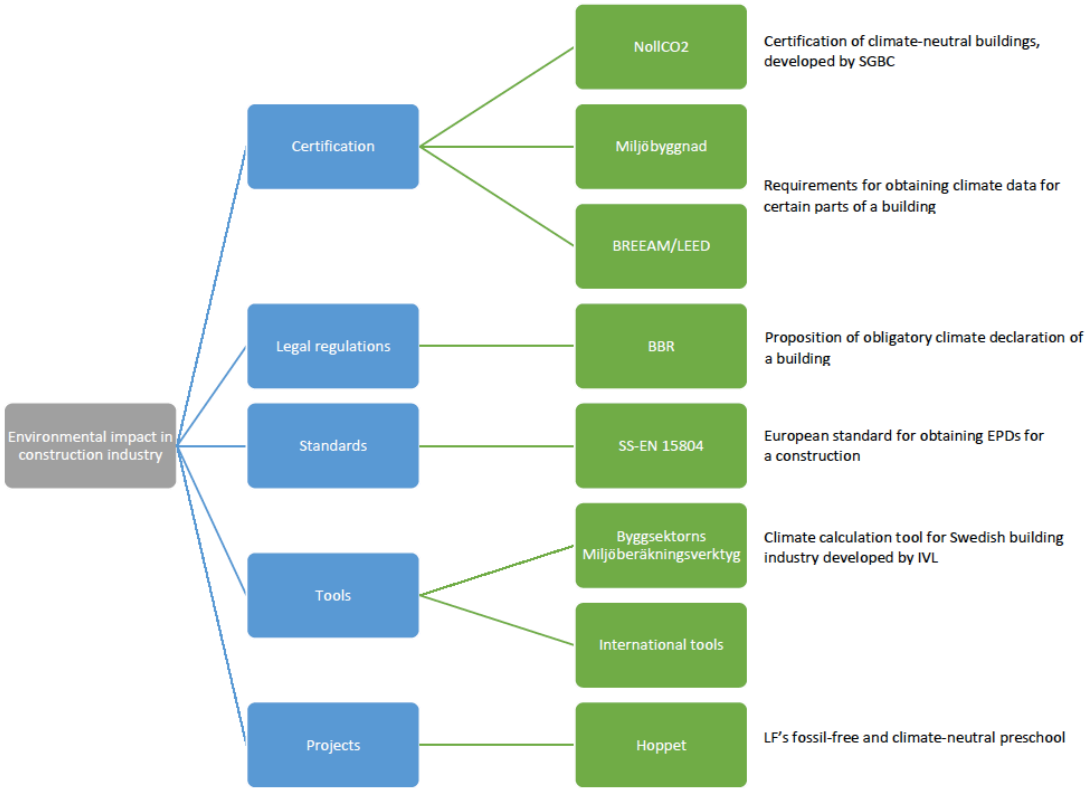


Figure 3.5 The current situation in environmental impact assessment in construction industry in Sweden (adapted and translated from LF, 2019).

In the model fossil-free preschool in project Hoppet there will be no commercial certification system used. Hoppet's goal is rather specific and striving to fulfill requirements within a certain system could divert attention from the main focus on fossil-free construction, as there is currently no certification aiming just for this aspect. Moreover, assumptions in Hoppet are strict – climate impact should be eliminated in the whole life cycle, from resources to operation and demolition. Any possible renewable energy production cannot be considered as a way to compensate for negative effect on environment.

Since the law does not regulate environmental impact in its current shape, there was a freedom of choice of how to evaluate it in project Hoppet. It has been decided that an attributional LCA will be carried out in accordance with SS-EN 15804, but exact method and system delimitations are still discussed. The focus will lie on phases A and B – product, construction and operation, in order to promote products which can in short-term perspective contribute to decreased emissions. Moreover, as the preschool is designed for 100 years, demolition and recycling methods are likely to change significantly. One more reason for such an emphasis is a possibility to compare the results with LCA which was performed for already existing preschools administrated by LF. However, phase C will be considered in the total environmental impact calculation (Göteborgs Stad Lokalförvaltningen, 2019).

4 Consequences of indoor air quality for users' comfort, health and performance

In this chapter some of the measurable indicators of functional requirements, which limit values must not be exceeded according to previously discussed regulations, are presented. Description includes indicators' definitions and their practical implications on human well-being in terms of health and comfort.

4.1 Thermal comfort

The following section describes indicators for the thermal sensation. PMV (Predicted Main Vote) and PPD (Predicted Percentage Dissatisfied) indices are presented and their components are briefly explained. This is followed by the description of indicators for local thermal comfort. Finally, some doubts regarding the application of PMV/PPD model are discussed.

4.1.1 PMV and PPD

PMV (Predicted Mean Vote) model of predicting thermal comfort was developed by Ole Fanger in 1970 and is currently a base for calculation in the commonly used international standard ISO 7730:2005 *Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria* (Teli, 2012).

PMV model is derived from human body's thermal balance equation. In a state of thermal equilibrium, a body produces as much heat in metabolic activity as it loses to its surroundings as a result of summarized heat exchange by radiation, convection and conduction (SIS, 2006). Thermal comfort starts to decrease when this balance is disturbed and in extreme cases health can also be affected – if metabolic rate is higher than heat losses, there is a risk of overheating, while the opposite relation leads to overcooling. Therefore, the factors that influence the heat exchange rate are determining the thermal sensation. The six primary ones are two personal parameters: metabolic rate and clothing insulation, and four environmental: air temperature, mean radiant temperature, air velocity and humidity (ASHRAE, 2004), all of which are explained further in Sections 4.1.1.1 to 4.1.1.6 and 4.2.

Fanger based the PMV model on the empirical tests carried out in the climate chamber with a group of Danish students as the subjects in the steady-state conditions. Obtained data allowed to find out how the parameters affecting the comfort should be combined and thus to develop a calculation method allowing prediction of the average thermal sensation of users in a given space (or vice versa – to design spaces meeting expectations of a given percentage of users). The equations of the model together with the assumptions and limitations are as follows (SIS, 2006):

$$PMV = [0.303 \cdot exp(-0.036 \cdot M) + 0.028] \cdot \{(M - W) - 3.05 \cdot 10^{-3} \cdot [5733 - 6.99 \cdot (M - W) - p_v] - 0.42 \cdot [(M - W) - 58.15] - 1.7 \cdot 10^{-5} \cdot M \cdot (5867 - p_a) - 0.0014 \cdot M \cdot (34 - t_a) - 3.96 \cdot 10^{-8} \cdot f_{cl} \cdot [(t_{cl} + 273)^4 - (\overline{t_r} + 273)^4] - f_{cl} \cdot h_c \cdot (t_{cl} - t_a)\} \quad (4.1)$$

$$t_{cl} = 35.7 - 0.028 \cdot (M - W) - I_{cl} \cdot \{3.96 \cdot 10^{-8} \cdot f_{cl} \cdot [(t_{cl} + 273)^4 - (\overline{t_r} + 273)^4] + f_{cl} \cdot h_c \cdot (t_{cl} - t_a)\} \tag{4.2}$$

$$h_c = \begin{cases} 2.38 \cdot |t_{cl} - t_a|^{0.25} \; for \; 2.38 \cdot |t_{cl} - t_a|^{0.25} > 12.1 \cdot \sqrt{v_{ar}} \\ 12.1 \cdot \sqrt{v_{ar}} \; for \; 2.38 \cdot |t_{cl} - t_a|^{0.25} < 12.1 \cdot \sqrt{v_{ar}} \end{cases} \tag{4.3}$$

$$f_{cl} = \begin{cases} 1.00 + 1.290 \cdot l_{cl} \; for \; l_{cl} \leq 0.078 \frac{m^2 \cdot K}{W} \\ 1.05 + 0.645 \cdot l_{cl} \; for \; l_{cl} > 0.078 \frac{m^2 \cdot K}{W} \end{cases} \tag{4.4}$$

where:

- M – metabolic rate $\left[\frac{W}{m^2}\right]$;
- W – effective mechanical power $\left[\frac{W}{m^2}\right]$;
- p_v – water vapour partial pressure $[Pa]$;
- t_a – air temperature [°C];
- f_{cl} – clothing surface area factor;
- t_{cl} – clothing surface temperature [°C];
- $\overline{t_r}$ – mean radiant temperature [°C];
- h_c – convective heat transfer coefficient $\left[\frac{W}{m^2 \cdot K}\right]$;
- I_{cl} – clothing insulation $\left[\frac{m^2 \cdot K}{W}\right]$;
- v_{ar} – relative air velocity $\left[\frac{m}{s}\right]$.

For simplification, metabolic rate is usually expressed in metabolic units [1 met = 58.2 W/m^2] and clothing insulation – in clothing units [1 clo = 0.155 m^{2}K/W]. 1 met corresponds to metabolic rate of average sitting, relaxed person (resting metabolic rate, RMR), 1 clo – approximately to the amount of insulation that allows a person at rest to maintain thermal equilibrium on a cool day.

The model should be only applied when six main parameters are in the following ranges: M between 0.8 and 4 met, I_{cl} between 0 and 2 clo, $t_a$between 10 and 30°C (so it does not apply to extreme thermal environments), $\overline{t_r}$ between 10 and 40°C, v_{ar} between 0 and 1 m/s, and p_a between 0 and 2700 Pa.

In more practical terms, PMV expresses a mean value of votes of a number of people on a seven-grade scale describing thermal comfort in a following way: -3 – very cold, -2 – cool, -1 – slightly cool, 0 – neutral, +1 – slightly warm, +2 – warm, +3 – hot (SIS, 2006).

PMV provides information about the mean thermal comfort, however, it does not inform how big percentage of users will find the environment unsatisfying or unacceptable and there will always be a certain group of them, as the votes are scattered around the average (SIS, 2006). For that reason, PMV is complemented with second index, PPD – Predicted Percentage Dissatisfied. It is derived directly from

PMV according to equation (4.1) below and informs how many percent of occupants will feel too cool (vote -3 or -2) or too warm (vote +2 or +3) under given conditions.

$$PPD = 100 - 95 \cdot exp(-0.03353 \cdot PMV^4 - 0.2719 \cdot PMV^2) \qquad (4.5)$$

4.1.1.1 Air temperature

Air temperature (t_a) describes the average temperature of the air surrounding the occupants, without consideration of heat radiation from the walls and other surrounding surfaces.

In practice, air temperature in a room is non-uniform, as it is usually colder close to windows and warmer close to the ceiling (the difference may go up to a few degrees in very high spaces). Moreover, air temperature's distribution is affected by forced air movement from ventilation, which in turn is affected by a room's interior design. In simulations it is sometimes assumed that average air temperature is the one that occurs in the middle of the room, 1.25 m above floor (Tillberg, 2015), but when it is referred to by standards and regulations, it is simplified as equal everywhere in a given space.

Air temperature is a vital factor influencing thermal comfort as it affects body's thermal balance. Furthermore, air temperature influences the effect of changed air velocity – lower t_a supports effectiveness of higher air speed used to increase heat loss (ASHRAE, 2004). Moreover, it has an effect on heating and sensible cooling loads (Teli, 2018b), which has a meaning for energy use.

4.1.1.2 Mean radiant temperature

Mean radiant temperature ($\overline{t_r}$) can be defined as "the uniform surface temperature of an imaginary black enclosure in which an occupant would exchange the same amount of radiant heat as in the actual nonuniform space" (ASHRAE, 2004). To obtain mean radiant temperature, the spatial average of surrounding surfaces' temperatures weighted by their view factors with respect to the body has to be calculated, as there is no possibility of direct measurements (Teli, 2018b).

In the most simplified method, the weights are equal to surface areas of surrounding walls, floor and ceiling. However, such an estimation neglects several aspects: posture and facing orientation, ceiling's height or influence of radiant asymmetry (see Section 4.1.2.4). To make a calculation more precise, factors such as an angle factor between a person and a surface or coefficients describing if a person is sitting or standing should be applied (Tillberg, 2015).

The proportion between convection's and radiation's share in heat loss from a body differs with surrounding conditions, but on cold days radiation can be dominant, therefore mean radiant temperature is usually as important as air temperature. The exception is in environments with air velocity above 0.2 m/s, as mean radiant temperature's influence on meaning of air movement for increase of heat loss is smaller than air temperature's influence (ASHRAE, 2004). This is reflected in operative temperature's calculation, see section below.

4.1.1.3 Operative temperature and directed operative temperature

Operative temperature expresses the combined effect of air temperature and mean radiant temperature. It can be therefore defined analogically to the latter as “the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual nonuniform environment” (ASHRAE, 2004).

The operative temperature is obtained as weighted average of t_a and $\overline{t_r}$. In conditions of air velocity below 0.2 m/s, no direct exposure to sunlight and near sedentary activity, it is simply an arithmetic mean. Otherwise appropriate weights depending on air velocity are applied in order to increase the influence of air temperature and decrease the one of mean radiant temperature (ASHRAE, 2004).

Operative temperature can be measured directly and is therefore often used in PMV calculations instead of t_a and $\overline{t_r}$ separately. Moreover, if PMV model is used in a reverse way, i.e. to obtain optimal conditions for given air speed, relative humidity, metabolic rate and clothing insulation, the result is expressed in operative temperature, which makes it independent of a space’s physical design.

Directed operative temperature does not have an official definition but is usually understood as operative temperature measured in a specific direction and calculated in the same way as regular operative temperature. Directed operative temperature is used mainly in Boverket’s regulations (Tillberg, 2015).

4.1.1.4 Air velocity

Air velocity (v_{ar}) is referring to average speed of air to which the body is exposed. Generally, minimum air velocity is preferable, otherwise the risk for complaints about draughts occurs (see Section 4.1.2.1); however, when v_{ar} is within range of 0-0.05 m/s people may perceive air as stagnant.

Air movement can have effect corresponding to a temperature drop of up to 3°C (Teli, 2018b). This influence is the biggest on warm summer days, when clothing insulation is small. It is reflected in ASHRAE standard, which considers a wider range of operative temperatures as acceptable thermal conditions when air speed is increased (Fong et al., 2011). It can be also seen in equation (4.3) where high air velocity determines convective heat transfer coefficient, which in turn decreases PMV in equation (4.1). Therefore, in warm conditions increased air velocity can be a way to allow for higher supply air temperatures and decrease cooling demand for ventilation. Fong et al. (2011) recall several studies (Cohen et al. (1989), Nakamura et al. (2008)) reporting increased thermal comfort thanks to cooling applied to facial area and proving that side and front directions of the occupant are much less sensitive than back direction (Toftum (1997), Mayer (1992)). These conclusions led to development of so-called stratum ventilation, where air is supplied horizontally to head-chest level at increased speed. Resulting small and reversible temperature gradient between feet and head helps to maintain comfort in warm environments (Fong et al., 2011).

4.1.1.5 Metabolic rate

Metabolic rate describes the rate of transformation of chemical energy into heat and mechanical work by metabolic activities within an organism, usually expressed in terms of unit area of the total body surface or met units. 1 met unit equals 58.15 W/m^2 which corresponds to the energy produced per unit surface area of an average person (~1.73-1.8 m^2) seated at rest (ASHRAE, 2004).

Metabolic rate enters the PMV formula twice – firstly, as an input data describing users' activity level, secondly – as a part of empirical equation, with value of resting metabolic rate of 58.15 W/m^2. It indicates clearly that the model is adjusted to adults. Children have a higher metabolic rate per 1 kg body weight, but when body surface area is used as additional factor, the resting metabolic rate is actually lower. Teli et al. (2012) refer to the study of Amorim from 2007, where the obtained child's RMR was equal to 48.8 W/m^2.

PMV works for metabolic rate between 0.8 and 4; the former corresponds to a person reclining, the latter to hard physical work or sport activities. ASHRAE standard and ISO 7730 give metabolic rates values for several activities, but in many cases it has to be estimated. In addition, for all activities except sedentary, metabolic rate will vary between people dependent on individual performance and circumstances. If a person is expected to change activity over time up to one-hour, metabolic rate can be obtained as weighted average. However, such an approach cannot be extended to different groups of occupants with permanently different metabolic rate (ASHRAE, 2004).

It is worth noticing that users' metabolic rate is important not only for their thermal sensation, but also for indoor climate *per se*. A part of heat is being released as moisture in form of sweat and humid breath, which affects RH and cooling effect for ventilation air (Tillberg, 2015).

4.1.1.6 Clothing insulation

Clothing insulation describes the thermal insulation provided by garments and clothing ensembles. ASHRAE (2004) gives two ways of including clothing insulation: either through insulation of clothing/ensemble (I_{cl}) understood as the resistance to sensible heat transfer provided by clothing (heat transfer through uncovered parts of the body is considered) or through garment insulation (I_{clu}), defined as increase of resistance thanks to garment added over the naked body. However, only I_{cl} is used in the standard. It is expressed in clo units.

In order to obtain a clo value of a certain ensemble, every piece of clothing is prescribed insulating ability. The resulting I_{cl} is a sum of clo values of individual garments. There is a limitation of this method due to the fact that same clothing can provide slightly different insulation dependent on the user's posture (sitting/standing). Insulation may also change together with movement as it leads to higher air flow through clothes. It is also possible that groups of users obliged or preferring different clothing will stay in the same space. Similarly, as in case of metabolic rate, this cannot be covered by one average value.

Clothing insulation has an important impact on thermal sensation. According to ASHRAE (2004), 1 clo of additional insulation corresponds to 6°C increase in optimum operative temperature.

4.1.1.7 Humidity

As the air humidity is related to several health issues and IAQ aspects, it is an important part of this chapter and it is discussed separately in Section 4.2.

4.1.1.8 Limitations of PMV model

PMV, even though it is the most commonly used thermal comfort model, has a lot of limitations that decrease its credibility and have led to attempts of finding more reliable way to provide optimal indoor conditions (Carlucci et al., 2018). ASHRAE (2004) already in the beginning of the standard warns that "because there are large variations, both physiologically and psychologically, from person to person, it is difficult to satisfy everyone in a space. The environmental conditions required for comfort are not the same for everyone". This is reflected in PPD equation (4.5) – it can be easily noticed that with PMV equal to 0, that is in theoretically neutral climate, PPD reaches its minimum value of 5%, implying that there will always be some users complaining. Moreover, several previous studies showed that neutral thermal state is not always the preferred option (Kwok and Chun (2003), Wong and Khoo (2003) as cited in Teli et al. (2013)), as some users enjoy cool or warm conditions more.

The methodology used for development of the model strengthens further this natural preferences difference's influence on PPD. The experiment was carried out in a climate chamber with steady-state conditions. In reality, the exposure or activity of a user prior to entering a given space can influence his or her perception up to one hour (ASHRAE, 2004). Another significant simplification compared to real life conditions is that in the climate chamber the subjects had no possibility of controlling the environment in order to adjust the conditions. Missing an influence, people raise their expectations and their vote may be more critical. ASHRAE (2004) refers to field experiments carried out in naturally ventilated spaces with operable windows controlled by occupants, where conditions required for thermal comfort were different than in air-conditioned ones. Furthermore, laboratory tests were limited to a group of people of same ethnic background and similar age.

Above-mentioned assumptions in Fanger's experiment led to the development of so called adaptive thermal comfort model. ISO 7730 mentions it only briefly, stating that in warm and cold environments occupants can to some extent adapt to prevailing conditions, firstly by adequate clothing and secondly by means such as changed body posture or activity level (there are also other ways, for instance adapting rate of working, diet, influencing ventilation and air movement (Teli, 2018a)). This is a reason to allow for designing for higher PMV values than given in the standard. Moreover, field studies showed that people living in hot climate have in general higher tolerance to increased temperatures, even without taking any special measures to counteract them. This is due to the long-term adaptation through body behavior in terms of control of shivering, skin blood flow and sweating, as well as on simply different expectations (Teli, 2018a). This phenomenon is considered more thoroughly in ASHRAE standard and in EN 15251 – both describe thermal comfort model for buildings without mechanical cooling, where opening and closing the windows is a primary method to regulate indoor climate, however there are differences in applicability of it – American standard allows for use of it for mean monthly outdoor air temperature between 10 and 33.5°C whereas European limits it slightly to outdoor running mean temperature between 10 and 30°C for upper limit and 15 and 30°C for over limit. Despite differences the general idea is though the same in both cases – the acceptable operative temperature lies within range given by limits, which are defined by a simple linear relationship to outdoor air temperature. These limits can be assigned to a certain acceptability level and by that information similar to PPD is included in the model. Adaptive comfort model has obviously its flaws as well and advantage of one model over the other is a subject for longer discussion.

Focusing again on PMV, another problem is that simplifications in terms of average body surface and metabolic rate were made as well. It leads to the situation where thermal comfort of groups such as children, the disabled or the infirm is not covered by the model. On one hand, according to ASHRAE (2004), it should not affect its credibility in a substantial way as "the information in this standard can often be applied to these types of occupants if it is applied judiciously to groups of occupants such as are found in classroom situations". On the other hand, field studies' results seriously undermine the applicability of PMV model to children. Teli et al. (2012) describe the study from English primary schools aiming for assessment of existing thermal comfort models' accuracy if they are used to predict children's sensation. Thermal sensation votes obtained from surveys were significantly higher than PMV value and comfort temperature for kids was around 4°C lower than for adults. Similar sxtendency has been found by Mors et al. (2011) in a study in Dutch schools, where children's mean vote was up to 1.5 point higher than estimations. Moreover, in Teli et al. (2012), four approaches to adjustment of PMV calculation method were tested, in which 1 met unit was recalculated based on metabolic rate for children or correction factor obtained from body surface area ratio and original formula for PMV was modified in terms of the value of 58.15 W/m^2, corresponding to 1 met for an adult. Results showed clearly that the divergence between theoretical and actual comfort temperature has been minimized when PMV model has been adjusted to kids' physiology. However, the same study lists a number of reasons for which even the adjusted PMV cannot be considered as an optimal tool for predicting thermal comfort. Among them both occupant related factors (such as psychical condition or lack of adaptive opportunities) and building-related factors (such as classroom orientation, glazing, or even interior design) can be found. One more issue is the fact that young children's school activity is varying throughout the day (from 1-1.2 met when sitting, for example while listening to teacher or drawing, up to around 2.7 met when intensively playing) and includes time spent in the outdoor environment, which makes steady-state conditions assumed in PMV even less adequate.

In addition, almost all main factors affecting thermal sensation – air and radiant temperature, air velocity, clothing insulation and humidity, may be nonuniform over an occupant's body, which in some cases may be determinant for the perception of comfort (ASHRAE, 2004). To account for these possible variations, criteria for assessment of local thermal discomfort are also introduced in ISO 7730.

4.1.2 Local discomfort

ISO 7730 defines thermal discomfort as "caused by unwanted local cooling or heating of the body. The most common local discomfort factors are radiant temperature asymmetry (cold or warm surfaces), draught (defined as a local cooling of the body caused by air movement), vertical air temperature difference, and cold or warm floors." These factors are briefly presented below.

ISO 7730 defines categories A, B and C of thermal environment which are analogical to categories I, II and III given by SS-EN 15251:2007 (see Section 2.1.4). Local discomfort indicators are used as criteria according to Table 4.1 below:

Table 4.1 Local discomfort criteria for thermal environment categories A and B according to ISO 7730.

Cat.	DR [%]	Vertical air temperature difference		Warm or cool floor		Radiant asymmetry				
		PD [%]	$\Delta t_{a,v}$ [°C]	PD [%]	t_f [°C]	PD [%]	Δt_{pr} [°C]			
							Warm ceiling	Cool wall	Cool ceiling	Warm wall
A	<10	<3	<2	<10	19-29	<5	<5	<10	<14	<23
B	<20	<5	<3	<10	19-29	<5	<5	<10	<14	<23

A detailed information about how local discomfort criteria are calculated can be found in Appendix A.

4.1.3 Thermal climate's comfort, health and performance implications

Indoor environment has an important influence on occupants' well-being, both in terms of feeling comfortable and being able to perform efficient and error-free work.

Frontczak and Wargocki (2010) carried out a literature review in order to explore how different factors of indoor environment influence human comfort. One of the conclusions was that according to buildings' users, good thermal conditions are the most vital factor for achieving overall satisfaction with indoor environment's quality. Zhang et al. (2016) notice that temperature affects the perception of air quality as it alters the cooling effect of the inhaled air.

Performance aspects are interesting, since, as Wyon and Wargocki (2013a) state, they may decrease in conditions of lowered air quality even if comfort- and health-related symptoms cannot yet be observed. Especially thermal comfort reported by occupants is not the most trustworthy indicator, as they may to some extent adapt to poorer environment by changing clothing or activity level.

Physiologically seen, the reason behind lowered performance in raised temperature is a mild acidosis, caused by an increase in CO_2 concentration in the blood and decrease of oxygen saturation, both of which can be directly translated to determinant for mental work (Lan et. al (2011) as cited in Wyon and Wargocki (2013a)).

Raised temperatures have been proved in several studies, conducted both in office and school environments, to decrease working rate, mostly in case of tasks requiring concentration, clear thinking and memorizing. At the same time no significant increase in number of errors has been found (Wyon and Wargocki, 2013a), as working slowly, paying more attention, is most likely just users' way to counteract poor work quality. Mendell and Heath (2005) recalls for instance studies of Witterseh et al. (2002) and Federspiel et al. (2002), carried out in controlled office conditions, showing that increase of temperature by about 5°C led to reported difficulty in thinking and concentrating, slower working rate and decreased self-estimated performance. Haverinen-Shaughnessy et al. (2015) found out significant correlation between temperature and percentage of students scoring satisfactory in mathematics and reading tests. Wargocki and Wyon (2007) conducted a study in schools with children aged 10-12 and established that when the temperature was decreased from 25 to 20°C, results obtained by the subjects in numerical and language-based tests improved significantly, especially in terms of speed. Another observation from the same study was that children described colder air as fresher and less dry, perceived classrooms as less bright and noisy and reported fewer headache cases in lowered temperatures, which may indicate that they were less stressed.

Apart from performance, health aspects are obviously of interest as well. Too high temperatures are associated with symptoms such as dizziness, exhaustion and headaches, and in extreme conditions – increased risk of cardiovascular diseases (Socialstyrelsen, 2005).

Providing optimal thermal conditions in school environments is more crucial than in office or home. Wyon and Wargocki (2007) states that the effects of temperature on performance of school kids is larger than that reported for adults. The magnitude of this decrease is estimated as up to 10% for adults (in field studies) and for children – over 20% (Wyon and Wargocki, 2013). There is a lot of reasons behind it, both mental and physiological. Teli et al. (2017) explain that school environments are characterized by young age of occupants, high occupancy density and limited possibilities of behavioral adjustments. Young children have bigger surface-area-to-mass ratio, greater metabolic rate per 1 kg body mass and lower sweating rate, which leads to lower share of evaporation in cooling processes and increased skin temperature. Moreover, their development stage influences their ability to detect temperature changes (Teli et al., 2013). Wyon and Wargocki (2013a) suggest also, that in school most of performed work is new to children, as they constantly learn and do not get a chance of becoming familiar with tasks, so their performance is affected more by unfavorable environment than in case of adults knowing their daily routines. One more conclusion was made by Mendell and Heath (2005), highlighting the importance of appropriate conditions in school – children spend there most of their time during the day and so the effects on learning and performance can have even lifelong consequences.

Children's higher vulnerability to increased temperatures is reflected in the results of thermal comfort surveys in which they are subjects. In research of Teli et al. (2012) neutral conditions as assessed by children were around 4°C cooler than predicted by PMV model. Wyon and Wargocki (2007) noticed that increased temperature conditions were perceived as slightly too warm, while lowered temperature was associated with nearly neutral thermal climate. Summarizing all evidence, it seems that lowest possible temperatures still fulfilling requirements for thermal comfort would be most beneficial.

Not only overly increased temperatures affect users' well-being and performance. Too low temperatures lead to distracted attention and generate complaints (Wargocki and Wyon, 2007). Arbetsmiljöverket (2009) mentions also that even small deviations from optimal temperature decrease muscle functions and fingers dexterity. Concerning health, Jevons et al. (2016) mention studies showing that in conditions below 18°C increase blood pressure and risk for blood cloths even of healthy people. The same paper names several chronic diseases of respiratory and cardiovascular nature which are exacerbated by exposure to low temperatures. Socialstyrelsen (2005) mentions that also rheumatism and muscle diseases can show more symptoms. Besides, even without scientific evidence it is intuitively understood by people that staying for a longer time in cool environment increases risk of getting symptoms commonly described as catching a cold. This is explained by "adverse effects of cold on the immune system's resistance to respiratory infection, and the fact that low temperatures assist survival of bacteria in droplets" (The Eurowinter Group, 1997). It can be thus concluded that an optimal range of temperatures for indoor environment is actually quite narrow.

Apart from above-mentioned direct effects, thermal environment has indirect effects as well. Chatzidiakou et. al (2012) recalls study of Mi et al. (2006) in which it has been found out that decreased indoor temperatures are beneficial for health as they reduce breathlessness among school students. The authors refer also to studies of Mysen et al. (2005), Wargocki (2008) and Zhang et al. (2011), proving that lower temperatures are associated to decrease in number of reported Sick Building Syndrome symptoms (non-specific health symptoms, such as headache, fatigue, dizziness, nausea, concentration difficulties, eye, nose, and throat irritation, stuffy nose, dryness in mucous membranes, throat infections, cough, hoarseness, skin reactions). Furthermore, thermal conditions may influence emission rates from materials and concentration of pollutants in indoor spaces (Chatzidiakou et. al, 2012). Finally, temperature has an effect on survival of bacteria and viruses. It is a complex phenomenon which depends on individual pathogens' character, but viruses' survival decreases generally with rising temperature and studies have shown that temperatures above about 24°C appear to universally decrease airborne bacterial survival (Tang, 2009).

Finally, thermal conditions are undeniably connected to relative humidity, as air temperature determines how much moisture it can contain without condensation. In increases temperature RH is more likely to be low which has its own health-related implications. More information about it can be found in Section 4.2 below.

4.2 Humidity

4.2.1 Definition

Air humidity describes moisture content of the air. It can be expressed in a number of thermodynamic variables (ASHRAE, 2004):

- absolute humidity (v),
- humidity ratio (x),
- vapour pressure (p_v),
- relative humidity (RH),
- dew point temperature (t_{dp}).

Absolute humidity v [kg/m^3] is the mass of water in grams per 1 m^3 of the air.

Humidity ratio x [g/kg], also called specific humidity, is, according to ASHRAE (2004), the ratio of the mass of water vapour to the mass of dry air in a given volume.

It is convenient to use as it does not change with changed pressure, temperature or volume.

Water vapour partial pressure p_v [Pa] is another way to express moisture content, as it, together with other gases, contributes to total air pressure. The relation between vapour pressure and absolute humidity can be derived from the General Gas Law (Hagentoft, 2001):

$$p_v = 461.4 \cdot (t_a + 273.15) \cdot v \tag{4.6}$$

Relative humidity [%] is the ratio of the partial pressure of the water vapour in the air to the saturation pressure of water vapour at the same air temperature and total pressure (ASHRAE, 2004). As the partial pressure in given temperature is only dependent on absolute humidity, relative humidity can be also calculated as:

$$RH = \frac{p_v}{p_{vs}} = \frac{v}{v_s} \tag{4.7}$$

Absolute humidity at saturation v_s [kg/m^3] – i.e. when the air reaches liquid-gas equilibrium and is thus not able to contain more vapour without condensation can be obtained from a formula given by German DIN-standard (4108) referred to in Hagentoft (2001):

$$v_s = \frac{a + \left(b + \frac{t_a}{100}\right)^n}{461.4 \cdot (t_a + 273.15)} \tag{4.8}$$

where:

- if 0°C ≤ t_a ≤30°C a=288.68 Pa b=1.098 n=8.02;
- if -20°C ≤ t_a ≤0°C a=4.689 Pa b=1.468 n=12.3.

Finally, dew point temperature t_{dp} [°C] describes the temperature at which moist air reaches 100% relative humidity when cooled at constant pressure (ASHRAE, 2004).

Different methods to express air humidity are advantageous in different contexts. Dew point temperature is useful for example in building physics when assessing the risk of interstitial water condensation in layers of building envelope. Vapour pressure is used in PMV model equation. Relative humidity is commonly referred to in weather forecasts as it gives a good idea about the probability of precipitation. Absolute humidity is used for moisture transfer modelling in building physics and humidity ratio – for psychrometrics when designing HVAC systems. To describe indoor environment relative humidity is the most convenient variable as it is dependent on air temperature and therefore gives better picture of overall conditions than absolute humidity or humidity ratio.

4.2.2 Health, comfort and performance implications

There is a certain difficulty in discussion about humidity's direct influence on users' comfort – namely the fact that humans do not have sensory organ for it. For that reason, reported dry or wet air may in reality be an expression of other issues, such as odour or dustiness, possibly exacerbated by humidity level (Wolkoff, 2018). Socialstyrelsen (2005) warns that a slight change of temperature makes people perceive air humidity as much lower or higher than it is in reality.

Regarding thermal comfort of the occupants, humidity is not a strong indicator. Theoretically, it has an influence on cooling effect of the inhaled air (Zhang et al., 2016), it is also influencing evaporative heat loss from a person – and so the efficiency of cooling by sweating – and consequently the general thermal comfort of the body (SIS, 2006). Sweat will not evaporate in conditions of 100% RH, which significantly amplifies perception of high temperature. In extreme situations this may lead to overheating and severe health reactions such as heat stroke and exhaustion (Arundel et al., 1986). Analogically, when RH is low evaporation happens easily, causing cooling of the body. However, this effect is opposite in cold weather, when evaporation has the smallest influence of body's heat exchange. It is due to the fact that in the air layer between skin and clothing insulation as well as on clothes themselves, water molecules may occur when RH is high. As water has higher specific heat than air, it intensifies heat loss from the body. In practice, described phenomena are perceptible mostly in outdoor environment. Concerning moderate indoor conditions, in SS-EN 15251 defined as temperatures below 26°C and activity level below 2 met, humidity has a small effect on thermal sensation. According to ISO 7730, 10% higher relative humidity affects feeling of being warmer in the same grade as 0.3°C increase of operative temperature. For that reason, the standard suggest that its effect may be disregarded when obtaining PMV for moderate temperature range.

Above-mentioned slight effect may explain why ISO 7730, SS-EN 15251 and ASHRAE standard pay little attention to humidity levels. The first of them states that "if humidity limits are based on the maintenance of acceptable thermal conditions based solely on comfort considerations – including thermal sensation, skin wetness, skin dryness, and eye irritation – a wide range of humidity is acceptable". The second suggest lower level of RH of about 15-20% as below these values dryness and irritation of eyes and airways may occur, this is however not a strict requirement. SS-EN 15251 warns also about risk of microbial growth under long-term high humidity, but again does not specify either what is "high" or "long-term". ASHRAE standard says explicitly that it does not give lower limit values for RH as there are no such limits established for thermal comfort, but non-thermal comfort factors, such as skin drying, irritation of mucous membranes, dryness of the eyes and static electricity generation may be determinant for placing these limits. However, a recommendation that dew point temperatures should not be less than 3°C, corresponding to 26% RH at 24°C is made (Wyon et al., 2002). For the upper limit, ASHRAE suggest that designed systems should be able to maintain humidity ratio of at maximum 0.012 kg/kg.

Nevertheless, as studies show, humidity can have a big influence on several air quality and health aspects which can be eventually translated to comfort. They can be divided into direct and indirect effects. The direct effects result from RH's impact on physiological processes, whereas indirect – from its influence on pathogenic organisms and chemicals (Arundel et al., 1986). Among direct health effects the following can be mentioned:

- eye irritation – can be caused by RH around 20% and lower (Arundel et al., 1986). Wolkoff (2017, 2018) gives explanation for that: on an eye's cornea PTF – precorneal tear film – can be found. Its goal is to provide a continuous smooth layer protecting an eye from excessive tear evaporation and other damages to its surface. In the conditions of lowered humidity, PTF becomes unstable, resulting in decreased tear production and exacerbation of water loss. Eye's drying-out leads to inflammatory reactions. Local dry spots are exposed and thus more vulnerable to sensory irritants and other pollutants. This causes ocular discomfort;
- upper airways irritation – airways are lined by mucous membranes. Their functions are strongly dependent on humidity as humidification and warming processes of the air are connected to water loss (Cruz and Togias, 2008; Naclerio et al., 2007, as cited in Wolkoff, 2018). As a result, RH lower than optimal causes changes in mucous viscosity and the mucociliary activity which eventually may lead to release of inflammatory mediators by epithelial cells (Wolkoff, 2018). Furthermore, epithelium's dryness may increase bacterial adherence and allows for greater penetration of particles (Naclerio et al., 2007, as quoted in Wolkoff, 2018). Finally, increased RH positively affects clearance – a defense mechanism against pathogens – time (Salah et al., 1988, as cited in Wolkoff, 2018). Arundel et al. (1986) based on experience of physicians, recommend relative humidity of 30-40% in order to maintain adequate nasal mucus transport and ciliary activity;
- skin irritation – it is less inconvenient than eyes and airways problems and therefore less often reported and studied. However, Wolkoff (2018) recalls a study of Trimble et al. (2007) showing a tendency to higher skin irritation in dry climate; Arundel et al. (1986) describe decrease in number of reported skin diseases such as urticaria, erythema, and eczema with RH increased from 30-40% to 50%.

All of above-mentioned types of sensory irritation contribute to the general perception of "dry air". Apart from direct effect on physiology, it can be caused also by an interaction between low relative humidity and chemicals emission (Arundel et al., 1986), which is described further in this section. This phenomenon is an important component of Sick Building Syndrome (Wolkoff, 2018). It is also worth to mention that susceptibility to airways irritation caused by dry air is higher for persons with asthma (Wolkoff, 2018), which severity has been shown to decrease in moderate to high humidity (Arundel et al., 1986).

However, there is one more direct effect – perception of odour and "stuffy air" – which on the opposite to the others is amplified by high level of humidity. Fang et al. (2004) state that air, even if clean, is perceived as unacceptably stuffy when warm and humid. Reinikainen and Jaakkola (2003) conducted a study in office environment and found out that introduction of artificial humidification increased perception of odour and feeling of stuffiness, as well as sneezing occurrence. Wolkoff (2018) gives a possible explanation – VOCs (Volatile Organic Compounds) may change their emission profile in condition of increased RH. They react with for example ozone and nitrogen oxides with results in production of new sensory irritants.

Indirect health effects are in turn associated with aspects such as:

- particles resuspension – particles in the air are a major risk to the health (see more in Section 4.4). Resuspension of particles is a complex subject as it depends, among others, on their size, shape, concentration and chemical character, but some relations have been found between increase of RH and decrease of concentration of respirable particles (Fromme et al., 2007, Lindgren et al., 2007, as quoted in Wolkoff, 2018). Moreover, Salimifard et al. (2017) noticed that hydrophilic particles, such as dust mites, are influenced by RH in higher grade than hydrophobic (for instance cat and dog fur);
- survival of airborne pathogens – general observation of behavior of viruses and bacteria under different humidity conditions cannot be made – it is strongly dependent on the type of their envelope (Derby et al., 2017). The reason for that is given by Arundel et al. (1986) – RH is thought to affect survival by altering the integrity of the cell wall or viral coat. Even more explanation is presented by Wolkoff (2018) – RH influences also bacteria and viruses' size, surface properties, water content, and consequently transmission and deposition.
  Nevertheless, some general trends can be shown. Viruses with lipid envelopes, including e.g. influenza or measles, survive longer at low RH of 20-30%, while non-lipid (e.g. respiratory adenoviruses and rhinoviruses) at high – 70-90% (Tang, 2009). Bacteria's behavior is more complex as it differs more between different kinds of them, however more studies speaks for mid-range humidities to more lethal. Arundel et al. (1986) presented several studies establishing various ranges for minimized pathogens survival, but were able to conclude that range 40-70% seems most beneficial.
- settling rates of aerosols – this parameter has an effect on diseases spreading as airborne pathogens are transported through aerosols produced during coughing and exhaling air. The higher is the settling rate, the smaller risk of being exposed to pathogens. High RH around 80-90% is favorable for this parameter as some aerosols size may increase because of water absorption (Arundel et al, 1986);
- respiratory infections – studies on frequency of occurrence of respiratory infections are strongly connected to the ones about survival of bacteria and viruses as well as aerosols' settling rates. Arundel et al. (1986) give examples of several research projects finding correlation between RH and absenteeism among school children due to infections: Green (1979) found out that RH increase from 22 to 35% decreased number of absences by 20%, Sale (1972) found 5.8% difference in absentee rate between kids from humidified environment compared to those from non-humidified. Also, the opposite end of RH range has been proved to be related to increase in number of infections – Melia et al. (1982) found out that children exposed to humidity over 75% in their home environment more often suffer from colds, wheezing, and bronchitis;
- presence of allergens – major part of allergies is caused by either mites or fungi. House dust mites are the most important allergen. Their population reaches its maximum size at RH around 80%. Arundel et. al (1986) recall a number of studies suggesting, that the number of mites per 1 g dust decreases rapidly at humidity below 50%. Fungi in turn are known to cause reactions such as asthma or rhinitis. They need most often humidity exceeding at least 60% for growth, but preferable is over 75% (Arundel et al., 1986).

- emissions of noxious chemicals – some of chemicals create irritants for skin and airways once they react with water vapour. Arundel et al. (1986) list the following compounds as most common:
  - formaldehyde – this water-soluble compound can be found in several materials such as insulation, plywood, carpets and textiles. Its off-gassing increases in high RH and causes occurrence of health reactions, for instance sensory irritation, respiratory disorders and allergies;
  - ozone – on the contrary to formaldehyde, high emission rates of ozone are supported by low RH, as in humid conditions its particles are rather adsorbed by indoor surfaces (Mueller et al., 1973, as quoted in Arundel et al., 1986). Ozone works as irritant to eyes and mucous membranes;
  - sulfur dioxides – respiratory irritant, creating even more harmful aerosols when reacting with water vapour;
  - nitrogen dioxides – reacting with vapour creates acids which decrease pulmonary functions and contribute to development of respiratory diseases.

In the Figure 4.2 below optimum RH range for different indirect health aspects are summarized:

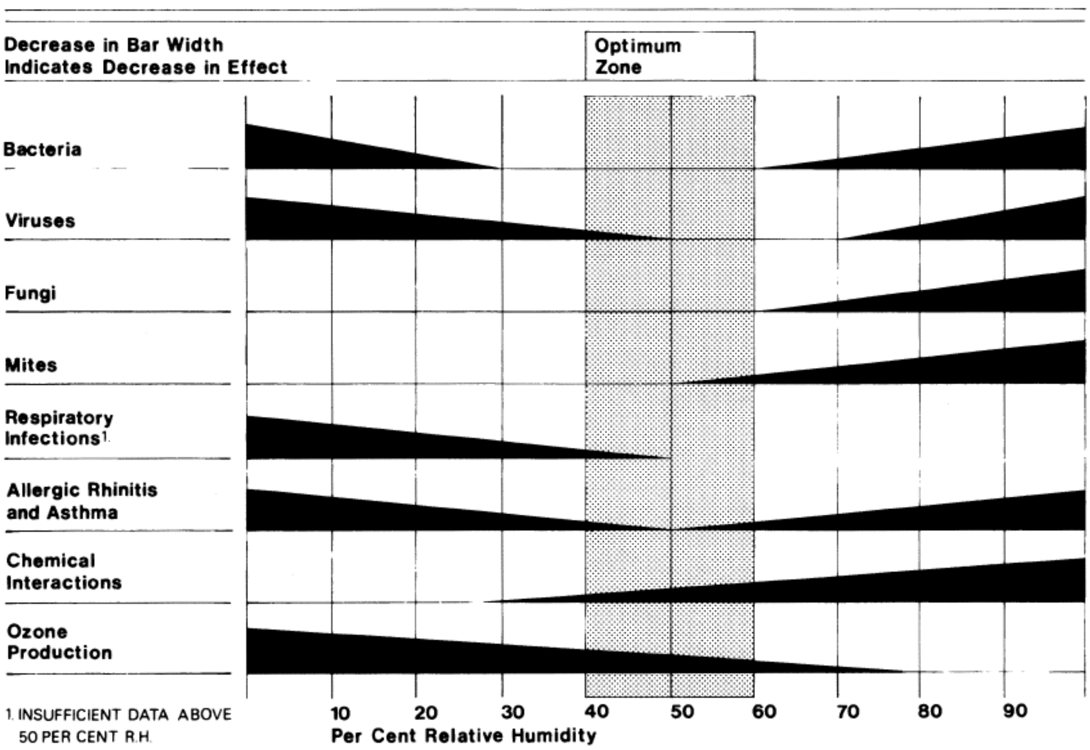


Figure 4.2 Optimum relative humidity range for minimizing indirect health effects (Arundel et al., 1986).

One additional comfort-related question is static electricity. Derby et. al (2017) describes, among others, study of Paasi et al. (2001) proving that for many materials commonly found in buildings, including users' own clothing, at room temperature electrostatic discharge was a concern below 20–30% RH, and of Nordström et al. (1994) where complaints about static electricity increased twice when RH was changed from 40-45% to 20-35%. Socialstyrelsen (2005) states that problems may occur already below 40% RH. The charge, apart from itself causing discomfort when discharging, can result in dust settling on the skin surface and increase risk of skin-related health symptoms.

Separating performance from all above-mentioned health effects may be difficult as most of the symptoms are inconvenient and as such may deteriorate concentration. However, Wyon and Wargocki (2013) mention that low RH, below 15%, may sometimes impair visual acuity and the performance of tasks requiring continuous acquisition of visual data.

When it comes to the effect humidity has on buildings, it is slightly easier to choose preferable conditions. Generally, high RH is considered to be an important risk for structures and building materials, especially that moisture-caused damages are one of most common. BBR requires for instance to design buildings so that moisture does not cause damages, odour or microbial growth, which in turn may affect hygiene or health. For materials vulnerable to bacteria or mould it is recommended to use well-documented critical humidity content and if it is not known, RH of 75% is suggested as a limit. Apart from already listed risks, BBR gives also other possible issues caused by high humidity, such as unacceptable chemical and electrochemical reactions, unacceptable moisture transfer, deterioration of mechanical and thermal properties of materials or presence of wood-eating insects. On the other hand, very low RH can have negative impact on construction as well. Big difference between outdoor and indoor absolute humidity will amplify moisture transport through building envelope, increasing risk of interstitial condensation and corrosion. Moreover, low RH can cause rapid drying of some materials, resulting in shrinkage and cracking. It is worth to point out that such damages to the structure, even if they are not directly a threat for users, influence perceived indoor environment quality in terms of safety and aesthetics, which may decrease mental comfort and raise complaints. Again, it can be seen that it is most beneficial to keep humidity within a certain safe range. However, as Wolkoff (2018) concludes, a distinction should be made between humidity near the breathing zone and phenomena connected to moisture-caused damage to the construction and different appropriate demands for humidity should be considered in both cases. Nevertheless, overall it can be cautiously concluded, that RH range of 40-60% seems to be an optimal compromise from all perspectives, as long as it is not combined with air temperature exceeding comfort limits.

4.3 CO_2 concentration

Concentration of CO_2 [ppm] describes the volume of this gas per unit volume of air. 1 ppm means 1 part per million, so it equals to 1 cm^3 CO_2 per 1 m^3 air. As humans produce and exhale CO_2, indoor concentration is higher than outdoor, which in Sweden can be averaged as approximately 350-400 ppm. Most regulations set the requirement for indoor carbon dioxide concentration to not exceed 1000 ppm longer than temporarily.

As CO_2 generation rate in a building and its outdoor concentration are, disregarding smaller variation, rather constant over limited amount of time, CO_2 concentration is often used as rough indicator of ventilation rates. As decreased air exchange would usually result in perception of lower air quality, high CO_2 concentration has been associated with poor IAQ as well as with health issues such as Sick Building

Syndrome symptoms, increased absence and lowered efficiency of work. However, historically it was assumed that this connection is only valid because low ventilation rates indicated by CO_2 levels are the reason for higher concentration of other pollutants, directly causing the aforementioned health effects (Mudarri 1997; Persily 1997 as quoted in Satish et al., 2012). What is interesting, the value of 1000 ppm, used in most standards, was first obtained in 19th century and based on unpleasant odours from individuals (Gustafsson and Rosén, 2019). CO_2 concentration in range usually occurring in indoor environments, i.e. 500-5000 ppm was assumed to have no impact on users' perception, health, work performance (Satish et al., 2012) or blood CO_2 levels (Kenichi et al., 2018). Higher content of this gas has had well-documented influence on health. Kenichi et al. (2018) describe the phenomenon of respiratory acidosis happening after about 30-minute exposure to CO_2 concentration above 10.000 ppm, resulting in increased CO_2 level in blood, causing acid-based imbalance and eventually problems as headache, confusion, anxiety, drowsiness, and stupor. At even higher CO_2 levels more severe symptoms occur, starting with breathing difficulties at concentration above 20000 ppm and ending with loss of consciousness above 100000 ppm (Lipsett et al., 1994 as cited in Satish et al., 2012), but it is not relevant for shaping buildings' IAQ.

As recent studies show, this assumption was not fully correct – several experiments conducted in controlled environment, with possibility of artificial increase of CO_2 levels without decreasing ventilation rates and general IAQ proved that this compound individually and already at low-level concentrations affects occupants' well-being and performance. Satish et al. (2012) conducted an experiment where they tested decision-making processes under CO_2 concentration of 600 ppm, 1000 ppm and 2500 ppm and noticed significant decrease of performance already in 1000 ppm, while at 2500 ppm an additional effect of overconcentration occurred, showing difficulty in functioning demanding excessive focus on details. Kenichi et al. (2018) recall for instance studies investigating physiological response to change of CO_2 concentration from 500 ppm to 4000 ppm, showing changes in heart rate variability and peripheral blood circulation (MacNaughton et al., 2016, Vehviläinen et al., 2016) or one finding increase of blood pressure and heart rate at change from 600 ppm to 1500 ppm (Kajtár and Herczeg, 2012). These reactions cause also stress on the human body which results in reduced performance. Furthermore, according to one of mentioned research, already above 1000 ppm cognitive (decision making, problem resolution), respiratory and sensory symptoms may occur (MacNaughton et al., 2016).

On the other hand, the above-mentioned conclusions are questioned again as well. Göran Stålbom (2017) in his debate-raising article criticizes outcomes of studies investigating direct effect of CO_2 on health and cognition, calling them „light" from scientific perspective. Moreover, he underpins his reasoning with, among others, NASA's report about carbon dioxide concentration in spaceships and theoretical knowledge about breathing physiology. Another study has been conducted by Zhang et al. (2016), where occupants' cognitive performance has been examined under conditions of increased CO_2 level, either artificially or naturally along with lower ventilation rate and resulting rise of bioeffluents concentration. Only in the second case statistically significant performance decrease has been observed, which indicated that CO_2 individually does not have impact on users. It is apparent that more research is required to draw unambiguous conclusions in this matter.

The first idea of using CO_2 levels for prediction of issues caused directly by other factors is less controversial and, so far, considered valid. Chatzidiakou et al. (2015a) carried out a comprehensive research to establish association between indoor CO_2 concentration and thermal climate and check if controlling these two factors can be a method to secure levels of other compounds, such as VOCs and nitrogen dioxide, particulate matter and microbes. The authors concluded that as long as information about the investigated building, for instance ventilation strategy, orientation, occupancy, glazing or thermal mass, are gathered to help interpret the results, CO_2 level can be a good indicator of VOCs level, PM concentration and even risk for overheating (as it arises from high internal gains and reduced ventilation); to maintain overall satisfaction with indoor environment, it has been suggested to keep existing recommendation of 1000 ppm. Moreover, same team continued the study to find connections between CO_2 and reported indoor air quality. They found out that all pollutants which presence can be estimated based on CO_2 cause some of SBS symptoms. Furthermore, temperature and CO_2 seemed to be the only significant predictors for general IAQ (Chatzidiakou et al., 2015b). Kenichi et al. (2018) listed additional studies justifying use of CO_2 level as indicator for risk of SBS symptoms: Norbäck and Nordström (2008) associated 100 ppm increase with headaches, Lu et al. (2015) – with sore throat, tiredness and dizziness and Azuma et al. (2018) – with dizziness and headache. General conclusion is that already at 700 ppm relation between CO_2 and SBS symptoms starts to be visible. Zhang et al. (2016) in their study on cognitive performance concluded that exposure to increasing levels of bioeffluents indicated by CO_2 concentration up to 3000 ppm not only amplifies neuro-behavioural symptoms but also odour intensity and worsens perceived air quality. Their results have not provided scientific evidence enough to define any specific threshold values for CO_2 level, however, the authors suggest that even present common requirement, 1000 ppm, may not be sufficient. It is apparent that further studies are needed to understand individual and combined effects of bioeffluents and other pollutants on different aspects on users' experience in an indoor space and to define plausible indicators along with their limit values.

Finally, Rudnick and Milton (2003), based on the assumption of occupants being the only significant source of carbon dioxide, used difference between CO_2 concentration in inhaled and exhaled breath to estimate what is the fraction of rebreathed air. As through exhaled air airborne infectious particles are distributed, the authors managed to develop equations allowing to directly assess risk of infection in the given environment, based only on CO_2 level and without having knowledge about for example ventilation rates or outdoor conditions. This does not result in specific recommended CO_2 concentration limits as diseases spreading depends on several building- and pathogens-related individual factors but strengthens the need of keeping CO_2 low.

4.4 Particulate matter

According to WHO (2018) particulate matter – PM – affects humans more than any other pollutant and for that reason it is used as proxy indicator of air quality. PM is a mixture of liquid and solid, organic and inorganic particles suspended in the air and consist mostly of sulfate, nitrates, ammonia, sodium chloride, black carbon, mineral dust and water (WHO, 2018).

In the Figure 4.3 below some sources of PM can be seen together with size limits for inhalable, thoracic and respirable particles (green – natural, red – man-made):

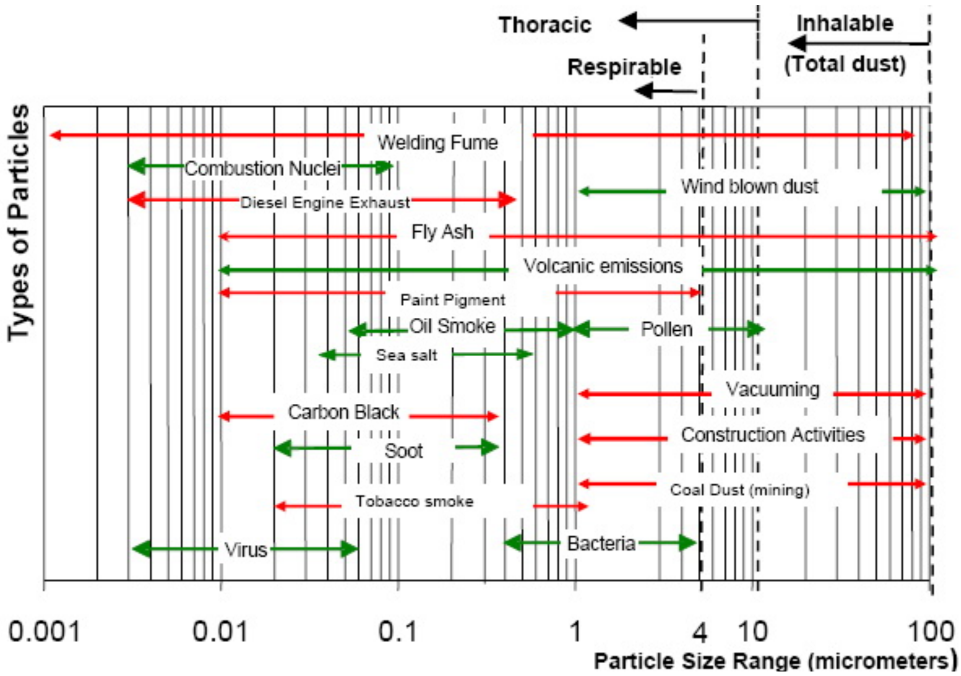


Figure 4.3 Types of particles with corresponding size (TSI, 2010, taken from Jin, 2017).

As can be seen in the figure, particles with size 10 µm or smaller (PM_{10}) can penetrate inside the lungs. As next size category 2.5 µm ($PM_{2.5}$) is usually used as particles with this size are small enough to penetrate into pulmonary alveoli and further to blood. Because of these properties, WHO uses $PM_{2,5}$ and PM_{10} as indicators for the air quality, setting limit values to 10 µg/m^3 annual mean, 25 µg/m^3 24-hour mean for $PM_{2,5}$ and 20 µg/m^3 annual mean, 50 µg/m^3 24-hour mean for PM_{10}. These limits concern outdoor air, but as there is no reason to believe that particulate matter form indoor sources is of less hazardous nature, they are applicable for indoor air as well. Moreover, in the presence of indoor sources, PM concentration there is usually higher than outside (WHO, 2010).

It can be questioned if this choice of requirements is sufficient. Jan-Erik Andersson, indoor environment expert in Göteborgs Stad Lokalförvaltningen in personal communication (2019-05-05) said that particles of size <0.3 µm (nanoparticles) are suspected to be able to, in extreme cases, penetrate through airways directly to the brain. Another issue raising doubts is the unit which considers only total mass of particles in the air, whereas, as Löndahl (2009) points out, it is the surface of particles that matters the most. It is on the surface where chemical reactions take place and it is maximized the smaller the particles are (compared to the same mass of bigger particles).

In indoor environment a part of particles comes with infiltrating outdoor air, the rest in generated inside. People are responsible for the biggest share in generation of pollutants indoors. The top layer of skin exfoliates continuously which results in around 25 million skin cells lost every day. They settle on the clothes' surface and are further transferred to the air where they get combined with dust. As on the skin cells microorganisms can be found, dust contains them too. While bigger particles lands quickly on horizontal surfaces, the smaller ones, due to adhesion and electrostatic forces, stick to vertical surfaces as well (Månsson, 1992). Resuspension of particles can be observed due to air movement or human activities and it results in exposure to inhaling them by users.

This can be to some extent counteracted by maintaining the proper organization and cleaning routines. Materials such as fabrics and paper, which may be a source of particle emission, should be kept in closed cabinets, outer garment should also be kept in appointed room. Filters in ventilation systems need to be regularly cleaned or replaced. It is important to keep in mind that ventilation itself is not able to remove particles and increasing the flow may, instead of resulting in cleaner air, cause whirling and more rapid resuspension. Removal of dust is of special importance in environments characterized by high level of activity – during physical effort up to 4 times as much particles is inhaled as during rest (Löndahl, 2009).

Exposure to high concentrations of PM_{10} and $PM_{2,5}$ can be associated with increased mortality or morbidity due to causing issues such as stroke, heart disease, lung cancer, and both chronic and acute respiratory diseases, including asthma. Bigger particles, for example dust, has not been proved to cause direct health problems, but are expected to have negative effects on chronic health problems (Wyon and Wargocki, 2013). They may also cause indoor environment to feel "dusty". Haverinen-Shaughnessy et al. (2015) refers to conclusions of Hussin et al. (2011) saying that dusty floors can be connected to higher concentration of fungi and bacteria. In addition, particles can work as a carrier for viruses, for instance influenza (Wolkoff, 2018).

As mentioned in previous sections, PM concentration can be directly associated with RH and indirectly – with air temperature and CO_2 levels.

4.5 Ventilation rates, type and performance

Ventilation rates decide about how many times under a given time air volume in the room will be replaced by fresh, mostly outdoor, air. Currently, most standards set minimum airflow to 0.35 l/s per 1 m^2 floor area + 7 l/s per person. The first number is based on an old rule of thumb requiring "half air change per hour", is calculated for typical room height of 2.5 m, and is supposed to handle emissions from building materials and equipment. The second was first roughly obtained back in the 1930s based on odours removal and confirmed in the 1980s by studying satisfaction with indoor air quality. It is supposed to take care of bioeffluents (Stålbom, 2018).

It can be thus expected that the bigger ventilation rate, the better should perceived IAQ be. There is plenty of research confirming this assumption. Bakó-Biró et al. (2012) present studies which showed that low ventilation rate result in weak attention, memory and concentration while higher rates are related to perception of fresh air, decreased sensation of dryness in the mucous membrane and eyes as well as increased alertness. Toftum et al. (2015) recalls study of Mendell et al. (2013) which found relation between 1.6% decrease in absenteeism and 1 l/s per person increase of air flow. Haverinen-Shaughnessy et al. (2015) noticed connection between ventilation rates and percentage of satisfactory scores in test as well as frequency of visits at school nurse related to respiratory syndromes. Wargocki and Wyon (2007) examined children's performance in a series of various numerical and linguistic tasks and noticed significant improvements when ventilation was increased from 5.2 to 9.6 l/s per person. This is just a small selection of numerous studies leading to similar conclusions. Therefore, Wyon and Wargocki (2013) reason that ventilation rates should be considered the most reliable indicator of indoor air quality effects, at least until individual pollutants impact will be better identified, even if this parameter is more inconvenient to measure than for instance CO_2 concentration.

However, despite these seemingly unambiguous results, studies giving completely opposite results can be found as well. Nordström (1995) describes research in Ystad's hospital showing that SBS symptoms were most common in new buildings with high ventilation rates, which is explained by resulting too low relative humidity (a phenomenon typical mostly for locations with cold climate). Kronvall (n.d.) presents results of study on indoor environment quality taking place in schools and preschools in Malmö. Examined buildings had on average low air exchange rate, below limits set by regulations. Surprisingly, number of reported inconveniences, such as dry or stuffy air, eyes irritation or headaches was higher in facilities with higher ventilation rates.

Required ventilation flows, mentioned in the beginning of this section, are very general and do not include a number of factors. With the development of the building industry less and less emissive materials are used. Humans adaptation to odour is being considered. A discussion about alternative solutions to improve air quality instead of increased flow is being raised, including ideas such as demand-controlled ventilation or increased significance of windows' opening. Overdimensioned ventilation, apart from humidity problems, is also inefficient from energy use perspective and thus characterized by unnecessarily big environmental footprint.

Toftum et al. (2015) examined relation between ventilation type in schools and learning outcome. The conclusion was that mechanical ventilation in every respect is advantageous compared to natural ventilation: pupils from mechanically ventilated schools scored higher at national tests, had better statistics regarding absenteeism and CO_2 levels in those buildings were lower. Another finding was that manual opening of windows is not sufficient measure of regulating IAQ as it is too dependent on teacher's or pupils' individual actions. It is confirmed by Wyon and Wargocki (2013) who stated that users will not open windows just to maintain air quality unless they also feel too warm, especially that it is often considered to be a waste of energy. But study described by Kronvall (n.d.) showed opposite trend – dissatisfaction with indoor environment quality was higher in buildings with mechanical ventilation compared to natural and one of significant factors were complaints about noise generated by fans.

Even in systems designed with sufficient properties problems may occur. Wyon and Wargocki (2013) point out that increased air flow will not improve indoor air quality if filters in the air handling system are old and full of dust, as it may lead to distribution of harmful particles, causing discomfort or health problems. Speaking of poorly maintained system components, humidifiers as well can be a source of problems. Arundel et al. (1986) draw attention to the fact, that these devices frequently get contaminated with fungi or bacteria, as these organisms find desirable conditions for growth in moist conditions under appropriate temperature. From there they can easily get distributed over the whole building in form of aerosol. Toftum et al. (2015) recalls study of Simons et al. (2010) which found relation between malfunctions in systems such as blocked ducts and dirty filters and high absenteeism rates in schools. These examples highlight the need of regular maintenance work and consequently also benefits of systems with thought-through accessibility.

4.6 Children's health and comfort aspect

Thuvander and Victorin (2006) describes health situation among children in Sweden. Even though it is overall good, asthma and allergies cases tend to increase in number (it more than doubled over last few decades, slightly over 25% children are diagnosed with some kind of allergy, most of them before they turn 5 years). They are neither free from SBS symptoms such as fatigue, headaches, sensory irritation and respiratory issues – cough and wheezing, which are generally reported in many countries (Thuvander and Victorin, 2006).

In Sections 4.1.1.8 and 4.1.3 it was already partly mentioned how children's physiology differs from the adult's one: they have bigger surface-area-to-mass ratio, greater metabolic rate per 1 kg body mass and lower sweating rate. Yet more differences can be listed. Chatzidiakou et al. (2015b) names these connected to air quality's impact: children are more vulnerable to airborne pollution because they inhale more air compared to their body size than grown-ups and breathe faster. At the same time their lungs are still developing and airways are narrower. Bakó-Biró et al. (2012) adds that they have smaller ability to handle toxins. This is due to the fact that immune system is one of maturing relatively late under adolescence. Moreover, in modern world the closest environment around children becomes more and more sterile, so their immune systems do not get sufficient stimulation (Thuvander and Victorin, 2006). This increased susceptibility results in higher health hazards, which may influence the future condition as well – children exposed to pollutants may have decreased lung functions as adults. Another risk is connected to development of asthma and allergies under influence of for example mites, tobacco smoke, mould or animal fur.

Because of this high vulnerability of kids, a lot of studies were carried out in school environments to establish if buildings designed based, most often, on rules and guidelines developed for office spaces and adult users, satisfy the needs of the youngest. The outcomes showed same tendencies as adults have – health issues are enhanced by presence of mould, dampness (Smedje et al., 1997), VOCs emissions (Kim et al., 2007), dust, formaldehyde, NO_2 (Norbäck et al., 2000) – but so far, they did not result in development of any children- or schools-specific standards or design methods.

Considering children's understanding of comfort, there are some complications when it comes to its assessment. Teli et al. (2013) describe that even if small children are able to understand thermal comfort rating scale, according to their teachers, concepts such as air velocity and humidity may be hard to comprehend. Moreover, asked about overall comfort, kids tend to answer based on factors as feeling of tiredness, the ongoing class activity, their physiological and psychological condition, or the time of day. Finally, as during school day outdoor activities are usually organized, especially among younger pupils, some aspects of poor IAQ may be compensated by staying in fresh air. The authors concluded that the way children answer in questionnaires differs from the way adults do and therefore children-adjusted assessment methods need to be developed.

4.7 Suggested adjustment of limits given by regulations based on health, comfort and performance

Once the effects of different indoor climate aspects on users have been reviewed, it can be asked if and how the current regulations could be adjusted to give them more consideration.

It has already been mentioned in Section 2.2 that a space for improvements has been identified in the applicable law. There are several regulations overlapping in scope and completing each other in terms of requirements, which creates consequent yet very strict design conditions, characterized by lack of flexibility. In many of them a tendency to assume that same limits will result in good indoor climate in all kinds of premises can be observed. It can also be questioned if indicators chosen to describe indoor environments are the ones reflecting its actual quality most precisely. To quickly remind current situation: after some simplifications a preschool should be able to provide operative temperature between 20 and 24°C in winter and 20 and 26°C in summer, PPD always at most 10%, air velocity at most 0.15 m/s, CO_2 concentration not exceeding 1000 ppm, air flow of 7 l/s per person and 0.35 l/s per 1 m^2 floor area. Let us verify legitimacy of these values.

Operative temperature range at first may seem reasonable from comfort point of view, but closer look raises doubts. Even if some may argue that 20°C is low, winter case should work for most environments as long as occupants wear clothes suitable for the season. This value is however questionable in summer case – there is a significant risk that a user dressed in typical light summer clothes and performing sedentary activity will find these conditions too cold. On the other hand, situation changes drastically with different activity – based on PMV model, the same set of parameters can result in too hot climate if an occupant is moving around with average pace of human walk. If previously discussed conclusion from studies on children's thermal comfort – that their perception of temperature is higher than adults' – is applied, the problem becomes even more complex. For example, 20°C can feel only slightly too cool for a child, even at rest, while 26°C will be too hot (whereas for a grown-up it is expected to be acceptable). The fact that perception of temperature depends on various factors, such as activities, clothing, age, adaptive skills and many more, one universal requirement feels unreasonable and almost impossible to be set.

Moreover, it is questionable if setting a requirement for maximum air temperature in summer makes sense at all. Ventilation is usually designed based on average, reliable assumptions, excluding extreme weather cases, especially for non-heating season. This means that at some point in summer, on extraordinarily sunny days with huge solar heat gains, in buildings without comfort cooling or with only limited possibility of air precooling (as considered in this thesis), indoor air temperature will not be able to be kept within given limits. Accepting this could be perhaps a base for developing more practical requirements, for instance concerning means of decreasing solar loads, such as shadings or even planting trees in proximity of a building.

PPD could work as a better indicator, but due to all issues mentioned in this chapter its credibility must be questioned. If it was used, the separate model for children should be worked out. It would also have to be decided which group of users is more important and whose preferences are determinant for indoor climate design. Considering that a preschool's main goal is to provide suitable environment for children to develop and also that their adaptability is usually lower than adults', an idea may be to use simultaneously PPD for pupils and adaptive model for members of staff, agreeing to compromises in favour of children.

Apart from comfort, performance and health aspects cannot be neglected. Based on several mentioned studies, the former seems to benefit from relatively low temperatures, the latter – from appropriate range of relative humidity, which, in climate such as Swedish, is again supported by rather cool conditions. These arguments would speak for keeping temperature low, with 20°C working rather as maximum than minimum value. A simple simulation for RH can support this conclusion: according to the report of Wert (2013), on typical winter day in Gothenburg outdoor air temperature is around 2°C and absolute humidity – 4 g/m^3 (average for January from 1996-2012). If a room with air temperature of 24°C is ventilated with outdoor air for a longer time, RH can be expected to drop to around 18%, while for a room with temperature 20°C it should stay at around 23%. The difference may not be big but can be crucial considering thresholds for symptoms such as sensory irritation. At this point it is worth mentioning that providing sufficient RH is currently one of biggest interests of Lokalförvaltningen, which believes that this parameter is associated with the most severe indoor climate issues reported in preschools in Gothenburg.

Air velocity of at most 0.15 m/s is required by FoHMFS 2014:17 if air temperature in the room does not exceed 24°C, but possibility of using air movement to cool down users on warm days is limited by BBR, which demands keeping air speed below 0.25 m/s outside the heating season. It could be argued that this requirement could be removed without risk for thermal comfort, especially considering that correctly designed ventilation should not result in uncontrolled air speed increase. In an environment where individuals have possibility to adjust air velocity to their needs in a limited zone, higher speeds should be allowed.

A requirement of 1000 ppm CO_2 causes a lot of controversies. Despite numerous studies it is still not fully clear if CO_2 itself can decrease perceived air quality and performance or if it is a pure indicator of other harmful pollutants' concentration. Regardless of the answer, keeping CO_2 demand feels justified, at least until any other easy to measure indicator of air quality is found. On the other hand, a limiting value can be discussed – 1000 ppm is rather low (for example in a classroom with average occupancy and basic air flow it can be achieved in less than 1 hour) and maintaining this level would require high ventilation rate, and in consequence – low RH issues in winter.

Air flow of 7 l/s per person and 0.35 l/s per 1 m^2 floor area is a very questionable requirement. The component supposed to take care of material emissions is obtained for a typical room in residential building, but with changing height of a space it can result in drastically different air exchange rates. On the other hand, it is usually on the floor level where people stay and the air quality close to the ceiling may be of small interest, but it depends on room's function and designed air distribution pattern. The component intended to handle bioeffluents has different weight depending on occupancy. For instance, in a classroom, relatively small room with a big number of people, 7 l/s per person may result in 3-4 air exchanges per hour, which feels too much and on winter inevitably results in low relative humidity. Moreover, a classroom, both in a preschool and in a school, is usually being left by occupants during breaks or outdoor activities, which reduces the pollutants emission and enables more excessive airing without risks for comfort.

Some of regulations mention 7 l/s per person as what ventilation must be able to achieve, but not what must be achieved all the time during its operation, which seem much more reasonable. However, in design practice a ventilation rate can never be assumed based only on emissions from people and materials – it is very often determined by a need of handling internal heat gains from users, equipment, lighting and sun, which in turn depends on, among others, building's location, shape, exposure, function or occupancy density, and therefore must be assessed individually in every case.

Summarizing, it seems that it would be beneficial to let most of the legal documents stay more generic and possibly refer to one source giving detailed values, as long as they are obtained with consideration for building- and activity-specific conditions. Situations where a regulation both refers to another and gives limits to follow should be avoided as it results in risk of contradiction if the first document changes. It may be though discussed if it is feasible to cover all possible cases by theoretical document. Perhaps a better solution would be to remove any specific requirements and leave only general demand on healthy, comfortable and hygienic environment, fulfilment of which would be a responsibility of the designer. However, in that case very exact definitions of what is health and hygiene would be necessary as it cannot be expected that every indoor climate engineer would have knowledge from the scope of medicine. Suggested aspects to be included are relative humidity, concentration of particles and gaseous pollutants.

If requirements became purely functional, the focus of law could be shifted from design parameters to follow-up measurements and control of building's functioning over its life time. This approach on the other hand raises the question about what would be done if performance of a given indoor environment would not be sufficient during operation – after all, legal consequences cannot improve the air quality in poorly designed building. The answer may be to develop more flexible ventilation systems which may be easily adjusted after construction phase.

5 Ventilation Systems

In the following chapter alternative solutions of ventilation system considered for Grönskan and Hoppet preschools are described in terms of basic design assumptions and operation principles. As a base for architectural design and FTX system documentation for model preschool Grönskan were used since at the moment of writing the following report technical documentation for Hoppet was still in preparation and the design of the building will not differ significantly from Grönskan. For hybrid ventilation with preheating in the ground pre-study for actual Hoppet preschool was used. Moreover, environmental impact for both systems is discussed in terms of risks and opportunities.

5.1 Reference preschool – building description

The model preschool Grönskan was designed with the idea of flexibility. The main assumption was to divide the two-storey building into the central core, consisting of kitchen and boiler room in the first floor and fan room and staff room in the second floor, and other parts containing preschool departments (Göteborgs Stad Lokalförvaltningen, 2017c). These departments are located in separate wings adjacent to the core in such a way that dependent on needs it is easy to design preschools with varying space by simply adding or removing one or two wings; examples of setup can be seen in sections in Figure 5.1. Several pre-studies were conducted for Grönskan, testing different number and kinds of departments, but based on plot's area and placement as well as on neighbourhood's needs it has been finally decided to design the building with 8 preschool departments. The same will apply to preschool Hoppet.

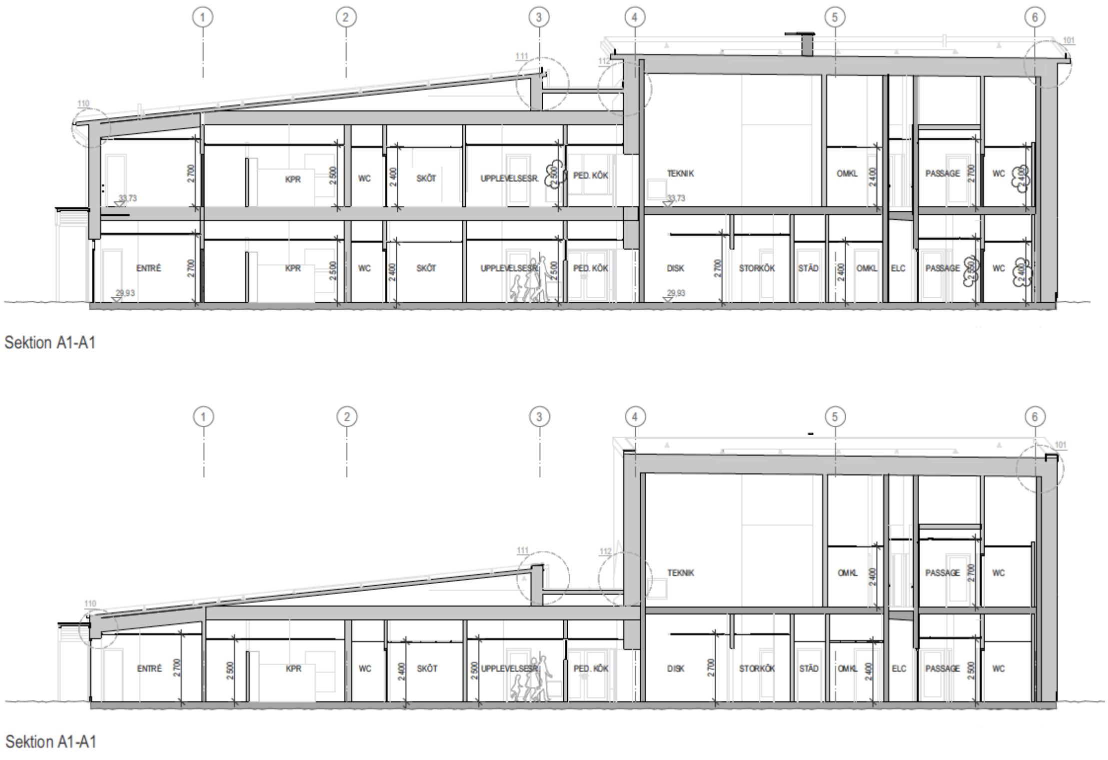


Figure 5.1 Grönskan – 8- and 6-department setup (Göteborgs Stad Lokalförvaltningen, 2017d).

This solution results in total heated floor area A_{temp} equal to 1674.2 m^2 and number of occupants equal to 170, of which 144 are children (18 per department) (Göteborgs Stad Lokalförvaltningen, 2017c). The sketches of first floor plan with suggested distribution of rooms in 8 department model preschool Grönskan can be seen in Figures 5.2 and 5.3 below:

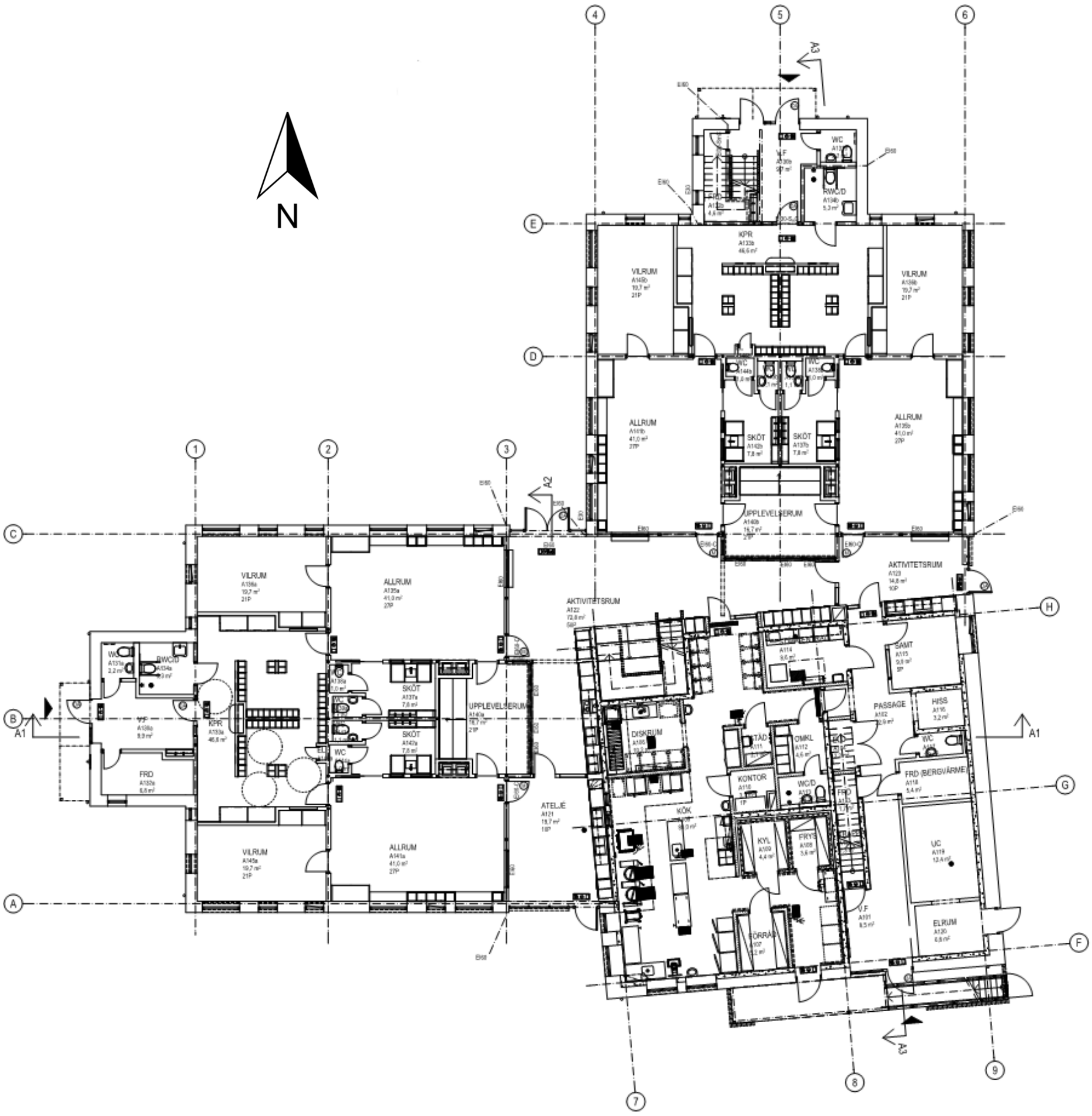


Figure 5.2 Model preschool Grönskan – first floor plan (Göteborgs Stad Lokalförvaltningen, 2017d).

Figure 5.3 Model preschool Grönskan – first floor sketch (Liljewall, Norconsult, 2016).

District heating is used for heating and hot tap water, with technical room located in the first floor. In the technical room heat exchanger for radiators, ventilation and hot water preparation can be found.

For ventilation two alternative solutions are described in sections below.

5.2 FTX system

FTX stands for a system with heat recovery, where both supply and exhaust air flows are forced by fans. It is nowadays one of most common systems as it allows for careful control of indoor environment and enables efficient energy use.

FTX system consist of two duct systems, one for supply air and one for exhaust air. The outdoor air is taken to the outdoor air duct with help of a fan and it is transported to an air handling unit, where it is conditioned before it is led further into the system. In AHU heat recovery unit is placed in order to pre-heat the incoming air with heat gathered by the exhaust air, as well as a heating coil and in some cases – a cooling coil, in case of heating or cooling need exceeding possibilities of heat recovery. AHU fits also a pair of air filters (Warfvinge and Dahlblom, 2010, as cited in Feldt and Nilsson, 2018).

FTX system for Grönskan is designed with two air handling units located in the fan room in the second floor – first for kitchen area and second for the remaining parts of the building, as significant differences between activities taking place in these two kinds of spaces would make it difficult to dimension appropriate flow in one system and could result in undesirable effects such as odour transfer. For simplification purpose, the system serving the kitchen will not be considered in this report.

The section of technical room showing air handling unit for preschool departments can be seen in the Figure 5.4 below:

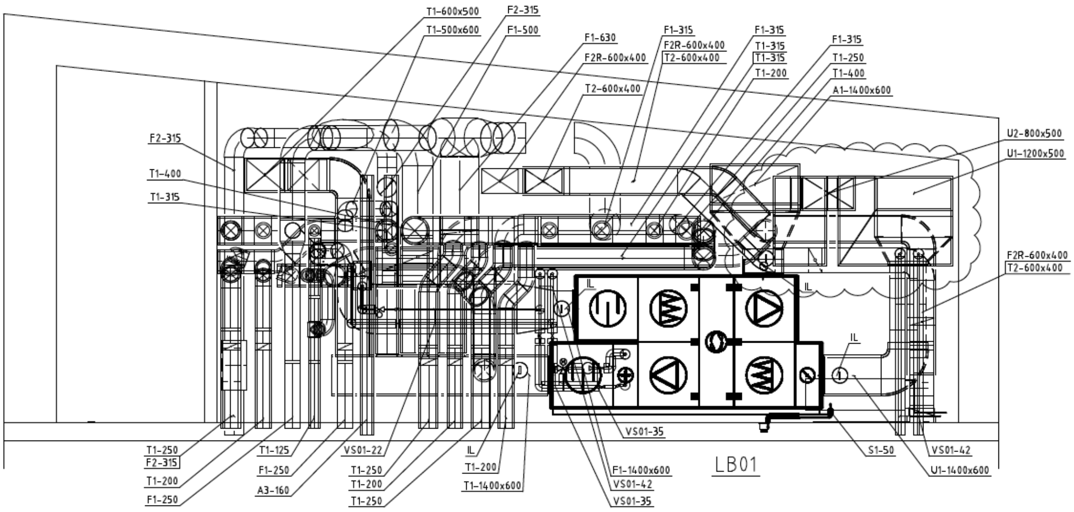


Figure 5.4 Model preschool Grönskan – air handling unit for the general part of the building (Göteborgs Stad Lokalförvaltningen, 2017d).

The FTX system for the preschool excluding kitchen is designed as VAV system with demand-controlled flow (by temperature and CO_2 concentration), rotating heat exchanger, maximum air flow of 3340 l/s, average air flow of 2700 l/s and SFP of 1.49 kW/m^3/s at average air flow (Göteborgs Stad Lokalförvaltningen, 2017c).

5.3 Hybrid system with preheating in the ground

The following description of hybrid system is based on the technical description of such a system prepared by Charlotta Berggren and Torkel Andersson from ByDemand AB for the Hoppet preschool in February 2019.

In the hybrid system the outdoor air is taken in by an intake tower and transported further through underground ducts to an underground culvert. At its end a speed-controlled axial fan with a silencer is mounted as well as temperature and pressure sensors. While passing this way the supply air gets heated in winter and cooled in summer so that it theoretically does not require additional heating or cooling. The flow is adjusted by building's control system according to demand defined by season and outdoor air temperature, because the cooler outside air wintertime (resulting in supply air temperature around 12-13°C) removes the surplus heat more efficiently than the warmer air summertime.

From the culvert the air is moved to concrete chambers, which, as they are equipped with fire doors, provide division into fire sections on the supply side. From the chambers further ducts lead the air to branches in rooms inside the building. The low supply air temperature allows for low flow rate.

The basic air flow to rooms varies with outdoor temperature through a change of pressure in the culvert depending on it. Supply air pressure increases with outdoor temperature's increase and consequently increases also the flow. Moreover, the air flow is controlled in sequence with heat generation from room's radiator through an actuator in radiator's valve.

Same as in the system described in Section 5.2, kitchen in hybrid ventilation is handled by separate installation – an FTX air handling unit located in the second floor is proposed. It should be possible to take air through the culvert to the AHU to get access to the cool air.

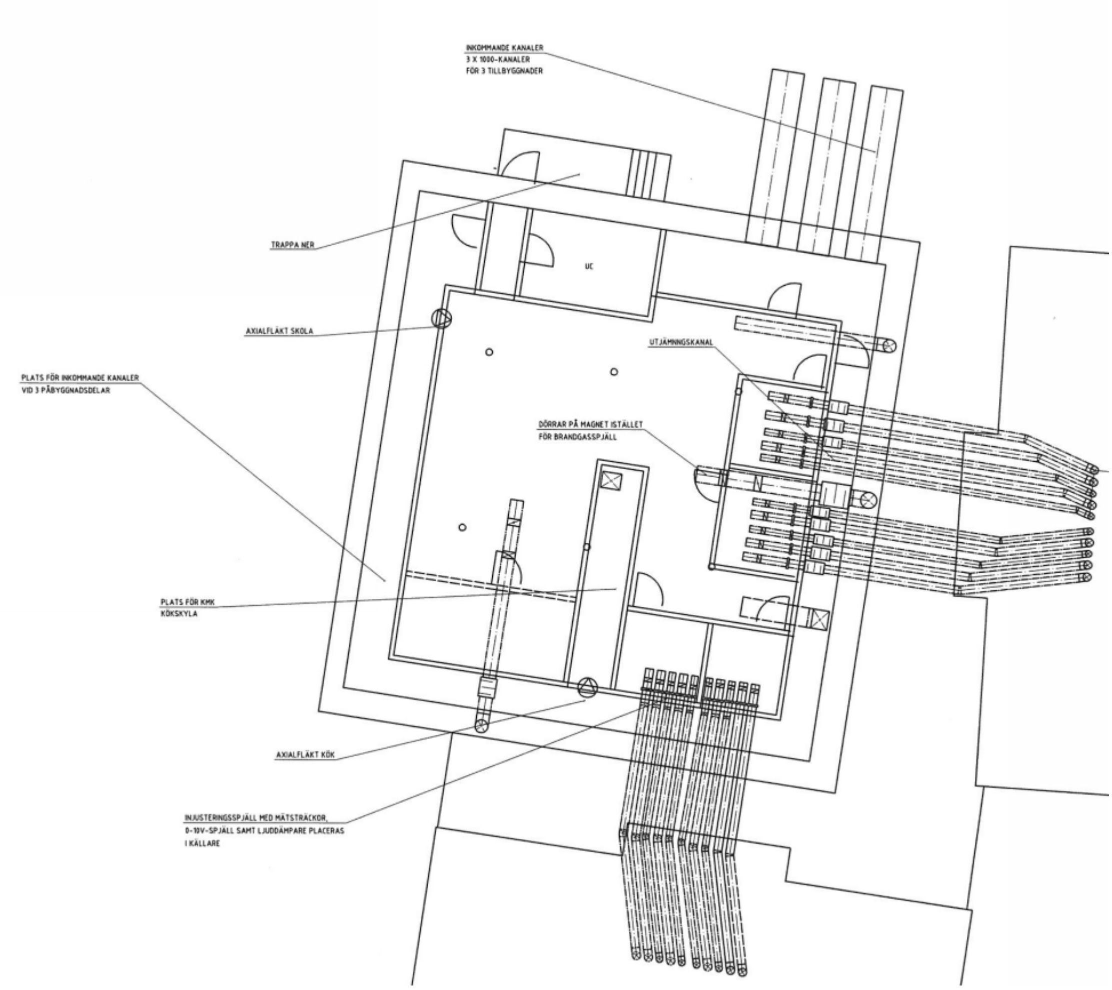


Figure 5.5 Hybrid ventilation – basement level (Berggren and Andersson, 2019).

Exhaust air is removed through air diffuser with fire damper to the closest staircase and further out through a cowl and damper controlled by overpressure. Exhaust air from toilets and nursery room is removed through speed-controlled fan placed on the roof, one per building. The air flow is adjusted to season. The exhaust air is compensated by basic flow to the rooms.

The hybrid system in Hoppet is design with maximum air flow 3000 l/s.

5.4 Comparison – advantages and disadvantages of the systems

FTX systems are much more common than hybrid and their advantages have become well-documented over the years of their continuous development. Heat recovery unit located in an AHU allows for significant savings of energy for heating as the supply air is to a great extent preheated by exhaust air. Flexibility of air handling units' construction enables adjustment of their design according to needs of specific conditions, for instance by adding or removing elements such as heating or cooling coil, humidifier or filters. This maximizes the possibilities of air conditioning and providing its best possible quality.

In hybrid ventilation the above-mentioned benefits cannot be found. The system lacks air conditioning components, so the only possibility of increasing humidity indoors is through change of air temperature by adjusting the flow and at the same time letting in less outdoor air with low absolute vapour content. Neither heat recovery is possible, as the exhaust takes place through a cowl on the roof. This however allows for significant decrease of materials used for exhaust air ducts – up to 90% (Feldt and Nilsson, 2018).

On the other hand, the simple construction of hybrid ventilation brings other benefits. It results in low pressure in the system and consequently – low pressure drops, which increase at higher air flow can be neglected in this kind of solution (Berggren and Andersson, 2019). For that reason, power demand for fans is decreased. Preheating in underground ducts compensates partially for the lack of heat recovery and in summer – when it works in the opposite way, lowering the outdoor air temperature – decreases the need for comfort cooling. According to the technical description of Berggren and Andersson (2019), electricity use for fans is around 10 times lower than in traditional solutions. Moreover, thanks to the low pressure setting, despite variable and, on summer, high air flow, the system is very quiet.

Filtration of the air is taken care of alternatively. The big area of the underground culvert results in decrease of air velocity, which in turn should allow for sedimentation of particles on the floor (Berggren and Andersson, 2019); however, the efficiency of this mechanism should be further investigated as currently it is not confirmed by measurements. Particles, if settled, can later be easily removed, for example by an automatic vacuum cleaner.

Hybrid ventilation system is also characterized by slightly higher flexibility in terms of possible adjustment to new conditions when a building is already finished – for example if a new wing was to be added to the preschool. Extra costs for even significantly increased flow are small compared to what such an increase means for traditional FTX system with comfort cooling, where the air handling unit with all components is chosen based on design air flow.

5.5 Environmental impact of ventilation

As it was mentioned in Section 1.1, ventilation may not contribute significantly to the total amount of materials installed in a building, but its small share consists mostly of fossil ones. Therefore, it is important to raise a discussion about how ventilation's environmental impact can be minimized.

It can be generally stated that CO_2 equivalents in ventilation are generated by need for heating (and cooling, if applied), energy for operation (fans and pumps mostly) and materials used for air handling unit and ducts. Thus, finding the system with optimized, minimum impact would require small components' dimensions combined with low demand for fan power and maximized possibility of using internal heat gains, heat recovery and free cooling. Below it is discussed how these can be achieved in FTX and hybrid systems.

5.5.1 Energy

CO_2 equivalents associated with energy production are considered in two ways. Firstly, emissions are generated in production of electricity. The way in which they are accounted for in Swedish energy mix has been described in Section 3.1.4. According to Gode et al. (2011), Swedish energy mix has an emission factor of 36.4 g CO_2/kWh, but since in newer data slightly different division of primary energy sources can be found, this value in reality may be a bit lower. Electricity in ventilation system is used mainly to run fans in AHU and pumps supplying water to heating coils and radiators. Minor energy consumption is generated by components, such as heat exchanger (if rotary), and control devices, such as sensors and dampers. The latter has been neglected in this report, as it can be assumed that controlling equipment will be nearly same in all cases and its energy demand is very small compared to other components.

Secondly, production of district heating used for heating coils and radiators is also a source of greenhouse gases. According to data of Göteborg Energi from 2018, emission factor for district heating is 78.0 g CO_2e/kWh. However, in reference case presented further in this chapter, data from 2017 were used, when emission factor was lower, 64.0 g CO_2e/kWh. It does not affect the general trends of environmental impact but it is worth keeping in mind that absolute values of emissions are in reality slightly worse than the ones presented here.

5.5.1.1 Energy for fans

Energy demand for fans operation is related to specific fan power, which in turn is determined by maximum air flow and power of individual fans, resulting from pressure drops in the system and fans efficiency. Assuming that the last factor is constant, the change of energy demand can be directly associated with either change of air flow or presence of components in the system that change the total pressure drop.

5.5.1.2 Preheating of the supply air

Preheating of the supply air can happen in two ways – in FTX system part of the process takes place in heat exchanger and additional heat, if needed, is provided by heating coil. The demand for preheating is thus defined by the relation between outdoor temperature, supply air temperature, heat recovery capability and air flow.

In hybrid system preheating happens to some extent in the underground ducts; however, detailed measurements of heat transfer between ground and air in the ducts in conditions representative for Gothenburg are required to get full knowledge about this solution's possibilities. In some cases, especially the ones with higher supply air temperature, additional source of heating (most likely a heating coil) somewhere in the system will be necessary to supplement preheating.

In most basic case, with no heating coils included, hybrid system would always perform better than FTX system in terms of electricity use, as the whole preheating would happen naturally. Performance of FTX will get better with decreasing air flow, as the only energy demand will be generated by rotation of heat exchanger. However, it does not seem likely that in Swedish conditions any of systems would be able to function without additional source of heat. Consequently, CO_2e generation will in both systems be associated with district heat production and heating coil power demand, and in case of FTX system also with heat exchanger power demand.

5.5.1.3 Energy for pumps

Energy needed for pumps operation is included in two ways: firstly, hot water must be supplied to heating coil in air handling unit in FTX system; secondly, in both solutions, hot water has to be pumped to radiators system in the building.

Power demand for pumps supplying water to the heating coil is directly connected to the need of preheating of the supply air, described above. It can be assumed that same relations between ventilation parameters and environmental impact change as mentioned there apply to pumps power demand.

Demand for radiators power is associated with supply air temperature, indoor air temperature, air flow and heat losses in the room. In the examined cases the need for radiators cannot be clearly seen – internal heat gains are always determining for the ventilation design parameters so the air does not require any heating inside the room. However, in real life, in some cases radiators will be necessary, for instance in night or under long holidays, when ventilation is shut off and no heat is generated in the room. In FTX system maintaining constant indoor air temperature is a prerequisite if removal of heating coil and depending only on heat exchanger is to be considered. In hybrid system radiators will be necessary when the designed supply air temperature cannot be reached by preheating in the ground.

Obviously, at the same air flow and supply air temperature, required radiators power will decrease with decreasing indoor air temperature; analogically, at a certain air flow and indoor temperature, increasing supply air temperature will result in smaller power demand and at constant supply and indoor temperatures increasing the air flow will increase power demand.

5.5.2 Materials

CO_2 equivalents obtained for materials or final products are result of their life cycle assessment and can be obtained from, among others, EPDs administrated by IVL Swedish Environmental Research Institute (see Section 3.1.3).

5.5.2.1 Materials use for ducts

Opportunities of decreasing environmental impact associated with ducts materials depend on how change of the dimensions would be followed by design parameters adjustments.

As it is explained below in Section 5.5.6, changing ducts size may not bring any benefits for environmental impact at all. However, materials use could be decreased without increasing energy demand for fans operation if ducts size was decreased simultaneously with air flow. Decreasing the flow while aiming for an unchanged pressure drop would result in smaller ducts size and thus smaller material use. On the other hand, if focus was shifted from materials to energy, decreasing the flow without changing the duct size could result in lower pressure drop and consequently smaller fan power demand.

Operation-associated emissions dominate always over materials-associated ones (this will be shown in Section 5.5.3), so concentrating on minimizing pressure drops rather than ducts diameter seems reasonable. However, this conclusion was made with some simplifications and in practice increasing flow, pressure drops and ducts size can happen simultaneously, so eventually it can be stated that decreasing air flow creates the potential to limit material-based CO_2e emissions.

Modifications that has undeniable potential are rearranging the space in a way enabling use of shorter ducts or using alternative, more environment-friendly materials. Both these solutions can be used with all combinations of indoor/supply air temperature and air flow, so analysis from this perspective would not help in assessing ventilation's environmental impact.

Hybrid ventilation requires more ducts than FTX system. Even though in hybrid solution the big saving is made on lack of return and exhaust air ducts, total amount of materials is higher due to long and wide underground ducts leading from the intake tower to the culvert. However, it is worth to notice that these proportion will decrease the more departments there is in the preschool, but only until a need of additional supply duct occurs. The relation between number of building's wings and number and diameter of underground ducts is a separate optimization question that requires further investigation. For this report, is has been assumed that hybrid ventilation for a given indoor environment parameters setup will always have bigger materials use than FTX system with the same design conditions.

5.5.2.2 Materials use for components

Any component added to the system would increase the total pressure drop, electricity demand and need for materials.

Theoretically, both FTX and hybrid system could work without any additional components such as heating coil, cooling coil or humidifier. In practice, it should be first decided what is a priority in indoor climate design. If focus is on environmental impact, risking with users' comfort could be accepted. If providing optimal indoor environment is more important, adding components should be considered. Below it is described for some of the components how their presence or absence would influence the total performance of the whole system:

Heating coil:

- if present:
  - additional pressure drops and increased fan power demand, bigger CO_2e generation for district heating;
  - in hybrid system location of the coil may be a problem as system lacks AHU;
- if removed:
  - for FTX system: risk that heat recovery will not be able to always provide required supply air temperature, leading to either increased power demand for radiators, generating additional pump power demand and shifting district heat consumption from heating coil to radiators, or low thermal comfort and users feeling too cold;
  - for hybrid system: a big risk of insufficient supply air temperature if heat exchange between ground and ducts is smaller than expected, leading again to either increased demand for radiators or bad thermal comfort.

Cooling coil:

- if present:
  - additional pressure drops, increased fan power demand, power demand for cooling coil;
  - in hybrid system location of the coil may be a problem as system lacks AHU;
- if absent:
  - for FTX it inevitably means too high indoor air temperatures on summer, when outdoor air has temperature similar to or even higher than indoor air and heat gains are the biggest; even including thermal inertia of the room, temperature rise will occur fast, leading to unacceptable conditions, worsening significantly comfort and performance;
  - for hybrid: less risk than for FTX as some cooling will occur in the underground ducts, however this effect is expected to be too low to provide optimal indoor climate anyway.

Humidifier:

- if present:
  - it could significantly increase indoor RH in winter, when even with small air flow it quickly reaches down to around 25%, which is too low from health point of view;
  - adding humidifier would increase materials use, pressure drops and power demand;
  - depending on the type of humidifier, dry bulb temperature of the air will be affected – in the one where water is injected it will decrease, increasing demand for preheating;
- if absent: in winter, and in case of very high indoor air temperature rise even in summer, it will not be possible to maintain preferred relative humidity in the room.

Filters:

- if present:

    - filters are normally responsible for quite big pressure drop compared to other components, so adding them will increase required fan power;
    - air quality can be controlled;
- if absent:
    - for FTX removing filters is not recommended as there will be high risk of damages to system's components and their repair or replacement would definitely increase the total environmental impact;
    - for hybrid system negative consequences for air quality could be avoided – if system was designed with low air velocity, particles could have time to sediment in the large intake ducts and the underground culvert, but as it was mentioned before in this report, effectiveness of this mechanism needs to be confirmed.

5.5.3 The reference case – CO_2 equivalents for ventilation in Grönskan

Feldt and Nilsson (2018) it in their bachelor thesis project – based on the project for Grönskan prepared by VCON VVS-konsult AB in March 2017, investigated how changes in the basic design can affect different parameters of the HVAC system and consequently its environmental footprint expressed in CO_2e. They compared FTX system with several variations, such as smaller, bigger or shorter ducts, basic hygienic flow or alternative ducts materials, as well as hybrid system with preheating in the ground. Their findings allowed to point out the most promising solutions.

The results were originally obtained for 6-departments setup of the preschool. Thanks to the buildings design, assuming repeatable wings of same arrangement, it can be roughly estimated that with changing size of the preschool, ventilation parameters and resulting CO2e amount will increase proportionally to number of departments. This allowed to define the reference case for 8-department building: FTX system with supply air temperature 14°C and VAV, maximal flow 3340 l/s and average flow – 2700 l/s. Considering number of people in the reference case building, it can be translated to around 17.34 l/s per person and 13.05 l/s per person at maximum and average, respectively, in the whole department. Recalculating this further, air flow in the room examined later in this report can be estimated to 4.50 l/s per person and 3.45 l/s per person at maximum and average, respectively.

The CO_2 equivalents for different aspects of different ventilation solutions are presented in Table 5.1.

Table 5.1 Environmental impact of reference FTX system, FTX system with modifications and hybrid system (adapted from Feldt and Nilsson, 2018).

Aspect	CO_2e [kg] (50 years analysis)							
	Reference FTX	Smaller ducts	Bigger ducts	Shorter ducts	Hygienic air flow	Alternative materials	Alternative components	Hybrid
Operation	17101	28125	14767	14789	10047	17101	13137	8122
Materials – AHU	10437	10662	10437	10437	4343	10437	9336	0
Material – ducts	9971	8218	12572	6107	9971	3385	9971	16847
Air pre-heating	559	559	559	559	559	559	559	185872
Sum	38068	47564	38335	31892	24920	31482	33003	210841

Smaller ducts would require less materials, including these used for insulation. Moreover, decreased dimensions would result in less space needed for installation and fewer transports. However, in small ducts pressure drops will increase, so to keep air flow unchanged, fans would require more power and they would have to be bigger. Using bigger ducts on the other hand would give exactly opposite results – small pressure drops would allow for less fan power, but the material use will increase. Instead of using smaller ducts, an idea can be to use shorter ones – by that appropriate air flow would not be jeopardized, less materials would be used, and the system would be characterized by smaller pressure drops. This solution, however, would imply a need of change of the interior design of the space, so that the rooms requiring more air were placed as close to technical room as possible. Next modification, replacing the design air flow with hygienic one, constant, would result in smaller size of required AHU and consequently decreased SFP, but indoor air quality would be put at risk. Then, as alternative material, ducts consisting only of hard, compressed insulation have been considered. This change would not result in any difference in terms of power demand. Steel sheets would be removed from ventilation system, but the total amount of insulation would slightly increase. Finally, last alternative for FTX system was to design it without heating coil and filters – components which are not used in hybrid ventilation. This solution would result in decreased pressure drops and consequently fan power, but simultaneously also in risk of increased particles concentration indoors and higher need for system's maintenance due to penetrating dust.

When all above-mentioned modifications have been investigated, it turned out that the biggest opportunities can be found in reducing the air flow, designing the system with shorter ducts and using more ecological materials, as these three options decrease CO_2e amount or leave it unchanged for all aspects. The hybrid system has not been assessed as especially promising for decrease of the environmental impact.

However, several factors that may have biased the results can be noticed. To start with, in order to maintain consistent assumptions, based on case study of a specific building with fixed characteristics of HVAC system, hybrid solution was considered to have the same air flow and supply air temperature as the FTX. It was not clearly stated what functional requirements were the base for the ventilation system design except for room temperature 20°C, which raises the question about the ventilations main goal and if its parameters were set optimally to reach it. Current TKA were followed without investigating if they could be adjusted in order to describe rather space performance aspects than ventilation design parameters. This approach practically erased the possible benefits of hybrid ventilation. Moreover, the degree to which air can get preheated in the ground was calculated based on data from Umeå, which is characterized by colder weather and consequently lower ground temperature. Furthermore, most of proposed modifications for FTX system could be applied to hybrid one as well, but such an option was not examined.

5.5.4 Hybrid systems performance in chosen schools

Meanwhile, the real-life examples show that hybrid systems with preheating can have low-energy performance. For instance, in Vargbroskolan in Storfors, which was rebuilt from scratch in 2008 with extra focus on low energy use, this kind on system was used together with other measures, such as thick insulation or solar thermal collectors. The culvert in the ground is about 100 m long. Under normal operation conditions, the school is mainly heated by gains from people, lighting and equipment, which is completed by a small number of radiators. Windows are not operable. The school manages to keep energy demand for heating of 35 kWh/m^2 per year (Elmström, 2017). The indoor environment in Vargbroskolan was later a subject of research in bachelor thesis of Gustafson and Månsson (2009). Their results have been slightly ambiguous – on one hand, noise level caused by ventilation has been assessed as unacceptable only by 4% users and CO_2 level hardly ever exceeded 1200 ppm, which is a bit more than regulations require, but should not imply health or comfort problems, especially if it occurs temporarily. On the other hand, thermal comfort has been assessed as rather bad. Temperature has been kept almost constant between 20 and 21°C, as ventilation is temperature-controlled. These was considered to be "sometimes too low" by 47% of users, it is however worth mentioning that only adult members of staff have been questioned. Surprisingly, 31% users found thermal environment "sometimes too warm", which proves again that human response can vary significantly. Moreover, 20% thought that it was draughty sometimes. Even this rather low temperature setting could not prevent RH from falling temporarily under 20%. Finally, particles filtration in the culvert has been judged as insufficient, but the result could be affected by bad cleaning routines.

Other schools with hybrid system with underground ducts are mentioned in a report from MEDUCA ((Model EDUCAtional buildings for integrated energy efficient design) project (Blomsterberg et al., 2002): Grongskolan in Norway and Hökegårdsskolan in Gothenburg. Both of them have been refurbished within a framework of the project and ventilation has been improved or redesigned. On the contrary to Vargbroskolan, both of them performed rather poorly in energy-efficiency, but were able to provide satisfying thermal environment for the users. However, it is worth noticing that the buildings are older than Vargbroskolan and their modification was not equally extensive. A very interesting feature can be found in the system installed in Grongskolan – it is provided with heat recovery. In the exhaust air tower, placed in the middle of the building, a fluid heat exchanger with efficiency around 50% is placed. This is a rather low performance, nevertheless any possibility of heat recovery in hybrid system is promising with thought about how it was considered impossible in Feldts and Nilssons (2018) project.

Summarizing, it seems that assessing hybrid ventilation as explicitly worse than traditional FTX system may be a little hasty. Preheating in the ground has a potential that can be exploited with a proper design of the ventilation system and building as a whole. All possible improvements should be always considered, and control and maintenance routines should be carefully followed to ensure system's optimal operation. It is also really important to already from the beginning clearly set the goals for a particular building in question. If the focus is put on indoor environment, perhaps it is better to use FTX system with variety of components, able to quickly change parameters such as supply air temperature or humidity. If the environmental impact is vital, maybe a better choice would be hybrid system with minimized amount of used materials, even if users' comfort is sometimes put at risk. In any case, the decision should always be preceded with a thorough analysis of specific conditions, including elements of LCA.

6 Consequences of functional requirements for indoor climate on ventilation system's design parameters and environmental impact

In the following chapter the relations between different aspects of indoor climate are investigated as well as the way in which they are translated to basic design parameters for ventilation system, what these parameters in turn imply for chosen technical solutions and, finally, how these solutions affect environmental impact.

Several sets of requirements concerning operative temperature and CO_2 concentration are chosen with the idea of fulfilling requirements for one of the following aspects – health, comfort or work performance. They are controlled in winter and summer conditions to check what flow and supply air temperature would satisfy them in the most optimal way. In addition, for every set RH is obtained as well as PPD and PMV according to basic and modified calculation model. Reasoning the other way around, it is checked what conditions would be required to maintain certain levels of RH and PPD. Finally, some aspects of thermal inertia are considered.

Furthermore, a simplified environmental impact for different solutions of ventilation is investigated. The analysis includes mainly energy needed for operation of fans and for preheating of the supply air. Other aspects discussed are pumps energy demand, materials use and need for additional components in the system.

6.1 Methodology

In this section it is described how room model and outdoors have been assumed, how functional requirements were set and how environmental impact will be discussed.

6.1.1 Room model

Relations between parameters describing indoor climate are investigated in a room which has been considered typical for a preschool – in a preschool classroom intended for use by a group of children and teachers during bigger part of the day for activities such as playing and learning. The room's characteristics where it was possible are based on the projects of Grönskan and Hoppet, in case of missing information assumptions have been made; it results in the following input data:

- two identical rooms but with different placement were considered for winter and summer case:
  - summer – second floor, facing south;
  - winter – first floor, facing north;
- room dimensions: area 41.0 m^2, height 2.7 m, volume 110.7 m^3;
- occupancy: 18 children in preschool age, 2 adult teachers;
- presence: 70%;
- CO_2 generation rates:
  - children – 0.0180 m^3/h (assuming activity of around 2.7 met);
  - adults – 0.0375 m^3/h (assuming activity of around 2.3 met);
- vapour generation rates:
  - adults – 0.08 l/h;

    - children – 0.02 l/h;
    - no other sources were assumed as in the room for daily stay no cooking or cleaning activities take place;
- U-values: 0.1 W/m^2K for a wall, 0.9 W/m^2K for windows; 0.1 W/m^2K for a foundation slab, 0.08 W/m^2K for a roof;
- l-value for air leakage: 0.2 l/m^2s;
- internal heat gains:
    - adults – 80 W/person;
    - children – 60 W/person;
    - solar heat gains – 26.64 W/m^2 in summer case, neglected in winter;
    - equipment, lighting – neglected; it has been assumed that gains from lighting will be small compared to gains from people and equipment generating most heat is expected to be located in non-considered kitchen;
    - losses from warm water installation – neglected;
- it has been assumed that the maximum time spent in the room without going out for a meal or outdoor activities is 2 hours.

6.1.2 Outdoor conditions

Outdoor conditions chosen for the simulation were supposed to reflect the typical weather during day in winter and summer season, respectively. As the calculations are not aiming for finding critical conditions for the design, there was no need to identify extreme cases. Values has been based on the report of Wert (2013) for SMHI (Sveriges Meteorologiska och Hydrologiska Institut) that gives averages of different weather parameters collected between 1996 and 2012. Conditions are chosen for Gothenburg region.

For winter case a January day has been chosen with average temperature of 2°C and absolute humidity of 4 g/m^3 (resulting in RH of 72%).

For summer case a July day has been chosen. The average temperature is 16°C and absolute humidity 11 g/m^3 (resulting in RH of 81%). However, as this average means that temperature during the day is higher and is compensated by cooler night conditions, to make results more relevant for the time when a building is occupied, air temperature of 19°C was used instead, with resulting RH of 67%.

Ground temperature was assumed constant 8°C for calculation of transmission losses through the foundation slab.

6.1.3 Functional requirements - the procedure and studied cases

The simulation is carried out in the following way:

1. A fixed CO_2 level is set, as it itself is returning a certain minimum air flow required to keep it below a chosen limit for given time and CO_2 generation rate indoors. The concentration at the starting point is assumed to be equal to outdoors concentration, which is 350 ppm. It is assumed that the part of the air flow varying in different cases is connected to removing pollutants originating from users, flow due to material emissions is constantly 0.35 l/s per 1 m^2. The equation (B.1) used to obtain CO_2 level after given time can be found in Appendix B.

2. Winter or summer conditions are chosen for further investigation. For assumed outdoor air temperature the transmission losses and heat losses due to air leakage are calculated. Internal heat gains due to users and solar radiation are obtained. Finally, total heat gains are calculated.
3. A fixed indoor air temperature is set. For previously obtained air flow and heat gains, a supply air temperature required to maintain chosen indoor air temperature at flow as close to minimum as possible is found (see equation (B.2) in Appendix B). However, certain limits were put – supply air temperature was not allowed to drop below 10°C. Moreover, in summer two cases were considered, so the supply air temperature could not be lower than:
    a. Case A – outdoor air temperature 19°C – for FTX system without comfort cooling;
    b. Case B – 10°C – to account for possibility of precooling in the ground in hybrid ventilation or cooling coil in FTX.

   It must be understood that assumption for Case B means neither that supply air temperature can be set so low without considering risk for user's thermal (especially local) discomfort nor that precooling in the ground would be able to provide it. This is just an extreme case used to investigate if significant change in minimum supply air temperature has a potential to improve IEQ and decrease energy use.
4. For a given indoor air temperature and obtained air flow, RH level is examined. It is assumed that at the starting point indoor RH equals 40%.
5. Finally, for every set of indoor conditions PMV and PPD are calculated in two different ways:
    a. According to classical model.
    b. Using model modified to better match children's physiology. Modifications have been made according to work of Teli et al. (2012): the most promising solution, in which body surface area correction of resting metabolic rate was applied to PMV equation and 1 met calculation has been used.

   Parameters which were not examined in more detailed way are assumed as follows: air velocity constant and equal to 0.15 m/s, operative temperature used and assumed to be equal to air temperature (surroundings radiation neglected), clothing insulation assumed 0.5 clo in summer and 1 clo in winter.

   Two different activity levels are checked: for playing 2.7 met is assumed for children and 2.3 met for adults (as teachers do not necessarily participate as actively as pupils), for sedentary activities 1.2 met for both children and adults.

The pairs of requirements that have been examined are presented in the Table 6.1:

Table 6.1 The sets of investigated indoor air requirements.

No.	CO_2 concentration [ppm]	Indoor air temperature [°C]
Winter cases		
1.	1000	19
2.	1500	19
3.	3000	19
4.	1000	20
5.	1500	20
6.	3000	20
7.	1000	24
8.	1500	24
9.	3000	24
Summer cases (A and B)		
10	1000	20
11.	1500	20
12.	3000	20
13.	1000	23
14.	1500	23
15.	3000	23
16.	1000	26
17.	1500	26
18.	3000	26

The CO_2 concentration levels to investigate have been chosen based on results from theoretical study: 1000 ppm is a value recommended by most of legal documents and 1500 ppm is used in LF's technical specification of ventilation systems. As last limit 5000 ppm was checked at first, as it is by some of studies considered to be the value below which none health effects associated only with carbon dioxide can be observed. However, since such a level was not obtainable under assumptions of the simulation, 3000 ppm has been tested instead.

Similarly with temperatures, for winter 20°C and 24°C are the ends of range given by FoHMFS 2014:17. Temperature of 19°C has been examined to check if slightly lowered requirements could improve RH indoors. For summer, 20°C and 26°C are again defined by FoHMFS 2014:17. Since temperature lower than 20°C seems impossible to achieve without comfort cooling and above 26°C is highly undesirable from comfort perspective, a value from the middle of range, 23°C, has been additionally investigated.

After the main calculations had been carried out, additional questions arising from the results obtained were investigated:

- What indoor air temperature would provide at least 40% RH in winter? Above which indoor air temperature RH may drop below 40% or exceed 60% in summer?
- What indoor air temperature would provide PPD below 10% in winter and summer, for adults and children, at different activity level?
- Limiting flow to realistic values, how much would the indoor temperature increase in summer? How including thermal inertia would delay temperature rise?

6.1.4 Ventilation's environmental impact

Since obtaining exact values of CO_2e for all different indoor and supply temperatures in two systems would be very laborious and complex, the analysis aims rather at identifying if a certain change of design parameters has a potential to decrease environmental impact or if it would increase it. The detailed explanation of considered aspects of environmental impact and relations between different characteristics of ventilation system, supported by results from a case study, can be found in Section 5.5

6.2 Results

In to following section only brief description of results is given along with references to corresponding appendices. Interpretation of results can be found further in Section 6.3.

6.2.1 Air flows, supply air temperatures and PMV/PPD

The results from simulations are summarized in Table C.2 and in Table C.3 in Appendix C. Column "CO_2 after 2h" in Table C.2 shows theoretical level used to obtained minimum required air flow per person, not the actual air flow resulting from need of heat gains removal, which in all cases would be lower. Green colour in Table C.3 marks cases when PPD is kept below 10%. In Appendix D diagrams showing change of CO_2 level and RH under examined conditions (under actual air flow resulting from heat gains removal) can be found.

6.2.2 Providing acceptable PPD

Assuming same conditions as for previous calculation of PMV/PPD and RH reaching steady state, the conditions providing PPD below 10% (rounded up to integers) are presented in the Table C.1 in Appendix C. "Minimum" and "maximum" for every case describes minimal or maximal indoor air temperature value with corresponding RH under steady-state conditions, providing PPD below 10%, "optimal" – indoor air temperature with corresponding RH giving PMV closest to 0.

6.2.3 Effect of thermal inertia

Air flow obtained for summer case, when indoor air temperature of 20°C has been kept, is unreasonably high (98.26 l/s per person). In reality, the system would be designed based on less extreme assumptions. On critical days it would be exploited up to its maximal ability and uncontrolled temperature raise above it would have to be accepted, if no comfort cooling was available in it. However, the change of conditions would not happen immediately, therefore it has been examined how including thermal inertia of the building would delay the temperature change.

It has been assumed, based on architectural design of Grönskan, that the room has light thermal mass. Since the biggest allowed air flow was set to 13 l/s per person, which is quite high, the resulting time constant was low and equal 0.87 h. Considering later the transient problem, the temperature change would be as pictured in the Figure 6.1 below:

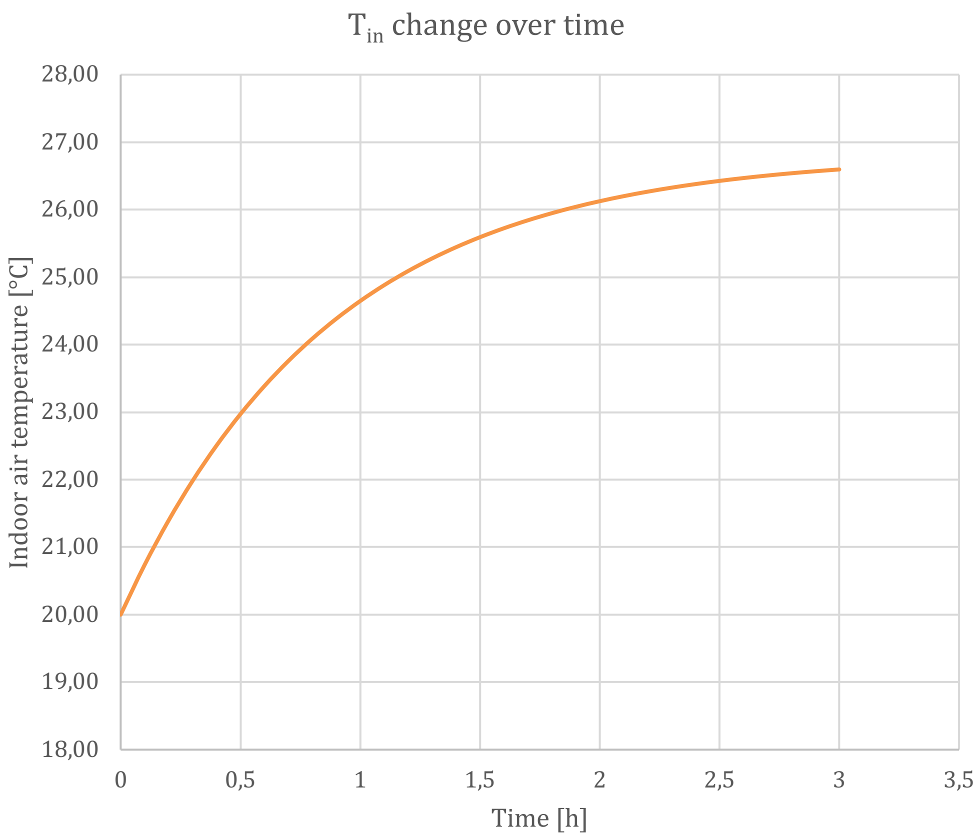


Figure 6.1 Temperature rise over time in summer at air flow of 13 l/s per person and supply air temperature 19°C (equal to outdoor air temperature).

6.3 Analysis of results

In the following section the obtained results are discussed with regard to three aspects of indoor environment – health, comfort and work performance. For each of them the reasoning explained in introduction in Figure 1.1 is applied.

6.3.1 Functional requirements for health

Based on findings from Chapter 4, it is assumed that requirement for health is mainly relative humidity within range of 40-60%.

With assumption that the only source of moisture indoors is its generation by humans in processes of transpiration and respiration, the absolute humidity in infiltrating ventilation air will always be determinant for relative humidity in the room under given conditions in terms of room temperature and air flow.

In winter case, when mean absolute humidity of the outdoor air is 4 g/m^3, indoor RH of 40% could only be kept if indoor air temperature was 11°C, assuming no additional humidification.

In summer case, when mean absolute humidity of the outdoor air is 11 g/m^3, indoor RH would drop below 40% if indoor air temperature exceeded 28°C. If the room temperature was lower than 21°C, RH would exceed 60%. However, absolute humidity of 11 g/m^3 would not be kept in supply air that underwent cooling process due to condensation in the cooling coil.

In Table 6.2 below selected simulation results for winter case are presented. It can be seen that change of air flow is of marginal importance compared to room air temperature in terms of determining RH. For t_a = 19°C even 67% reduction of air flow (see case 1 and 3) has no effect on RH. Comparing cases 2, 5 and 8 it can be seen that at similar air flow increase of t_a by only 1°C reduces RH by 2% and by 5°C reduces RH by 6%.

Table 6.2 Selected results from indoor conditions simulations for winter cases – air flow, temperature, relative humidity.

No.	CO_2 after 2h [ppm]	Min. air flow per person [l/s pers]	Min. total air flow [l/s]	t_a [°C]	t_{supply} [°C]	Actual air flow per pers. [l/s pers]	Actual air flow [l/s]	RH after 2h [%]
Winter cases								
1.	996.0	7.9	132.85	19	16	8.77	145.88	25
2.	1495.3	4.0	74.35	19	14	4.88	87.53	25
3.	2928.3	0.9	27.85	19	10	2.29	48.63	25
5.	1495.3	4.0	74.35	20	15	4.74	85.52	23
8.	1495.3	4.0	74.35	24	19	4.21	77.46	19

The results show that in none case preferable RH of minimum 40% can be obtained in winter without additional means of humidification. The best outcome can be observed in case 3 – relative humidity is the biggest and air flow, thanks to low supply air temperature of 10°C, is low as well. Taking this setup further to technical solution choice, some consequences for ventilation systems design can be considered. In FTX system it could be possible to remove heating battery and depend only on heat recovery. This in turn would reduce energy use for fans, distract heating demand and materials use for the component itself. In hybrid system removal of heating coil may be possible (with same benefits for environmental impact) if it had capability to preheat the air underground up to 10°C.

If, on the other hand, healthy environment was defined as not only sufficiently humid, but also characterized by low concentration of CO_2, indicating low content of other possible pollutants in the air, result would be the best in case 1. Such a set of requirements would put more demands on technical systems. In FTX providing supply air temperature of 16°C would require intensified heat recovery, especially at relatively low room temperature, which would increase power use. In hybrid such a supply air temperature is unlikely to achieve without a heating coil. In both systems increased air flow would require more fan power.

In Table 6.3 below selected simulation results for summer case are presented. It can be seen that for most of the examined requirements sets relative humidity lies within desired range. Same as in winter case, indoor air temperature is the most determinant for RH – from cases 10A, 13A and 16A it can be seen that its 3°C increase result in around 10% decrease of relative humidity. On the contrary to winter case, since the air flow is generally higher as it must handle massive internal heat gains, in none of cases there is a risk of significant IAQ decrease due to CO_2 or other compounds. With smallest actual air flow in case 17B, CO_2 after 2 hours would reach around 1300 ppm.

Table 6.3 Selected results from indoor conditions simulations for summer cases – air flow, temperature, relative humidity.

No.	CO_2 after 2h [ppm]	Min. air flow per person [l/s pers]	Min. total air flow [l/s]	t_a [°C]	t_{supply} [°C]	Actual air flow per pers. [l/s pers]	Actual air flow [l/s]	RH after 2h [%]
Summer cases								
10A.	996.0	7.9	132.85	20	19	98.26	1488.29	64
13A.	996.0	7.9	132.85	23	19	23.34	364.48	54
16A.	996.0	7.9	132.85	26	19	12.64	203.93	45
10B.	996.0	7.9	132.85	20	10	8.97	148.83	54
13B.	996.0	7.9	132.85	23	13	8.76	145.79	54
14B.	1495.3	4.0	74.35	23	10	6.52	112.15	46
16B.	996.0	7.9	132.85	26	16	8.56	142.75	45
17B.	1495.3	4.0	74.35	26	10	4.99	89.22	39

From health perspective cases 13A, 10B, 13B and 14B could be assessed as equally good – characterized by RH of 46-54% and indoor air temperature that should generally not result in overheating. But for each of them implications for technical solutions would be different.

Case 13A was calculated with assumption that the minimum supply air temperature is equal to outdoor air temperature. In such a case the obtained air flow is high, probably higher than would be allowed in real-life case. Such a high air exchange would result in very high fan power demand, ducts diameter would also have to be increased to prevent too high air velocity. In FTX system cooling coil would not be necessary. Considering implications for hybrid system has no point for such a setup – outdoor air would be, even if in minimal grade, cooled in the underground ducts. To reach 19°C it would have to be warmed up again, which would be absurd.

At this point it is also worth mentioning that the assumption of outdoor air temperature equal to 19°C can be discussed. On the hottest days, when heat gains are the highest, the outdoor air could be warmer than that. In this case, for FTX with no possibility of cooling, the preferred air flow, on the contrary to results obtained for cases 10A, 13A and 16A, would be as low as possible, as long as CO_2 requirement was met. In such a case indoor air temperature would rise rather quickly due to small thermal inertia (see Figure 6.1) and RH of at least 40% would only be kept until around 28°C. Predicting consequences for the hybrid system would require better knowledge about its precooling capability.

Cases 10B, 13B and 14B are similar. If FTX system was used to provide supply air temperature of 10 or 13°C, it would have to be equipped with cooling coil, which would increase pressure drops, required fan power and electricity demand. Neither hybrid system would be able to provide so low temperatures, but thanks to precooling in the ground power demand of cooling battery would be lower. Comparing cases 13B and 14B it can be seen that higher supply air temperature is associated with higher air flow. Assessing both setups effect on environmental impact would require comparison of fans and cooling coil's energy consumption.

6.3.2 Functional requirements for comfort

As can be deduced from Chapter 4, defining comfort is complicated. However, for the purpose of the following analysis it can be described with RH of 30% (due to sensory irritation) and, based on classical PPD thermal comfort model for adults with assumption of 0.15 m/s air velocity and 1.2 met activity, operative temperature around 22.5°C in winter and 26°C in summer.

Without additional means of de-/humidification in the examined room such a set of parameters would not be obtainable. Considering local conditions, sets of optimal operative temperature and RH pairs for users at different age and different activity level are presented in Table 6.4 below. Full results can be found in Table C.1 in Appendix C.

It must be understood that in some cases, due to very high activity level combined with thick clothing insulation, optimal temperatures obtained from the model go extremely low, even to minus values. It does not mean that the author suggests that such a temperature should be kept inside. It is rather a way to highlight that extreme cases cannot be used as a base for indoor environment design as well as that in these cases users cannot expect the environment to provide perfect thermal comfort.

Table 6.4 Indoor climate characteristics for minimal PPD for adults and children at low and high activity level.

Case	Indoor air temperature [°C`]	Relative humidity [%]	PMV / PPD [- / %]
Winter (v_a = 0.15 m/s, clo = 1.0)			
Adult 2.3 met	13	35	-0.03 / 5.0
Adult 1.2 met	23	19	0.03 / 5.0
Child 2.7 met	-5	100	0.01 / 5.0
Child 1.2 met	14	31	-0.02 / 5.0
Summer (v_a = 0.15 m/s, clo = 0.5)			
Adult 2.3 met	18	72	0.06 / 5.1
Adult 1.2 met	25	48	-0.07 / 5.1
Child 2.7 met	4	100	0.02 / 5.0
Child 1.2 met	19	67	0.06 / 5.1

When sets of parameters investigated earlier in order to obtain required air flow and supply air temperature due to CO_2 and heat gains were checked for PMV/PPD, only some of them (and only in some cases) provided PPD below 10%. They are presented in Table 6.5 below; full results can be found in Table C.3 in Appendix C.

Table 6.5 Selected results from indoor conditions simulations – conditions with PPD below 10%.

No.	t_o [°C]	RH [%]	PMV / PPD [- / %]			
			Adult		Child	
			2.3 met	1.2 met	2.7 met	1.2 met
Winter cases (v_a = 0.15 m/s, clo = 1.0)						
7.	24	18	1.33 / 41.7	0.25 / 6.3	>3.00 / 100.0	1.36 / 43.6
8.	24	19	1.33 / 41.9	0.25 / 6.3	>3.00 / 100.0	1.37 / 43.8
9.	24	22	1.35 / 42.7	0.27 / 6.6	>3.00 / 100.0	1.38 / 44.6
Summer cases (v_a = 0.15 m/s, clo = 0.5)						
10A.	20	64	0.40 / 8.4	-1.54 / 53.0	2.67 / 96.4	0.25 / 6.3
11A.	20	64	0.40 / 8.4	-1.54 / 53.0	2.67 / 96.4	0.25 / 6.3
12A.	20	64	0.40 / 8.4	-1.54 / 53.0	2.67 / 96.4	0.25 / 6.3
16A.	26	45	1.44 / 47.6	0.22 / 6.0	>3.00 / 100.0	1.43 / 46.9
17A.	26	45	1.44 / 47.6	0.22 / 6.0	>3.00 / 100.0	1.43 / 46.9
18A.	26	45	1.44 / 47.6	0.22 / 6.0	>3.00 / 100.0	1.43 / 46.9
10B.	20	54	0.36 / 7.7	-1.59 / 55.8	2.63 / 95.7	0.22 / 6.0
11B.	20	54	0.36 / 7.7	-1.59 / 55.8	2.63 / 95.7	0.22 / 6.0
12B.	20	54	0.36 / 7.7	-1.59 / 55.8	2.63 / 95.7	0.22 / 6.0
16B.	26	45	1.44 / 47.6	0.22 / 6.0	>3.00 / 100.0	1.43 / 46.9
17B.	26	39	1.41 / 45.8	0.17 / 5.6	>3.00 / 100.0	1.39 / 45.1
18B.	26	39	1.41 / 45.8	0.17 / 5.6	>3.00 / 100.0	1.39 / 45.1

It can be seen that in case of children model with activity level of 2.7 met, none conditions are even close to fulfilling the 10% PPD requirement given by some of current regulations. One explanation could be an error in the calculation model, which was built from scratch for this thesis based only on a description from a scientific paper. However, the original model was in fact developed based on empirical results from a study conducted in certain conditions – outside the heating season, with low activity level and assumption of rather light clothing insulation. Looking at the results in Table C.1 it can be seen that for such a case the results are quite reasonable, which may indicate that the model needs improvements to fit wider range of input conditions.

Comparing theoretical conditions with results of simulations it can be seen that, based on adults at low activity level, cases 9 for winter and 17B for summer are the closest to optimal. To discuss consequences of lack of cooling possibility, also case 16 A is considered. They are recalled in Table 6.6 below:

Table 6.6 The optimal conditions for adults at low activity level in winter and summer.

No.	CO_2 after 2h [ppm]	Min. air flow per person [l/s pers]	Min. total air flow [l/s]	t_a [°C]	t_{supply} [°C]	Actual air flow per pers. [l/s pers]	Actual air flow [l/s]	RH after 2h [%]
Winter case								
9.	2928.3	0.9	27.85	24	11	1.03	29.79	22
Summer cases								
16A.	996.0	7.9	132.85	26	19	12.64	203.93	45
17B.	1495.3	4.0	74.35	26	10	4.99	89.22	39

The temperature of 22.5°C in winter was not originally examined, but for 3000 ppm limit it would give results similar to case 9 – t_{supply} of 10°C, air flow of 1.19 l/s per person and RH of 22%.

Fulfilling the above requirements again would imply certain consequences for the technical solutions of ventilation.

In winter case FTX system would be expect to have great performance – big difference between indoor and supply air temperatures would support heat recovery and make heating battery unnecessary. Very low air flow, almost 7 times lower than required currently by regulations, would contribute to decreased fan power demand, small size of AHU and ducts. Hybrid system would get the same benefits as long as it would be able to maintain supply air temperature of 11°C by preheating, which as mentioned many times before, is questionable. RH resulting from this setup is slightly lower than recommended, thus adding humidifiers could be considered in both systems.

In summer case 17B, if conditions were to be maintained by FTX system, it would have to be equipped with a cooling battery. A hybrid system, if it was able to precool the air to such a low level, would not require comfort cooling and consequently its energy demand, pressure drops and resulting required fan power would be lower, that is however not very likely. Cooling in the system would probably be required, but in such a case, thanks to partial precooling, power of the cooling coil could be lower than in case of FTX. Summer case 16A can only be considered with FTX system – when supply air temperature was the same as outdoors, no extra components would be required, which would reduce energy consumption and pressure drops, but due to the need of handling heat gains the required air flow (and resulting fan power) is so high that it would overbalance possible savings.

As it was already discussed for health, this is only valid with the assumption of outdoor air temperature lower than desired room temperature. On extremely warm summer days described relations between air flows and supply air temperatures would change.

If comfort stood in focus of the design, comfort cooling should be considered in the system even if it would imply impaired energy performance. Without it, providing optimal room temperatures would require unreasonably high, not realistic air exchange rates, moreover it would only be possible if outdoor air temperature was at least slightly lower than the desired room temperature, which is not possible all year round. As it has been shown in the Figure 6.1, with realistic air flow of 13 l/s per person, even rather cool room gets warm fast. Under conditions of the simulation, for an adult threshold for comfort in summer is at 27.8°C, a temperature likely to occur in non-cooled room. Considering children's higher thermal sensation, conditions would become unacceptable for them much earlier. However, supply air temperature as low as 10°C, even if providing comfortable environment all over the room, may cause local discomfort, especially if users were dressed lightly. Therefore, in reality it is more likely to apply parameters as in case 16B – with t_{supply} of 16°C for the price of higher air flow.

Finally, it is worth to mention that there is no full certainty about what factors would be determinant for comfort in a given space. For the purpose of the above discussion it has been assumed that RH close to 30% is important, thus case 9 in winter has been assessed as best. In reality, ventilation rate and resulting concentration of bioeffluents may have bigger impact – in such situation case 7 would be optimal. However, air quality is not included in any quantitative comfort model, therefore analysis in this section focused mostly on thermal comfort.

6.3.3 Functional requirements for performance

Drawing again on the finding from Chapter 4, space supporting effective performance can be described by moderate temperature around 20°C and air exchange rate sufficient to remove pollutants impairing cognitive skills. As there are no specific limits for compounds other than CO_2 and also CO_2's concentration in blood can to some extent have separate influence on mental work, 1000 ppm value would be used as indicator of good ventilation. Based on this, optimal conditions for performance have been summarized in Table 6.7 below:

Table 6.7 The optimal conditions for efficient performance in winter and summer.

No.	CO_2 after 2h [ppm]	Min. air flow per person [l/s pers]	Min. total air flow [l/s]	t_a [°C]	t_{supply} [°C]	Actual air flow per pers. [l/s pers]	Actual air flow [l/s]	RH after 2h [%]
Winter case								
4.	996.0	7.9	132.85	20	17	8.55	142.53	23
Summer case								
10B.	996.0	7.9	132.85	20	10	8.97	148.83	54

Maintaining preferable conditions in winter would require FTX system with heating coil, as the difference between indoor and supply air temperature is small and supply air temperature is significantly higher than outdoors. Hybrid system would perform worse in this case, as its preheating capability would be much lower than heat recovery in FTX, so the additional heating coil would have higher power demand.

In the summer case FTX system would have to be equipped with a cooling battery. This applies most likely also to hybrid system, as it probably would not be able to lower temperature down to 10°C, but power demand for the comfort cooling would be lower than in FTX thanks to partial precooling in the underground ducts.

It is worth to notice that when performance is prioritized, air flows obtained for summer and winter case are almost the same, which would be beneficial for ventilation design, as it would simplify dimensioning.

6.3.4 Functional requirements for environmental impact

If focus was switched to environmental impact instead of a space's effect on users, the reverse way of thinking could be applied – it could be investigated how different measures to reduce the impact would affect fulfilment of functional requirements.

Decrease of the air flow would reduce the amount of CO_2e associated with required fan power. In winter it would also affect positively heating demand, either for system's components or complementing equipment in the room (radiators). In FTX system AHU's size and heat recovery unit's power demand would be smaller. In summer, on the other hand, decreased air flow would increase cooling demand. Reduced ventilation rate in winter may support indoor RH, but as it was shown in Section 6.3.1 it is of rather secondary meaning compared to room temperature. Looking from any other perspective, low air flow would be expected to impair IEQ due to high bioeffluents concentration, feeling of stagnant air and risk for uncontrolled temperature rise.

Another way to work towards low environmental impact is to remove components from ventilation system – lack of heating and cooling batteries, filters and humidifiers would result in significant decrease of total pressure drop, which in turn would allow for lower fan power. In addition, energy demand for components' operation would disappear as well as need for district heat supplied to the ventilation system. However, for IEQ such a move would cause risk of uncomfortable wide and uncontrolled indoor air temperature range both in summer and winter, as it would strongly depend on outdoor conditions and heat generation indoors. This could be to some extent counteracted by heat recovery and radiators, but in such case these components would have higher power and heating demand. Without humidifiers RH in winter would never be able to reach level 40% preferable from health's perspective. Lack of filters would result in increased level of particles concentration indoors, causing both health hazards and inconvenience, and high need for system's maintenance.

Alternatively, reduced CO_2e generation could be achieved by decreasing amount of materials used for the system. This would require ducts with small diameter and small size of the AHU. Decrease of ducts size without changing the air flow would result in higher pressure drop and increased fan power demand, but also in increased air velocity, which could cause inconvenience for users due to draught and high noise level. If on the other hand duct size reduction were made with assumption of constant pressure drop and decreased velocity, air flow would have to be reduced, which consequences have already been mentioned before.

Considering above-described relations, cases most beneficial for ventilation's environmental impact have been presented in Table 6.8 below:

Table 6.8 Cases most beneficial for environmental impact.

No.	CO_2 after 2h [ppm]	Min. air flow per person [l/s pers]	Min. total air flow [l/s]	t_a [°C]	t_{supply} [°C]	Actual air flow per pers. [l/s pers]	Actual air flow [l/s]	RH after 2h [%]
Winter case								
9.	2928.3	0.9	27.85	24	11	1.03	29.79	22
Summer cases								
16A.	996.0	7.9	132.85	26	19	12.64	203.93	45
16B.	996.0	7.9	132.85	26	16	8.56	142.75	45
17B.	1495.3	4.0	74.35	26	10	4.99	89.22	39

In summer a few cases have been marked out as choosing the optimal one would require calculation of the difference in CO_2e generation by decreasing the air flow while increasing cooling demand.

Comparing results from the table above with results from Sections 6.3.1-6.3.3 it can be seen that requirements for environmental impact show quite good correlation with these for comfort, but understood only as thermal comfort for adult users, calculated with classical PMV/PPD model.

7 Discussion

After analysing separately different aspects of indoor environment and making an attempt to combine them through environmental impact, it appears that they are like puzzle pieces that do not exactly fit together. Every time one factor is favoured, some of the remaining ones are not anymore handled in a best way. Therefore, a suspicion may arise that design of an indoor space is a question of optimization. However, in the following discussion alternative approach is applied – it is investigated what would it mean for different aspects if one of them was strictly prioritized regardless of all possible negative outcomes for a building as a whole.

When considering first only functional requirements for a space in terms of providing healthy, comfortable environment supporting efficient work or education, it can be seen that already these three basic aspects are in partial contradiction to each other. Admittedly, it is complex to clearly set boundaries for them – it is not likely that a user feeling sick will perform well even if theoretically surrounding is favourable, he or she will probably neither feel comfortable due to health symptoms. Good performance is not obtainable if users will experience inconveniences. It can also be discussed if a certain physiological response is just a threat to comfort or a health issue – for instance feeling of dryness in the nose may be only unpleasant unless it also indicates that RH already reached the level at which mucus's functions are impaired and the tipping point may be very difficult to define. Nevertheless, such a simplified distinction is carried out below.

Defining health as minimized risk for spreading of bacteria and viruses, asthma, allergies and respiratory diseases occurrence, if it was given priority in the indoor environment it would imply that the biggest focus would have to be put on relative humidity indoors. Keeping RH at level around 40-60% would guarantee decreased pathogens survival, mites and fungi occurrence and particles resuspension. However, to achieve it without additional humidification, in winter conditions indoor air temperature would have to be minimized below reasonable level. As it was showed in Section 6.3.1, with average absolute humidity wintertime, indoor air temperature of 11°C would have to be kept to result in RH of 40%. An additional measure could be to decrease the air flow, but simulation shows that it is not an efficient solution: if temperature was kept at 19°C, even air flow of 0.35 l/s per 1 m^2 without any addition for number of users would decrease RH from initial 40% to 34% within an hour. If initial RH was higher, the decrease would take longer (for example if starting RH was 50%, after 1 h with 0.35 l/s per 1 m^2 it would drop to 41%), but there is no reason to believe that any extra vapour generation will occur in the room; in fact, even the 40% initial RH assumption is quite optimistic. Nevertheless, a decreased air flow would have a positive effect on particles being raised from horizontal surfaces, which also supports health. For work performance such a setup would have ambiguous effect – on the one hand low temperature seems to support it, on the other hand small air exchange, leading to increased level of CO_2 and bioeffluents, impairs it. Comfort would be even more problematic as RH in the suggested range may make the air feel stuffy and low temperature could be unacceptable, especially for adult users. On the other hand, PPD for following conditions: operative temperature 19°C, air velocity 0.1 m/s, RH 40%, activity level 1.2 met and clothing insulation 1 clo is around 13%, only slightly above desired value. It could be easily reduced to 10% just by increasing clothing to 1.1 clo but a question arises if wearing such a thick layer of clothes would not decrease comfort understood as freedom of movement. It is worth to add that the same set of indoor environment parameters would be in theory almost perfect (PPD 5.1%) for children if clo value was reduced to 0.5. However, in practice the comfort may be again worsen by higher concentration of bioeffluents and perception of stuffy air, especially perceptible at low air velocity.

If a priority was on the opposite given to comfort, understood here mainly as thermal, preferred RH could be estimated to around 30% – a level at which sensory irritation in airways and eyes should not be problematic, static electricity issues would cause none or only slight inconvenience and the air should not yet feel stuffy as odours and material emissions would not be intensified. Ventilation rates should be kept high as it usually improves perception of air quality which is assessed as fresh. However, defining temperature limits becomes very complex. Using as a reference case classical PPD for adults and conditions of 30% RH, 0.15 m/s air velocity and 1.2 met activity, optimal operative temperature would be around 22.5°C in winter and 26°C in summer. But in practical terms it is more complicated as perception of thermal comfort is different for children and adults, for people with different clothing insulation level and in some cases it just differs between users without an obvious reason. Another issue it that RH of 30% may be hard to maintain both in summer and winter without additional means of de- and humidification, respectively, which can be seen in Table C.2.

A vital question is whose comfort should be prioritized in a preschool building and according to the author it should obviously be children's. They are main users of a space which most important purpose is to provide them with environment supporting their learning and development, both physical and mental, in the best possible way. Moreover, they outnumber adults significantly (144 to 26 in the case-study preschool), they have also much smaller adaptive abilities and tendency of not reporting perceived discomfort. This suggest that especially air temperature which perception is characterized by biggest divergence between kids and grown-ups should be designed with regard to the former. However, as results from Chapter 6 indicates, this should be done carefully, with reasonable assumptions and well-developed, reliable thermal comfort model. Even though children play a lot during a typical day at preschool, metabolic rates resulting from high activity level cannot be used for the design as they return extremely low temperature values; in addition, intense games do not last long and overheating due to them can be considered temporary.

An interesting observation is how big influence clothing insulation has on perceived thermal comfort. It is often forgotten as this parameter is not dependent on indoor space's designers, who focus more on temperature, humidity and air velocity. However, at the same environmental conditions but with different clothing, perception of comfort can vary drastically, from completely unacceptable to ideal. It indicates that this factor should be carefully considered already at the early stage of design and expected clothing routines should be examined in advance. Another idea is to keep users aware of clo value used when other parameters were defined. If parents of children attending a preschool were informed how they should dress them, risk of situation in which environment cannot be adjusted to biggest possible number of users would be minimized. It is even more important with thought about that adults in general have tendency of dressing children too thickly, which is pointless considering children's higher thermal sensation.

Putting the focus on comfort affects in turn performance and health aspects. While for performance the effect is partially favourable, as it benefits from high ventilation rates (but not from warm environment), for health defined as before it would be unfavourable due to low RH in winter – it can be seen for example in results section in winter case 7: it provides thermal comfort (PPD below 10%, but only for adults at low activity level) (see Table C.3) and keeps CO_2 below 1000 ppm but for a price of RH equal to 18%, much below minimum level defined for health – 40% (see Table C.2).

It could be cautiously questioned if there is any point prioritizing thermal comfort at all as it never really results in obtaining values which could be trusted as absolutely objective. Moreover, thermal comfort, being a mixture of numerous factors is sensitive to varying conditions and even if designed in the best way possible, it can be lost under operation phase. In addition, faulty thermal environment can relatively easily be compensated by users' adaptive behaviours. Perhaps a better approach would be to design with focus on more measurable aspects and then within remaining flexibility of shaping a space create best possible prerequisites for optimal thermal comfort.

It is worth noticing that term "comfort" does not necessarily have to mean only thermal comfort. It is a wide concept including aspects such as safety, satisfaction with acoustics, lighting, space's functionality etc., and some of them may be more or less indirectly connected to indoor climate design. For instance, adequate lights may generate increased heat gains leading to temperature rise and air flow may be limited by requirements on noise. For that reason, in real life case comfort should be analyzed in more comprehensive manner than for the purpose of this discussion.

Finally, when putting performance as priority, focus in indoor space design should lie on relatively low air temperature and high air flow, two factors which, as it was reasoned in Chapter 4, support concentration, memory and other cognitive functions. Such a setup is partially beneficial for both health and comfort – the former is supported by cool environment, the latter by efficient ventilation. It seems that concentrating on performance may have the biggest potential to balance different requirements, which is quite logical – effective work would not be possible if a person got distracted by discomfort or poor health. On the contrary, comfort and health (in slightly limited meaning) seem to be in opposition. A simplified idea about how fulfilling requirements for health, comfort and performance counterweigh each other can be seen more vividly in the Figure 7.1.

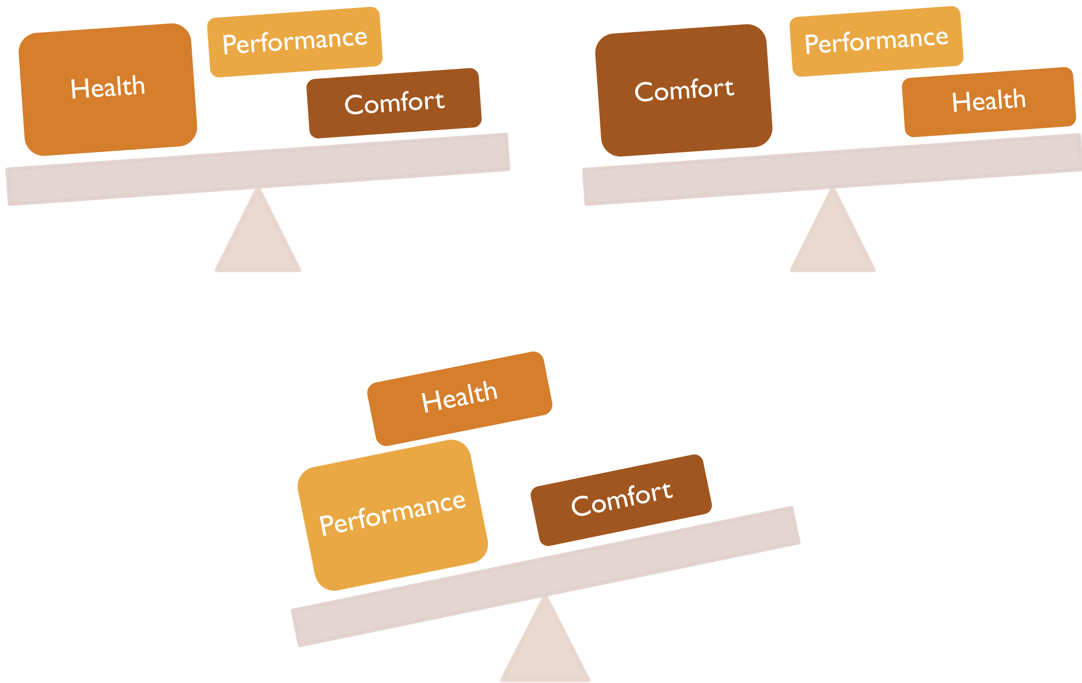


Figure 7.1 Weighing health, comfort and performance against each other.

One difficulty may be how to describe performance of a preschool pupil. Studies mentioned in Chapter 4 were all based either on office workers or on school children and test used to assess performance under various conditions were either complex problems to be solved or simple tasks resembling routine office/school work: basic calculations, proofreading etc. Activities at preschool are significantly different – even if some more organized forms of education are introduced, most of learning takes place through playing, which does not require same concentration on details and error-free results. One may therefore wonder if in case of young kids' performance would not be simply supported by providing healthy and comfortable environment, which unfortunately leads back to already stated contradiction.

If instead of prioritizing one of aspects, an attempt to optimize the environment was made, the following could be done: high ventilation rates supporting performance and comfort should be combined with moderate air temperature and additional humidification working mainly in winter. In summer comfort cooling should most likely be installed to prevent space from overheating. Air velocity should be utilized to increase the acceptable air temperature and prevent the sensation of stagnant, stuffy air. Cleaning routines should be carefully followed to avoid particles resuspension and perhaps installation of air purifiers should also be considered as even the best ventilation may not have a capability of removing all solid pollutants from the indoor air.

Combining the previously described relations between health, comfort and performance with an effect they have on technical solutions and the environmental impact of ventilation system is a second step in finding the balance.

Starting again with health – it was concluded that it mostly needs high humidity in range of 40-60%, supported by low air temperature and, in winter, low air flow. For the design of FTX system it would bring the following consequences:

- in winter – with efficient heat recovery a heating coil could be unnecessary, low flow will result in small required fan power, humidifier should be added;
- in summer – RH is not a problem unless indoor air is very warm and air flow very low; without comfort cooling, if outdoor air temperature was much higher than desired indoor air temperature, ventilation should be decreased to prevent hot air from entering the space, but temperature rise would still take place and at some point RH may fall below 40%; with comfort cooling on the other hand absolute vapour content in supply air would be lower and at high indoor air temperature RH may drop (see cases 17B, 18B in Table C.2); in practice however it is not likely to allow for high air temperature once comfort cooling is installed; summarizing, if health was a priority, it seems reasonable to keep either humidifier or cooling coil in the system as a safety measure;
- all the year – efficient filters to minimize the amount of dust and particles.

For the hybrid system on the other hand consequences are as follows:

- in winter – same as for FTX, small air flow would reduce fan power and low supply air temperature may eliminate the need of preheating, this however depends on underground ducts' heat exchange capability; humidifier should be added, which may require untypical solutions as hybrid system lacks central AHU;
- in summer – since the system can to some extent cool the outside air in the underground ducts perhaps comfort cooling would not be required, however it depends on heat exchange efficiency; if it is not sufficient same issues as described for FTX may occur, which indicates that humidification may be needed sometimes.

If bigger focus was put on comfort and performance, understood here mostly as high air exchange rates, it would imply the following for the ventilation:

- in winter, when internal heat gains are moderate, high air exchange rate would result in high supply air temperature, which in turn will require more work for heat recovery unit in FTX system and bigger efficiency of preheating in the hybrid one, and in worst case installation of a heating coil;
- in summer, if no comfort cooling is installed, flow does not affect supply air temperature as in any case the coolest available air will be used (see cases 10A-18A in Table C.2); however, this applies only if outdoor air temperature is lower than indoor, otherwise high air flow would result in excessive overheating (these outdoor conditions variations make choice of CAV system, recommended by TKA, highly questionable); if on the other hand comfort cooling (or precooling possibility) is considered, higher air flow allows for higher supply air temperature so energy demand for cooling coil or demand on hybrid system's efficiency is slightly reduced;
- in any case, high air flow will always result in increased fan power and required energy for operation.

One way to, in both systems, reduce energy use due to high required air flow without compromising IEQ, is to utilize possibility of supplying the air directly to users' breathing zone. It would require alternative inlet devices and ducts distribution, but if demands on air exchange were not applied to the whole space, total air flow and resulting fan power could be decreased.

If also thermal comfort, understood this time as providing optimal air temperature, is to be considered, it will be a bit difficult to predict exact consequences for ventilation system, since grasping the very idea of thermal comfort is already complex, as explained before. Nevertheless, thinking about thermal comfort's changeability, it seems reasonable to provide ventilation system with all components possible to assure ability to quick adjustment.

It is difficult to with full certainty state the advantage of one ventilation solution over the other. Hybrid ventilation is said to surpass classical FTX because of low air flow that is possible thanks to low supply air temperatures, which in both winter and summer should be obtainable without additional means only by heat exchange with the ground. An additional benefit is supposed to be low fan power demand thanks to lack of filters and other components. While removing filters from FTX is not a reasonable action as the AHU should be protected from dust, decreasing the air flow and supply air temperature seem like improvements that could be easily applied there, especially in winter when it would only require turning down the heat recovery unit. In general, if clear choice of functional requirements is at the root of the selection of ventilation system, it cannot be stated that any solution can have "better" air flow or supply air temperature – systems must provide same functions and their parameters must be chosen so that requirements are fulfilled. Only once this is secured, consequences for the construction of different systems can be discussed. Moreover, as indicated by the results in Table C.2, in winter cases supply air temperature significantly lower than this usually seen in practice is only occurring when air flow is so low that it would probably impair perceived IAQ because of increased concentration of bioeffluents. In addition, supply air temperature around 10-12°C may be discussed as too low, causing risk of discomfort due to cold downdraught or requiring alternative distribution patterns. Comparing data from ByDemand's project of ventilation for Hoppet and energy analysis for Grönskan, the designed air flow in the hybrid system was around 90% of maximum air flow in FTX, a difference which is rather small. It seems also a bit baseless to assume that hybrid system will be always able to condition the incoming air sufficiently as none results from actual measurements in Gothenburg-like climate were available at the time of writing this report. If components for air conditioning, such as heating/cooling coil or humidifier were to be mounted, FTX would have an obvious advantage because they will all easily fit in AHU. In case of hybrid system their location would be a problem – they could be installed either in the chamber in the basement, where they would have to handle a big volume of air, which could make it energy-inefficient, or in every individual supply duct, which would make the whole system complex from control perspective and would require more space and energy. Placing the components in the main underground supply ducts seems unfeasible with thought about maintenance. Alternatively, compensation for insufficient air conditioning would have to be provided by room components such as radiators or split air conditioners, but that would result in worse energy performance.

On the other hand, hybrid ventilation may have some less obvious advantages. For instance, as the underground culvert is constructed in concrete, under first years of operation it has a potential to decrease CO_2 concentration indoors thanks to carbonation of concrete. This effect may however be of small importance as CO_2's influence on health is questionable.

To be able to definitely assess which system works better in a given case, more thorough analysis than presented here would be necessary. It is not unlikely that under certain preferable conditions hybrid system without additional components would be able to provide optimal supply air temperatures allowing for minimizing the pressure drops and fan power. This would require, firstly, calculation of heat exchange capability, secondly, investigation of many more indoor-outdoor conditions combinations. In this thesis project simplified assumptions for both winter and summer case were made, such as estimation of constant average temperatures and absolute humidity levels, because main goal was to show effect on indoor air quality under typical operation. In practice ventilation is often designed with consideration of extreme conditions, which would change relations obtained in Chapter 6. Moreover, calculations were made assuming CAV system, which is in accordance with TKA, but reference case systems in Grönskan and Hoppet are both designed as VAV. In demand-controlled VAV system supply air temperature is constant and the air flow changes, in CAV – on the opposite. Presented results did not include any transient aspects and were carried out for steady-state conditions, neglecting also thermal mass of the building. Summarizing – assessing simultaneously two different systems working in two different operation modes, with numerous variables in terms of indoor and outdoor conditions is an approach too broad to give answers more specific than observations of trends on very general level. This can be pointed out as a source of possible errors.

One observation, independent of all above-mentioned uncertainties, is that the range of reasonable operative temperature indoors in relatively narrow compared to the range in which outdoor temperature can vary between seasons and times of day. Therefore, it feels that hybrid ventilation may perform better in climate characterized by rather constant and mild weather conditions. With currently ongoing climate change, resulting in more and more common heat waves and extreme weather phenomena it can be carefully forecast that the demand for air-conditioning solutions more efficient than natural regulation will rather increase than decrease.

Of course, two presented ventilation solutions are not the only ones possible. Perhaps a certain chosen indoor environment could be easier obtained with different type of hybrid system where mechanical installation is supported by airing through windows or different ways of using natural driving forces. Another option, although it is not likely to work well in a space characterized by big density of occupancy and high generation of bioeffluents, is waterborne cooling system. The general conclusion is that taking shortcuts is not recommended when designing indoor climate. A ventilation system should not be chosen in advance because it may lead to a situation when IEQ parameters are compromised to match systems most efficient operation mode. Design should happen in the opposite way - once the prioritized aspect in space is chosen, a variety of conditions and solutions should be examined in order to find the suitable ones.

Since the base for the whole project was a fossil-free preschool with intention of minimizing the environmental impact of construction, also this perspective should be considered as possible priority instead of any of aspects of indoor environment. In such case in ventilation system design process focus would lie on:

- decreasing air flow to minimize required fan power and AHU size;
- reducing number of components to decrease pressure drops;

- decreasing heating and cooling demand;
- maximizing heat recovery capability;
- benefitting from natural driving forces;
- decreasing length and diameter of ducts.

Results from previous work presented in Section 5.5.3 were obtained with a number of delimitations and while they work well as a simplified tool to compare possibilities of different modifications, they cannot be treated as full information about absolute amount of CO_2 released to atmosphere because of ventilation system in the case-study building. Just to mention two of them, aspects such as radiators power demand or concrete needed for construction of the culvert in hybrid solution were neglected. Moreover, different variations in the FTX system were mainly limited to one parameter without adjustment of the remaining ones, which makes them difficult to translate into real-life practice. CO_2e values were calculated for VAV system with fixed characteristics and for that reason using them to assess environmental impact of CAV system with variety of settings could only be done on general level, talking rather about trends, risks and possibilities.

In general, optimal system would be the one with minimum interference, as self-regulating as possible, as any additional components decrease environmental friendliness due to increase in energy demand and materials use. However, as discussed before, due to variety of outdoor conditions and complex relations between health, comfort and performance, simplifying a system as much as possible would probably result in impossibility of providing optimal IEQ. Less developed ventilation could be to some extent compensated with other methods, for instance increased (or reduced, depends on the case) thermal mass, shading, location, orientation, chosen building materials etc., but every of these means would imply some changes in total environmental impact, which should be always considered as a whole, using LCA tools.

Working towards decreased environmental impact of building industry, which nowadays is responsible for a big share in total CO_2 emissions is an important goal, especially looking at some of alarming signals that can be recently observed. In Gothenburg only between 2017 and 2018 amount of CO_2e generated in production of 1 kWh district heating increased with 22%. Just a few years ago global concentration of CO_2 in the air permanently exceeded 400 ppm. Counteracting these dangerous changes is of great interest. Nevertheless, it can be questioned if a preschool, addressed to users with quite specific needs and more than normally sensitive, should be a proving ground for this kind of innovative approach, especially considering limited time frame for the design stage.

Finally, going back to the starting point – legal regulations for indoor climate and ventilation, it can be seen that in current shape they do not really support smart design practice.

In Section 4.7 it was already discussed how current law attempts to ensure good indoor environment and conclusion was not optimistic – limit values for temperature are not related to users' age or expected behaviour, not fully trustworthy PPD is used as indicator, air velocity is limited instead of being benefitted from and ventilation rates are unrelated to actual levels of CO_2 or other, more relevant for health and comfort, chemical compounds. This way of expressing functional requirements releases designers from responsibility for thorough analysis of local, case-specific conditions. The suggested solution of this issue was to let the requirements be more generic and focus on follow-up control of building performance in operation phase.

An interesting observation is that in R1 guidelines, which are not technically seen a legal regulation and thus do not need to be followed unless directly referred to in project specification, more detailed information about air quality can be found. Air quality classes are referring to factors such as for instance expected percentage of users dissatisfied due to mucous membranes irritation and they define limits for concentration of different pollutants and bacteria. Considering findings of this project, perhaps these guidelines should be returned to and used as starting point for the discussion about update of applying regulations.

In terms of environmental impact, Section 3.2 proves that so far no detailed limits, expressed in measurable indicators, are set. There are naturally some single requirements that need to be fulfilled, such as SFP or building's total primary energy consumption, but the scale of information they give is almost negligible compared to desired knowledge about building's total environmental impact during its whole life span. Developing limits for, for instance, CO_2e emissions per area unit of a building would be a great help in environmentally-friendly design but considering the number of variables describing every individual project it would be extremely complicated to do and consequently could result in creation of law that would not enough match reality.

A part of this project's aim was to investigate if functional requirements for indoor climate can in some way be translated directly to decrease of environmental impact. However, with suggested generalization of regulations regarding air quality and ventilation, the best way to secure environment's interest seems to be to introduce separate set of documents regulating this aspect, for example through demand on specific building materials or energy sources.

7.1 Model for final evaluation

Ideally, this thesis project would be able to give a base for development of universal model for design of indoor climate in preschool buildings. Unfortunately, due to variety of circumstances and approaches, guidelines can be only very general:

1. Define clearly the prioritized aspect of a building/space (healthy, comfortable, supporting efficiency, environmentally friendly, fossil-free?).
2. Define indoor environment's characteristics necessary to fulfil requirements for a given prioritized aspect (RH, air quality, etc.).
3. Consider building's specific prerequisites (analyse users' routines, site characteristics, climate, etc.).
4. Choose ventilation system most suitable to maintain prioritized indoor environment's parameters.
5. Adjust the system's design so that fulfilment of requirements for remaining non-prioritized aspects is optimized and in accordance with legal regulations.

7.2 Further studies

The findings from this thesis project bring to mind several fields in which further studies should be conducted.

First of all, it would be very beneficial for the future design of indoor environment if individual impact of different chemical compounds and bioeffluents on users was investigated and quantified. Currently there are some limits for several pollutants but in practice IAQ is almost always assessed only by CO_2 level indicating efficiency of air exchange. Since it is not even fully agreed upon in scientific world if carbon dioxide itself causes any damage or not, using its concentration as design parameter may lead to missing harmful impact of other compounds. Obviously, aiming in design for very low CO_2 levels would most likely ensure relatively good air quality since the flow would have to be high, but at the same time the risk of too low RH and overdimensioned ventilation would occur. Having knowledge about exact influence of different pollutants and being able to identify their source in a building would allow for more optimized ventilation, perhaps applying local solutions instead of increasing the total flow.

Another aspect that would be interesting to investigate is a potential of hybrid ventilation with preheating in the ground. Such a system should undergo thorough measurements in climate conditions matching Gothenburg in all seasons so that its possibility of gaining heat or cold could be quantified. A separate optimization question is finding a relation between underground ducts' length, diameter and number, heat exchange capability and environmental impact of required materials. Moreover, a study similar to Feldt's and Nilsson's (2018) but concerning hybrid solution could be carried out to identify possible improvements for the system, adjusted to its decentralized structure.

Third field recommended to examine is thermal comfort model for children. The model adapted for calculation in Chapter 6 has been developed under summer conditions and for low activity level. It seems to work fine with similar assumptions but values given by it for winter case are not realistic. Moreover, research on children's metabolic rate at different activity levels could be conducted simultaneously to obtain plausible values. One more idea is to look into differences between various age groups of children – currently working on development of models for school kids instead of adults is being considered innovative, but a further distinction is needed. The term "school kids" may comprise young people aged between around 7 and 18 years, whose physiology differs significantly, especially that it is under childhood when human body undergoes most extensive and fast changes. In addition, also methodology aiming for indoor climate assessment for the youngest kids should be developed since, as it was discussed briefly in Section 4.6, they may not be able to understand what aspects they are exactly asked to give their opinion on. Perhaps in their case it would be recommended to rather measure physiological response than collect any, even most simplified, questionnaires, but on the other hand it may be controversial to conduct any tests on such young subjects.

8 Conclusions

- Current legal regulations for indoor space in a preschool are strict, not well grounded and prevent designers from including case-specific conditions. Functional requirements are expressed in indicators which reliability can be questioned. Environmental impact is treated rather vaguely in law, which allows for free interpretations.
- Health in indoor space is supported mostly by RH within range 40-60%, moderate air temperature around 20°C, performance – by moderate air temperature and high ventilation rate, which currently, due to lack of better indicators, can be associated with CO_2 level below 1000 ppm. Thermal comfort is a complex issue, varying significantly between different age groups and individuals, vulnerable to changing conditions, which makes it questionable if it should be used as a primary design criterion.
- Functional requirements for health and comfort are the most contradictory, while these for work performance support partially others aspects as well. Thus, if compromise between these three were searched, design for work performance seems to be a good starting point.
- When designing an indoor space, generally the order "functional requirements – ventilation design parameters – ventilation technical solutions – environmental impact" should be followed. A ventilation system should not be chosen in advance but once the prioritized aspect in space has been defined along with suitable functional requirements and a variety of conditions and solutions has been examined.
- If focus in a given project is put strictly on environmental impact, the opposite reasoning may be applied – a system best in fulfilling demands for ventilation within limitations set by for instance energy or materials use can be chosen and in next step the effect on functional requirements should be checked. They may be compromised to some extent, however without significantly impairing the space's functionality.

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Appendices

Appendix A: Local discomfort criteria

Draught

Air velocities in range 0-0.2 m/s are usually considered as imperceptible. Above these values air movement can cause discomfort due to draught. The percentage of people complaining about draught is expressed in draught rate, DR [%] and can be calculated from the equation given by ISO 7730:

$$DR = \left(34 - t_{a,l}\right)\left(\bar{v}_{a,l} - 0.05\right)^{0.62}\left(0.37 \cdot \bar{v}_{a,l} \cdot T_u + 3.14\right) \tag{A.1}$$

where:

- $t_{a,l}$ – local air temperature [°C] - model applies when between 20 and 26°C;
- $\bar{v}_{a,l}$ – local mean air velocity $\left[\frac{m}{s}\right]$ - min. 0.05 m/s;
- T_u – local turbulence intensity [%] - when unknown, 40% may be used.

However, this calculation model is quite limited as it applies mostly to people at light sedentary work with nearly neutral thermal sensation and expected to experience air movement at the level of the neck (the effect is not as strong at the level of hands or feet as there is not so many heat sensors in skin there).

As it was already mentioned in Section 4.1.1.4, increased air velocity can under appropriate conditions beneficially counteract increased operative temperature. It highlights that draught rate should be used as a support rather than a determinant while assessing local discomfort and considered together with other factors.

Vertical air temperature difference

A temperature difference between head level and ankles level can be a cause of discomfort, mainly when the temperature increases upwards. ISO 7730 gives a formula to calculate percentage dissatisfied, which applies to differences up to 8°C:

$$PD = \frac{100}{1+exp\left(5.76-0.856 \cdot \Delta t_{a,v}\right)} \tag{A.2}$$

where:

- $\Delta t_{a,v}$ – vertical air temperature difference between head and feet [°C].

Similarly as in case of discomfort caused by draught, this indicator should mostly be applied to lightly clothed persons engaged in near sedentary physical activity. With better insulation and more intensive activities the risk of experiencing local discomfort is low (ASHRAE, 2004).

Warm and cool floors

Both too high and too low temperature of floor surface can cause discomfort. ISO 7730 gives a following formula to predict percentage dissatisfied:

$$PD = 100 - 94 \cdot exp\left(-1.387 + 0.118 \cdot t_f - 0.0025 \cdot t_f^2\right) \quad \text{(A.3)}$$

where:

- t_f – floor temperature [°C].

This model applies only to users wearing light shoes and it is not suitable to either barefoot occupants or persons sitting on the floor (ASHRAE, 2004). It also cannot be used for spaces with underfloor heating.

Radiant asymmetry

The last indicator for local thermal discomfort is radiant asymmetry. It describes the situation where thermal radiation field over a body is nonuniform (ASHRAE, 2004). Analogically to vertical temperature difference, this effect is the strongest with temperature increasing upwards – therefore radiant asymmetry resulting in warm ceiling is much more disturbing than for instance warm wall. For that reason, every direction of asymmetry is described with separate equation in ISO 7730:

Warm ceiling:

$$PD = \frac{100}{1+exp\left(2.84-0.174 \cdot \Delta t_{pr}\right)} - 5.5;\ \Delta t_{pr} < 23°C \quad \text{(A.4)}$$

Cool wall:

$$PD = \frac{100}{1+exp\left(2.84-0.174 \cdot \Delta t_{pr}\right)};\ \Delta t_{pr} < 15°C \quad \text{(A.5)}$$

Cool ceiling:

$$PD = \frac{100}{1+exp\left(2.84-0.174 \cdot \Delta t_{pr}\right)};\ \Delta t_{pr} < 15°C \quad \text{(A.6)}$$

Warm wall:

$$PD = \frac{100}{1+exp\left(3.72-0.052 \cdot \Delta t_{pr}\right)} - 3.5;\ \Delta t_{pr} < 35°C \quad \text{(A.7)}$$

where:

- Δt_{pr} – radiant temperature asymmetry [°C].

The relation between radiant temperature asymmetry and PD for every direction is pictured by the Figure 4.1 below:

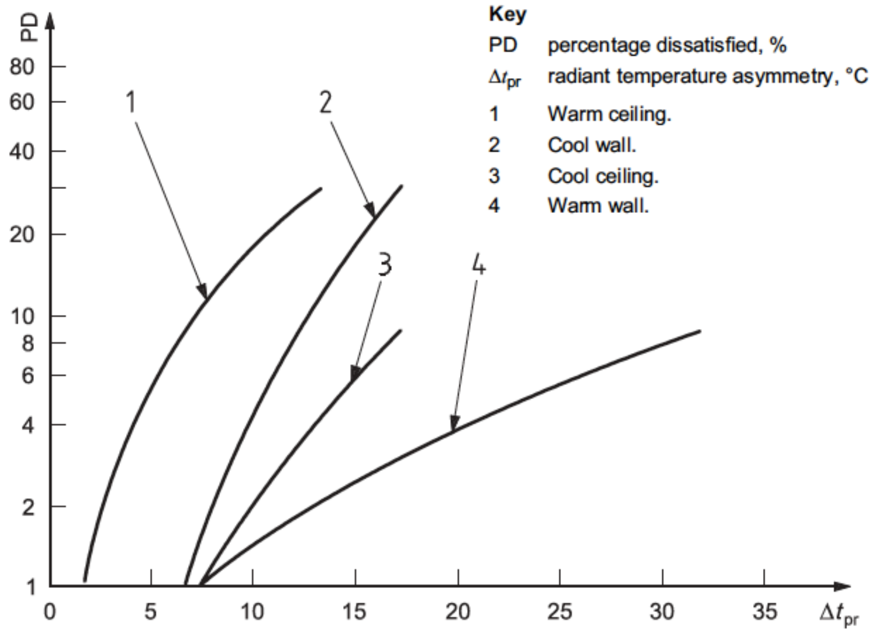


Figure A.1 Local thermal discomfort caused by radiant asymmetry for different surfaces (SIS, 2006).

Appendix B: Equations used for modelling the indoor climate

CO$_2$ concentration:

CO$_2$ concentration was calculated based on mass balance model, according to the equation (B.1) below:

$$C(\tau) = C_0 \cdot exp\left(-\tau \cdot \frac{V}{V_r}\right) + \left(\frac{m \cdot 10^6}{V} + C_S\right) \cdot \left(1 - exp\left(-\tau \cdot \frac{V}{V_r}\right)\right) \tag{B.1}$$

where:

- τ – time $[h]$;
- C_0 – concentration when the source of contaminant (CO$_2$) is introduced $[ppm]$;
- V – air flow $\left[\frac{m^3}{h}\right]$;
- V_r – room volume $[m^3]$;
- m – rate of generation of contaminant (CO$_2$) $\left[\frac{m^3}{h}\right]$;
- C_S – concentration of contaminant (CO$_2$) in the supplied air $[ppm]$.

Required supply air temperature:

Supply air temperature required to remove heat gains at a given air flow was calculated based on equation (B.2) below:

$$Q = V \cdot \rho_a \cdot c_{pa} \cdot \Delta t \tag{B.2}$$

where:

- Q – internal heat gains $[W]$;
- V – air flow $\left[\frac{l}{s}\right]$;
- ρ_a – density of the air $\left[\frac{kg}{m^3}\right]$;
- c_{pa} – specific heat capacity of the air $\left[\frac{J}{kg \cdot K}\right]$;
- Δt – difference between indoor air temperature and supply air temperature $[K]$.

Absolute humidity:

Absolute humidity was similarly to CO$_2$ concentration calculated based on mass balance model:

$$v(\tau) = v_0 \cdot exp\left(-\tau \cdot \frac{V}{V_r}\right) + \left(\frac{m \cdot 10^6}{V} + v_S\right) \cdot \left(1 - exp\left(-\tau \cdot \frac{V}{V_r}\right)\right) \tag{B.3}$$

where:

- τ – time $[h]$;
- v_0 – vapour content when the source of moisture is introduced $\left[\frac{g}{m^3}\right]$;

- V – air flow $\left[\frac{m^3}{h}\right]$;
- V_r – room volume $[m^3]$;
- m – rate of generation of moisture $\left[\frac{m^3}{h}\right]$;
- v_S – vapour content in the supplied air $\left[\frac{g}{m^3}\right]$.

Appendix C: Full results of the indoor climate simulations

Table C.1 Indoor climate characteristics for sufficient PMV/PPD.

Case	Indoor air temperature [°C`]	Relative humidity [%]	PMV / PPD [- / %]
Winter (v_a = 0.15 m/s, clo = 1.0)			
Adult 2.3 met – minimum	10	43	-0.39 / 8.1
Adult 2.3 met – optimal	13	35	-0.03 / 5.0
Adult 2.3 met – maximum	17	28	0.49 / 9.5
Adult 1.2 met – minimum	21	22	-0.38 / 8.0
Adult 1.2 met – optimal	23	19	0.03 / 5.0
Adult 1.2 met – maximum	25	17	0.45 / 9.3
Child 2.7 met – minimum	-9	100	-0.46 / 9.5
Child 2.7 met – optimal	-5	100	0.01 / 5.0
Child 2.7 met – maximum	-1	88	0.47 / 9.6
Child 1.2 met – minimum	11	40	-0.43 / 8.9
Child 1.2 met – optimal	14	31	-0.02 / 5.0
Child 1.2 met – maximum	17	28	0.39 / 8.2
Summer (v_a = 0.15 m/s, clo = 0.5)			
Adult 2.3 met – minimum	15	86	-0.45 / 9.2
Adult 2.3 met – optimal	18	72	0.06 / 5.1
Adult 2.3 met – maximum	20	64	0.40 / 8.3
Adult 1.2 met – minimum	24	51	-0.37 / 7.9
Adult 1.2 met – optimal	25	48	-0.07 / 5.1
Adult 1.2 met – maximum	26	45	0.22 / 6.0
Child 2.7 met – minimum	2	100	-0.32 / 7.1
Child 2.7 met – optimal	4	100	0.02 / 5.0
Child 2.7 met – maximum	6	100	0.35 / 7.6
Child 1.2 met – minimum	17	76	-0.32 / 7.2
Child 1.2 met – optimal	19	67	0.06 / 5.1
Child 1.2 met – maximum	21	60	0.45 / 9.2

Table C.2 The results from indoor conditions simulations in a typical preschool class – air flow, temperature, relative humidity.

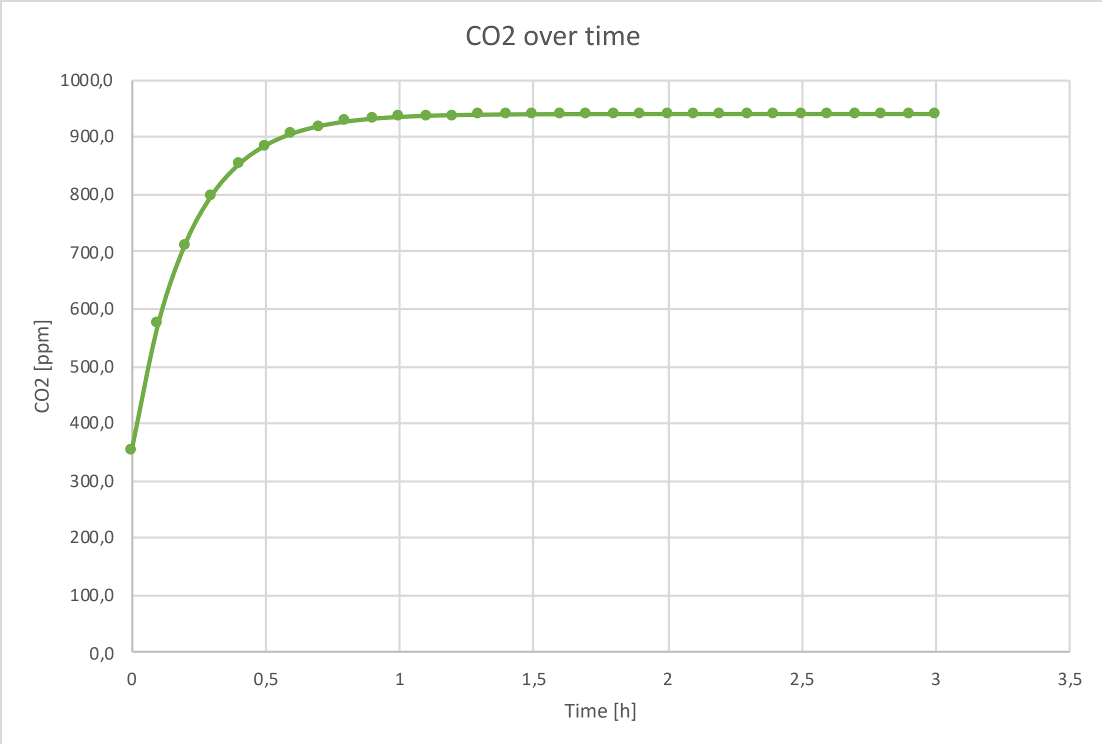
No.	CO_2 after 2h [ppm]	Min. air flow per person [l/s pers]	Min. total air flow [l/s]	t_a [°C]	t_{supply} [°C]	Actual air flow per pers. [l/s pers]	Actual air flow [l/s]	RH after 2h [%]
Winter cases								
1.	996.0	7.9	132.85	19	16	8.77	145.88	25
2.	1495.3	4.0	74.35	19	14	4.88	87.53	25
3.	2928.3	0.9	27.85	19	10	2.29	48.63	25
4.	996.0	7.9	132.85	20	17	8.55	142.53	23
5.	1495.3	4.0	74.35	20	15	4.74	85.52	23
6.	2928.3	0.9	27.85	20	10	1.89	42.76	24
7.	996.0	7.9	132.85	24	22	11.95	193.65	18
8.	1495.3	4.0	74.35	24	19	4.21	77.46	19
9.	2928.3	0.9	27.85	24	11	1.03	29.79	22
Summer cases								
10A.	996.0	7.9	132.85	20	19	98.26	1488.29	64
11A.	1495.3	4.0	74.35	20	19	98.26	1488.29	64
12A.	2928.3	0.9	27.85	20	19	98.26	1488.29	64
13A.	996.0	7.9	132.85	23	19	23.34	364.48	54
14A.	1495.3	4.0	74.35	23	19	23.34	364.48	54
15A.	2928.3	0.9	27.85	23	19	23.34	364.48	54
16A.	996.0	7.9	132.85	26	19	12.64	203.93	45
17A.	1495.3	4.0	74.35	26	19	12.64	203.93	45
18A.	2928.3	0.9	27.85	26	19	12.64	203.93	45
10B.	996.0	7.9	132.85	20	10	8.97	148.83	54
11B.	1495.3	4.0	74.35	20	10	8.97	148.83	54
12B.	2928.3	0.9	27.85	20	10	8.97	148.83	54
13B.	996.0	7.9	132.85	23	13	8.76	145.79	54
14B.	1495.3	4.0	74.35	23	10	6.52	112.15	46
15B.	2928.3	0.9	27.85	23	10	6.52	112.15	46
16B.	996.0	7.9	132.85	26	16	8.56	142.75	45
17B.	1495.3	4.0	74.35	26	10	4.99	89.22	39
18B.	2928.3	0.9	27.85	26	10	4.99	89.22	39

Table C.3 The results from indoor conditions simulations in a typical preschool class – PMV and PPD.

No.	t_o [°C]	RH [%]	PMV / PPD [- / %]			
			Adult		Child	
			2.3 met	1.2 met	2.7 met	1.2 met
Winter cases (v_a = 0.15 m/s, clo = 1.0)						
1.	19	25	0.71 / 15.6	-0.79 / 18.3	2.77 / 97.5	0.67 / 14.3
2.	19	25	0.71 / 15.6	-0.79 / 18.3	2.77 / 97.5	0.67 / 14.3
3.	19	25	0.71 / 15.6	-0.79 / 18.3	2.77 / 97.5	0.67 / 14.3
4.	20	23	0.83 / 19.6	-0.59 / 12.3	2.88 / 98.5	0.80 / 18.6
5.	20	23	0.83 / 19.6	-0.59 / 12.3	2.88 / 98.5	0.80 / 18.6
6.	20	24	0.84 / 19.7	-0.59 / 12.2	2.89 / 98.5	0.81 / 18.8
7.	24	18	1.33 / 41.7	0.25 / 6.3	>3.00 / 100.0	1.36 / 43.6
8.	24	19	1.33 / 41.9	0.25 / 6.3	>3.00 / 100.0	1.37 / 43.8
9.	24	22	1.35 / 42.7	0.27 / 6.6	>3.00 / 100.0	1.38 / 44.6
Summer cases (v_a = 0.15 m/s, clo = 0.5)						
10A.	20	64	0.40 / 8.4	-1.54 / 53.0	2.67 / 96.4	0.25 / 6.3
11A.	20	64	0.40 / 8.4	-1.54 / 53.0	2.67 / 96.4	0.25 / 6.3
12A.	20	64	0.40 / 8.4	-1.54 / 53.0	2.67 / 96.4	0.25 / 6.3
13A.	23	54	0.92 / 22.9	-0.66 / 14.2	>3.00 / 100.0	0.84 / 19.9
14A.	23	54	0.92 / 22.9	-0.66 / 14.2	>3.00 / 100.0	0.84 / 19.9
15A.	23	54	0.92 / 22.9	-0.66 / 14.2	>3.00 / 100.0	0.84 / 19.9
16A.	26	45	1.44 / 47.6	0.22 / 6.0	>3.00 / 100.0	1.43 / 46.9
17A.	26	45	1.44 / 47.6	0.22 / 6.0	>3.00 / 100.0	1.43 / 46.9
18A.	26	45	1.44 / 47.6	0.22 / 6.0	>3.00 / 100.0	1.43 / 46.9
10B.	20	54	0.36 / 7.7	-1.59 / 55.8	2.63 / 95.7	0.22 / 6.0
11B.	20	54	0.36 / 7.7	-1.59 / 55.8	2.63 / 95.7	0.22 / 6.0
12B.	20	54	0.36 / 7.7	-1.59 / 55.8	2.63 / 95.7	0.22 / 6.0
13B.	23	54	0.92 / 22.9	-0.66 / 14.2	>3.00 / 100.0	0.84 / 19.9
14B.	23	46	0.88 / 21.5	-0.71 / 15.7	>3.00 / 100.0	0.80 / 18.6
15B.	23	46	0.88 / 21.5	-0.71 / 15.7	>3.00 / 100.0	0.80 / 18.6
16B.	26	45	1.44 / 47.6	0.22 / 6.0	>3.00 / 100.0	1.43 / 46.9
17B.	26	39	1.41 / 45.8	0.17 / 5.6	>3.00 / 100.0	1.39 / 45.1
18B.	26	39	1.41 / 45.8	0.17 / 5.6	>3.00 / 100.0	1.39 / 45.1

Appendix D: CO_2 concentration and RH change in the studied room for different functional requirements sets

<u>Winter cases:</u>



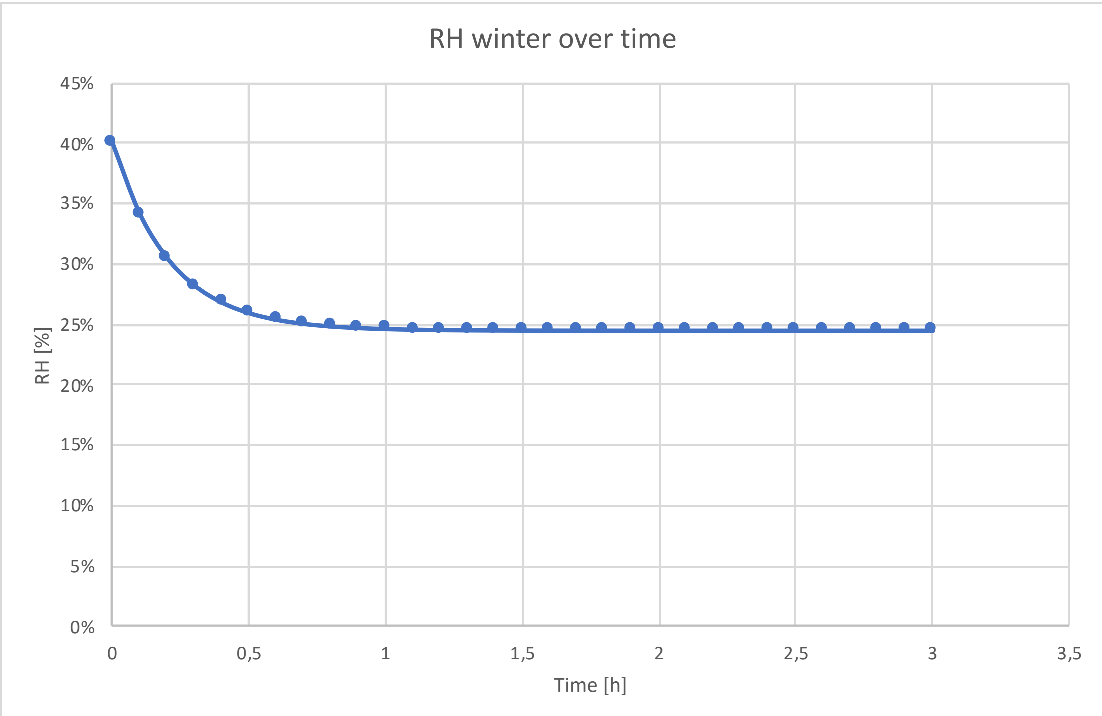


Figure D.1 CO_2 concentration and RH change over time in winter case 1.

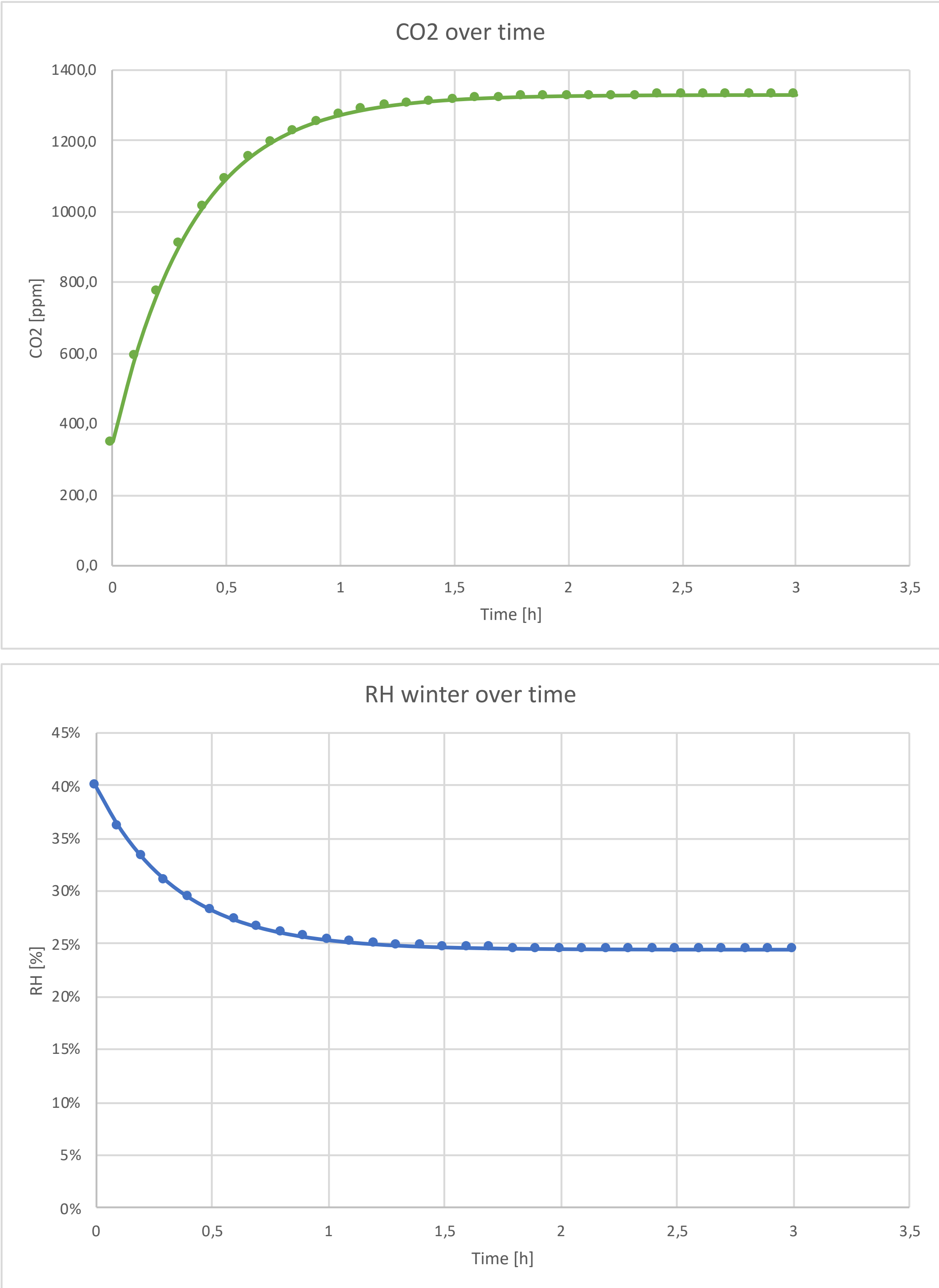
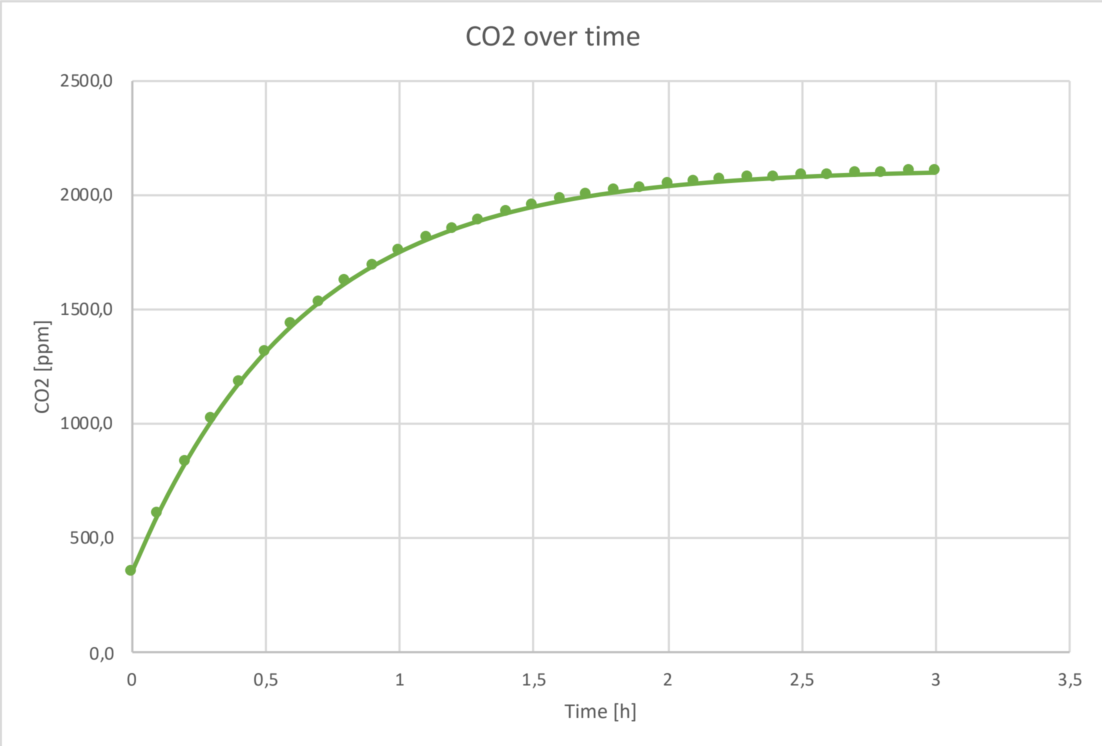


Figure D.2 CO_2 concentration and RH change over time in winter case 2.



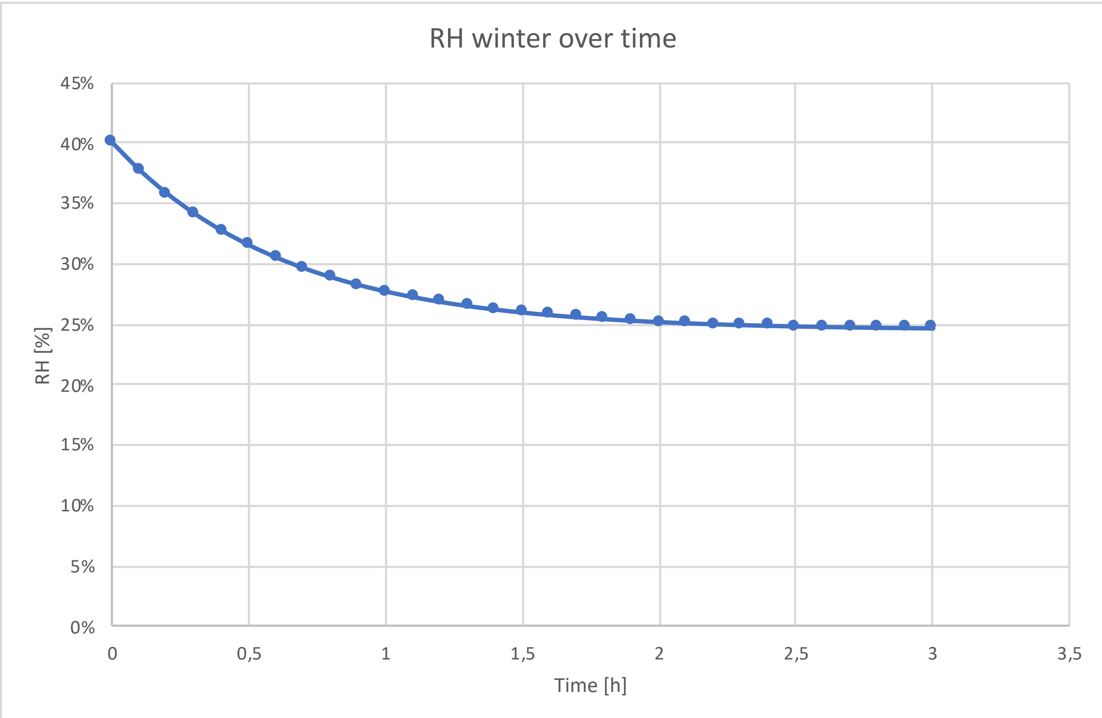


Figure D.3 CO_2 concentration and RH change over time in winter case 3.

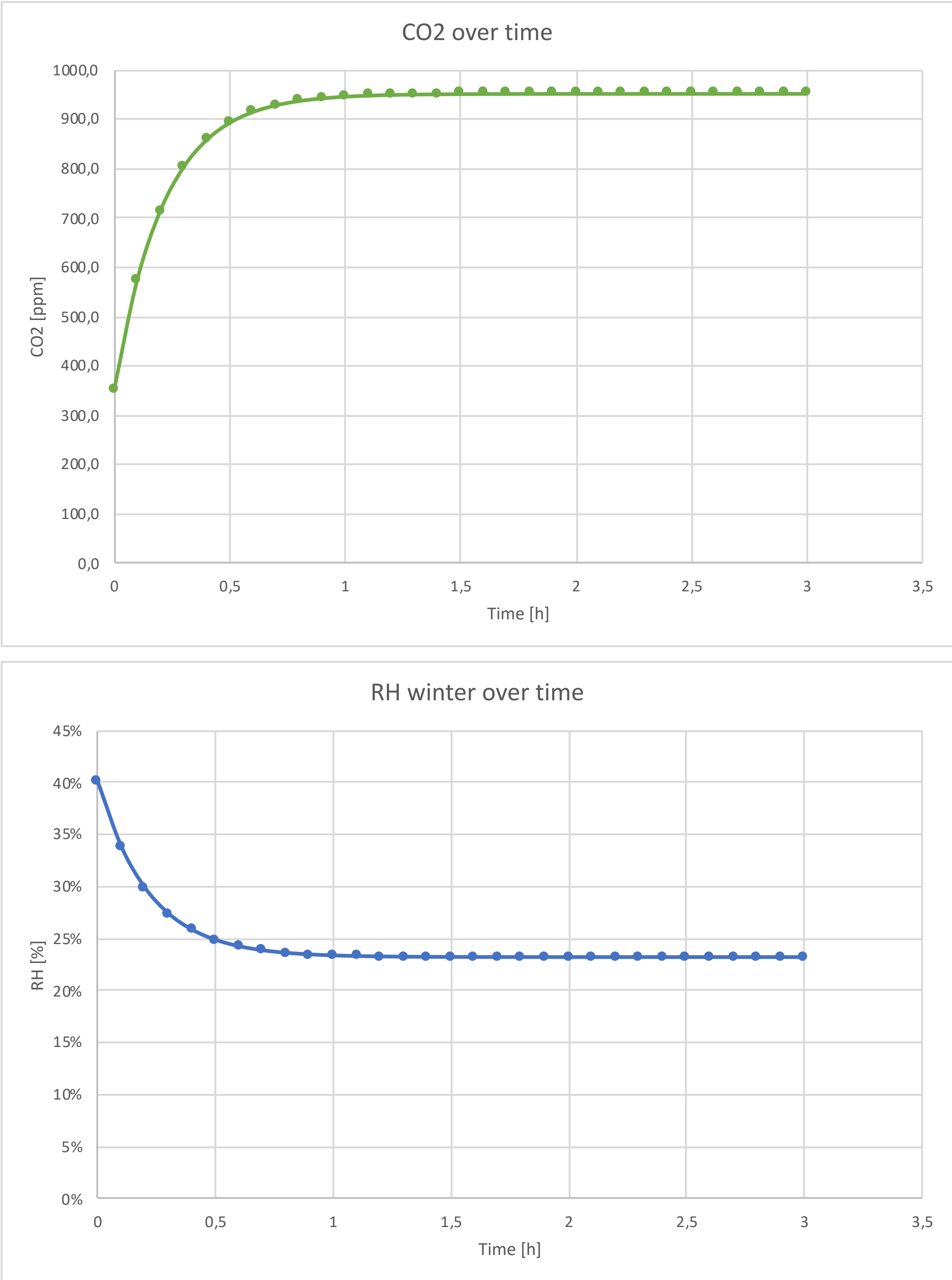


Figure D.4 CO_2 concentration and RH change over time in winter case 4.

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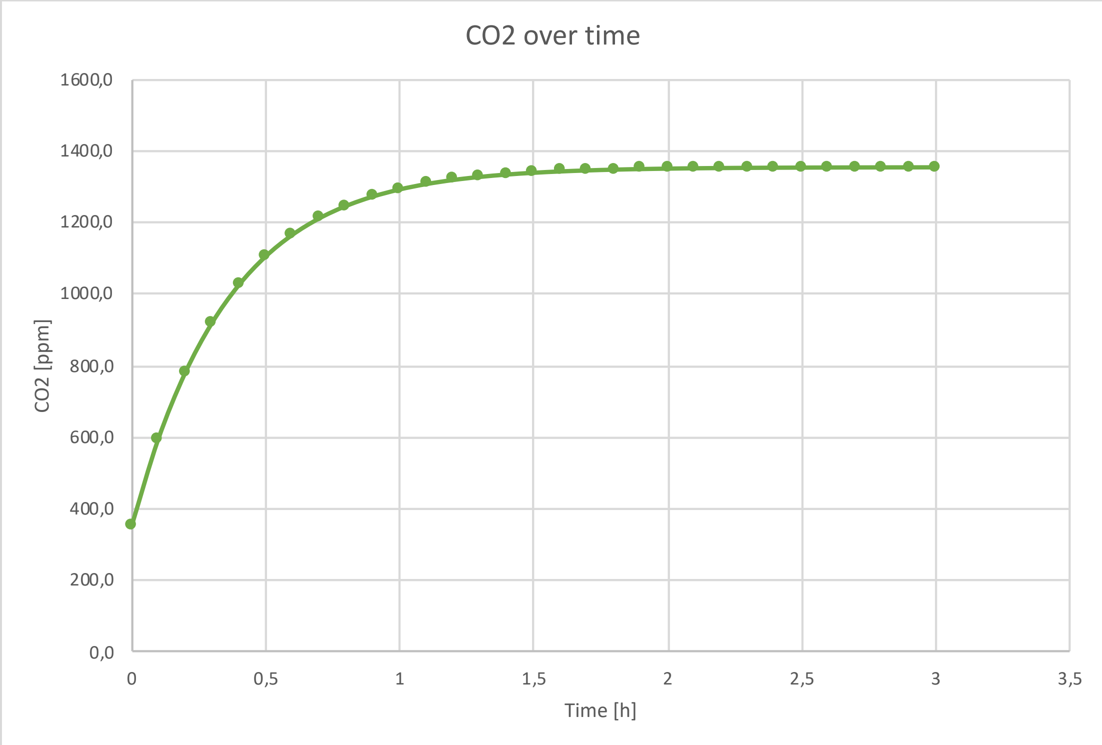


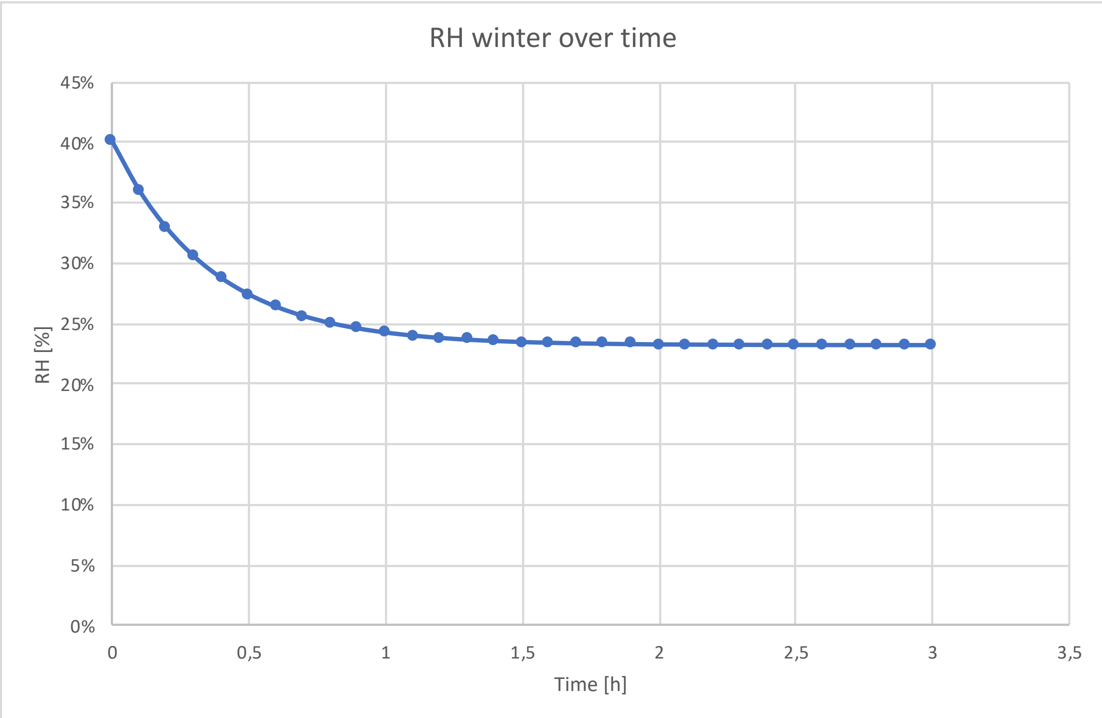
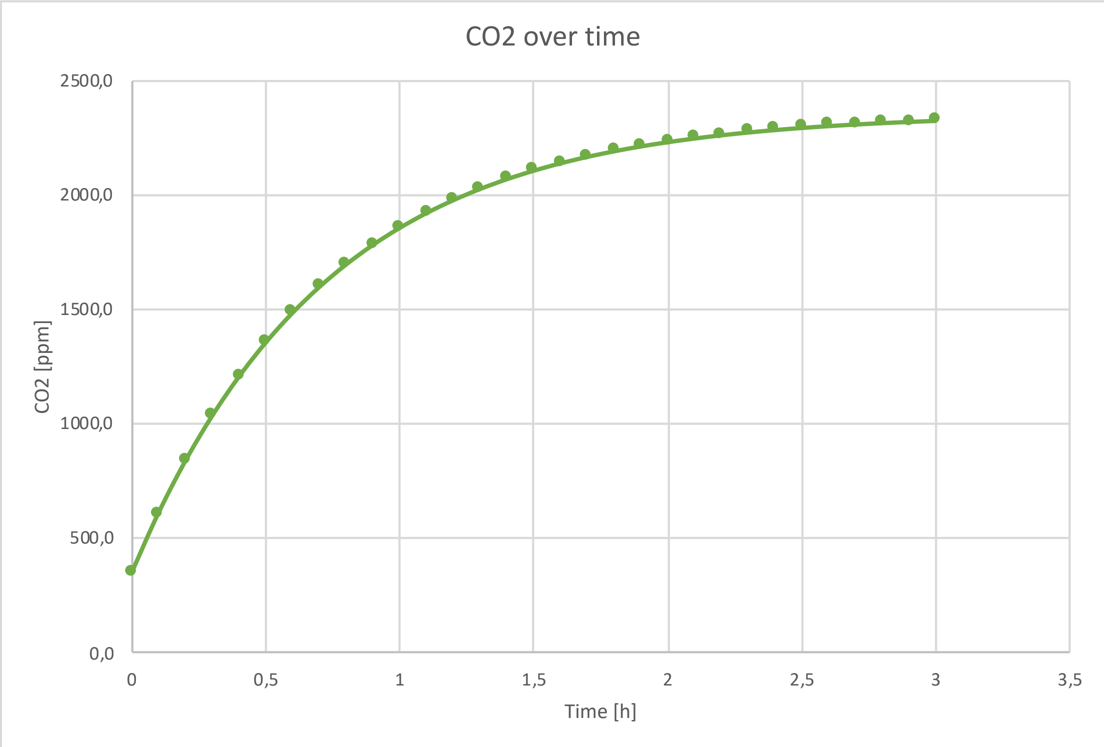


Figure D.5 CO_2 concentration and RH change over time in winter case 5.



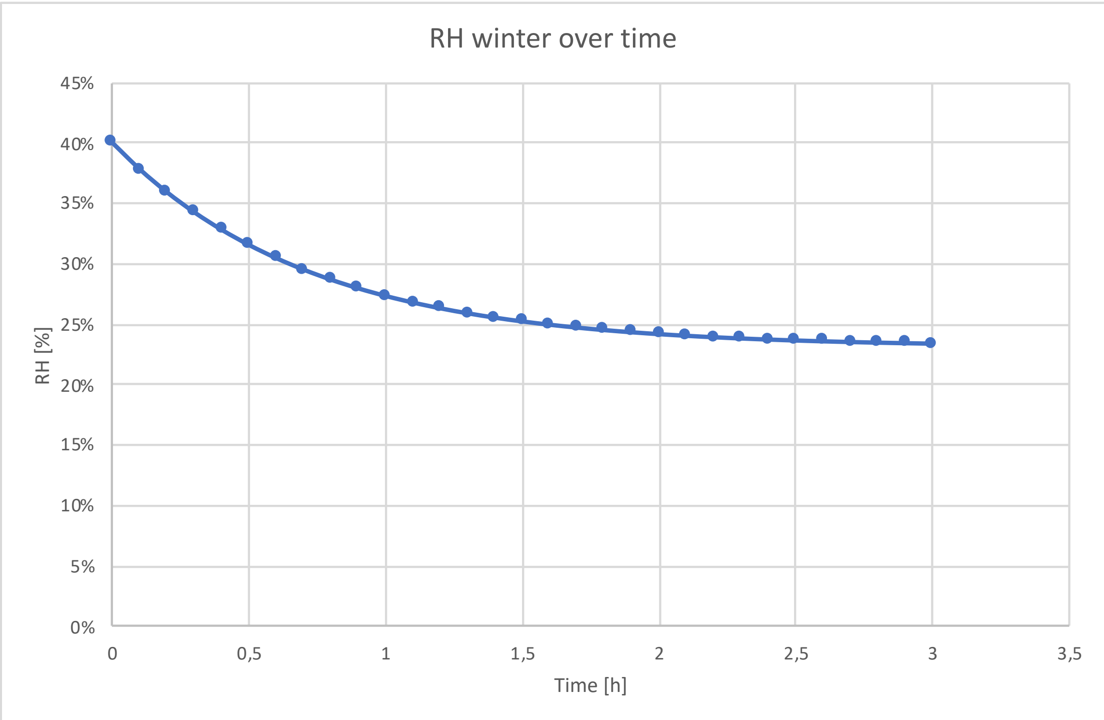


Figure D.6 CO_2 concentration and RH change over time in winter case 6.

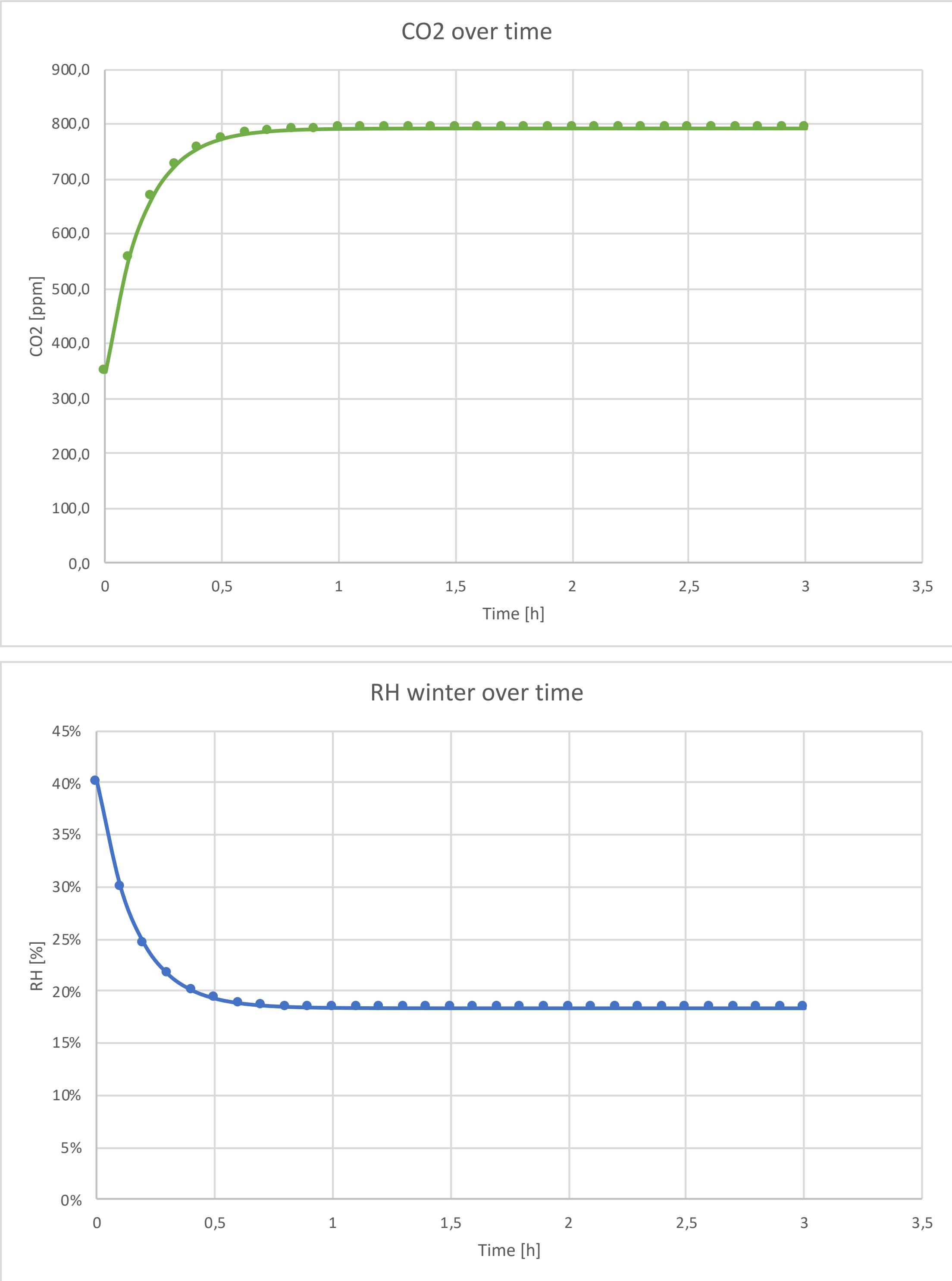
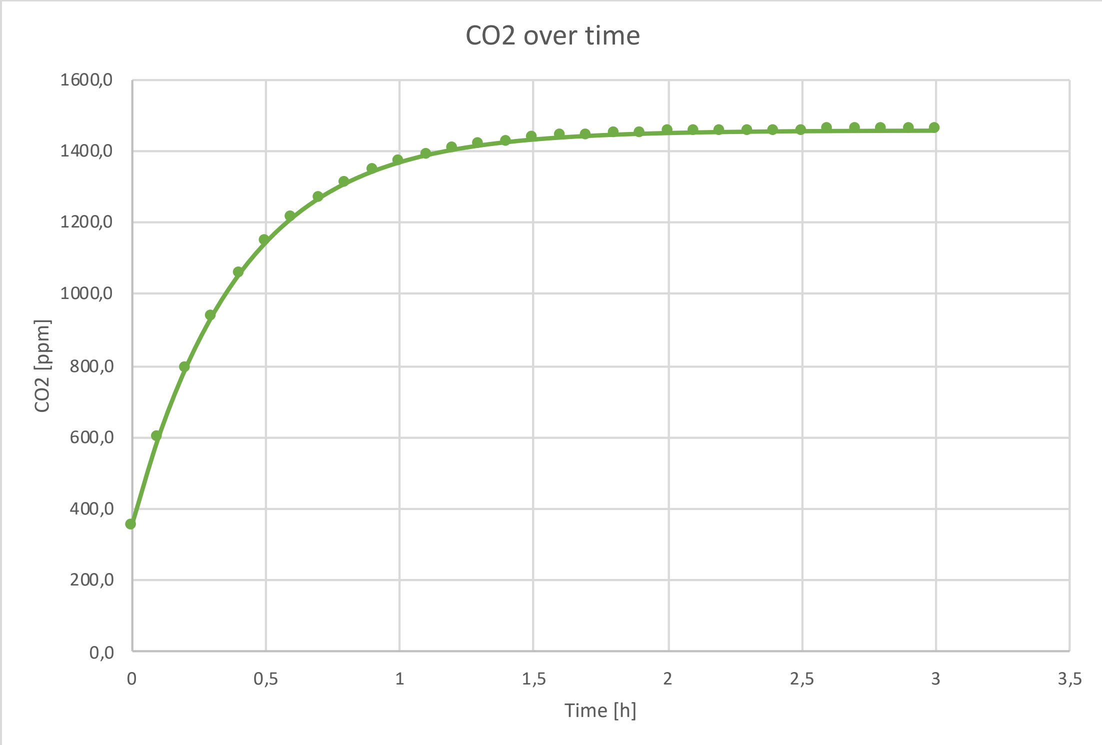


Figure D.7 CO_2 concentration and RH change over time in winter case 7.



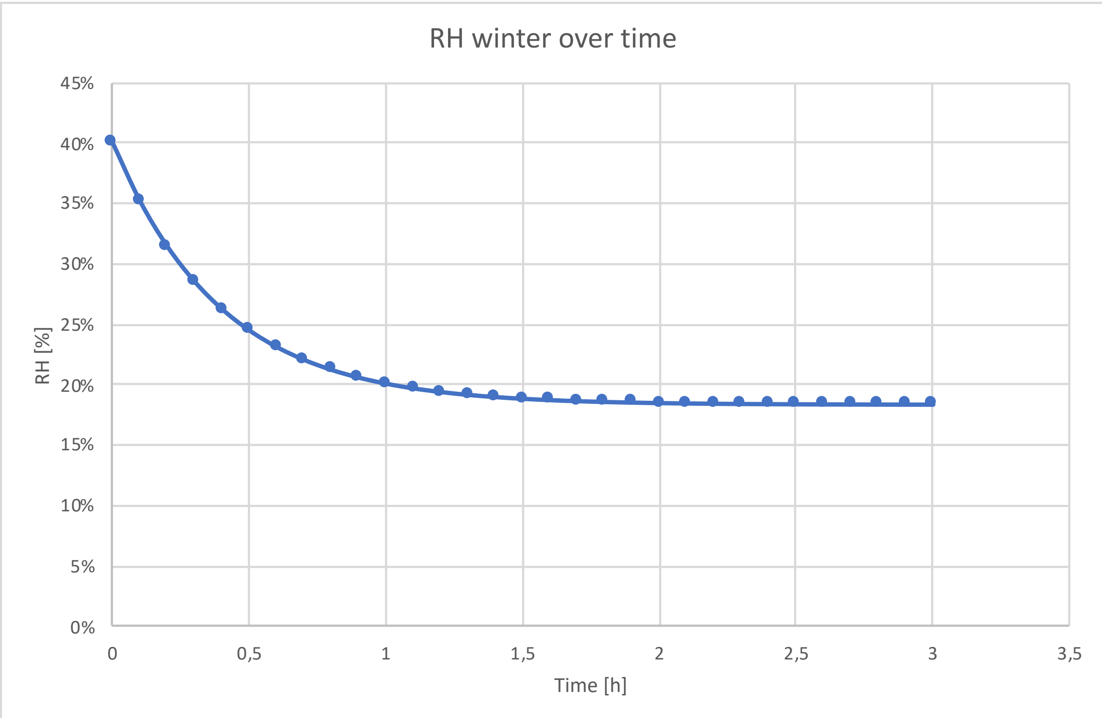


Figure D.8 CO_2 concentration and RH change over time in winter case 8.

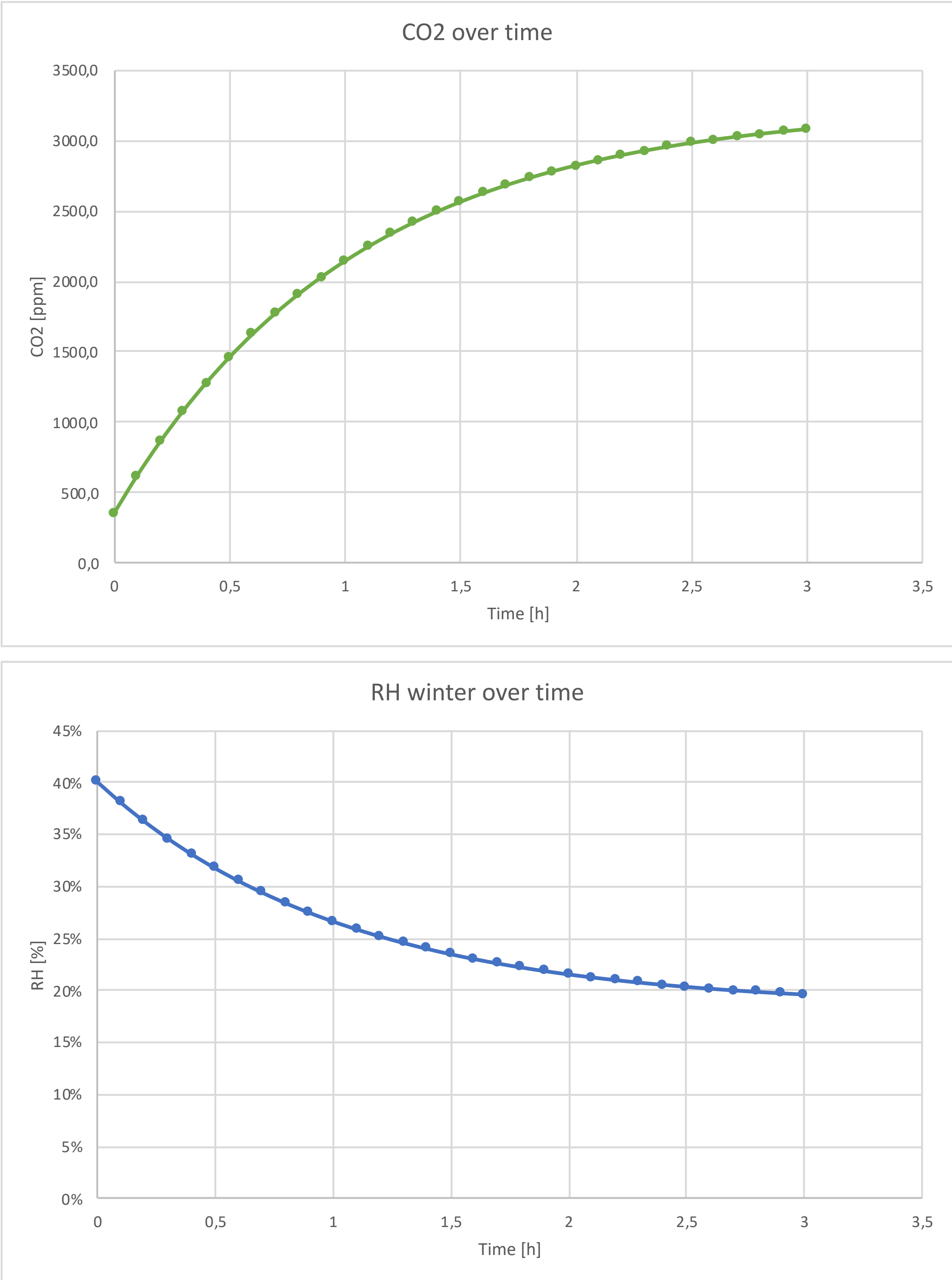
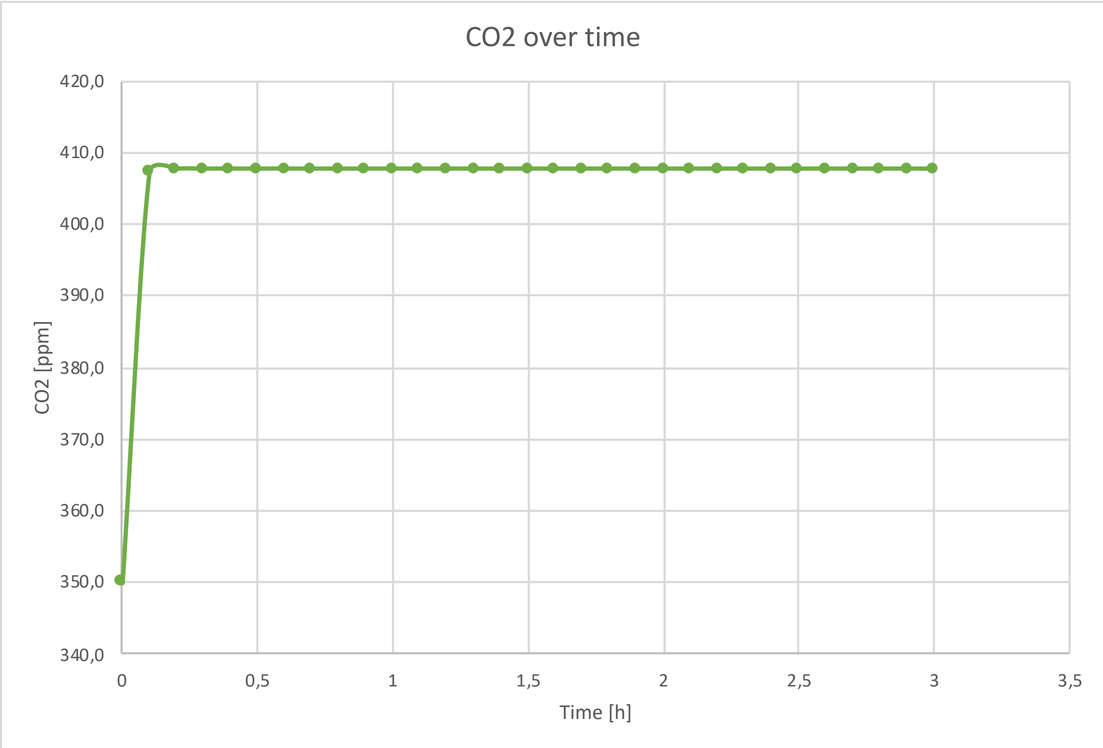


Figure D.9 CO_2 concentration and RH change over time in winter case 9.

Summer cases:



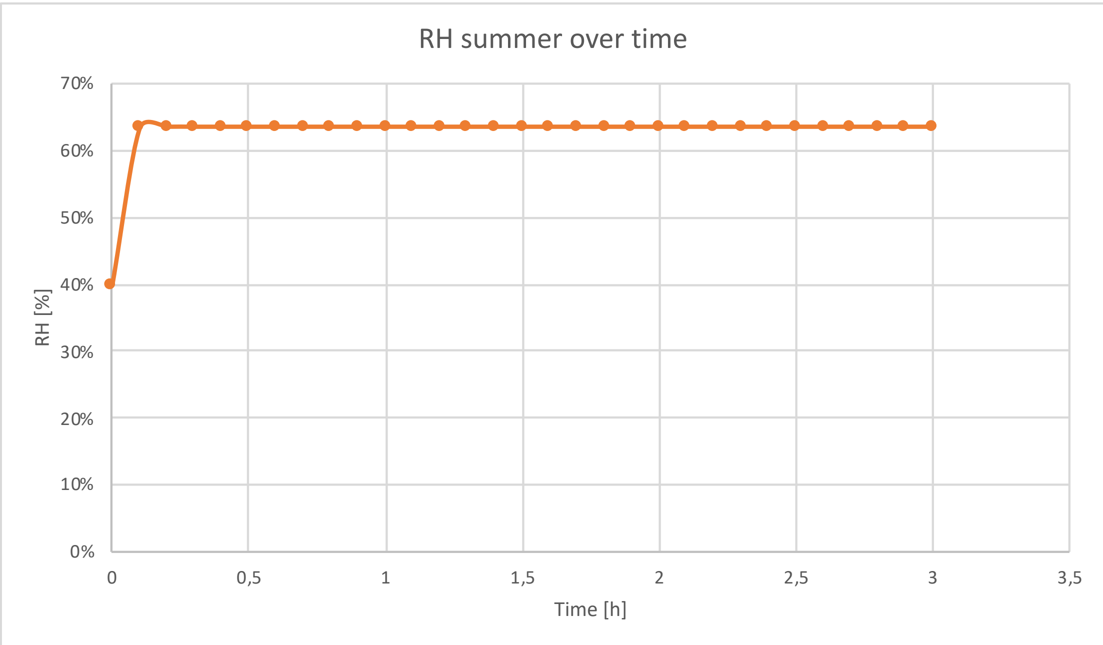
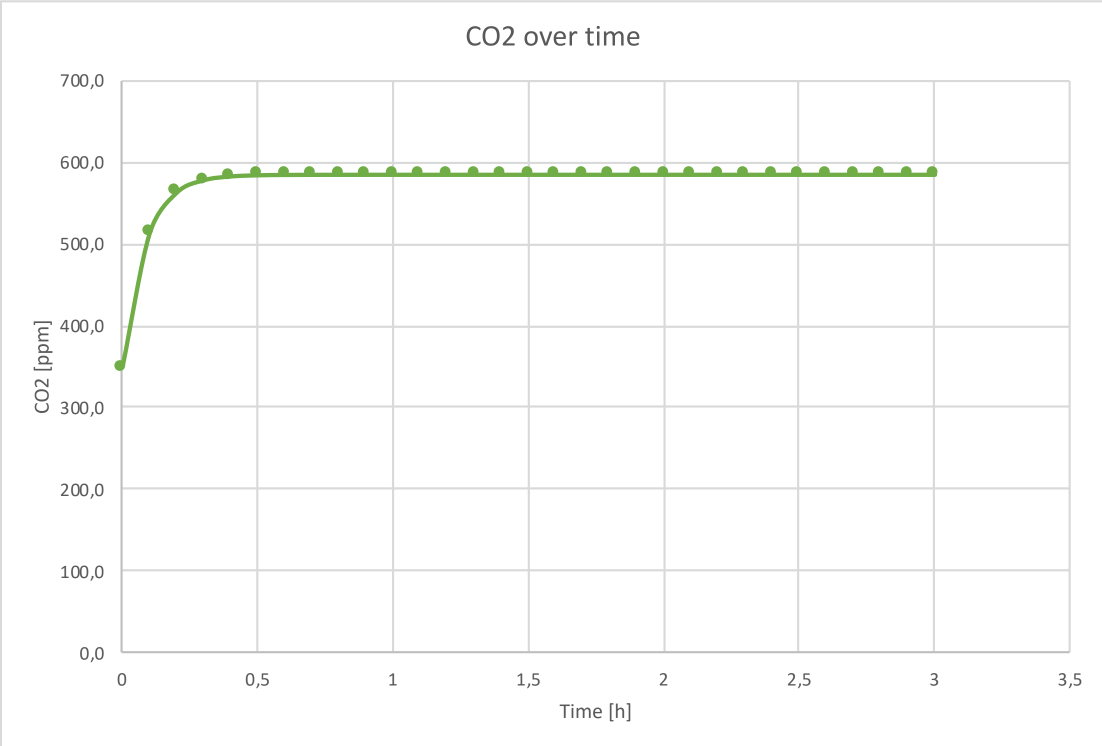


Figure D.10 CO_2 concentration and RH change over time in summer case 10A, 11A, 12A.



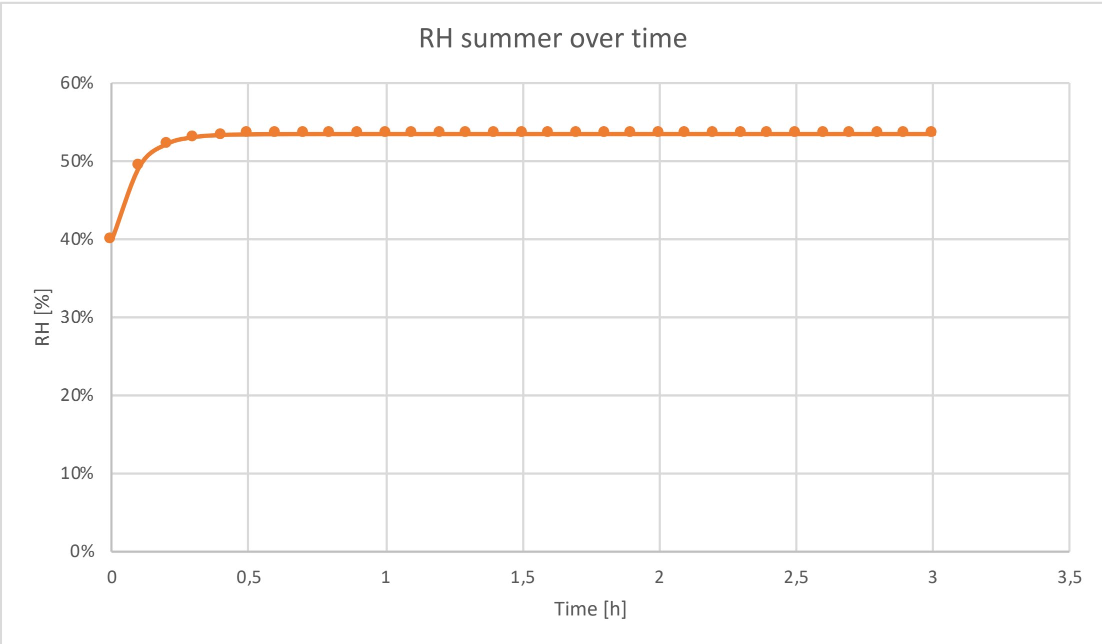
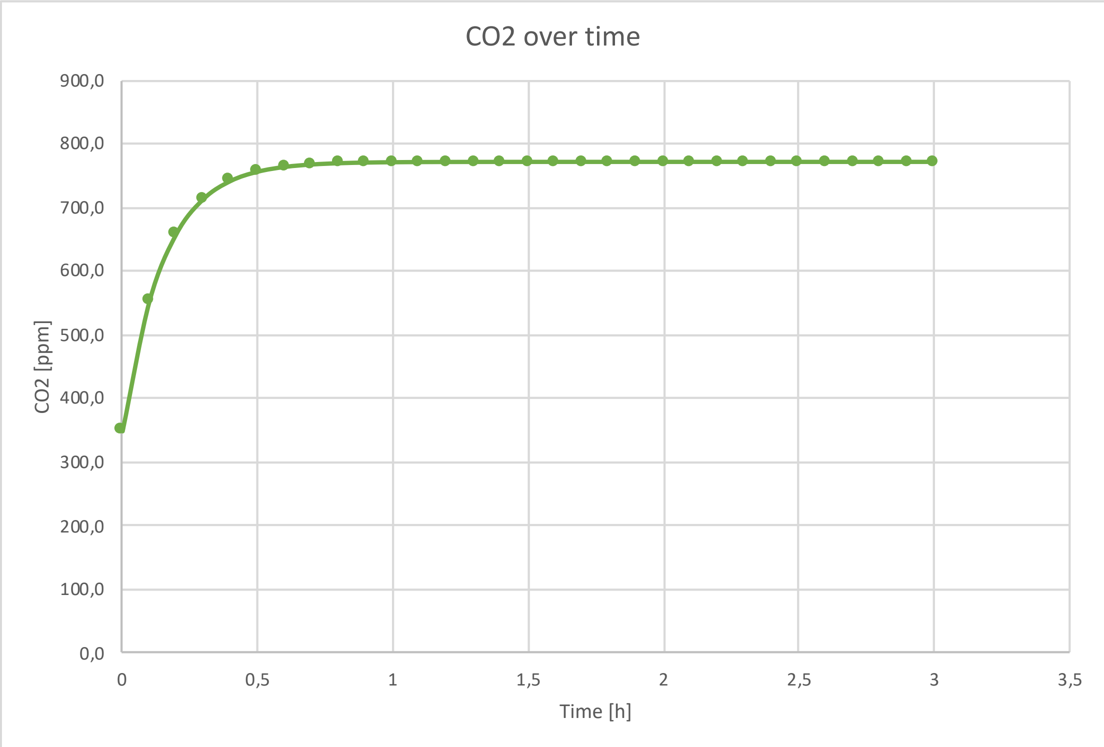


Figure D.11 CO_2 concentration and RH change over time in summer case 13A, 14A, 15A.



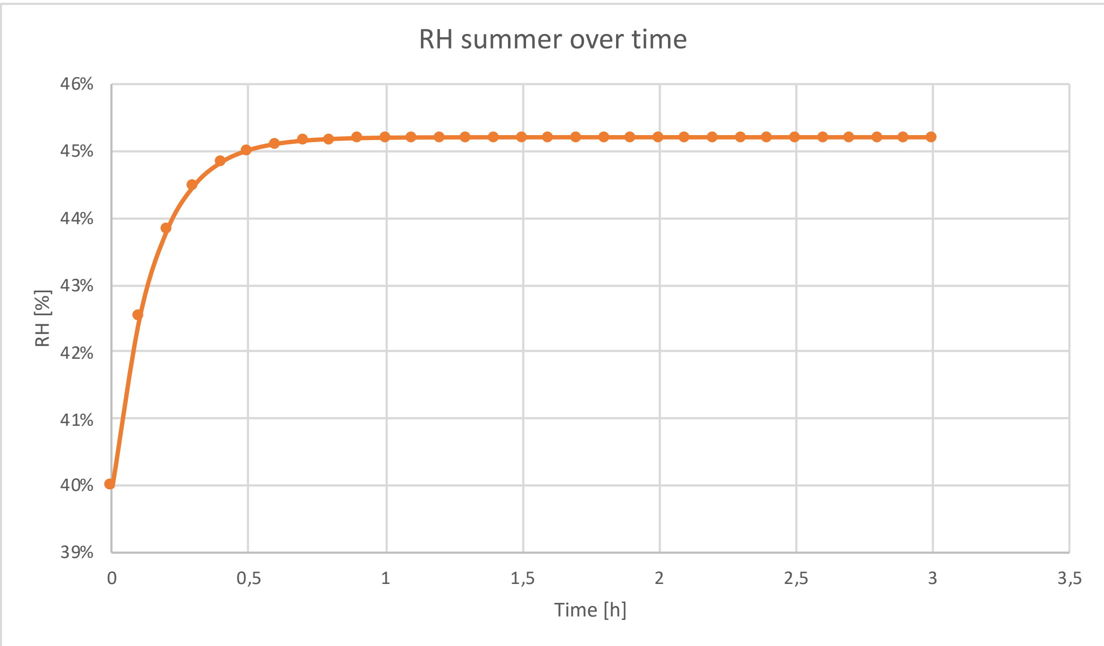


Figure D.12 CO_2 concentration and RH change over time in summer case 16A, 17A, 18A.

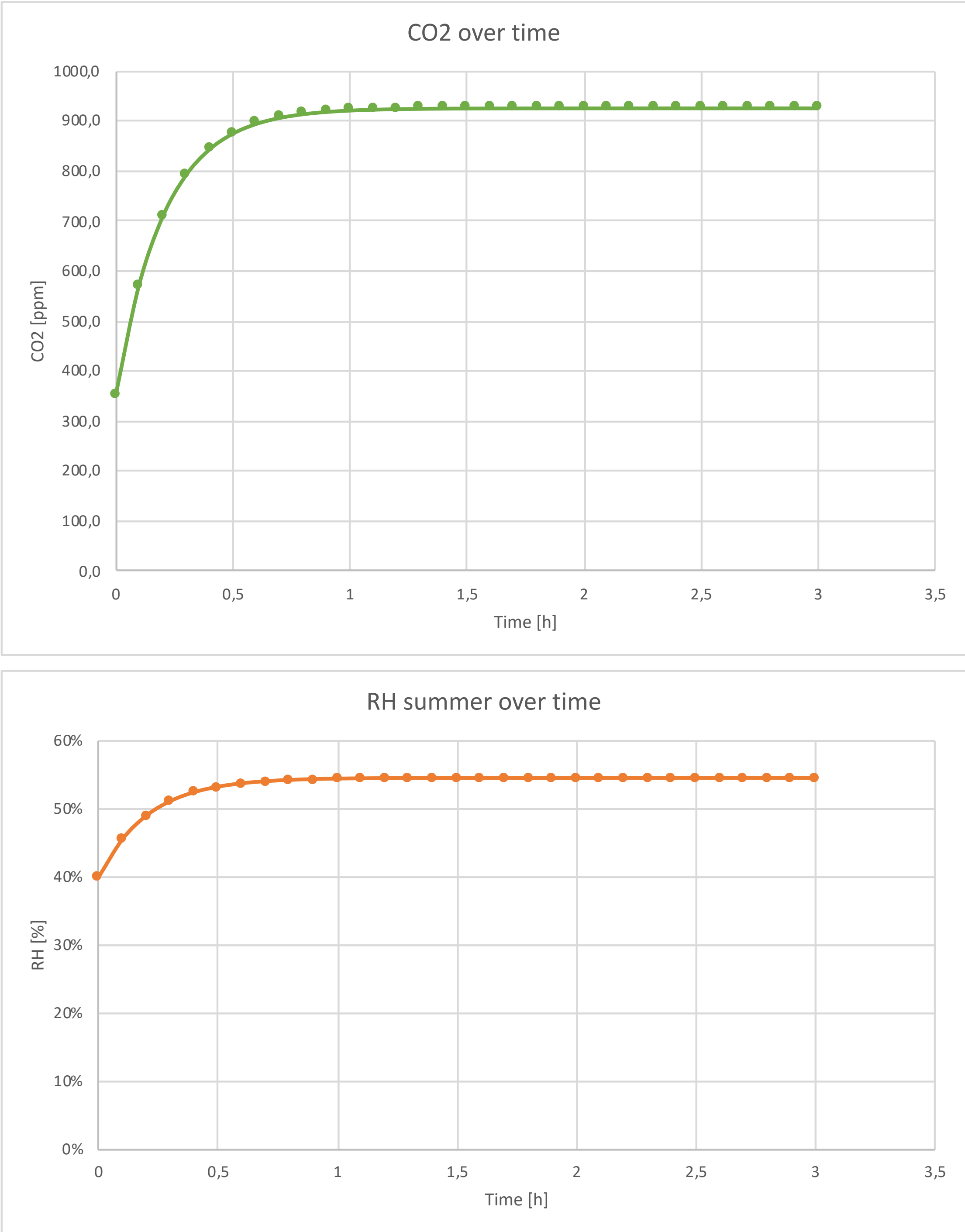
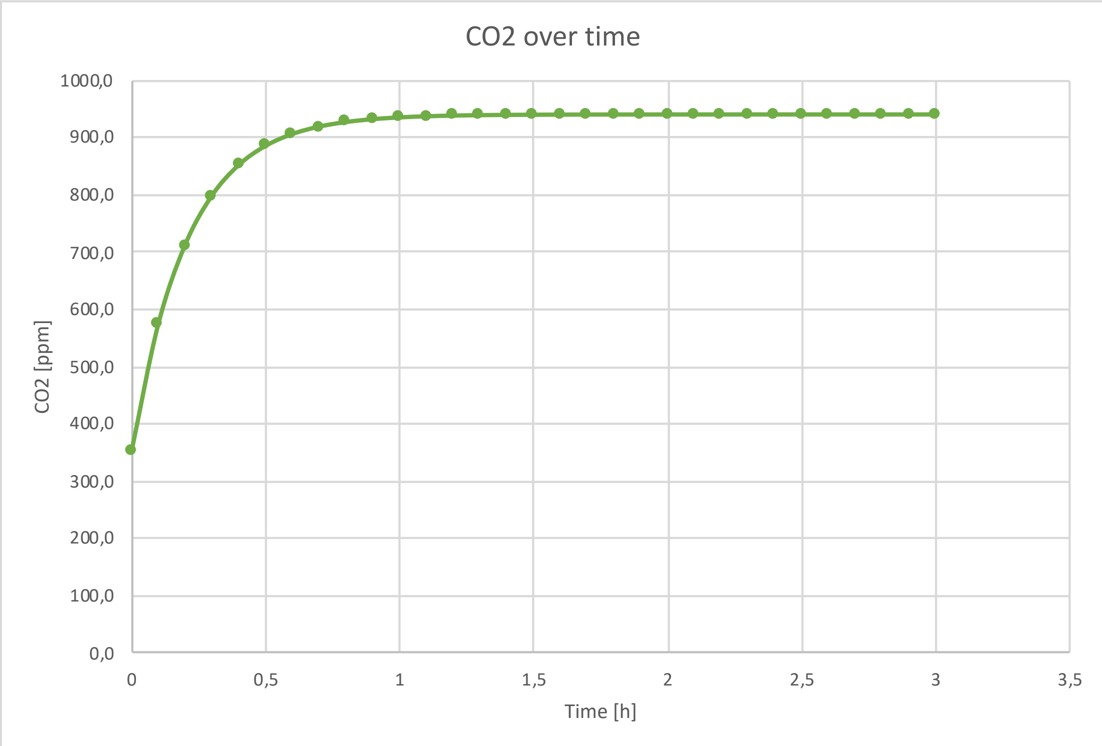


Figure D.13 CO_2 concentration and RH change over time in summer case 10B, 11B, 12B.



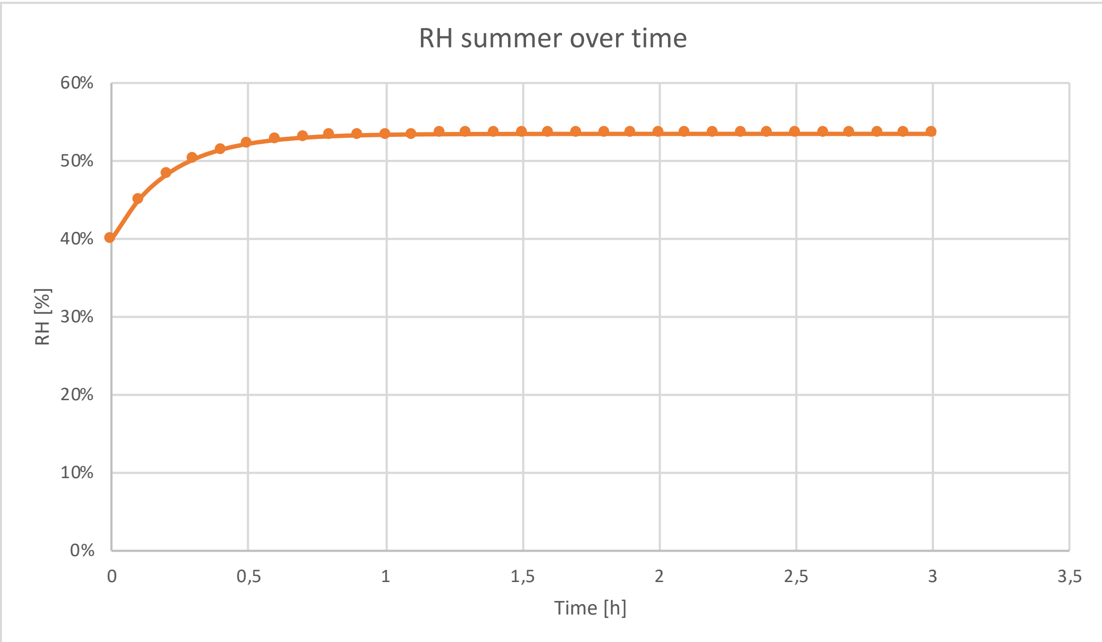
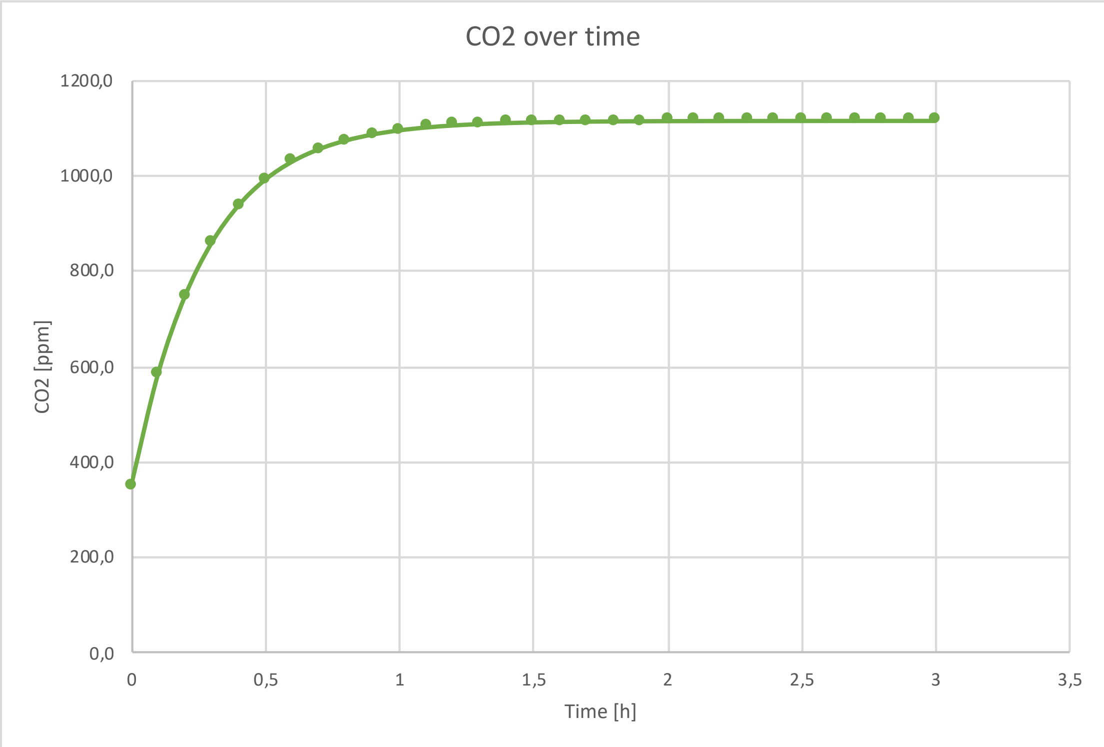


Figure D.14 CO_2 concentration and RH change over time in summer case 13B.



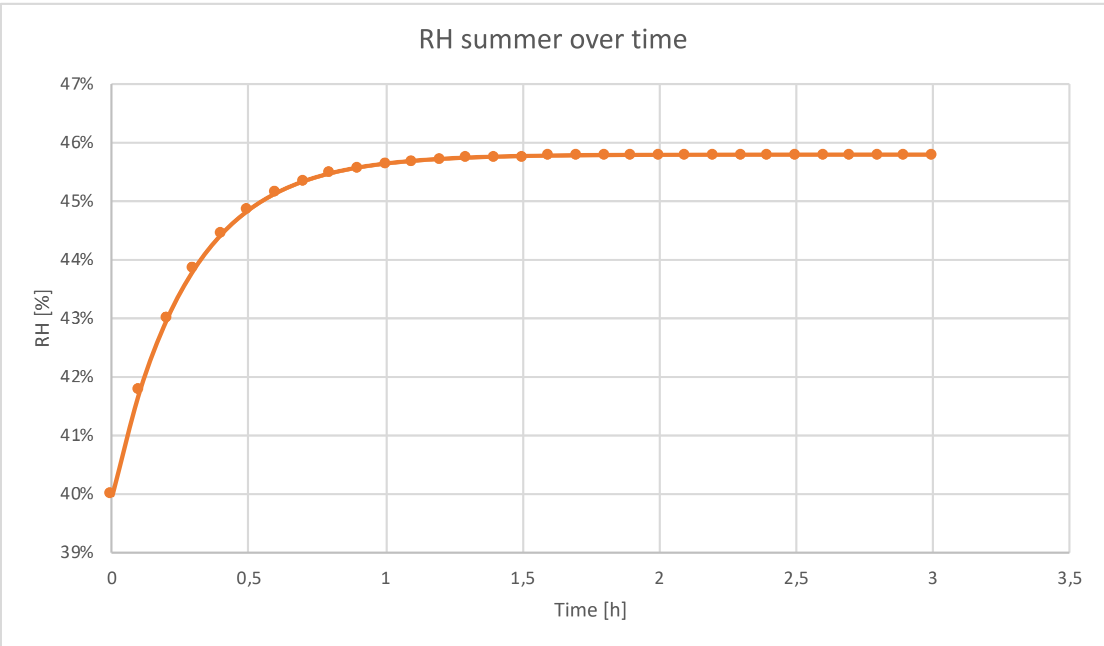
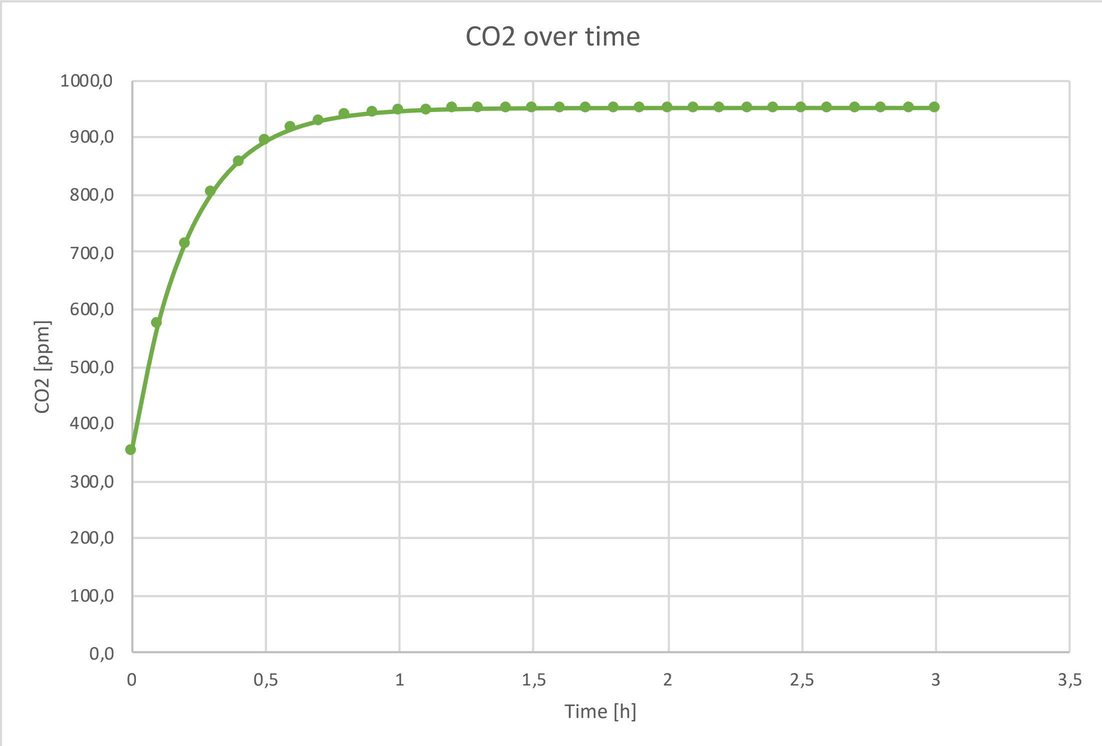


Figure D.15 CO_2 concentration and RH change over time in summer case 14B and 15B.



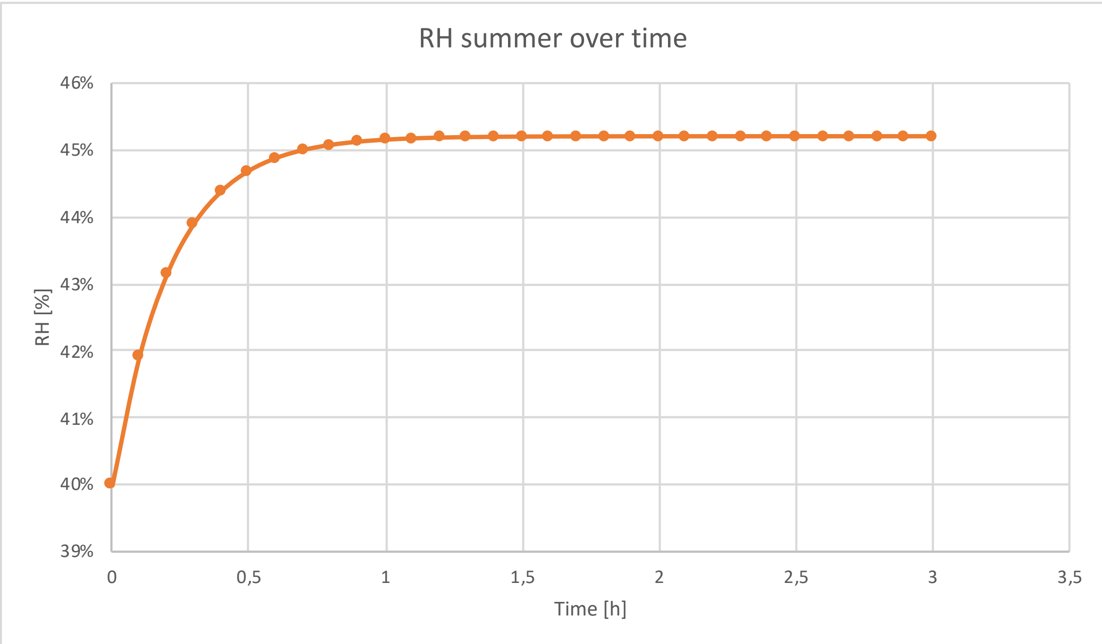


Figure D.16 CO_2 concentration and RH change over time in summer case 16B.

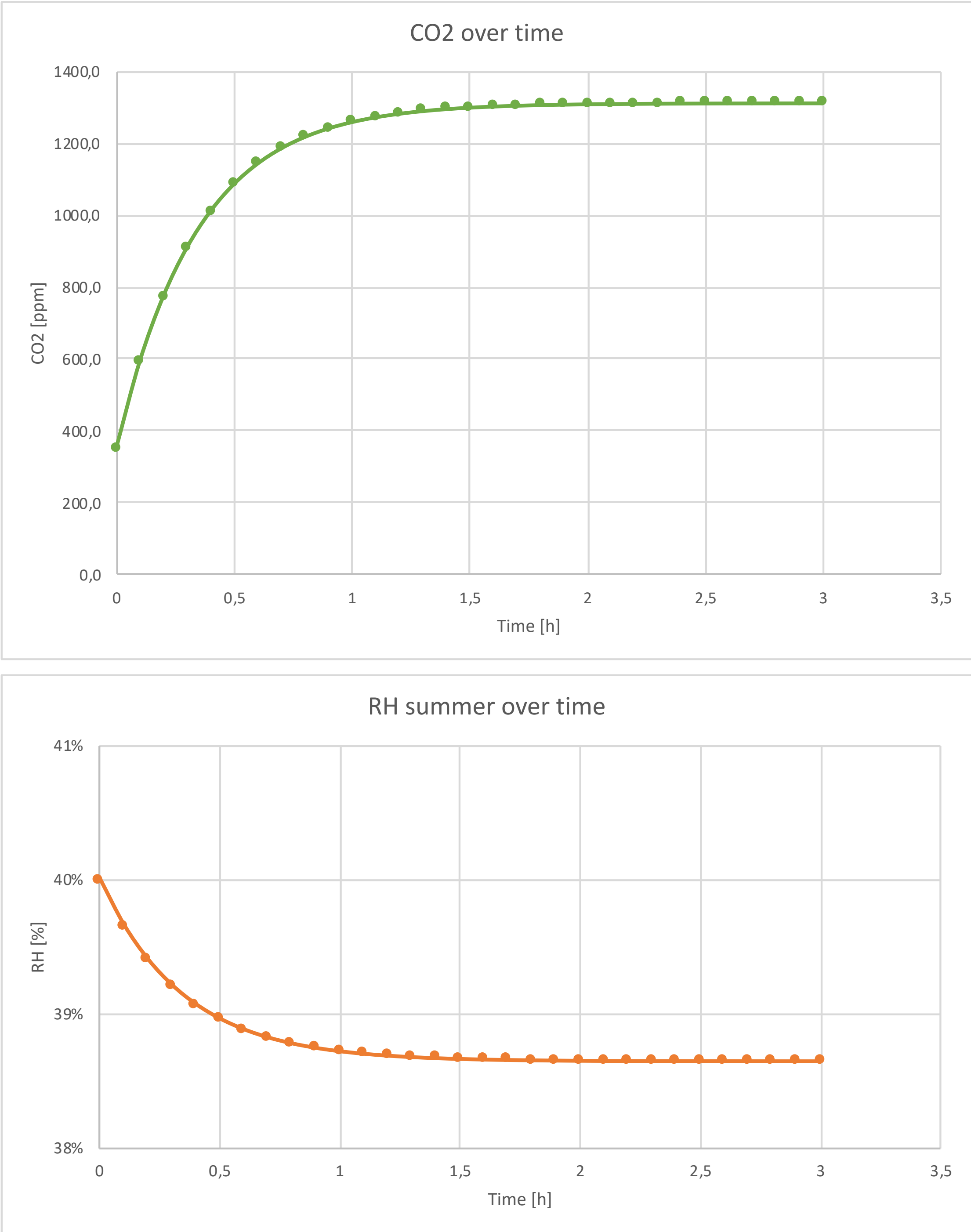


Figure D.17 CO_2 concentration and RH change over time in summer case 17B and 18B.