EVALUATION AND SELECTION OF COOLING SYSTEMS IN OFFICES

From a Life Cycle Perspective

MATHILDA RYDSTEDT HOPSTADIUS
OSCAR STRÖMBERG

KTH Industrial Engineering and Management

Master of Science Thesis
Stockholm, Sweden 2012

EVALUATION AND SELECTION OF COOLING SYSTEMS IN OFFICES

From a Life Cycle Perspective

Mathilda Rydstedt Hopstadius

Oscar Strömberg

Master of Science Thesis MMK 2012:52 IDE091

KTH Industrial Engineering and Management

Machine Design

SE-100 44 STOCKHOLM

Examensarbete MMK 2012:52 IDE091

KTH Industriell teknik och management

Utvärdering och val av komfortkylesystem i kontor

Från ett livscykelperspektiv

Mathilda Rydstedt Hopstadius

Oscar Strömberg

Godkänt	Examinator	Handledare
2012-mån-dag	Conrad Luttropp	Conrad Luttropp
	Uppdragsgivare ÅF AB	Kontaktperson Sara Beltrami

Sammanfattning

ÅF:s huvudkontor i Solna invigdes den 26 november 2008 som Sveriges första certifierade Green Building, en miljömärkning utvecklad av the European Commission riktade mot företag, fastighetsägare och förvaltare som vill förbättra energieffektiviteten i deras faciliteter. Det syftar till att främja miljöeffektiva byggnader som är byggda för att minska koldioxidutsläpp, och kravet är att energikonsumtionen är 25% lägre än Boverkets krav på nybyggnationer. Detta visar på aktivt miljöarbete, vidare bekräftat av ÅF:s miljömål; att reducera koldioxidutsläppen med 50% till 2015.

Att bygga för framtiden är ett globalt mål då inte bara ökande energikostnader utan även klimatförändringar och energitillgång är växande angelägenheter. Denna avhandling vilar därför på argument från bland annat Kyotoprotokollet och Agenda 21, och bryter ner dem till en användbar arbetsgång för utvärdering av kylsystem. Syftet är att hitta det kylsystem som bäst överensstämmer med de energi- och kostnadsrelaterade kraven och preferenserna, och därigenom också föreslå en välgrundad arbetsgång för utvärdering av kylsystem ur ett livscykelperspektiv. Arbetsgången utvecklades genom en faktisk utvärdering av kylsystem genom att använda de mest exakta metoderna och programmen och täcker följande steg; Modellering, Energiberäkningar, Klimatmätningar, Kostnadsanalys och Miljöpåverkansanalys ur ett livscykelperspektiv.

Det mest miljövänliga kylsystemet av de två utvärderade alternativen är CBS baffel-systemet som ska användas i den nya ÅF-byggnaden i Göteborg, med 140 kg mindre CO_2-utsläpp. Detta system har också de lägsta livscykelkostnaderna med drygt 5 500 000 SEK mindre än CBC baffel-systemet över den 20-åriga livscykeln, och klimatmätningarna visar att det ändå tillhandahåller ett *komfortabelt termiskt klimat*. De ekonomiska vinningarna från detta, tillsammans med de rekommenderade programmen, metoderna och direktiven, förklaras närmare i avhandlingen.

KTH Industrial Engineering and Management	**Master of Science Thesis MMK 2012:52 IDE091** **Evaluation and selection of cooling systems in offices** *From a Life Cycle Perspective* Mathilda Rydstedt Hopstadius Oscar Strömberg

Approved	Examiner	Supervisor
2012-month-day	Conrad Luttropp	Conrad Luttropp
	Commissioner	Contact person
	ÅF AB	Sara Beltrami

Abstract

ÅF'S head office in Solna was inaugurated on 26 November 2008 as Sweden's first certified Green Building, an eco-label developed by the European Commission aimed at businesses, property owners and managers who want to improve the energy efficiency in their facilities. It aims at promoting eco-efficient buildings that are built to reduce emissions of carbon dioxide into the atmosphere, and the requirement is that the energy consumption is 25% lower than what the general new building requirements from the Swedish National Board of Housing, Building and Planning. This shows active work on environmental issues in order to reduce environmental impact, further affirmed by the sustainability goal at ÅF; to reduce the CO_2 emission by 50% by 2015.

To build for the future is a global mission as not only increasing energy costs but also climate change and energy supply are growing concerns. This thesis rests on statements from for example the Kyoto Protocol and Agenda 21, and breaks them down into a usable working path for evaluating cooling systems. The purpose is to find the cooling system that best corresponds to the energy and cost related requirements and preferences and by that also propose a well-founded workflow for procurements that covers the life cycle perspective. The working path was developed from performing an actual system evaluation by using the most accurate methods and programs, and covers the following steps; Modeling, Energy calculations, Climate measurements, Life Cycle Cost analysis and Life Cycle Assessment.

The most environmentally friendly cooling system of the two alternatives is the CBS beam system due to be implemented in the new ÅF building in Gothenburg, using 140 kg less CO_2. Also, this system has the lowest life cycle costs with ca 5 500 000 SEK less than the CBC beam system over the 20 year life cycle, and the climate measurements show that it still provides a *comfortable thermal climate*. The economical gains from this, as well as the recommended programs, methods and directives are explained further in the thesis.

PREFACE

In this chapter the authors wishes to express their gratitude towards people who has supported, inspired, helped and in any other way been important to conduct this thesis.

This Master Thesis has been conducted during February – June 2012 at ÅF BA Buildings in Stockholm, and concludes the Master program Industrial Design in Design and Product Realization at KTH Royal Institute of Technology.

Several people have assisted and supported during this work, and although it is not possible to mention all in at few sentences we would like to thank those who have been particularly important. Therefore we wish to send a special thanks to our supervisors for the support and guidance throughout this thesis, Sara Beltrami, Conrad Luttropp and Mathias Nordgren – thank you!

There are many people to whom we feel great appreciation, among them Jörgen Persson, who answered our many questions in the very beginning and got us started in the theory. Throughout the work we always focused a bit extra when we met you in the corridors. Mats Andersson, who traveled far to educate us in Revit MEP, it would not have been an easy task to learn a completely new program without your help. We also wish to express our gratitude to Jonas Gräslund for the effort and guts to let us make the climate measurements, this thesis would not have been possible without your approval.

Thank you also to Erik Wedin, Yang Cheng, Kjartan Gudmundsson, friends and families!

Mathilda Rydstedt Hopstadius & Oscar Strömberg

Stockholm, June 2012

The notations and abbreviations that are used in this Master thesis are presented here.

Notations

Symbol	Description
Clo	Clothing insulation
Σ	The sum of the expression to the right
Met	Activity
P	Productivity relative to the maximum value
T_F	Room temperature in Fahrenheit

Abbreviations

BIM	Building Information Model
CAD	Computer Aided Design
ENEU	Energy efficient procurement (*Energieffektiv Upphandling*)
.ifc	Industry Foundation Classes
LCA	Life Cycle Assessment
LCC	Life Cycle Cost

TABLE OF CONTENTS

1 INTRODUCTION

This chapter introduces the reader to the work, describes the background and purpose of the thesis, and defines the problem and the delimitations. It also presents the report structure.

1.1 Background

ÅF’s head office in Solna was inaugurated on 26 November 2008 and is Sweden’s first certified Green Building, an eco-label developed by the European Commission aimed at businesses, property owners and managers who want to improve the energy efficiency in their facilities. It aims at promoting eco-efficient buildings that are built to reduce emissions of carbon dioxide into the atmosphere, and the requirement is that the energy consumption is 25% lower than what the general new building requirements from the Swedish National Board of Housing, Building and Planning (Boverket). A Green Building certified building is awarded with a diploma and will have right to use the Green Building logo to demonstrate that it uses 25% less energy. This shows active work on environmental issues in order to reduce environmental impact; in addition it also reduced operating costs.

The ÅF-house was projected in collaboration with the construction company Skanska, and many of ÅF's own sectors were involved in, among other things, designing the buildings cooling system. A modern office building contains energy consuming systems for indoor cooling and it is therefore of importance when designing a cooling system to have a clear understanding of how the costs related to these systems differ.

The initial goal with the project of the ÅF building was to work towards a Green Building certification and therefore the main focus lay on a low environmental impact. Skanska's decision support for technology choices in buildings is generally based on the four areas environmental impact, life cycle costs, flexibility and simplicity. A cooling beam is a temperature control module with pipe connections for incoming and outgoing water of different temperatures that controls the room temperature, the climate. A complete system generally consists of one or more cooling beams along a chain of tubes which branches off and reaches all the rooms in the building. These can be either passive or active; the latter would impose necessary regular manual control and regulation.

The current market offers a variety of active beams that serves similar main purpose, but might have slight variations such as utilization of different in and out temperatures on the water, different designs etc. In recent years the conventional active beam, described above and employed in, among others, the ÅF-building are being exposed to competition by the so called self-regulating beam in office buildings. This beam, further on referred to as the CBS-beam, is designed similar to the CBC-beam (the active beam used in the ÅF-building), but with some changes, the most important being use of higher temperature delta and the lack of mechatronic control units that regulates the flow. Both of these beams are still in use and available from suppliers, however a detailed comparison analyzing the economical benefits of these products does not exist at ÅF:s dispense.

1.2 Purpose

The purpose is to find the system that best corresponds to the energy and cost related requirements and preferences and by that also propose a workflow for procurements that covers the life cycle perspective.

In detail, the work was divided into an extensive background research to examine the systems currently on the market and their respective pros and cons to state a recommended new cooling system. Thereafter, their performance was examined through calculations and measurements and the two systems were modeled in accordance with existing architecture plans on the building. The modeling was done in Revit MEP which for ÅF meant a sought-after analysis of the program itself. The two systems were then examined through a life cycle perspective including both economical and environmental aspects, to investigate the differences between them and thereby establish the optimal system.

1.3 Functional unit

When performing a comparative analysis between two factors, it is important to define a functional unit. This can be described as a quantitative and measurable feature that the compared factors perform. In this case, when two products are compared from an economical perspective, the functional unit was defined as the delivered customer values; provided indoor climate. When the unit is defined, it needs to be broken down into measurable values, for example: indoor climate could be defined with values of air temperature, humidity, air velocity etc. A more extensive description of how the functional unit is quantified is stated under *2.5 Defining the functional unit*.

1.4 Method strategy

In order to obtain the results stated in the *Purpose* section above, an extensive technical background analysis is needed. The purpose of this background analysis can be summarized as a way to define the functional unit of the investigated systems and conclude how the systems achieve this unit.

Step one is to implement these systems in an environment where they perform the same functional unit. In this case, the chosen environment was Hagaporten III, an office building in suburban Stockholm. The analyzed systems need to be implemented so that their performance can be evaluated. In this case, one of the systems was already up and running in the building, making an evaluation of that system easy. The other system however, was not. In order to evaluate the other system, experimental measurements on provided climate was done on another, similar office building at a location nearby Hagaporten, where the other system was implemented. These measurements were done similarly for both systems. These climate measurements provided data on how each system performed the functional unit, making them comparable. Further, to complete the measurements the other system was designed in Hagaporten, first in thermal simulation software and then in a CAD software, to further conclude how the other system would be designed to perform the same functional unit as the first system.

This first step provides data on how both systems needs to be designed and how they perform, in order to provide the functional unit. Hence all costs related to both implementation and use of the systems can be defined, which leads to the second step – to perform the actual life cycle analysis. This includes calculating the total cost for each system over their respective life cycle to compare and find the most economical system, performed through well established guidelines. Not only actual costs affect the evaluation and choice of system from a life cycle perspective, also the environmental impact of the systems is important. The systems were therefore compared and assessed through a software designed for environmental evaluations, through the performance data from step one – the values that were needed to obtain the functional unit.

The evaluation of the systems was performed in steps during the research and the final assessment was performed with all background research, information and result.

1.5 Delimitations

The work was limited by the 20 week time frame given for master theses but it was aimed towards presenting a complete and well-founded evaluation, as far as possible. Some delimitations were necessary to make it possible to reach this goal. The most significant delimitation is therefore the decision to only suggest changes to the cooling system and only to analyze the distribution part of the cooling system, even though obtaining a complete view of the climate system in the building requires understanding and analyzing the heat and ventilation systems too. Only two alternatives were compared after an extensive research to find the most appropriate systems.

The modeling was based on one dimensioning floor which was multiplied by the number of office floors in the building, to limit the work put on modeling but still get an adequate model for the purpose. Regarding the energy use analysis the model was limited to specific areas in the building acting as dimensional areas. When determining the limits of this section, it should fulfill the requirements to acquire satisfying results from the simulation, but not being unnecessary large. The outcome, calculated in percent, was assumed to apply to the whole system.

1.6 Report structure

The thesis begins with an abstract in both Swedish and English, a preface and a nomenclature list. The report is structured by chapters.

CHAPTER 1	Introduces the reader to the work, describes the background and purpose of the thesis, and defines the problem and the delimitations.
CHAPTER 2	Presents the frame of reference by describing the used data sources divided into primary and secondary data. This chapter also describes and motivates the considered systems, the programs used and the functional unit.
CHAPTER 3	This theoretical chapter explains and motivates the methods used for solving the problem stated in Chapter 1. It includes a description of

	the energy calculations, modeling, life cycle cost analysis and assessment, climate measurements, and how the climate is connected to performance and thereby the economical aspect.
CHAPTER 4	Presents the results from the previous chapter, and is the main chapter in this thesis. Note that the theoretical background and motivations for using the methods were presented in the previous chapter and will thus not be discussed any further here.
CHAPTER 5	Includes the critical review of the thesis and discusses the methods, delimitations and results.
CHAPTER 6	This chapter provides a conclusion, recommendations based on the results and suggestions for future work.

A reference and appendix list follows.

2 FRAME OF REFERENCE

The reference frame is a summary of the existing knowledge and former performed research on the subject; it describes the considered systems, the programs used and the functional unit.

2.1 Data collection

The data collection is, according to Skärvad et al. (1999), often divided into two parts, primary and secondary data. Primary data is defined as the data collected by the researcher, while secondary data is information available that has already been collected elsewhere.

2.1.1 Primary data

Interviews, measurements and calculations form the base for the primary data collection. The interviews were conducted mainly to get an understanding for the different types of systems but also to get an input for the energy, environment and cost calculations for example, which in turn are also part of the primary data.

2.1.2 Secondary data

The secondary data in this thesis consists of extensive literature research including academic literature and previously conducted theses with a connection to this thesis, as well as a thorough background research on the cooling systems' function from various sources. Included here is also information gained from manufacturers and suppliers of different materiel, as well as information from official agencies and institutes.

ENEU

What often is included in the *economical evaluation* in procurements is solely the acquisition cost, lately also adding delivery times, quality, service and maintenance to the evaluation. But the most significant cost is during the usage phase due to long life times. The Association of Swedish Engineering Industries (VI) in collaboration with consulting company Bengt Dahlgren AB therefore put a series of guidelines together, financed by the Department of Energy Efficiency at the Swedish National Board for Industrial and Technical Development (NUTEK). This was driven by a holistic and long-term approach where long operating times, a presumed increased energy price as well as environmental concerns and resource management called to look at an investment's life cycle cost assessment when various tenders are involved. These guidelines, or directives, are compiled and called ENEU (from the Swedish ENergiEffektiva Upphandlingar; energy effective procurements) [1], which takes the complete life cycle cost into consideration when evaluating investments on energy efficient equipment. It emphasizes profitability thinking, and presents the current performance requirements related to energy efficiency for various types of equipment.

ENEU 2000 is the latest version of three published versions, which also takes into consideration experiences from using the two previous versions and therefore the most accurate in this case. Furthermore, ENEU is in line with the Public Procurement Act. In SFS 2007:1091 in 12th Chapter 1§ it says, free translation, "A contracting authority shall accept either 1. the most economically advantageous bid, or 2. the bid with the lowest price. In considering which tender to is most economically advantageous, the authority shall take into consideration the various criteria's connected to the subject of the contract, such as price, delivery or completion, environmental characteristics, operating costs, cost effectiveness, quality, aesthetic, functional and technical characteristics, service and technical support etc" [2].

The tool proves helpful in combination with existing procurement documents when conducting investment evaluations, comparing alternatives and calculating costs. First of all it is necessary to frame the scope of the LCC, i.e. the life cycle, but also the system and components to be analyzed. Useful for that is the Swedish AMA Standard [3] (Allmän Material- och Arbetsbeskrivning in Swedish, or general material and work description, for effective documentation and communication throughout the construction process) to which ENEU 2000 is joined. The life cycle cost is then calculated as the sum of the investment cost and the equipment's energy throughout its lifetime, both adjusted to present value using *the Present Value method*. Also the equipment's future maintenance and environmental costs are converted to present value in the same way.

2.2 Current system design

Thermal energy is removed from the system in two forms: public cooling and free cooling. Economically there is a distinct difference between these two outlet forms; expenses related to the public cooling is directly proportional to the amount of energy removed, since it is provided by a municipal supplier that charges for energy amount. The cooling energy provided by the free cooling system on the other hand, is free. Hence, the operational cost of the cooling system is proportional to the amount of public cooling needed. The free cooling can be described as a heat exchanger typically mounted on the roof of the building, to cool down the water in the circuit. Hence, it can only provide cooling when the ambient temperature is below the temperature of the water that enters the cooling beams. Since the capacity of the free cooling varies with the ambient climate, the amount of needed public cooling varies. The public cooling supply is referred to in the cooling system as the primary circuit, KP01. The primary circuit is led into a heat exchanger KB01-VVX01 were it cools down the water in the secondary circuit KB01.

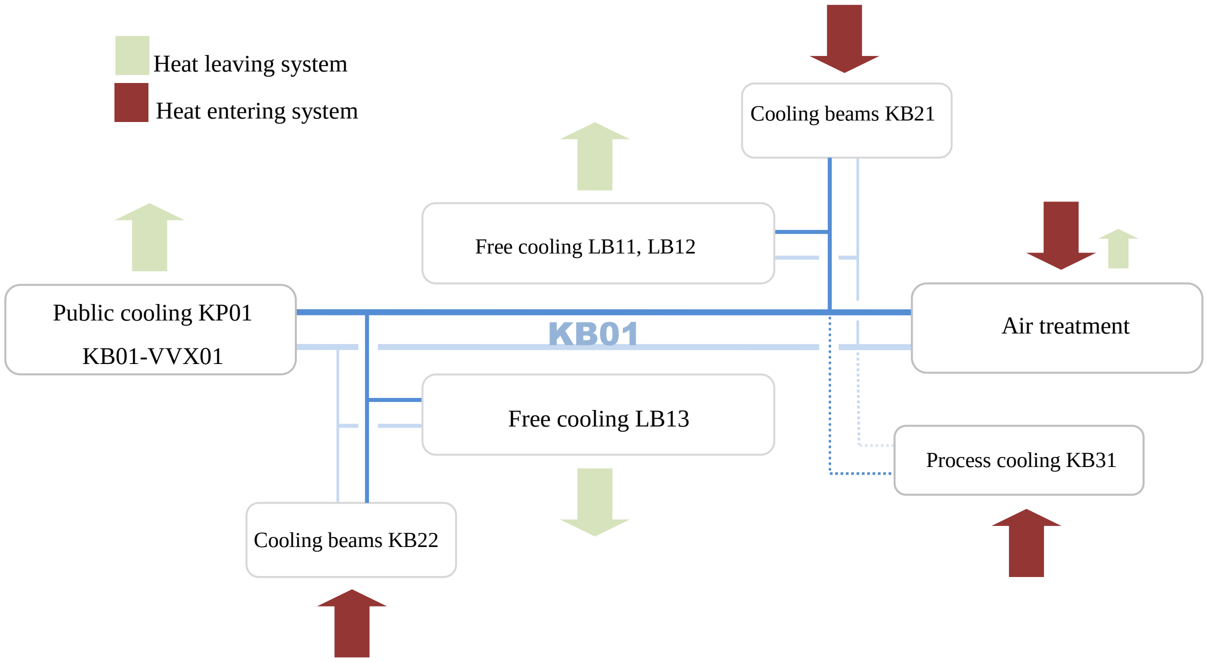


Figure 1: Schematic design and energy flow in the system

KB01 is the circuit that connects all the heat inlets and outlets in the system, hence transporting heat from places where it is unwanted to places where it can be absorbed. The design of the cooling system is displayed in Figure 1. When studying the cooling system inside the building, KB01 can be seen as the “main circuit”. The amount of energy removed by public cooling is regulated by keeping the temperature delta of the primary water circuit over the heat exchanger constant while varying the flow through it. When the water in circuit KP01 enters KB01-VVX01 it has a temperature of 6°C which rises to 16°C. The water in circuit KB01 enters KB01-VVX01 with the temperature 19°C and is chilled down to 9°C.

The cooling system provides cold to the building via a complex system of heat exchangers. Although these vary in design and application, a distinction can be made between two main types: air treatment cooling batteries in the ventilation shafts that chill the supply air when it enters the building, and cooling beams that chills the air while it is distributed in the public areas. In addition to air treatment and cooling beams there is also process cooling. With a nominal cooling power demand of less than 100kw, the process cooling units is considered of less significance to the total power consumption [1][2]. The supply air treatment is distributed on four aggregates: LB11, 12, 13 and 14. Air treatment in these units can provide cool for the air from the cooling system as well as heat from the buildings heat system depending on the need. The aggregates are also equipped with heat recovery systems that adjust the fresh supply air to the temperature of the waste air on its way out of the building.

2.2.1 Distribution of cooling beams and free cooling

The secondary circuit KB01 is branched out into two sub circuits, KB21 and KB22. The cooling beams in the building are divided between these sub circuits. These sub circuits are placed in two separate parts of the building and makes it possible to individually adjust them if, let's say, one part is used more than the other, which makes it possible to occupy only half of the building without cooling down the other half. Free cooling batteries in LB11 and LB12 are connected over KB21 while Free cooling in LB13 are connected over KB22. The water enters the sub circuits at 9°C but is warmed up to 16°C before it enters the beams. The warming of the water is done in a shunt group, where the 9°C water is mixed with the return water from the cooling beam at 19°C. This way the capacity of the cooling system isn't wasted due to raise of the temperature before the cooling water enters the beams. The adjusted temperature delta over the beam circuit is done due to requirements of the beam. Shunting the temperature means that a beam with another required temperature delta can be implemented in the system without changes being required on the rest of the system. This because any supply temperature demanded by the beam can be acquired by mixing it with the warmer return water in the shunt group [3]. The free cooling is connected parallel to the beams so that the water can flow in a closed circuit between the beams and the free cooling device when the capacity is sufficient.

2.2.2 **Cooling beams**

The system cools the air in the public areas via cooling beams distributed on every floor mounted folded into the ceiling. A cooling beam can be described as a radiator or heat exchanger in which cold water is heated by ambient air passing through the beam, increasing the water temperature which results in a decrease of the temperature of the air. The beam employed in this system is of active type. An active cooling beam is connected to the air supply, which is distributed from the air treatment aggregates into the public areas via a diffuser inside each beam. Typical design is displayed in figure 2. This distinguishes the active beam from the passive, which is not connected to the air supply and thus relies solely on natural convection for heat exchange. If passive beams are used, the air is distributed via separate diffusers in the room [4].

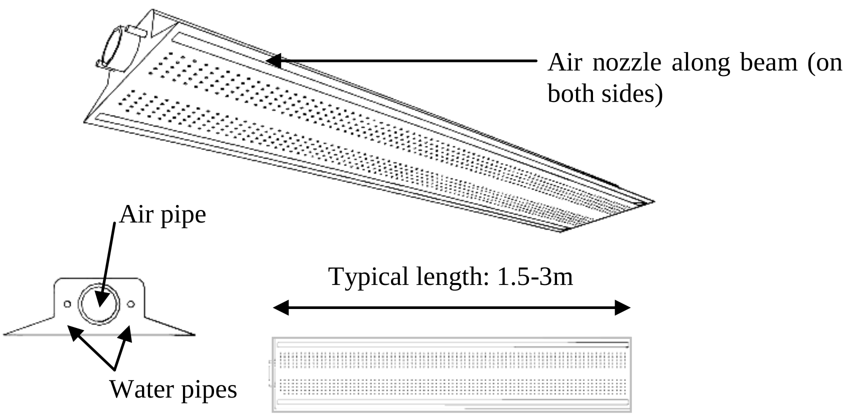


Figure 2: Geometrical data and basic design of cooling beam

As stated, the free cooling device removes energy from the cooling beam circuit by use of ambient air of a lower temperature than the indoor climate. The use of the free cooling is limited by the requested water supply temperature in the beam, in this case 16°C. Cold can thus only be obtained from the free cooling when the ambient temperature is lower than 16°C. This defines a significant flaw in the cooling system, since the demand of cooling increases with the ambient temperature.

2.3 Alternative system

As stated, the cooling beams employed in this system suffers from the flaw of not being able to utilize free cooling once the temperature outside exceeds 16°C. Considering that the demand of indoor cooling rises with the ambient temperature, this is considered a problem with this type of beam. Because of this, another type of beam has been developed to replace the traditional active beam. The *self regulating beam* resembles the active beam in that it is still used as diffuser as well as cooling device but works with a temperature delta of 20-23°C making it possible for it to use free cooling up to 20°C. Further the beam is designed so that it transfers cooling to the air without the use of mechatronic control devices, reducing the cost for such in comparison to the traditional beam. It has also been argued by the developer that the self regulating piping is in no need for thermal insulation due to the higher temperatures on the water, cutting down on the cost of both investment and installation costs. Since the return temperature in this case is equal or almost equal to the requested indoor temperature of the occupied zone a slightly larger cooling fin is needed, this means that in general, the self regulating beam tends to be slightly bigger than the active beam for the same delivered power. Further, as stated under *Current system*, the water temperature delta is adjusted from 9-19°C to a delta suitable for the beam used. Therefore, the alternative system is assumed to employ the same piping equipment and the same temperature delta of 9-19°C before the shunt. [1]

2.4 Programs

2.4.1 Revit MEP

Revit MEP is a Building Information Modeling (BIM) supporting software developed by Autodesk, a 3D modeling program where MEP refers to the Mechanical, Electrical and Plumbing engineers who are provided specific tools to design complex building systems [1]. This was the program used for modeling the systems in this thesis and an analysis of the program itself was performed to communicate opinions on the function and usability.

2.4.2 CES EduPack

A tool for evaluating the *environmental impact* of different materials, modes of transport, manufacturing and waste is CES EduPack, created by Granta Design [2]. It is a software that provides extensive information on material properties and processing, and is used to scheme, compare, and apply that information for a specific product. The possibility of input of different required material characteristics simplifies the search for a material most fit for a specific purpose. The ECO Audit Tool in CES EduPack is an effective tool used to calculate the energy and carbon footprint of a product at different stages in its life cycle and clearly present it with graphs and charts and enables automated and clear categorization and environmental impact in all stages of the life cycle. CES EduPack was used partly for the extensive information database on materials, uses, manufacturing methods and disposal possibilities, but also for the easy to use analysis and clear presentation.

2.4.3 IDA ICE

IDA Indoor Climate and Energy (IDA ICE) is a BIM supporting tool for dynamic simulation of indoor climate and energy, developed by EQUA Simulation AB [3]. According to EQUA, it is a "multizone simulation application for accurate study of thermal indoor climate" which can be performed both for distinct zones and to evaluate the energy consumption of an entire building. It is used for calculating and reporting the considered systems' energy demand due to climate requirements, and the user interface makes it easy and efficient to compare different systems and results.

2.5 Defining the functional unit

When performing an analysis of a product or system over its life time, it is necessary to determine a *functional unit*. In order to compare two products and determine if one is environmentally better or more economical than another, both products has to meet the same needs or be related to the same function. The functional unit describes the usefulness, or technical benefit, of a product and helps to make a fair comparison and delineation of two different product systems. The functional unit in this case is a *comfortable thermal climate,* as described in Arbetsmiljöverket's regulations on workplace design, AFS 2009:2 [1]. This would apply both to offices, open plan offices and meeting rooms. The objects of investigation were admittedly already determined as the CBC and the CBS cooling beam systems, but the hypothesis is that both types of systems give so similar a climate that they are considered to provide the same functional unit, yet involve other costs and different energy consumption. The functional unit would therefore be provided by the two cooling systems with either CBC or CBS cooling beams.

2.5.1 Comfort or discomfort

The requirement of a comfortable thermal climate is a generally formulated term of functional requirements, and what temperature that is acceptable must be evaluated case by case. Therefore, an assessment of the whole situation is required to apply the rules. Inconvenience and discomfort of cold or heat cannot be judged solely on the measurement of air temperature, as the perceived temperature depends on several factors. The climate factors are air temperature, radiant temperature, air velocity and humidity. Work intensity and clothing are other factors that influence climate experience. Activity is measured in met (1 met = 58 W/m^2 or 50 kcal/m^2h for sedentary work) and the thermal resistance from clothing is measured in clo (1 clo = 0,155 m^2 °C/W or 0,18 m^2h °C/kcal), (Gagge et al., 1941) [2].

In general, in physical light and sedentary work, comfort is achieved at typically about +22°C in normal clothing, or at about +24°C in a light summer clothes. It is necessary to ensure that the thermal climate is further examined if the air temperature is more than about +26°C for a longer period. The examination is preferably done by means of the standard SS EN ISO 7730 (AFS 2009:02, §29 p60). In this case, this examination aims to ensure that the thermal climate is similarly comfortable with both systems [3]. Discomfort occurs even at small deviations from the ideal climate as the body's heat production is low. A feeling of distress that causes the discomfort occurs when one part of the body is cooled and the temperature distribution on the body surface becomes uneven. This might be due to too high air movement created by the ventilation system or cold drafts, cold floors or walls or an uneven temperature distribution in the room.

2.5.2 Performance

If the climate diverts extremely from the ideal climate it will affect the body physically, numbness in fingers being only one example of an effect that directly affects office work. Apart from that there are also psychological effects from a non-ideal climate, which among other things includes impaired memory, motivation and concentration. The report "Effects of workplace thermal conditions on safe work behavior" by Ramsey et al., 1983 [4] shows that these psychological effects increase with greater thermal load, Seppänen et al. (2003) [5] found a more specific 2% decrease in performance per degree °C rise of temperature above 25 °C. This was investigated and evaluated in Climate and Performance through Measurements.

The human body cannot adapt to temperatures lower or higher than a certain temperature range, which is why people working in extreme conditions has to dress thereafter, nor can the body adapt to a poor indoor climate even if it is accepted and people get accustomed to it. The International Ergonomics Association defines ergonomics as “the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimize human wellbeing and overall system performance” [1]. In other words, workplace ergonomics would be fitting the job to the employee instead of vice versa. Every workplace is different and everyone has different preferences regarding their workplace. It could be concrete things like the chair height or whether it is soft enough to sit on, table height or light. Some people feel more comfortable working in complete silence, while others wants background noises to keep the concentration up. Ergonomics is commonly used for designing for the user which directly applies to things like an office chair. Aspects to take into consideration would be usability for different users with different characteristics, such as a person’s length or task to be performed while sitting on the chair and the possibility to re-set chair height for example if the seats are switched [2].

The same thinking path is applied to the more abstract aspects of workplace design, such as light, sound and thermal climate. To evaluate whether a workplace has a good indoor climate is difficult as it depends on many factors; subjective as well as objective, personal preferences as well as environmental factors. As for designing an office chair the ergonomic thinking path applied for thermal climate says that this is something that the user should have the possibility to change to fit their personal preferences. A poor indoor thermal climate and no possibility to personally affect it could mean physical symptoms like a stiff neck, blue fingers or a more subjective feeling of slight discomfort without necessarily knowing why. Even unnoticed these things steal attention from the everyday tasks which in turn decreases performance, which makes it important from several viewpoints to ensure a good indoor thermal climate, comfort and performance connected costs being two examples. The following chapter discusses the connection between the indoor climate and the performance, and addresses the invisible economical issues this causes.

3.1 Climate and performance

“Buildings that contain housing, work areas or similar spaces where people spend time, shall be designed so that a satisfactory thermal indoor climate can be obtained” according to the Swedish National Board of Housing, Building and Planning, BFS 1998:38 6:41.

Today the time spent indoors is about 80-90 % [3] and a big part of that time is the time spent at work, for that reason it is important to ensure that the indoor environment is satisfactory to as many as possible that spends time there. Indoor environment is of course partly expressed in terms of psychosocial aspects and such but also physical aspects as light, sound level, ventilation and temperature. The Swedish National Board of Housing, Building and Planning (BFS) [4] suggest guidelines or limit values, in connection to the above citation from 1998:38, to evaluate whether there is an appropriate thermal climate in an indoor area. Those suggestions include among other things a targeted operational temperature of at least 18ºC, a surface temperature on the floor in the occupied zone of between 16 to 27ºC and an air velocity in the occupied zone below 0.15 m/s. Regarding offices, these requirements should be possible to achieve with normal window area, normal heating and the effect of thermal bridges, taken into account when designing the building. There are of course many regulations and suggestions on the thermal indoor climate and how to achieve it, examples being the Work Environment Authority's (AV) [5] Writers Collection (AFS) 2009:2, *Workstation design, regulations on air quality, ventilation and thermal environment* and the Work Environment Act (AML). AML is a work environment law of which the fifteenth edition was published in collaboration with Arbetsmiljöforum January 1st 2010. The work environment characteristics are described in Chapter 2, § 3 "the work room must be arranged and equipped so that it is suitable from an environmental standpoint" [6]. 3-8 § are generally designed regulations on various factors affecting the physical environment, and 4 § states that "the labor hygienic conditions of air, sound, light, vibrations and such shall be satisfactory."

Per Fahlén, who is a Professor of Building Technology at Chalmers University of Technology, suggests about indoor temperature limit values that follow the regulations declared by law and other general guidelines, but adds an aspect so far not mentioned; the performance. He means that an appropriate thermal indoor climate is important for good health, wellbeing and performance much because of the large amount of time spent indoors, good health and wellbeing being *psychological* factors affecting the mood and thereby performance. A person with a high level of general job satisfaction is or can be motivated to work more efficiently, but if psychological or physical demands exceeds a person's capacity over a longer period of time the self-confidence, motivation and thereby performance decreases. The different climate regulations states that people generally feel optimally when the indoor temperature is between 21 and 25ºC, not to mention aspects as operational temperatures or draughts, and the same goes for performance. It is if the temperature rises to above 25ºC or decreases to below 21ºC that the performance quickly impairs [7][8]. The fact that people exposed to temperatures that are only slightly lower or higher than the optimal temperature are not performing at their best ability has also been examined in several other studies, some are compiled in Figure 3. A higher value on the y-axis means a lower performance by the corresponding percent.

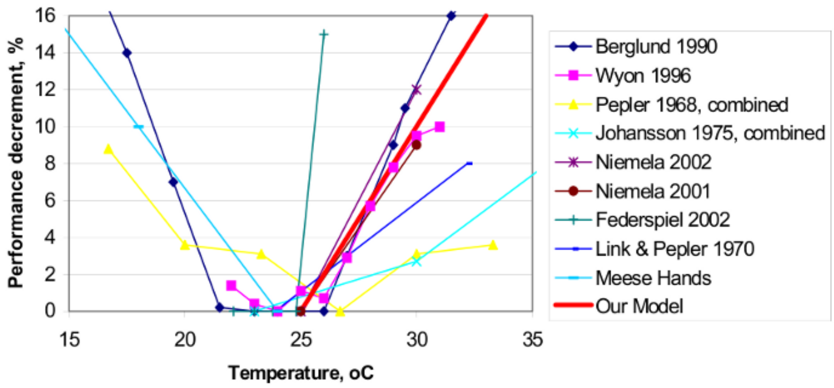


Figure 3: Performance decrement % at various temperatures, grokcode.com [9] 2012-05-30

One example is an ergonomic analysis by Pilcher et al. with the goal to examine the effect of higher or lower temperatures, as earlier studies showed these performance-versus-temperature tendencies but did not present any conclusions from the extensive test results. It showed that hot and cold temperature exposure resulted in a 7.61 % performance decrease in comparison with the neutral temperature condition (Pilcher et. al., 2002) [10]. Another example is a statistical analysis of ten studies assessing the average relationship between temperature and work performance showing a 2% decrease in performance per degree Celsius over 25°C (Seppänen et al., 2003) [11]. Federspiel et al. showed in their study *Thermal comfort models and complaint frequencies* 2003 [12], a summary report based on a previous extensive study from 2000, that no significant affect on productivity was found between 21,5 to 24,75°C and the complaint rate was very low between 22.2 to 23.9°C. Therefore, a thermally neutral temperature, with the highest comfort and performance level, would be between 22 and 24°C.

The conclusion is that to subjectively *feel* healthy positively affects the wellbeing and acts as a psychological incentive for performing at a higher level. "People who feel good are performing well" (Setterlind, 2004) [13], which not only apply to the psychosocial work environment. Every workplace is different and every employee has different wishes and demands to feel comfortable, for example chair and desk height due to personal length, but also light, sound and temperature. Some people feel more comfortable or concentrated working in complete silence, while others wants background noises. In the same way some people wants or needs to work in heavy clothing such as suits or safety clothes and therefore wanting the room temperature to be slightly lower than someone working in jeans and t-shirt. The possibility to individually control the climate at the personal workplace is one solution to try to adapt to the differences in wishes and demands, even though it is a more expensive climate control system it might have such positive effects on the performance it is the more economical solution in the long run.

To be able to mark out how to create a comfortable and motivational workplace for optimal performance it is necessary to state what aspects that could possibly decrease comfort and motivation. Not feeling healthy at a workplace could be caused by several factors that might not even be connected to the workplace itself such as personal or family reasons, but also factors such as the psychosocial climate at the workplace, causing uncomfort or even stress. The workplace related physical aspects on the other hand, like the physical climate, are also included in the work environment. Stress caused by the physical climate at the workplace could possibly mean a risk of musculoskeletal disorders and health risks if the temperature is *much* lower or higher than the optimal range. One example being that the Labor Inspectorate, by referring to 13 and 14 § in AFS 1995:3 when inspecting a work environment with questionable thermal climate, requested an employer to retroactively correct and improve the work area so that an appropriate thermal environment was gained. This was to ensure that the employees were not subjected to draught and such causing medical issues. The probability for such a heavy body reaction is low, headache and concentration difficulties being more probable results of a poor physical work environment, which leads to a decrease in performance and thereby economical issues. Sven Setterlind further comments that ”the stress does not necessarily mean that you are having problems, but that you are very well aware of the risks and that stresses you”. Of course, the work environment is a complex structure of many aspects of different nature, thereby also applying to the possible workplace related reasons for uncomfort or stress, but the focus in this work is the physical climate. A decrease in performance does lead to economical issues in the long run, though this is an invisible cost. A statistical analysis at Lawrence Berkeley National Laboratory of 24 studies of climate and performance during office work showed that the decrement in performance can be calculated with Equation 1. [14]

$$P = -5{,}5893 + 0{,}2394 \cdot T_F - 0{,}002824 \cdot {T_F}^2 + 0{,}00001068 \cdot {T_F}^3 \quad (1)$$

where P is productivity relative to the maximum value and T_F is room temperature in Fahrenheit. As work performance is connected to both the physical and the psychological wellbeing it is interesting for a business to evaluate the economical gains from a better and perhap more expensive climate system. For example, if the performance level in a specific temperature is 95%, the hourly loss can be calculated with a 95% decrease of the employee’s hourly salary. At a performance level of 100%, the hourly loss would be 0. By connecting the individual’s situation to effectiveness and quality aspects stress and illness are raised from the individual to an organizational level. A comfortable thermal climate is therefore something that does not only ensure the comfort of the employees and their performance, but is also by that directly connected to the company’s economy.

4 CLIMATE MEASUREMENTS

The Swedish National Board of Housing, Building and Planning, has stated in BFS 1998:38 6:41 [1] that buildings "shall be designed so that a satisfactory thermal indoor climate can be obtained". But what is a satisfactory thermal indoor climate? Validating that *people feel good* in a specific workplace is difficult because of the many individual preferences affecting the general view, discussed in Climate and performance, but also the differences in work tasks, clothing, location with regard to cardinal points etc. Though, this validation is important to confirm both systems' functionality, and if people feel good – they are performing well (Setterlind, 2004) [2]. The intention with measuring the climate is therefore to evaluate the comfort level to ensure that both office buildings, thus, both cooling systems, provide a comfortable thermal climate. The goal is to investigate the climate in the occupied zone in office environments where the cooling systems are equipped with on one hand CBC cooling beams and on the other hand CBS cooling beams, to experimentally verify that the functional unit is achieved with both alternatives. Rules and temperature range recommendations for the climate in buildings are formulated by Boverket and Socialstyrelsen, in Boverkets Nybyggnadsregler BFS 1988:18 [3] and Boverkets författningssamling BFS 1993:57 [4]. The measurements should be performed in accordance with these rules and used to examine whether the temperature levels lies within BFS's recommended range. If the climate measurements show that a comfortable thermal climate is obtained in both cases the difference in system function is none, but there might be differences in life cycle cost or environmental impact that makes one or the other more desirable.

Necessary to mention is that the investigations were performed in two different office buildings. Since the existing system is located in Hagaporten III in Solna examinations of that system could be performed without obstruction, but the theoretically replacing system had to be measured elsewhere. Because of that it was necessary to find another, corresponding office building with the theoretically replacing system to make the climate studies in, and as the measurements thereby were performed in two different office buildings there should be no comparison between the results. There are differences in types of walls, windows as well as ceiling and flooring that affect the outcome, and there are differences in equipment and lighting. Also, the two buildings are located differently, where insulation from other buildings and location with regard to cardinal points also affects the outcome as of solar radiation. The two systems were of course respectively adjusted to fit these differences as well as the employees' preferences and the type of work to be performed in both buildings. The test result most true to reality would be gained from performing the investigations in identical rooms, for example at the test facilities at the manufacturer, which unfortunately was not possible for such a small investigation. Therefore it was decided to perform the climate assessment in two different office buildings, one equipped with a cooling system with CBC beams, and the other equipped with CBS beams. The climate measurements were made solely to ensure that a comfortable thermal climate was obtained with both system types, regardless of the different adjustments that the two office buildings once needed. Notable is that these adjustments are possible to make for any of the systems retrospectively. The differences in surrounding factors were taken into consideration and the measurements were adapted to these conditions as far as possible.

4.1 Measurements

It was assumed that these dimensioning rooms are used business days from eight to five with a one hour lunch break in the middle of the day, thus, eight hours in use per day. As the utilization rate varies depending on time of day the measurements should be performed during a whole day, though variations depending on day of week or period of year was not taken into account. More importantly the dimensioning day was chosen based on outdoor conditions, to get the worst case scenario. Temperature graphs over the last five years shows that the temperature generally is highest in July, and Taesler (1972) [5] showed that the solar radiation is highest in June, measured in Wh/m2,day through double glazed windows in Stockholm (latitude 59° 21'N, longitude 18°4'E). An optimal dimensioning day would through that be by the end of June. The measurements should be carried out in the occupied zone, i.e. within 0.6 meters from the wall/external wall and 1 meter from the door / window. The measurement points must be at the heights 0.1, 0.6 and 1.1 meters above the floor depending on the measurement type.

Klimatdata för Sverige (free translation: Climate data for Sweden) by Taesler was published through a collaboration between Statens Institut för Byggnadsforskning (SIB) and Sveriges Meteorologiska och Hydrologiska Institut (SMHI). The noteworthy age of this publication (1972) could be discussed as a source of error, but it presents the results of extensive research over a long period of time and was after a discussion considered accurate enough for the minor impact it could have on the climate assessment, as its purpose was to point out when it would be most advantageous to perform the measurements.

In this case it was considered necessary only to carry out an indicative measurement, primarily because of the complexity inherent in performing a good detailed measurement with the large amount of varying surrounding factors in the two office buildings. As the operational temperature is the mean value of the air temperature and the radiant temperature this test result that would to a large extent be dependent on the factors that are specific for the different rooms and locations. Because of that, neither the operative nor the radiant temperature was taken into consideration. An indicative measurement was considered adequate enough to demonstrate the climate in the relevant rooms. Therefore, the air temperature [t_{air}] and the vertical temperature difference [Δt_1] were measured with *Mitec SatelLite-T temperaturlogger* at certain points above the floor. This was to get both the room temperature and to examine whether the temperatures at different levels were constant as this affects the perceived comfort. The logging of air temperature was performed during one dimensional day at both locations. The air velocity [v_{air}] is usually measured with tracing smoke, something that was not used in this case to avoid disturbing the everyday job. Instead, the air velocity was measured with a manual *TSI* at certain points by the cooling beam to examine whether it causes draught. Since the results from the measurements can be directly connected to the performance level as described in *Climate and performance*, the economical gains or losses with the two systems could be evaluated. Important to take into consideration then is that there might be differences in personal opinions on the desired climate in the two office buildings. In one office it might be preferred to have a lower room temperature, which if not considered would appear as a difference in system function or a performance decrease cost.

4.1.1 Air velocity

The velocity of the supply air entering the room is of importance for the quality of the climate. Especially in this case, where each beam acts as a diffuser, which means that the cooling of the temperature is done by cooling the supply air enough to create a mixture resulting in an acceptable temperature in the occupied zone. Since the beams are located directly above the desks in the offices and the suggested new design contains a different number of beams and hence a different orientation of them in comparison to the orientation of the desks, that are assumed to stay unchanged, it is of importance to study how the air speed differentiates in the area beneath it. Figure 4 shows how an active beam is designed to distribute the air flow and consequently, the air flow differs in the area beneath the beam.

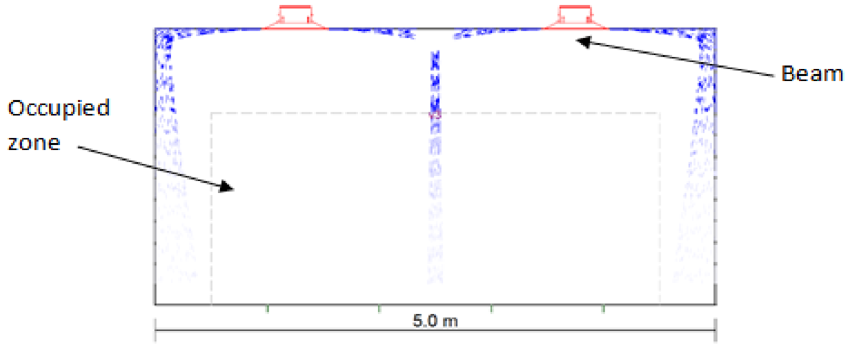


Figure 4: Air flow from beams

The air velocity measurement was therefore performed by measuring at nodes arranged in a grid on different heights, similarly in both offices; level 1 located just underneath the ceiling at 2,8 m, level 2 located at 2.1 m and level 3 located at 1.6 m. In the CBC beam system, the beams in the office landscapes are of equal size and located at a constant distance of 2.1 m. The grid was set up with six nodes on each level, as displayed from a horizontal view in Figure 5. Three of them right underneath the beam's nozzle and three in a line in between two beams.

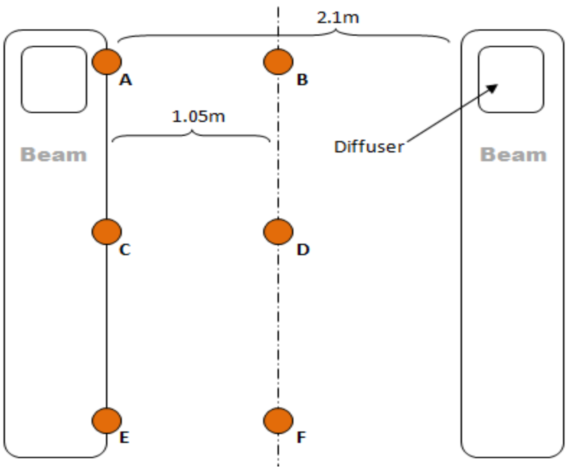


Figure 5: Measuring grid

The CBC beam measurements were performed in two sessions on June 21st, the first at 9^{00}-9^{30} and the second at 16^{00}-16^{30}, where the time interval is due to the time necessary to conclude all the measuring as they are done with the same instrument. Similar measurements were performed for the CBS beams, but on June 29th. The equipment used is only capable of measuring the air in one direction. In order to provide richer data two measurements were performed in each node, one to measure the horizontal flow and one measuring the vertical. The total air speed was then calculated for each node. From the data a number of key values were calculated and extracted. In order to give an easily overlooked view of how the air speed differs in the grid the values measured in every node (horizontal and vertical) were calculated into a total air speed at each node. This is done for both the early and the late session and is then combined to form a mean value for each node over a typical day. This provides inputs on how the air moves depending on its distance from the diffuser. To get a good picture of how the air moves throughout the occupied zone the average value of the air speed on all the levels are calculated. Using an average of six nodes per level reduces the effect of eventual irregularities that possibly can be traced back to mistakes or exterior factors in the measuring. Since the value beneath the diffuser is noticeably higher than the other nodes, especially at the higher levels, the average is calculated by median.

4.1.2 **Temperature**

In order to understand the how the temperature affects the sensation of the climate two thermometers are placed within each office and the test environments in both offices are set similar to each other. The thermometers are equipped with loggers set to register the temperature every two and a half minute under a designated period of time. The logger combines every value into mean values for every five minutes. The thermometers measure temperature on a workspace located between two beams on 1.1m respective 0.1m above the floor. This provides a good idea of both the absolute temperature at the workspace and its fluctuation as well as the difference between typical torso and foot height of a person stationed at a desk. The time period for the logging is aimed to show how the temperature behaves throughout a typical day, including both weekdays and weekend days. Because of this the CBC system was logged from Thursday the 21th of June 2012 (the 22th being a holiday with low expected attendance at the office) until Monday the 25th. The CBS system was measured Friday the 29th to Monday 2nd of July. This way, both the measurement sessions registers over two normal weekdays and over one weekend.

4.2 Evaluation of results

When the measurements have been performed an evaluation of the results should be carried out. ISO 7730:2005 [6] describes a method for evaluating the thermal environment and conditions of thermal comfort; calculating the PMV and PPD indices. The PMV index indicates the value of a person’s thermal experience when working in an environment, while PPD plots the percentage of people in that area who would be unhappy with the conditions. The PMV index should be calculated as a mean value over one hour, and necessary input information is first and foremost to decide the activity level and clothing insulation, where after the air temperature, radiation temperature, humidity and air velocity should be measured. The PMV and PPD indices give a clear view on the perceived comfort but the needed input values are site specific and in many aspects would in this case show differing results without, in reality, necessarily meaning a differing comfort level. This evaluation method is the most accurate and recommended for these types of climate evaluations, but will due to the many site specific tests solely be used for indicating the comfort quality similar to the measurement itself. The PMV and PPD indices are then translated into a quality level, see Table 1.

Table 1: Indoor climate quality values

	Value in quality category		
Indoor climate factor	A (PPD<6%)	B (PPD<10%)	C (PPD<15%)
Floor temperature [°C]	19-29	19-29	17-31
Air temperature [°C]	21-23 (23,5-25,5)	20-24 (23-26)	19-25 (22-27)
Vertical temperature difference [°C]	<2	<3	<4
Air velocity [m/s]	<0.2	<0.2	<0.2

The BFS and BBR rules also provides design guidelines for creating a good indoor climate, that includes guidelines for air velocity, air temperature differences and floor temperature, which is close to the ISO 7730 requirements. These guidelines are used for comparison of the evaluation results. Regarding desired test results, Federspiel et al. proposed in a study from 2000 a complaint prediction model based on extensive studies and climate measurements and showed in their study from 2002 that no significant effect on productivity was found between 22.2 to 23.9°C, which led to the conclusion that a thermally neutral temperature would be between 22 and 24°C. The comfort and performance was optimal within this temperature range. [7]

4.2.1 **Air velocity CBC system**

The measuring indicates that the air speed decreases with distance from the diffuser. As displayed in Figure 6 the air speed at level one is highest underneath the diffuser at a value of 1,36m/s and no node on this level the registers a value higher than 0.6m/s, less than 50% of the value in node A.

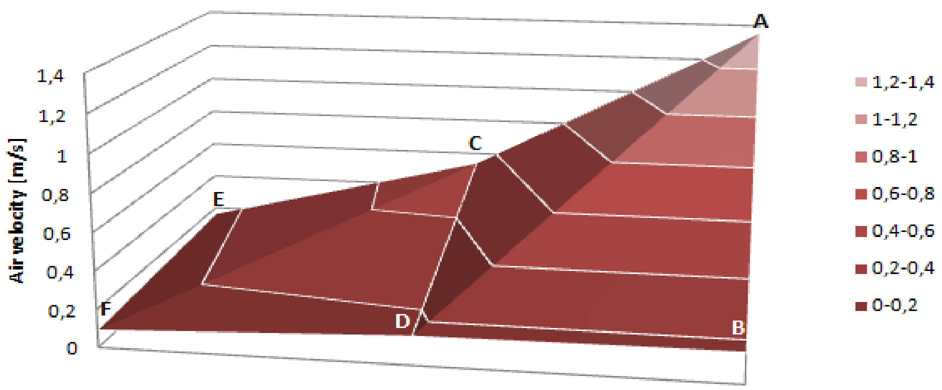


Figure 6: CBC Air velocities at level 1

Respective values for level 2 and 3 are displayed in Figures 7 and 8. The value in these levels are of more relevance since level 2 is bordering the occupied zone from above, and level 3 are located at the height of the head of a sitting person. In can be noted that not one of the nodes in level 2 or 3 registers a value of more than 0.16 m/s and on average, both levels register a speed of 0.1 m/s. Key result values are displayed in Table 2.

Table 2: CBC Key results CBC

CBC				
Median velocities [m/s]		Max velocity [m/s]		Node
Level 1	0.16	Level 1	1.36	A
Level 2	0.1	Level 2	0.16	A
Level 3	0.1	Level 3	0.16	A

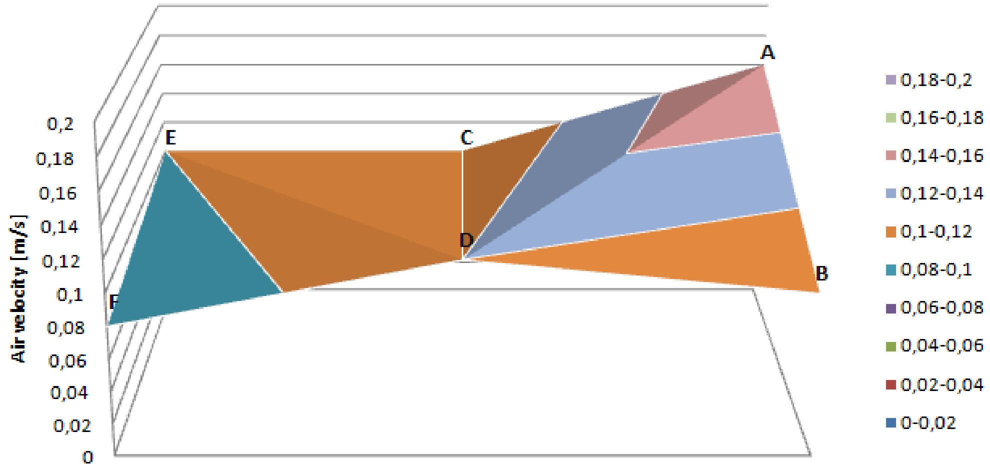


Figure 7: CBC Air velocities at level 2

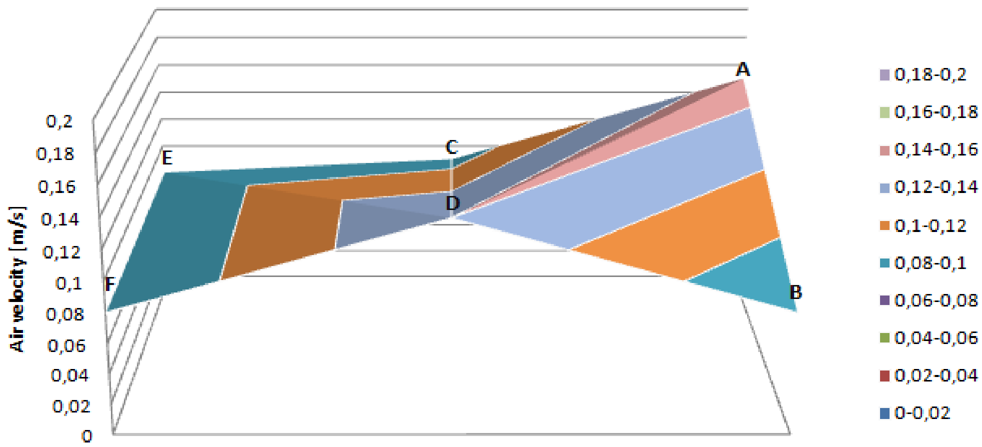


Figure 8: CBC Air velocities at level 3

4.2.2 **Air velocity CBS system**

Due to limitations in time during the measurement section of the CBS-system only one measurement were performed, whereas the results from the CBC measuring are based on an average between two sessions. The CBS measuring were performed at 15^{00} on the 28^{th} of June 2012. Figure 9 shows the air speed at ceiling level. In general, a comparison can be made between these results and the corresponding measurement done on the CBC-system, concluding that the air flow in general is at lower levels.

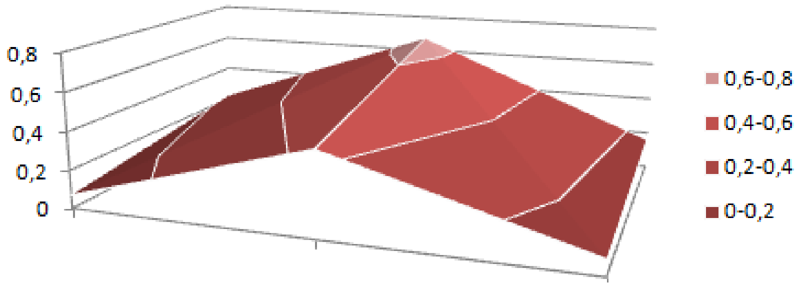


Figure 9: CBS Air velocities at level 1

Figures 10 and 11 displays the temperature on level 2 and 3 located at the same heights as at the CBC-system, it can be concluded that these results do not follow the same ordered pattern as the CBC air flow. Notable is that some values in level 3 are greater than at the same node in level 2 which might feel a bit odd considering the greater distance to the source. It can also be noted that the value on node A, closest to the diffuser, does not dominate in any of the levels in the same way is in the CBC-system. Further and more important is that none of the nodes displays a value higher than 0.2m/s in the occupied zone, and the mean level values are in the acceptable span as displayed in table 3.

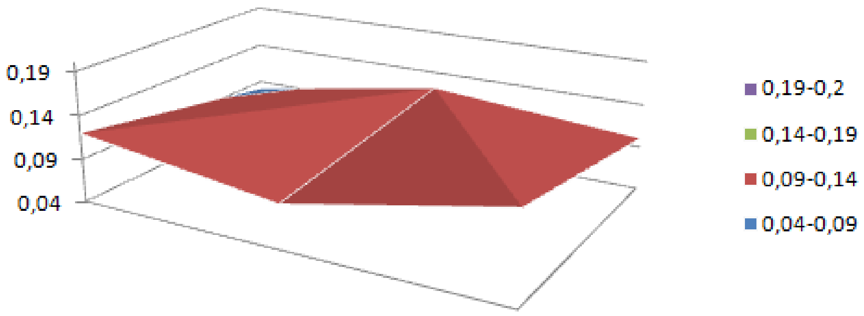


Figure 10: CBS Air velocities at level 2

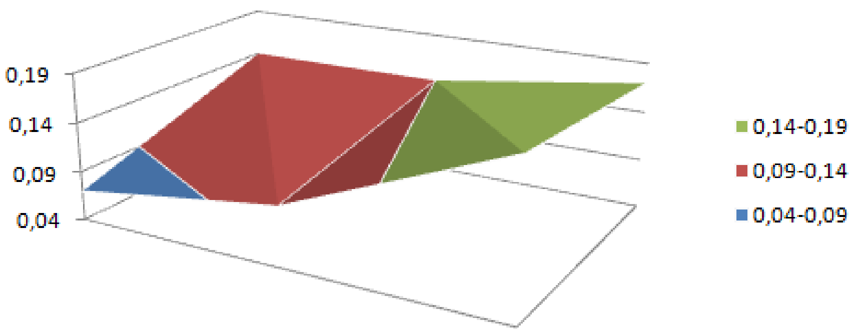


Figure 11: CBS Air velocities at level 3

Table 3: Key results CBS

CBS				
Median velocities [m/s]		Max velocity [m/s]		Node
Level 1	0.19	Level 1	0.43	D
Level 2	0.11	Level 2	0.14	B
Level 3	0.14	Level 3	0.17	A

4.2.3 Temperatures CBC system

Figure 12 and 13 shows the absolute temperature on each height. It can be noticed that the temperature generally fluctuates between 22 and 23.5°C. In addition, a comparison between the graphs shows that the two curves follow the same general pattern, both of these facts indicates that the provided climate in the occupied zone is qualitative. To further clarify the difference between the registered temperatures figure 14 indicates the distribution of temperature difference. It can be noticed that in 10% of the time the temperature is similar (anomaly being less than 0.01°C). Further, temperature at 1.1m registers higher in 70% of the cases.

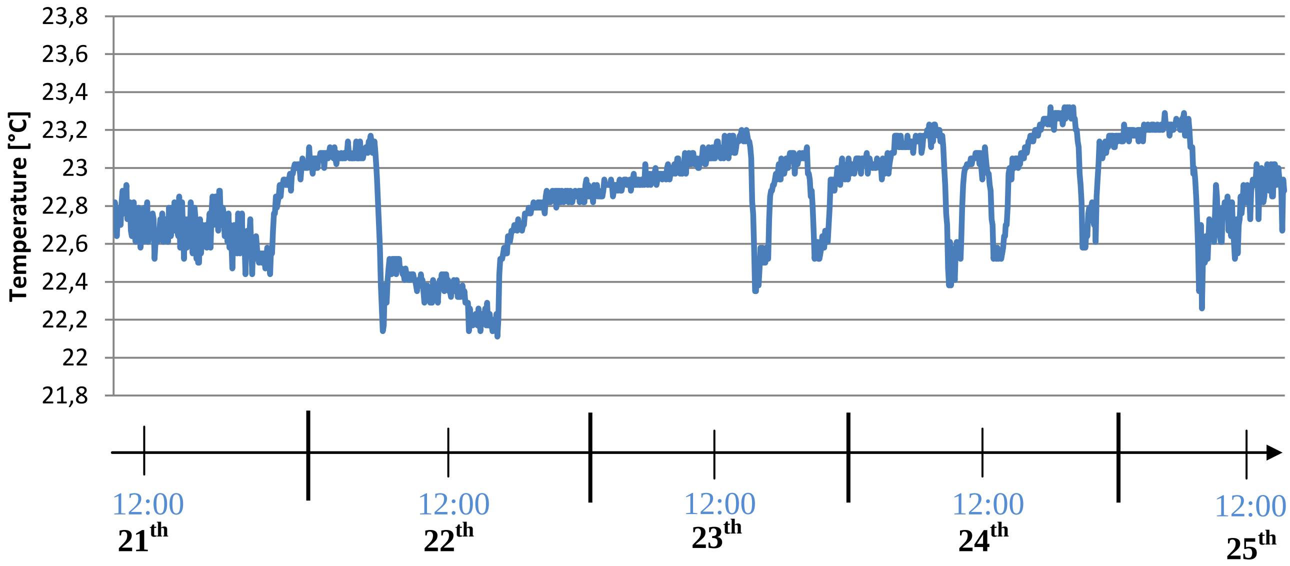


Figure 12: Temperature at H=1.1m

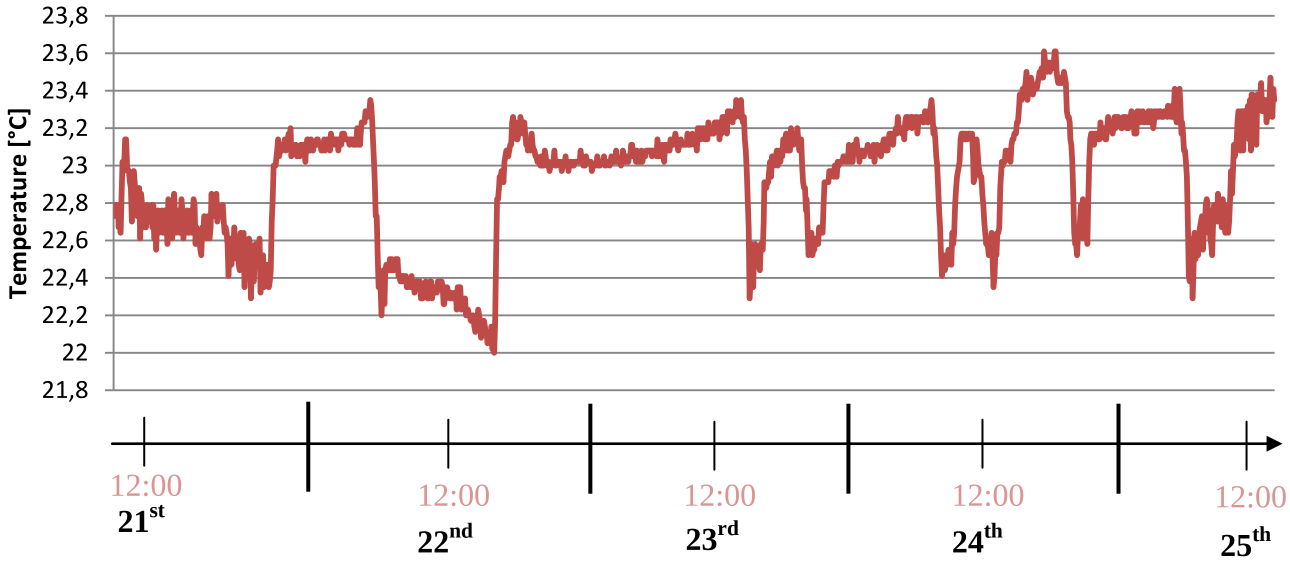


Figure 13: Temperature at H=0.1m

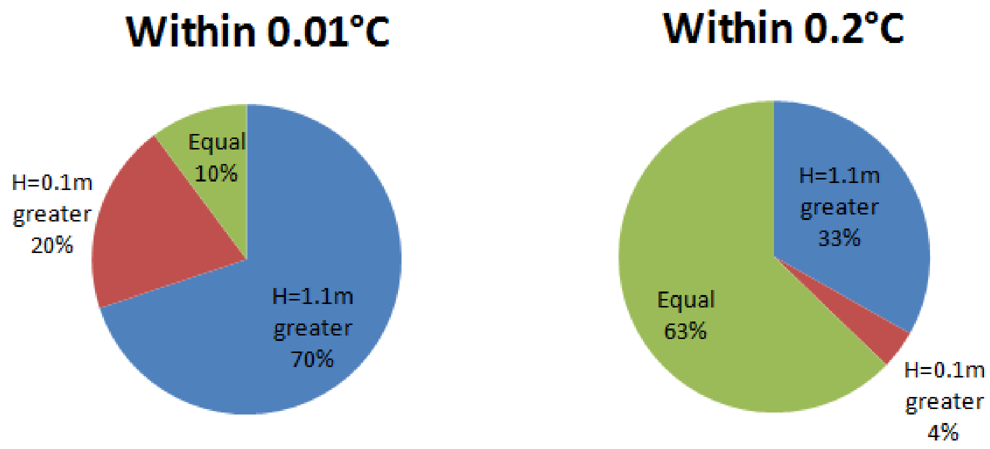


Figure 14: Distribution of temperature difference CBC system

Table 4 displays a number of key values obtained from the registered data. Values calculated and displayed are based on registered data between 8^{00}-17^{00}, in order to provide a clear image of a typical indoor day climate for days with low respective high attendance at the office. It can be noted that average temperature (both mean and median value) over the total period as well as for all days lies between 22 and 24°C and standard deviation on the 21st and 25th in this case being weekdays and therefore more significant for how the temperature behave under normal conditions, is 0.15 respective 0.32°C.

Table 4: Key values CBC-system

CBC	**H = 0.1m**			**H = 1.1m**		
Date	*Mean*	*Median*	*Standard deviation*	*Mean*	*Median*	*Standard deviation*
21st	22.7	22.7	0.08	22.74	22.73	0.15
22nd	22.36	22.25	0.15	22.33	22.35	0.17
23rd	23	23.02	0.18	23.01	23.11	0.22
24th	22.95	23.05	0.25	23.02	23.11	0.31
25th	22.79	22.82	0.16	22.1	23	0.32
21th-25th	*22.76*	*22.76*	*0.29*	*22.83*	*23.79*	*0.37*

4.2.4 Temperatures CBS system

The results from the measuring of the CBS system are obtained and presented in a similar way. Figure 15 and 16 displays the absolute temperatures registered at 1.1 and 0.1m. From regarding these graphs as well as the graphs in figure 11 and 12, it can be concluded that the temperature in the two offices lies within the same general span with generally in the interval of 21-23°C which is within the accepted interval.

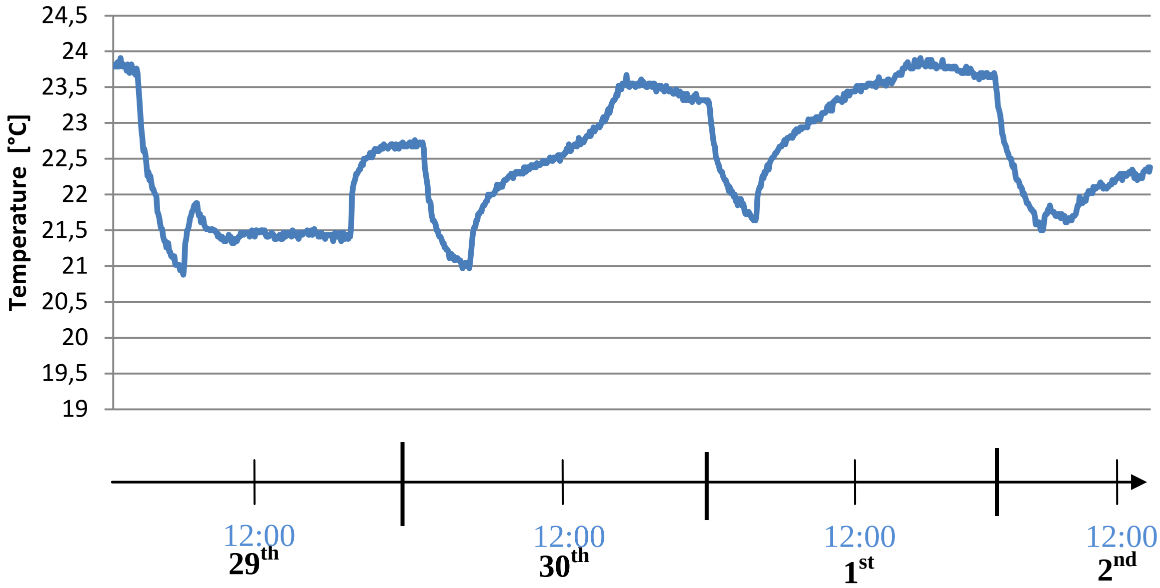


Figure 15: Temperatures at H=1.1m

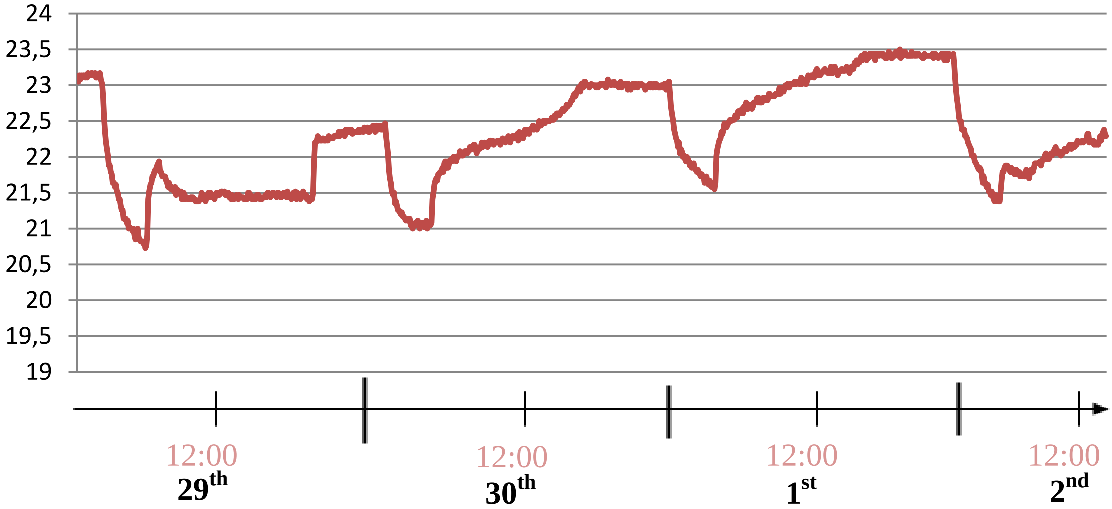


Figure 16: Temperature at H=0.1m

Figure 17 displays the distribution of the temperature difference between the two loggers. To give an idea of both quantitative and qualitative differences in temperature, two pie charts are included in the figure. It can be concluded that during 17% of the time, the difference is smaller than 0.01°C, whereas only during 37% of the time the difference is greater than 0.2°C. It can also be concluded that the higher thermometer tends to register a higher value.

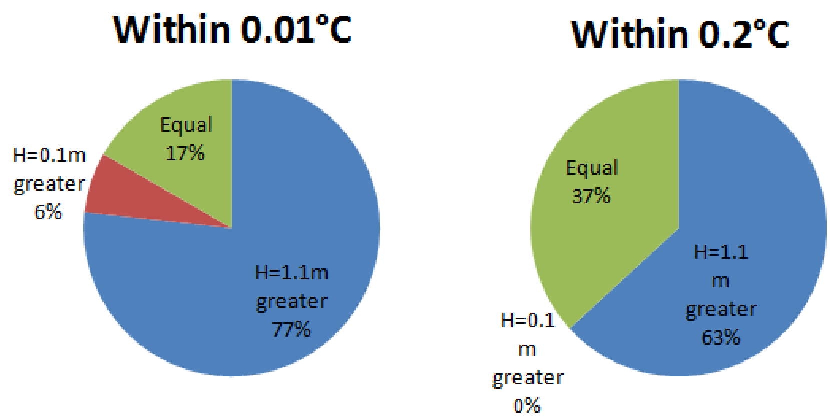


Figure 17: distribution of temperature difference CBS system

Table 5: Key values CBS-system

CBS	H = 0.1m			H = 1.1m		
Date	Mean	Median	Standard deviation	Mean	Median	Standard deviation
29th	21.45	21.44	0.04	21.44	21.44	0.04
30th	22.36	22.29	0.20	22.62	22.55	0.28
1st	23.05	23.07	0.21	23.31	23.41	0.31
2nd	22.13	22.11	0.16	22.17	22.14	0.20
28th-2nd	22.30	22.20	0.63	22.46	22.41	0.75

5 ENERGY CALCULATIONS

The climate measuring provides data necessary to map and define the performance of the substituting system compared to the current. The data obtained in these measuring focus mainly on the air quality in the occupied zone, but lack information regarding total energy consumption from the cooling system as well as how the new system will perform in the designated building when implemented with the stated initial conditions. Both of these parameters are of relevance for the LCC and needs to be accounted for. The purpose of the climate simulation is to provide these data. In general, when interpreting and evaluating the quality of theoretical results, it must be taken into consideration that the reliability is heavily questionable due to a large amount of assumption and simplifications embedded in the model. The strategy is therefore to compare the results of the model with the results of the modeling performed on the current system. The new model will be assumed to validate the new design if the results are in the same typical size.

When designing HVAC systems the performance is usually predicted by using software developed for these types of simulations. The software used for this simulation is IDA ICE, since it was used in simulations of the current. In IDA, the building is modeled within the program, by using pre fabricated elements for walls, slabs, roofs climate systems etc. All of these elements are customizable so that they resemble the real building in every way of relevance for thermal simulations. The model further includes effects such as weather, shadows casted by ambient buildings, heat transferred through occupants and electrical devices. The indoor climate analysis can generally be divided into two main categories depending on requested outcome. A *sizing analysis* are done in order to decide the peak loads during the systems life cycle, hence providing of a supposed “worst case scenario” that will form a boundary condition in the design of the system. A *yearly energy analysis* on the other hand, provides data on the annual energy consumption of the system in order to meet the demands requested of it. The results of a typical energy analysis can be measured in energy output or cost. In this case, the strategy stated above will be interpreted into two analyses. The first one determining that the system will be able to handle an accepted climate in an extreme condition, in this case a summer’s day with climate varying between 18 and 27°C. The second monitors the indoor climate over a year, determining the temperatures and providing the annual energy demand.

5.1 Model design strategy

Since the most essential function of the beam system regarded in this analyze is the ability to maintain a certain temperature, the new system will be designed primarily in order to provide the same cooling power. This is done by calculating the total cooling power of the current system in every zone by regarding number of beams in the particular zone and the amount of cooling power every beam are providing. The number of beams in the new system is then, for each zone, estimated by reversing the same process. Further, an important assumption is that the entire air supply in the entire model is supplied via the beams. The current system has been simulated with an expected air flow of approximately 1.5 $l/(sm^2)$. Hence the new initial suggestion of the new design will be aimed towards creating a flow with at least the same amount. Table 7 displays initial demands on the current system. With these demands in mind, the initial suggestion of the design of the new system will be performed with similar demands and verified within IDA.

Table 6: Demands on current system

Type	Quantity	Unit	Comment
Landscape 1			
Number of beams	60	pieces	CBC: L=2.4m; space between (rows)=2.7m
Cooling power (beams)	30	kW	500 W/beam
Cooling power (beams+air)	38	kW	640W/beam
Air supply	1,5	l/s/m2	
Occupants	60	ppl	7-17 weekdays
Landscape 2			
Number of beams	62	pieces	CBC: L=2.4m; space between (rows)=2.7m
Cooling power (beams)	31	kW	500W/beam
Cooling power (beams+air)	40	kW	640W/beam
Air supply	1.5	l/s/m2	
Occupants	62	ppl	7-17 weekdays
Office Cell			
Number of beams	1	pieces	CBC: L=2.4
Cooling power (beam)	0.5	kW	
Cooling power (beam+air)	0.64	kW	
Air supply	1.5		
Occupants	2	ppl	9-12; 15-18 weekdays (approx mean use)

The beams used in the new system does, similar to the current beam type, come in sizes varying from 1200 to 3600mm with 300mm interval, the investment value being constant and only dependant on the length of the beam. In order to cut the selection process short the needed beam is assumed to be in the interval of 2400 to 3000, leaving three possible candidates. The climate measuring shows that the CBS beam system works with satisfying results when implemented in a similar setup as the one in Hagaporten, but employs beams with rather different output. The CBC beam produces higher power than a CBS of similar size and air flow. A comparison can be made between beams of size 2400mm. with an air flow of 20l/s at 20°C the CBS produces a power output of 448W (excluding the power of the air), noticeably lower than the assumed output of the beam implemented in the current system at 500W with the same statistics. If the rather bigger, 3000mm CBS beam is used, an output of 684W (535W without the air power) are obtained with the airflow of 25l/s. This means that a total of 56 beams used in *Landscape 1* will provide the same total power, although a slightly higher airflow of 1,8l/s/m^2.

Changing the number of beams in the current system means that the layout needs to be modified. the measuring of the indoor climate at the CBS system concluded that the climate (temperature and air velocity) are satisfying regardless of if the beam is located right above a work station (represented by nodes A, C and E in the measuring) or if the work station is located right between two beams (nodes B, D and F). Therefore rearranging the beam grid is not assumed to have any effect on the climate.

5.2 Model geometry

The climate in the entire building will be represented by a number of type environments all with similar settings and demands, simulations will be done in one of each of these strategic *zones* to determine the energy demands by area unit, thus making an estimation of the total energy demand. First of all, all the office floors are assumed to be similar in terms of geometry, occupation degree and exposure to sun and weather. This means that only one floor needs to be taken into account Next step is to divide the building into thermal zones. A thermal zone is a segment of the building with assumed homogenous demands of cooling (meaning that the all the thermal loads; number of occupants, sun radiation on windows etc. are assumed to be unchanged throughout the zone). In addition all the cooling supply is assumed the same in each zone. [1].

Electing type zones are a multi step process and performed as such; since the entire cooling supply is divided on each floor into KB21 and 22 and these systems operate in parts of the building separated by walls, this works as a proper initial diversion. To limit the simulation only KB21 is taken into consideration, as it operates in the only part of the building that has exterior glazing with exposure to the south. It can also be concluded that the cooling system is divided into office areas and atriums (the later including both the open corridors and the two kitchen areas) were only the office areas are equipped with cooling beams. The office areas are divided into office cells, smaller rooms with only one beam each and an estimated occupation degree that vary during a typical day, and open landscapes employing a system of several beams and an assumed relatively constant occupation degree over the day. Finally, none of the office cells are exposed to external windows or walls and though they might vary slightly in size, they are considered to be identical from a climate/energy perspective. The open landscapes on the other hand, vary in terms of exposure to glazing in different directions and number of beams. Therefore the two landscapes are considered as two different zones.

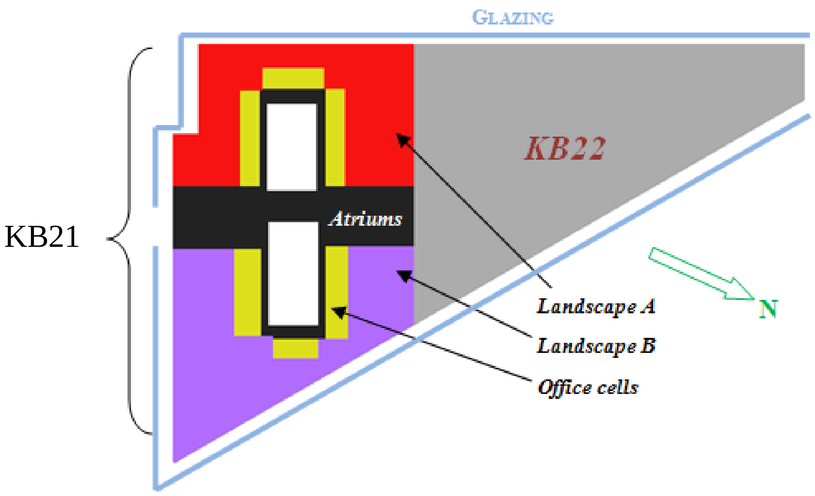


Figure 18: Plane view of office with elected thermal zones

These steps results in thermal zones displayed in Figure 18. Atrium areas are regarded irrelevant since they do not contain any cooling beams nor do they serve as working space. Hence, three type zones remains to be built into the model; two landscapes and one office cell. Figure 19 shows the model layout of the in IDA. The total numbers, regardless of it being energy demands, mean temperatures etc, are concluded by running the simulation for each zone and then adding each individual result to the total score.

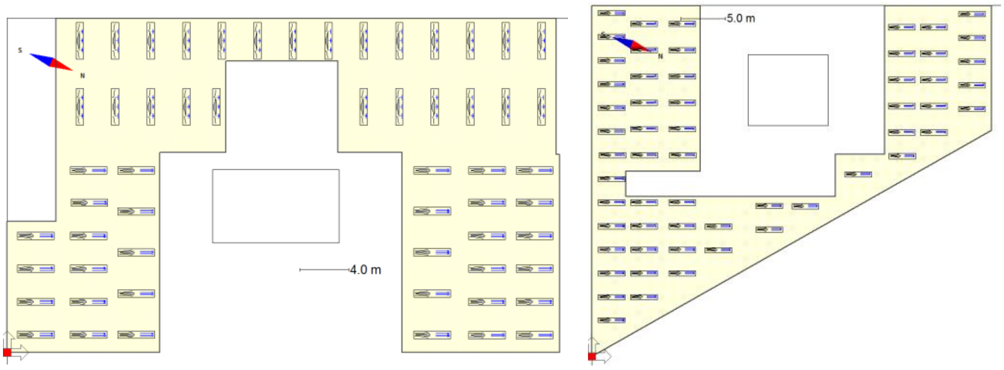


Figure 19: Beam layout in landscape A (left) and Landscape B (right)

Further, the closed office cells are all similar in design and ambient constrains, which means that only one of these are included in the model. The rest considered identical.

Geometrical data, as well as a majority of the technical data from the buildings climate systems and its components are obtained from the official construction documentations for Hagaporten III and are displayed in Table 7.

Table 7: Obtained setup data

Type	**Value**	**Unit**	**Comment**
Climate fluctuation	18-27	°C	Difference on one day, 26/6, Synthetic summer
Temperature setpoints	21-24	°C	Regulation for cooling beam and radiator
Occupation	1	Ppl/beam	1.0 met, 07.00-17.00 weekdays
Illumination	5	W/m^2	07.00-17.00 weekdays, 25% remaining time
Equipment (emitted heat)	75	W/ppl	Consumed power per occupant, 07.00-17.00
Cooling power	530	W/beam	Power at indoor temperature 24°C
Airflow (constant)	1.5	$l/s/m^2$	Approximately 20 l/s/beam
Supply air temperature	20	°C	19°C in LB, 1°C expected rise in supply air fan

5.3 Simulation results

Two types of simulations needs to be performed. First, the replacing systems ability to perform an acceptable climate needs to be verified. The requested outcome of this analyze is to conclude an optimal design for the new system. The results are evaluated by comparison to similar simulations done to the current system. The date chosen for this analyze is the 26th of June, in which the cooling demand is assumed to be the greatest and also the date chosen to simulate on when the current system was designed. Figure 20 shows the mean temperature of each hour of the simulated period obtained in the type zones.

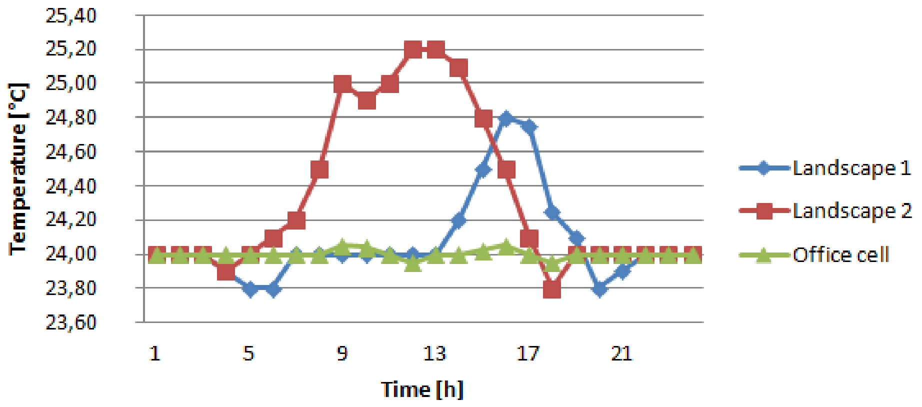


Figure 20: mean temperature during the 26th of June

The temperature is kept relatively constant on the controller set point of the cooling system in the office cell zone, while fluctuating more in the landscapes. It can however be stated that in all of the zones, the temperature is kept below 26°C during the entire day. The second simulation is performed over a year. This provides data on expected annual energy consumption and means temperatures for the zones for each month, giving a richer view on the climate in the zones. As can be seen in figure 21 the cooling system consumes most power in June, similar to the expectations on the current system. The total power consumption here is divided on beams and air handling unit (AHU) a device embedded in the simulation to represent the pre cooling of the air in the air treatment battery during warm months.

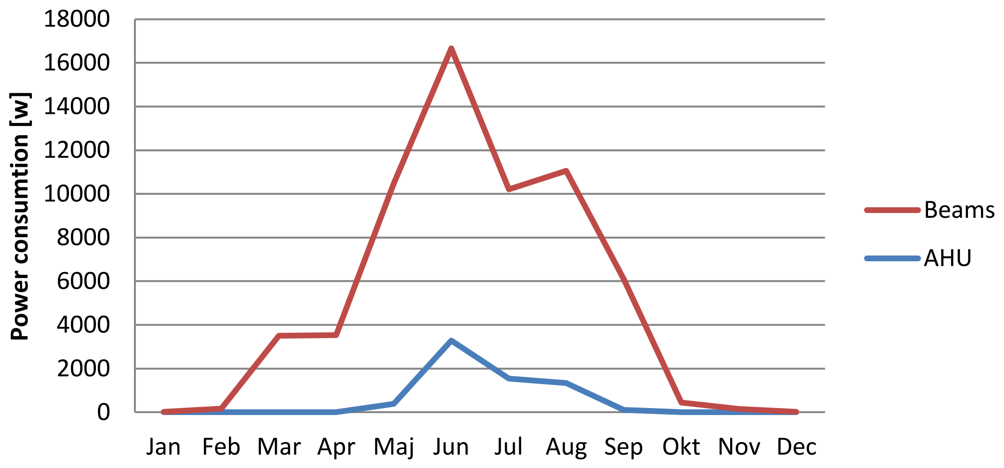


Figure 21: Consumed power each month

This consumption is equivalent to an annual energy consumption displayed in table 8. The annual energy consumption is calculated by multiplying the mean value of each cooling unit with the total number of hours equivalent to a year.

Table 8: Energy demand

Type	AHU	Beams
Mean power [kW]	0.55	4.6
Annual energy consumption [kWh]	4 854	40 667
Energy/area [kWh/m^2]	3.12	26.2
Total energy/area [kWh/m^2]	29,3	
Adjusted for utilization of free cooling when mean ambient temperature is below 20°C		
Mean power [kW]	*0.55*	*3.49*
Annual energy consumption [kWh]	*4 854*	*30 562.2*
Energy/area [kWh/m^2]	*3.12*	*19.6*
Total energy/area [kWh/m^2]	*22.8*	

The total amount of energy consumed is in the same typical size as the current system (25 vs. 22.8kWh/m^2) the simulation is assumed to be valid. Figure 22 displays the mean temperature in each zone for every month during the year. It can be concluded that in all the zones, the monthly mean temperature does not rise above 24 degrees.

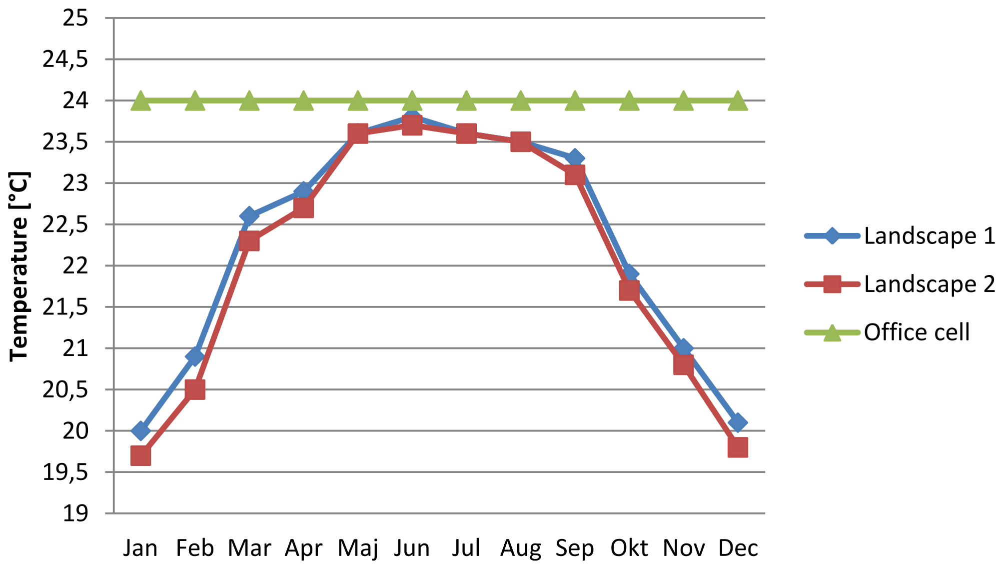


Figure 22: Mean temperature for each month

"The architects have to put pictures of texts on the walls, with information on wall properties, so that we get that information", a HVAC designer explains while working in AutoCAD.

Building Information Modeling (BIM) is a way to handle information from the design and construction process. For example, when working in extensive collaborations where architects, electricians and installation engineers etc. all contribute with their own model files for the same project a great risk is the information loss connected to it. As all contributors often work in different CAD programs it is necessary for them to export their model files into a neutral format, commonly IFC format, so that the files could be put together – often in two dimensional drawings. BIM work is a concept that includes CAD but extends from the traditional 2D drawings with three dimensional models, spatial relationships, light analyses, geographic information, manufacturing details and so on. It is said that BIM works in 5D, where time would be the fourth dimension and cost the fifth. All of which is information that otherwise would have been lost. BIM is a strongly recommended modeling concept that simplifies collaborations and reduces the time and energy spent on trying to pass the information through to the next step or the next involved designer in the process. Putting pictures of texts about wall properties on the walls and adding that information in each step would not be necessary, that information would follow with the wall itself.

6.1 Workflow

The office floors are equally structured which justifies the project delimitation to only model one floor, acting as the dimensioning floor vertically multiplied to simulate the building's complete system. For this matter the fifth floor was chosen as dimensioning and thus the base for modeling the two systems. The choice was made upon the existence of different kinds of office environments such as offices, open plan offices and conference rooms. Autodesk AutoCAD is a software application for computed aided design (CAD) and drafting in both 2D and 3D formats, and is the program in which the system design was initially made and merged with designs from other applications such as architecture and electricity.

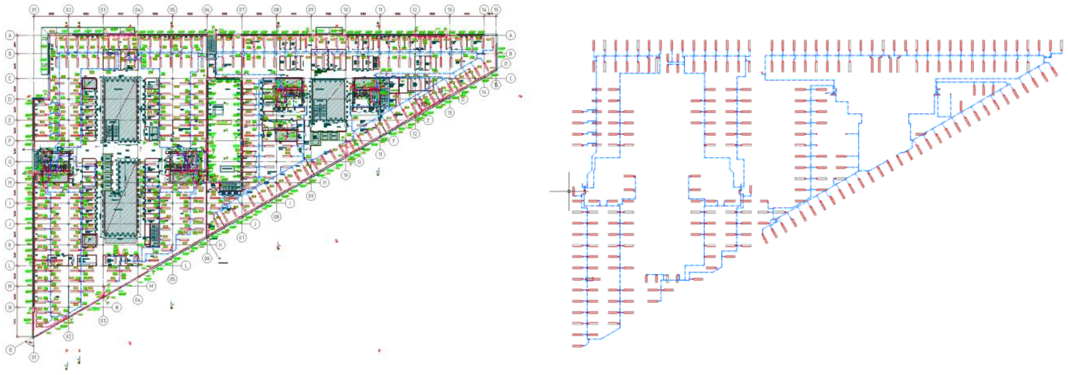


Figure 23: Simplifying the workplane

Before modeling it was necessary to simplify the workplane in AutoCAD so that the aforementioned base would only include the cooling beams and piping, designed after the architecture files. As AutoCAD works with layers where the designer assigns one layer for one kind of component or group of components with similar function, the unnecessary layers could be turned off leaving only cooling beams and piping visible, see Figure 23. This was used solely as a visual representation of the design and later deleted.

The resulting workplane from AutoCAD was inserted into Revit MEP. There are two main options when inserting files into Revit MEP; Link and Import. The option most connected to BIM work is Link CAD, as Revit through this automatically updates the geometry to reflect changes in the original file. If the architect makes a change in a file that was imported into Revit MEP with Link CAD, it will be updated to match the architects file. Likewise for all involved instances. In this case it was not necessary to link to a file that might be in use as the project was finished several years ago and ÅF AB moved into Hagaporten III in 2004. Since no changes were expected Import CAD could be used in this case. It is important to choose "Positioning: Auto - Origin to Origin" when inserting a file, as the coordinates otherwise would be misleading for the program, therefore making changes made in the original file appear in the wrong place. This mainly applies on linking CAD files but is recommended also for importing CAD files.

The tool Cooling Beam for inserting cooling beams to the model is found under MagiCAD Ventilation, where it primarily is possible to search an Internet Database for the correct type. Not all manufacturers have joined this database, including Halton, which is the reason for specifically requesting both types of beams from CADCOM and Progman Oy. The model files for the CBS beams were provided in .qpd format which is an editable format for MagiCAD Product Modeller. The CBC beams on the other hand is of a more universal type of cooling beam and were recommended by CADCOM to be edited based on the general types of beams already provided in Revit MEP's database.

6.1.1 Modeling the system

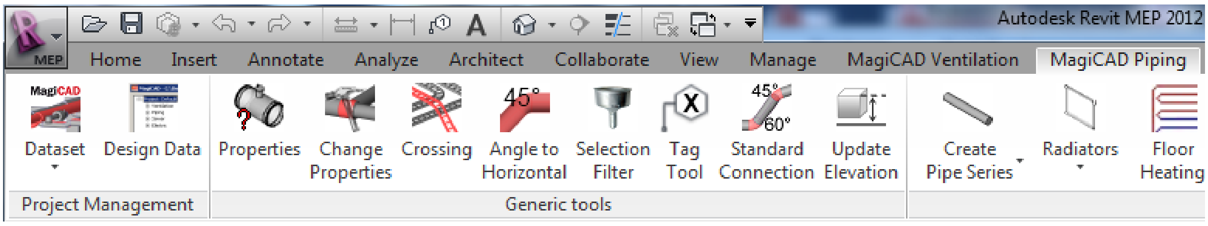


Figure 24: Project Management

The existing system is the initial system that was modeled and built in Hagaporten III. It uses a temperature difference of 16 °C to 19 °C, with free cooling operating at temperatures at 15 °C and below. With the base imported and pinned in place as described in the previous section, it was important to define these system properties, as well as component properties before starting to model. This action is made in Dataset in Project Management, found under MagiCAD Ventilation and MagiCAD Piping as shown in Figure 24. The Heating/Cooling systems, as well as the different kinds of valves, to be used in the project were chosen and when necessary edited in the Dataset. The existing cooling system works with the temperature difference 16 °C for supply and 19 °C for return, which was defined here as KB21T and KB21R. As described in the previous section it was recommended to base the CBC beams on a general type of beam already provided through the Revit MEP product database. This tool is found under Ventilation and the beams were edited to match the properties for the CBC beams in the existing system, technical information from datasheets from Halton's website.

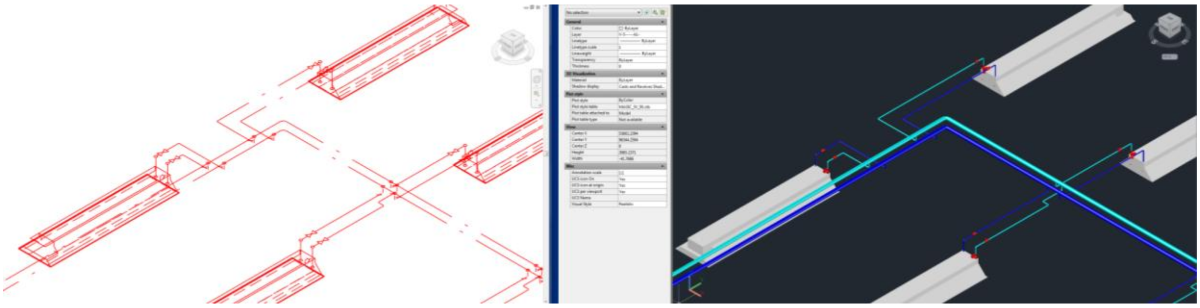


Figure 25: Level comparison, Revit MEP and AutoCAD

With all technical information and properties for the included components set it was possible to start modeling. The piping was modeled on top of the base in Revit MEP, using input values from the initial model in AutoCAD and the Construction Documents last updated in 2008 including materials, dimensions and isolation and so on. As shown in Figure 25 the beams and piping is modeled on different levels where the bottoms of the beams are at 2800 mm height above the floor, which is the lower edge of the suspended ceiling. All parts should fit in the area between the suspended ceiling and the ceiling, which is 600 mm.

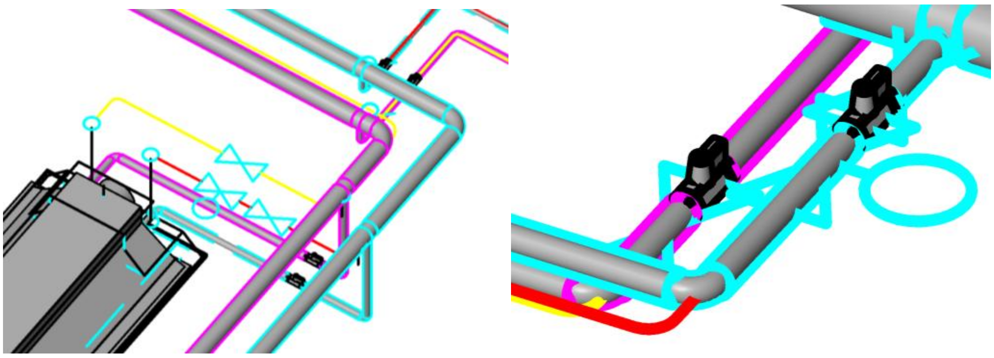


Figure 26: Valves

The CBC beams require stop valves on both inlet and outlet connections, as well as a check valve on the outlet. The tool Piping Components is found under MagiCAD Piping, and as for the Cooling Beam tool it is possible to search for and view properties for different kinds of valves and other components. Figure 26 shows where the valves were placed in the original model compared to where the valves were placed in the new model.

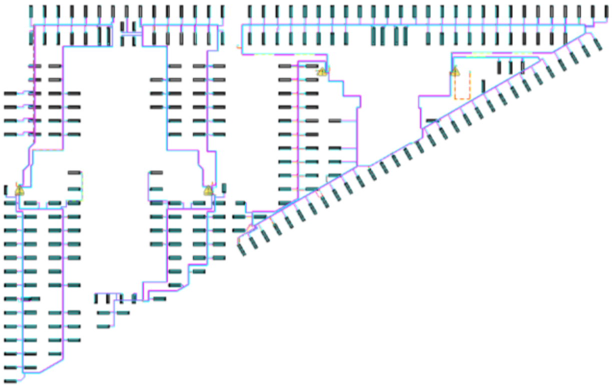


Figure 27: Floor 5

The complete system consists of four shafts from which the subsystem branches out, see Figure 27. To enable calculation on the system in Revit MEP it is required that each subsystem only has one inlet and one outlet, and that they are not ring fed. Because of this requirement it was decided that each subsystem would be opened up and plugged in the ends the furthest away from the shafts. This is a simplification and not the original design of the system, but it was decided together with the supervisor. Further on, as the figure above shows, the two right shafts shares three ring fed subsystems where two of them are also connected to each other. According to the decision to model branches to be able to calculate the system, these were opened up in such a way that the two right shafts consist of three separate branches of beams.

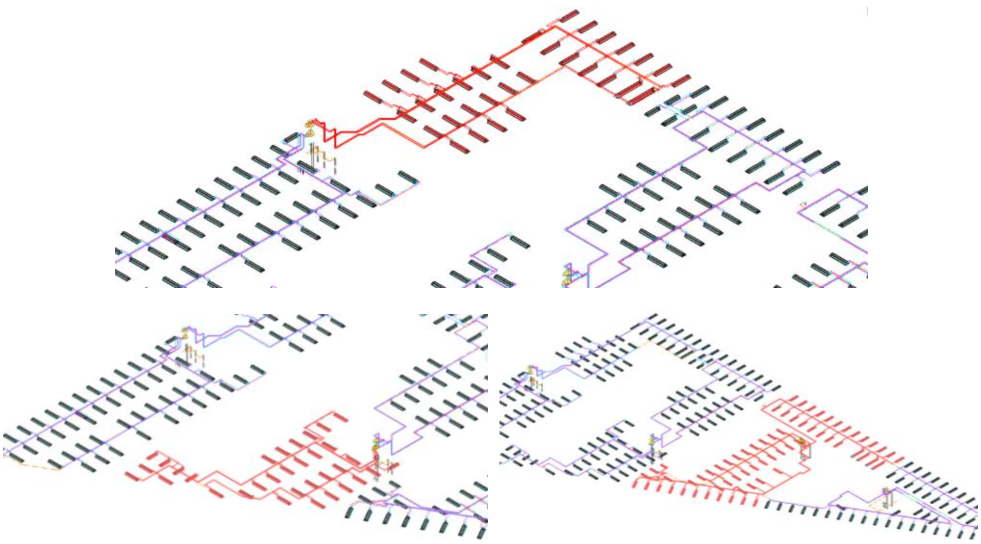


Figure 28: Positively calculated subsystems

Before multiplying the dimensioning floor, sizing and balancing calculations were made on every part of the system as shown in Figure 28, to evaluate the calculation possibility on the complete system. As every subsystem was calculated with good results it was determined credible that the complete system would also be calculable. The color red in the figure simply marks the system on which subsystem the calculations have just been performed, it does not mark faults.

The level difference between the floors was measured in the original AutoCAD 3D file for which the resulting value was 3700 mm, measured in y direction from system to system. Furthermore, the building consists of six office floors above ground where the first four consists of the complete dimensioning system and the top two floors only consists of the three left shafts and the subsystems connected to them. This is also a simplification to simulate the building's complete cooling system but only architecturally adjust the design to the dimensioning fifth floor. Also, the ground floor was not modeled as this consists of many open spaces and the lunch restaurant. The original top floor does not completely correspond to the design of the simplified version of the top floor, as of an actual arcuated outer wall which the simplified version does not have and some of the cooling beams are not located in the same places. Though, the two designs correspond with engineering precision and thereby the simplified system is considered accurate enough for its cause.

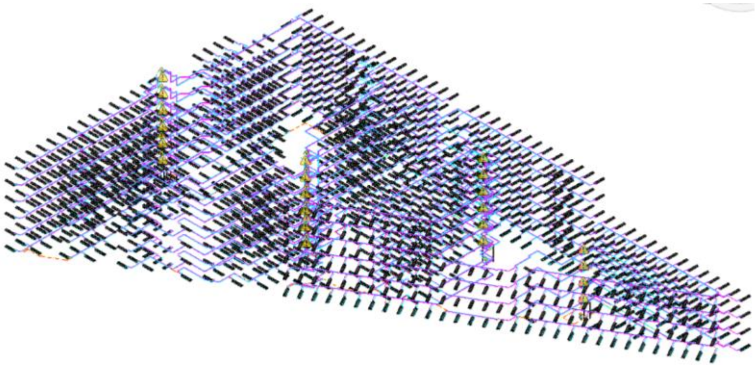


Figure 29: The simulated complete system

Based on these arguments the dimensioning floor was multiplied in its entirety for the bottom four floors, and only the three left shafts was used for the two top floors. Figure 29 shows the complete simulation of the six office floors. The subsystems' inlets and outlets were drawn to their respective shaft areas, and the shafts are structured in such a way that the subsystems are collected in control rooms on the floor above.

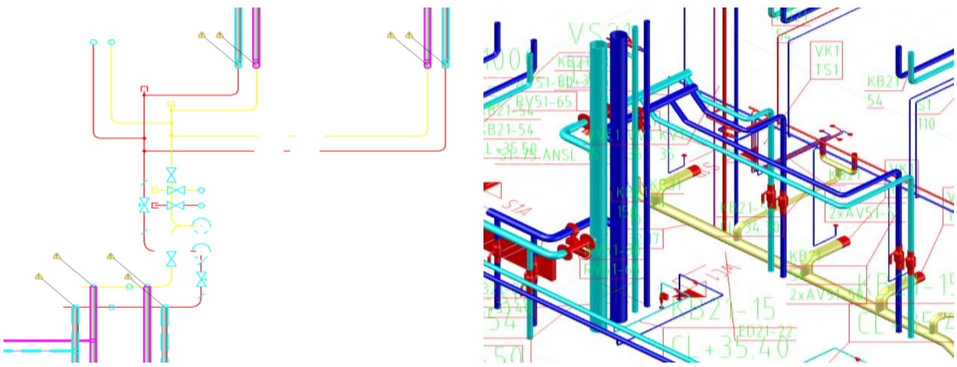


Figure 30: A shaft in Top and Isometric view, Revit MEP (left) and AutoCAD (right)

Figure 30 shows such a control room, where all inlet pipes in one section of the building are connected to a main inlet pipe in that section's shaft, likewise all outlet pipes are connected to a main outlet pipe. All four shafts in the simulated building were designed as in the figure, and like the control calculations for each branch, each of the four sections were calculated through sizing and balancing. All shafts were then connected through a main pipe in what would be the basement, and calculations were performed on the complete system, see Figure 31.

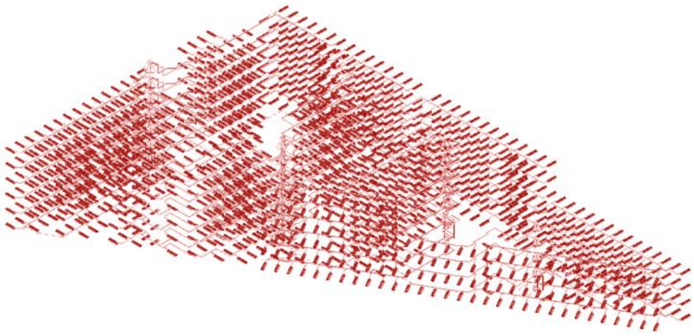


Figure 31: The simulated and calculated complete system, sizing and balancing

7 LCCA: LIFE CYCLE COST ANALYSIS

Hitherto, the focus of attention during procurement processes has often been on the investment costs, the acquisition cost, when choosing not only between different cooling systems but as a general trend in all procurements. This even though all costs related to a product or system can be illustrated with an iceberg, acquisition alone representing the top part. The views on how to look at the costs for a system have changed in the past couple of years, much as several studies upon the subject have shown that the biggest cost units are found during the usage phase [1], especially for long life equipment such as the cooling systems on which this work has been focused. Since the usage phase of a system is where the biggest cost lies, energy efficiency is of great significance for reducing costs. Therefore, energy efficiency is becoming more and more important not only as an environmental aspect but also as a cost unit, especially when it comes to these long life equipments. Investigating the environmental impact has lately been adding great value to the evaluation and consequently the choice of equipment.

Today cost investigations during procurement processes often consider the whole life time of a system, looking at everything from raw material and it's handling, to delivery aspects, but also quality, efficiency, environmental impact and end-of-life handling to name a few. This is commonly known as a cradle-to-grave approach. A great difficulty when trying to look at the whole life cycle for investments of this size, and the reason it has not been common up until now, is that several actors usually are involved. With one actor responsible for the initial investment and another left to handle the costs in use there are usually also different accounts for the different cost units, which mean that budgets and ownership are difficult to decide. This often means that investors choose the system with the lowest initial costs which might not be the most efficient system, meaning higher invisible costs like energy and maintenance that the operators might not have the required monetary resources for. As this kind of equipment often is in use for a long time, and might live through a change in business or renter in a building, operational and maintenance costs are of greater significance than what investors allow their budgets to admit. As systems get older their efficiency level decreases, forcing the usage costs up. This leads to a higher total cost during the whole life cycle, in other words, a higher Life Cycle Cost (LCC).

"The result of an economical analysis where all cost and income items for a system or a product is compiled over its complete period of life", SEK Svensk Elstandard's definition of the life cycle cost in SS-EN 60300-3-3 [2].

A Life Cycle Cost Analysis (LCCA) is an economical evaluation technique, a method for determining the total cost of a facility over its complete life time. The *total* cost means that every cost related to acquiring, using and disposing is taken into consideration. The LCCA can be used to evaluate the initial as well as future costs of full range projects, from an entire site complex to a specific component. It can also be implemented at any level of the process; therefore it can also be an effective tool for evaluation of existing building systems. According to Whole Building Design Guide [3] it is especially useful for comparing two product or system alternatives that accomplish the same required tasks, but differ in initial, operational or maintenance costs.

As mentioned, the total cost of a product or system is often described as an iceberg where only the acquisition cost is visible, but just as the non visible part of an iceberg is the biggest part, the total cost includes much more than that. Table 9 gives examples of what those costs might be, with white symbolizing the top of the iceberg. Notable is that the chart is not complete but solely stands as an example, and not all cost categories are relevant in all projects. Furthermore, if costs in a particular cost category are equal in the project alternatives, they can be documented as such and removed from consideration in the comparison. This is possible because an LCC merely is a cost calculation, to which expenses are added and income is removed.

Table 9: Examples of what costs that might be linked to a product or system

Types of Life Cycle Data				
Cost Data	Physical Data	Occupancy Data	Performance Data	Quality Data
Acquisition cost	Floor area	Hours of use	Maintenance cycles	Pump
Capital cost	Type of system	Functionality	Cleaning cycles	Pipe work
Taxes	Window area	Occupancy Profile	Electricity	Road surfacing
Inflation	No. of occupants	Particular features	Thermal conductivity	Sanitary fittings
Operating cost	Functional areas		Gas	Decorations
Management cost	Walls			Fabrics
Replacement cost	Ceilings			Furnishing
Discount rate	Sanitary fittings			
Maintenance cost				
Cleaning cost				
Demolition cost				
Insurance				

Worth to mention is that the capital cost found under Cost Data in Chart 2 is an expression for the combined requirements that the company has on invested money. Necessary to consider is the *real interest rate* that the company can get on borrowed money, other investment opportunities and the risk associated with the investment. In this context a high interest rate means that a quick return on investment is required, while a low-interest rate allows for repayments over a longer period of time.

7.1 LCC Calculation

The economical evaluation of the two cooling systems is a life cycle cost analysis based on guidelines from the Swedish Energy Agency and the ENEU directives, and aims to evaluate which of the two systems is the most economical. The LCCA was divided into *CBC beam system* and *CBS beam system* whereas a comparison was made between them. The input information was as far as possible based on the building documents as these are highest in the information hierarchy, though it was necessary to base some information on the model files and by discussing with the involved instances. It was desired to include all costs independent on extent, and a complete list with all included components and equations can be seen in Appendix A. The Life Cycle Cost was calculated with Equation 1.

$$LCC_{tot} = \text{investment cost} + LCC_{energy} + LCC_{maintenance} \tag{1}$$

where LCC_{energy} and $LCC_{maintenance}$ was calculated with equations 2 and 3:

$$LCC_{energy} = \text{annual energy cost} \times \text{PV factor} \tag{2}$$

$$LCC_{maintenance} = \text{annual maintenance cost} \times \text{PV factor} \tag{3}$$

7.1.1 **The Present Value method**

It is of up most importance to first evaluate whether any energy saving measure means such a significant saving effect that it is reasonable. Therefore it is necessary to have a reliable method for comparing a one-time saving and annual savings as today's money will not be worth the same in five years since money can be placed and remunerated. "Money breeds money" is a popular expression within the corporate economy that illustrates this fact. This requires that a calculation is made based on how much the planned future costs are worth today to make a total life-cycle estimate (Olsson et al., 2001) [8]. The method for investment calculations that is used in the LCCA is called the Present Value method (the PV method). It is characterized by the fact that the comparison between all revenues and expenditures takes place at the present point even though the investment itself takes place several years ahead. All future annual savings and expenses are therefore recalculated to present value. The rate by which all expenses are recalculated should represent the lowest profitability that can be accepted for an investment to be implemented, which is a rate that is unique within a company. To calculate the present value of future costs or savings, the amount is multiplied by the Present Value factor (hereafter referred to as the PV factor). The PV factor is determined differently depending on whether the amount is resulting from a single time or on annual basis and if price increases are taken into account. Any residual value can also be included in the calculation. The PV factor is usually equal to 11.47, which can be calculated by values from a PV factor table. However, fluctuations in energy prices and company associated investment factors etc. is not taken into consideration in charts like that. Instead it can be calculated by hand by entering these case-to-case depending factors. "The error that commonly arises will then be negligible", states VVS Special on the subject [9].

The two major cost categories in an LCCA are initial and future expenses. Initial expenses are all costs linked to the period before e.g. occupation of the facility, while future expenses are all costs linked to the period after. The residual value is a future expense. In this case, it would describe the net worth of the system at the end of the life cycle. If, for example, the knowingly will recover 10 % of the acquisition price after its life cycle, the residual value is equal to the acquisition price times 0,1. This value can be either positive or negative, which is unlike other future expenses. Since an LCC is a summation of costs related to the system during its life cycle, the residual value indicates if there is a remaining value after the system's life time. Positive cost units shows outgoing money while negative cost units show incoming money, thus, a positive residual value shows that there are costs needed to be paid after the system's life time. This might be because of the costs related to handling hazardous materials or complex demolition. A negative residual value on the other hand shows that there is a value still remaining in the system after its life time. Zero residual value does rarely occur as it shows that there is neither a cost nor a value connected to the system at the end of life.

Needed for calculating the PV factor is the system's lifetime in years, the real interest rate and the energy price increase. According to the Swedish Board of Housing, Building and Planning the lifetime for cooling systems is usually 20 years [10], and thus the calculated-with lifetime. The energy price increase is based on studies upon the energy prices for district heating and cooling stating it is between 4,9 to 5,5%, whereas 5% was used in the calculations [11][12]. Other studies has shown similar tendencies for the maintenance price increase with a 4,6 to 4,9% range, therefore 5% was used also for that. Table 10 shows a summary of the needed calculation data.

Table 10: Calculation data

Life cycle [n]	20 years
Real interest rate [r]	7 %
Risk	*2 %*
Inflation	*2 %*
Policy rate (Sveriges Riksbank)	*3 %*
Price increase, energy and maintenance [i]	5 %

The *real* interest rate is a combination of the inflation and the risk free interest rate. Since the project initially had a tenant the risk is rather low and set to 2%. Based on information from Sveriges Riksbank and Statistics Sweden, the inflation today is 1,9% but calculated with as 2%, The interest rate is based on Sveriges Riksbank's policy rate and set to 3% due to the long calculation period despite the policy rate today being as low as 1,5% [13]. This was a safety measure made to ensure the calculation's accuracy despite possible future inflation rate increases, but note that it was an assumption that should be handled thereafter. Since the real interest rate is the sum of the risk, the inflation and the interest rate it was therefore calculated as 2 + 2 + 3 = 7%. It should be noted that the recommended calculation rate is 8%, if there are no specific figures regarding this in the company. If, for example, the energy price is expected to increase by 2% per year, the assumed real interest rate is reduced by 2% for calculating the PV factor. Likewise, annual percentage increases of maintenance costs can also be taken into account. Since the energy price increase was assumed to be 5% and the real interest rate was calculated as 7%, the difference is 2% and thus resulting in a PV factor of 16,35 based on the PV factor chart in the ENEU guidebooks, see Table 11.

Table 11: The PV factor at various life cycles, excerpt from ENEU and Energimyndigheten [14]

	Real interest rate [r] – Energy price increase [i]					
Life cycle	-4 %	-2 %	0 %	2 %	4 %	6 %
10 år	12.60	11.19	10.00	8.98	8.110	7.36
20 år	31.56	24.89	20.00	16.35	13.59	11.47
30 år	60.07	41.66	30.00	22.39	17.29	13.76
50 år	167.47	87.29	50.00	31.42	21.48	15.76

7.1.2 **Energy cost**

Eventual future increases in energy prices should be taken into account when conducting the cost analysis, especially for any energy saving measures. If it is assumed that the future energy prices are growing faster than the normal cost this increase should be included on top of the inflation in the calculations. The economic conditions for calculating the total life cycle energy cost would therefore include the energy price today, the expected energy price increase during the life cycle, the real interest rate and the life cycle in years. There are many predictions on how energy prices might fluctuate in the future, all showing a different outcome, but by using the calculation methods in ENEU any uncertainty about estimates without reference or proof is erased. The above input values gives the discounting factor and thereby the present value. The discounting factor needed to calculate the present value is a table value, for which the input values are the life cycle in years and the difference between the real interest rate and the expected energy price increase. Table 12 shows the, for this work, significant part of the extensive chart provided in ENEU.

Table 12: The discounting factor at various life cycles

	Difference between real discount rate and expected energy price increase					
Life cycle	-4 %	-2 %	0 %	2 %	4 %	6 %
10 år	12.60	11.19	10.00	8.98	8.110	7.36
20 år	31.56	24.89	20.00	16.35	13.59	11.47
30 år	60.07	41.66	30.00	22.39	17.29	13.76
50 år	167.47	87.29	50.00	31.42	21.48	15.76

The limitations with the ENEU directives lie within its accuracy, as it was formulated in simple but understandable and usable terms instead of more correct but also in a more complicated way.

7.1.3 **LCC Investment cost**

The investment cost consists of the sum of all component prices for both systems and include the different types and lengths of cooling beams, where the amounts were taken from the building documents and the prices were collected from the manufacturer, but also piping, valves and control equipment, insulation and installation. This was to get comparable cost units, for even though the existing system's real acquisition cost is a contract price which is slightly lower it would otherwise not be comparable to the replacing system. The information was based on building documents which were controlled with both the AutoCAD and Revit MEP model files. The difference between the investment costs amounts to 1 371 889 SEK to the CBC beam system's advantage, see table 13. [15]

Table 13: Sum of the investment costs

	CBC beam system	CBS beam system
Investment cost [SEK]	10 834 620	12 206 509

7.1.4 LCC Operation cost

The operation costs include all maintenance and energy related costs. The input information for calculating the energy costs was based on directives from the energy supplier Norrenergi, see Appendix B, which together with the characteristics of the two systems regarding the period of use and the present value factor means a difference of 6 017 140 SEK to the CBS beam system's advantage, see table 14. Regarding maintenance costs the difference amounts to 915 600 SEK.

Table 14: Sum of operation costs, recalculated to present value

	CBC beam system	CBS beam system
Energy cost [SEK]	26 783 182	20 766 041
Maintenance cost [SEK]	1 118 120	202 520
Operation cost [SEK]	27 901 302	20 968 561

Included in maintenance costs is education of maintenance personnel, repair, inspection and cleaning costs, as well as costs for personnel, materials, machinery, vehicles, supervisory staff and contractors. The Control Description document from 2007 describes in detail how and how often maintenance and general service should be conducted on the system. It also proposes a training model that includes a four hour theoretical course and two full days of on-site education at the beginning and in the end of the guarantee time, which in this case was not calculated with. The service visits and maintenance of installations should be performed at least two times per year and desirably four times per year, the cost calculations therefore include four occasions per year. Regarding the cooling beams, a major maintenance check was recommended once a year, but also a couple of times of minor service like wiping off the front panel. These checks shall be performed by skilled personnel who have the necessary knowledge within the area. The cost per hour shall reflect an average in Sweden in the procurement of maintenance contracts and is calculated through Grundfos recommendations [16] as 970 SEK/h for qualified personnel and 700 SEK/h for service technicians. No transportation costs such as gas and mileage allowance are included in maintenance costs, which nevertheless are an important factor for the maintenance costs, which makes the calculations slightly misleading. It was not taken into consideration since there was no information on the distance to the service company, and made similarly for both systems.

7.2 Result

Figure 32 shows the complete life cycle costs for the two systems, the results of the calculations, where the difference is 5 560 851 SEK over the complete life cycle of 20 years. It was calculated as the sum of the investment cost, the energy cost and the maintenance cost, using a PV factor of 16,35 in accordance with the ENEU documents.

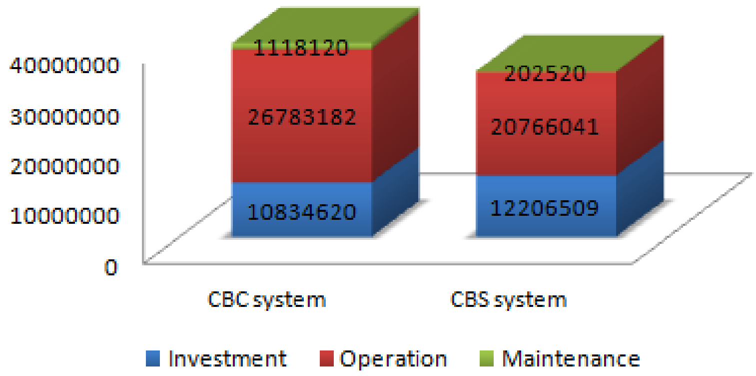


Figure 32: The total life cycle cost of the two systems

The allocation of costs is shown in Figure 33 for CBC and CBS beams, showing that the greatest costs are found during the usage phase which is also stated by Energimyndigheten [16] among others, and it is therefore desired to minimize the impact of the costs in the use phase.

Figure 33: The total life cycle cost of the CBC system (left) and the CBS system (right)

When looking at the cost allocation for the two systems the use phase for the CBS beam system stands for eight percentage points less than for the CBC beam system. That means that the costs under the use phase in the CBS beam system will not affect the complete life cycle cost to such an extent as the CBC beam system would. Due to the decision not to take transportation costs into consideration for maintenance this cost unit only amounts to three and almost one percent, which is a weakness in the calculations. The same decision on simplification of the calculation was taken for the replacing system, which means that it does not affect the outcome because of difference. Usually the cost allocation looks like the allocation in Figure 34, with maintenance amounting to 9% of the total costs. [17]

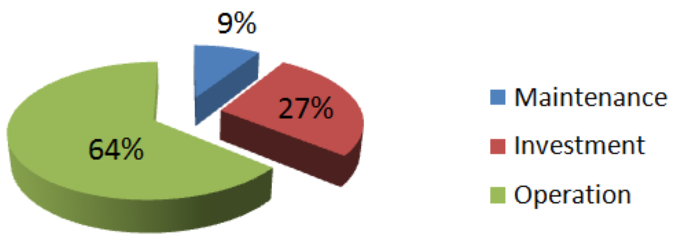


Figure 34: Usual cost allocation for cooling systems

In any cost calculation there might be a residual value linked to the system at the end of life. The residual value, which is the remaining value of the system after its life cycle, is an assumption based on the difference between technical and economical life time. Although it is recommended and customary to calculate on a 20 year life cycle, the beam manufacturer Halton states that the beams' life cycle is 25 years, which would mean a five year residual value. In other words, the system should be taken out of operation after 20 years but the cooling beams could in theory be used another five years. Even so, installing those beams in a new system and having to replace them after five years is more expensive than disposal after the first 20 years, and the residual value for investments with a longer life time than 10 years is generally considered small [18].

Also, according to the energy supplier Norrenergi, each MWh from district cooling emits 9 kg of carbon dioxide (9 g CO_2 per kWh, 2011) [19], which would mean a CO_2 emission of 6 552 kg with the CBC beam system and 5 292 kg with the CBS beam system over the 20 year life cycle. The difference is 1 260 kg of carbon dioxide not affecting the environment with the CBS beam system. That is 20% less, which is considered a big step towards ÅF's sustainability goal to reduce the CO_2 emission with 50% by 2015. Therefore it was interesting to further evaluate the environmental affect of the two systems themselves, see Chapter 8 LCA: Life Cycle Assessment, to recognize whether the biggest impact was during usage or if any other impact motivates choosing one or the other system.

7.2.1 Critical review

Figure 35: Life cycle cost for Halton cooling beams (left) according to Olof Granlund Oy

To evaluate whether these LCC results were probable, similar studies and calculations were read and compared to this study. One example being a study performed by Olof Granlund Oy on request of the beam manufacturer Halton Oy, concerning three types of comfort cooling systems where one was a cooling beam system [20]. The study was made upon a 10 000 m^2 office building that was in use 365 days per year. The system in that study is therefore about three times smaller but used about three times longer than the CBC beam system in this calculation, and both studies showed a life cycle cost of about 4 M€ or 38 MSEK, see Figure 35. Based on that this LCC calculation was considered accurate.

The environmental impact and its significance

The usage phase of a system is also where the biggest cost lie, making energy efficiency of great significance for reducing costs. Evidently these costs can be expressed in real money and the environmental focus could significantly reduce these costs, but can also be expressed as *environmental impact*. Not only increasing energy costs but also climate change and energy supply are growing concerns, and it is desirable to reduce the carbon footprint. The consequences from not working for a sustainable environment could be extreme, leading to global warming and sea level rise, extreme weather and endangered species not adaptable to drastic changes in the climate being a few examples. Agenda 21 [1] is an example of an international action program to encourage sustainable development, adopted at the UN Conference on Environment and Development in Rio de Janeiro 1992, describing the importance and how to work towards it. The goal to reduce greenhouse gas emissions is described in the Kyoto Protocol [2], an international agreement adopted in Kyoto 1997 by the Climate Committee (UNFCCC) and another example of the worldwide concern for the environment. Although Sweden in whole is making progress in establishing a sustainable energy future, according to the Swedish National Energy Administration [3] there is still a lot that can be improved in this area, further commenting: "Improved energy efficiency is an effective way of attaining reductions in the amount of energy required to provide energy services such as transportation, indoor climate control, lighting..."

The global mission of having a sustainability focus is an important part of the business strategy at ÅF [4]. On the website it is stated that ÅF wants to "…constantly improve the impact we have on creating a sustainable future", and by that they have also set up three goals to reach by 2015; the first being decreasing the CO_2 emission by 50%. Consequently, it is necessary to evaluate the environmental impact of the two systems. As the environmental awareness increases in importance it becomes interesting to see the big picture rather than the parts. The *life cycle perspective* provides an opportunity for decision making in which all aspects are taken into account. Assessing a product or a system of products from an environmental point of view breaks down the environmental impact over the life cycle and clearly shows where this impact is biggest and what opportunities and gains there are to lower it. By comparing various products those that give minimum overall environmental impact can be selected (Rydh et al., 2002) [5].

8.1 Background

The development of life cycle assessments started during the oil and energy crisis in the 1970s. By that time the primary reason was to find and assess alternative energy sources in contrast of any environmental values, but as pollution emissions increased the vision changed. To reduce emissions and to produce reusable and recyclable products the Life Cycle Assessment methodology was developed at an accelerating rate (Moberg et al., 1999; NVF, 1996; Rydh et al., 2002 and Stripple, 1995) [6][7][5][8].

A Life Cycle Assessment (LCA) is now defined primarily as an environmental evaluation technique, a method for evaluation of the environmental impact of a product throughout its life cycle. The procedures of the LCA are part of the ISO 14000 environmental management standards and according to ISO 14040 *Environmental management – Life Cycle Assessment – Principles and framework* [9] LCA is "a systematic set of procedures for compiling and examining the inputs and outputs of materials and energy and the associated environmental impacts directly attributable to the functioning of a product or service system throughout its life cycle." All stages are taken into account regarding the product's life cycle when performing an LCA; the major stages being raw material acquisition, manufacture, use, maintenance and waste management. In other words, LCA has a cradle-to-grave approach. It is used to evaluate the life cycle carbon footprint of a product for taking decisions within all stages during a product's life time, as well as decisions for purchasing renewable energy certificates or carbon offsets. Baumann et al. (2004) [10] states some of the purposes for an LCA as assessing a product's environmental impact, choosing between two or more products from an environmental point of view or examine the consequences of changing a process or material. Further on, the system boundaries, as well as assumptions and limitations to be addressed in each stage should be clearly presented for ease of use and understanding.

8.1.1 **Limitations with an LCA**

As a life cycle assessment normally is not location specific, no account is taken to location characteristics such as resistance to various pollutions, which might in fact have significance in many cases. For example, the local weather affects the system's function in terms of for how long a period it is possible to use free cooling. An LCA for the same system in Gothenburg would therefore show different results as the weather conditions are slightly different, but Stockholm and Gothenburg might have different resistance to pollutions caused by the cooling system and these differences might compensate for each other, something that would not be taken into consideration. "The Life cycle analysis therefore shows the *potential* environmental impacts which might cause some margin of error in the results", according to Det Norske Veritas, 1996 [11].

8.2 Goal and Scope

It is a requirement in the ISO standards to clearly set the framework for the LCA, which includes stating what information is needed based on the system boundaries as well as how and to whom this information is to be presented. It also includes stating technical details such as the functional unit, the system boundaries, assumptions or limitations, the chosen impact categories and the allocation methods used to divide the load if there are several products or functions included in the same process or system. The Life Cycle Assessment should therefore start with determining which industrial benefits to be studied, and what environmental impact to consider. In this case it was a combination of both a product and a service, as the environmental impact of the two different cooling beams were studied in a case where both were to provide a comfortable thermal climate, meaning different technical requirements in the usage phase. When studying the extent of the life cycle assessment an initial mapping of the product system was performed. All included products, components, materials and energy were roughly estimated and listed to get a picture of what to look at when performing the LCA, and acts as a guidance and framework. The goal was therefore to evaluate the environmental impact of the two systems to distinguish the more environmentally friendly one and in which phase the impact is biggest.

8.2.1 **Product system**

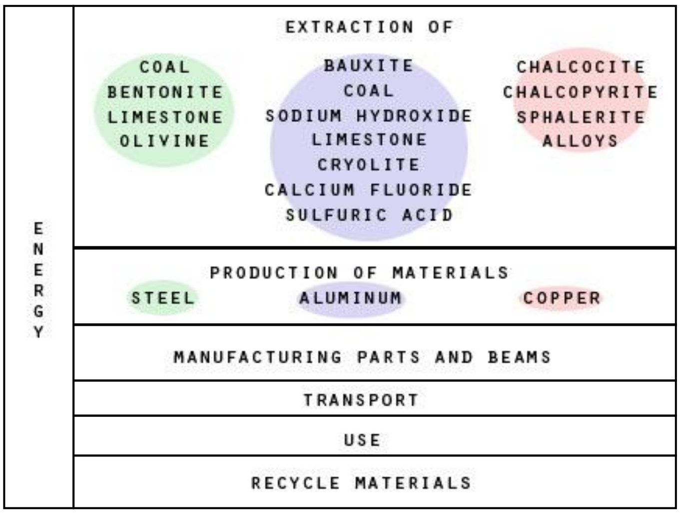


Figure 36: The product system

The studied product system, which should include all of the different processes in a products life cycle, is based on the two types of cooling beams; CBC and CBS. By using the manufacturer's information on beam structure and comparing to material information in CES EduPack regarding composition and possible processes the theoretical product system could be translated into a more concrete version, as seen in Figure 36. While the aim is to make a complete life cycle assessment, from the extraction of raw material to final disposal, the focus lies on the usage phase as the target group is the users. Some simplifications have therefore been made, for example by excluding the waste along the supply chain, with the handling of the waste from the extraction and production of raw materials.

8.2.2 **Product system function**

The functional unit was formulated as a *comfortable thermal climate*, which more concretely for the LCA means "cooling beams that provides a room temperature of 22-24 C and an air flow of about 10l/s,person". The energy needed for creating the same climate with the two systems could be calculated through energy calculations, see *Energy Calculations*, which in turn gave the operational environmental impact. According to these calculations, the existing system provides the functional unit through 1667 CBC cooling beams and the replacing systems provides it through X CBS cooling beams.

8.2.3 **Impact categories**

Manufacture: No changes can be made in this category, but it can act as a base for an evaluation on which type of cooling beam is the most environmentally friendly and therefore a comparison between no manufacturing processes and the finishing process powder coating were performed.

Transport: It was assumed that the two systems' different cooling beams were transported from the same factory in Kausala, Finland. Note that transport of raw materials to the factory was not taken into consideration.

Use: This category was the most important since the target group is the users, but also since use is considered the most impacting category.

Disposal: The method and possibilities for disposal of the parts was based on the material characteristics and information on the manufacturer's website.

8.2.4 **Data quality requirements**

With demands for a high-quality analysis, the data sources used includes the manufacturer Halton [13], the Energy Agency [14] and the LCA tool used at KTH Royal IT; CES EduPack, which are considered accurate and providing data with desirable quality level.

8.2.5 **Allocation method**

Since ISO 14040 does not recommend allocating but instead to extend the product system to include all the processes associated with product system, the product system was chosen to be framed by the system boundary as widely as described in that section. Recommendations on which cooling beam to use, thus cooling system, would be based on the results on environmental impact in the usage phase but the other stages are also interesting from a life cycle perspective.

8.2.6 **Critical review**

A critical review of the life cycle assessment should be performed in order to guarantee that the used methods are scientific and technically acceptable, and corresponds to the international LCA standard. It should evaluate whether the used data is correct and reasonable for the extent of the LCA, that the interpretation reflects the goal and limitations of the LCA. The assessment work should be transparent and reflect the results, and will be performed by the project members in first hand, if a deepened review is necessary this would be discussed with the supervisors.

8.2.7 **Assumptions**

Actual transport and distances are rough simplifications, but it shows the approximate portion that is the use phase. Regarding beam types, one limitation to avoid an unreasonable extensive LCA is to base it on the most occurring type of cooling beam in each system. For example, the LCA on existing system therefore only includes beams of 2400 mm length. Furthermore, as stated by Pålsson (2008) [15], a comparing life cycle assessment allows simplifications to the extent that characteristics that are similar for both compared systems can be excluded. Therefore no piping was included in the LCA, it was a feature that was assumed similar enough to be excluded from the assessment.

8.3 Inventory Analysis

This step includes making an inventory list of the energy flow to and from the system within the framework stated in the previous step, meaning stating the type and amount of materials and components necessary to manufacture the products, type and amount of energy, equipment impacting the process, and emissions to throughout a product's life cycle. It should be performed within the framework stated in the previous step, as of which the energy flow is focused on the stages manufacturing, transporting, using and any energy gain or loss from disposing the materials. If there is information missing secondary data can be used, such as information gathered earlier or information from national databases etc. In that case, it is important to ensure that the secondary data source properly reflects regional conditions, and that the data properly answers as the information needed.

The specific type and amounts of beam materials were therefore calculated partly from information from the manufacturer, but also assumptions based on available information on material characteristics such as normal use, manufacturing techniques and disposal possibilities. The secondary data used in this section includes information about the materials and typical processing from CES EduPack, as well as information from the manufacturer including the environmental approach affecting the choice of material and manufacturing process but also factory location affecting the energy burden from transport.

8.4 Impact Assessment

By using the inventory analysis, the impact assessment is aimed at evaluating the significance of potential environmental impacts and shows where in the life cycle this impact is biggest, and acts as a base for decisions on *if* and in that case *how* to change it. According to ISO 14044:2006 [16] the impact measurement is a requirement and often acts as the conclusion of the impact assessment, necessary to state is the impact categories, how to classify the inventory units in order to place them in the correct category, and how to measure the impact. All information from the inventory analysis was therefore summarized and presented in charts and graphs through the ECO Audit tool to clearly show where the impact is biggest.

8.5 Interpretation

The interpretation includes identifying, measuring according to the structure decided in the Impact Assessment step, and then evaluating the information gained from each of the previous steps. The results from the inventory analysis and impact assessment are summarized and the outcome of the interpretation is a set of conclusions and recommendations. The interpretation should include an identification of significantly impacting factors, an evaluation, and conclusions, limitations and recommendations, according to ISO 14040:2006. As the LCA was performed to evaluate which one of the two systems that have the least environmental impact no other recommendation than which one is better to use from a strict environmental perspective will be presented.

8.6 LCA RESULTS

”By the year 2015 ÅF aims to have halved its CO_2 emission”, ÅF AB.

The life cycle assessment aims to *compare* the cooling beams CBC and CBS to evaluate their respective environmental impact from a life cycle perspective by examining the cradle-to-grave impact of the two, as the hypothesis was that the replacing system has a significantly lower environmental impact than the existing. This is to add another dimension to the evaluation of the two cooling systems, where thus both economical and environmental aspects are similarly important whilst preserving a comfortable thermal climate. When performing a *comparing LCA* the parts of the systems that are similar are not necessary to include (Pålsson, 2008). The results are aimed to ÅF AB, as a part of the master thesis.

8.6.1 **Inventory Analysis**

MATERIALS AND PROCESSES

The beams' respective structure of components and materials were based on the information on the manufacturer's website and the differences in the beams apply to the dimensions of the parts, through that the needed processes was found. That acted as a base for further examination of what is included in each stage. Both types of cooling beams are manufactured with the same part types and in the same materials; the manufacturer has an environmental focus and manufacturing all types of cooling beams in the same materials and parts is both economical and environmentally friendly as this means the least amount of different processes. The discharge due to material composition was also examined in this stage, but no hazardous emissions were found for the phases from manufacturing and forwards in the product's life cycle. Table 15 displays material data for the CBC beam in detail.

Table 15: Input information for the CBC beam system

Component	Material	Recycled content (%)	Mass (kg)	Qty.	Energy (MJ)	%
Bottom plate	Coated steel, steel, galvanized	Typical %	9	1667	2.3×10^5	11.6
Side plates	Coated steel, steel, galvanized	Typical %	7	3334	3.6×10^5	18.0
End plates	Coated steel, steel, galvanized	Typical %	4	3334	2.1×10^5	10.3
Supply air plenum	Coated steel, steel, galvanized	Typical %	2	1667	5.2×10^4	2.6
Brackets	Coated steel, steel, galvanized	Typical %	0.88	1667	2.3×10^4	1.1
Exhaust valve	Coated steel, steel, galvanized	Typical %	4	1667	1×10^5	5.1
Coil pipes	Brass, cast, (high-tensile manganese bronze)	Typical %	3.36	1667	2.8×10^5	13.8
Coil fins	Aluminum, LM25-TB7, cast	Typical %	2.36	1667	5.3×10^5	26.4
Electric heating foil	Aluminum, LM25-TB7, cast	Typical %	1	1667	2.2×10^5	11.2
Total			33,6	18337	2×10^6	100

The materials were chosen mainly from the manufacturer's data sheet on the beams stating that 80% was powder coated galvanized steel, 10% copper and 10% aluminum. The specific copper and aluminum compositions were chosen from the information in CES EduPack, based on limitations and input values such as price, energy use and application possibilities. The chosen material mixture was the one that withstood the expected manufacturing techniques and the usage requirements such as temperature and load, and the fact that it should still be possible to recycle to a great percentage when disposing. The materials of which the cooling beam parts are composed were then translated into their equivalents in the ECO Audit tool, see Table 16. For example, the bottom panel was stated in the datasheet as made of *pre-epoxy-painted galvanized steel*, which in the ECO Audit tool translates into *coated steel*, *steel*, *galvanized* expressed as the finishing, the base material and whether the material has been processed in any way. Note that the chart only shows the CBC beams and acts as an example of the input information in the ECO Audit tool.

Halton states that the beams weighs totally 14 kg/m, and since the calculations in the chart were based on 2,4 m CBC beams, the total weight was 33,6 kg. The parts masses were then calculated based on density, dimensions and the material percentage. The quantity of parts was based on the total amount of cooling beams in the system, where two end plates and two side plates are used for one beam, therefore each amounting to 3334 pieces. The Recycled Content (%) in the chart was set to a typical percentage for the specific material. For instance, aluminum is characteristically made of a typical percent of recycled aluminum mixed with virgin aluminum. This was made due to the manufacturer's environmentally friendly profile. The beams are according to the manufacturer also fully recyclable except for some traces of glue, expressed among many other statements with "...our products utilize materials and structures that can be easily and efficiently recycled", *Halton Oy*, motivating to choose recycling as the disposal method. This was confirmed by the CES EduPack material information.

TRANSPORT

Figure 37: Map showing the distance from Kausala to Solna.

The direct distance from the factory in Kausala, Finland, to Solna, Sweden, is 491 km. Assumed distances from a map shows that half the distance would on land and half the distance would be on water, 245,5 km each. These simplified input values did not take into consideration any deviations of the route from the straight line shown in the map in Figure 37. The accuracy of the results should therefore be discussed, as the assumed transport route is not concordant with the actual transport route and the environmental impact of this stage would therefore be slightly misleading. Since the main focus of the life cycle assessment was the usage phase the transport route deviations were therefore considered to provide such a minimal impact that the difference could be neglected. The modes of transport were thereby chosen as big trucks driving from the factory to the port in Finland with a 245,5 km distance, and from there sea freight starting from the port in Finland to the port in Sweden with a 245,5 km distance. The choice of transport was made upon the load and the available modes of transport in the ECO Audit tool.

Figure 38: Temperature graphs over the past five years, www.temperatur.nu 2012-06-01

Use was set to 499 W per CBC beam, 152 days per year and 11 hours per day. This input information was based on the data sheets from the initial project Hagaporten III stating that the beams uses 499 W from 7:00 to 18:00. Correspondingly for the CBS beams, use was set to 535 W for 122 days and 11 hours per day. The different days in use were based on the system characteristics compared to when those temperatures occurs, see Figure 38.

8.6.2 Impact Assessment

All input values were compiled in the ECO Audit tool resulting in a clear presentation with graphs and charts over the environmental impact from cradle to grave, including the impact categories chosen in the first step, the complete output can be seen in Appendix C.

CBC WITHOUT MANUFACTURING

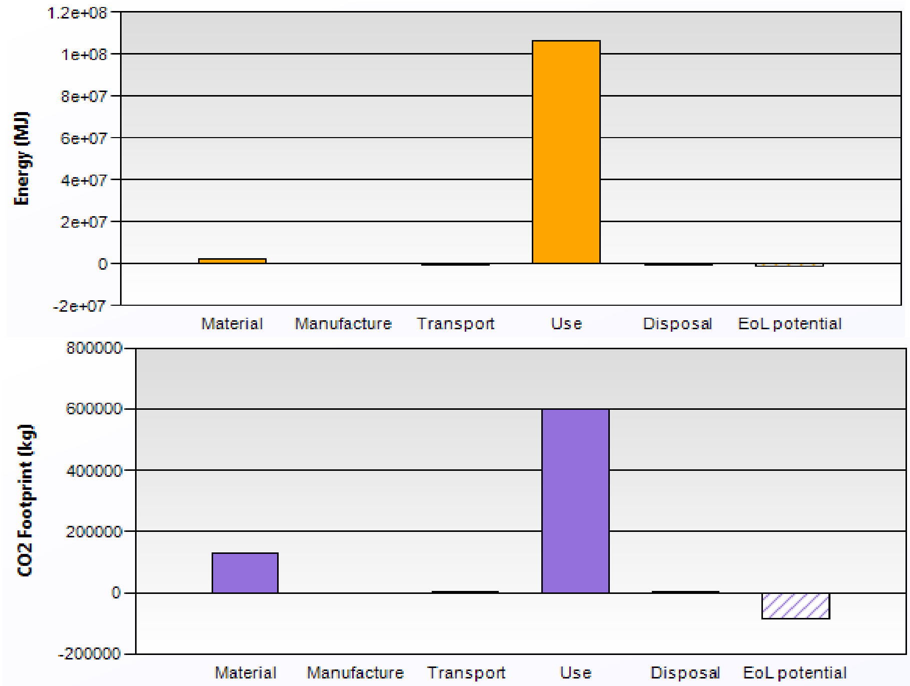


Figure 39: Energy and CO2 footprint allocation diagrams

Figure 39 shows the energy and CO_2 footprint allocation in the system, though not including any manufacturing methods. Use stands out as the heaviest phase. In both categories there is an end of life potential, -1,33×10^6 MJ and -8.44×10^4 kg CO_2, that comes from recycling the materials. Since the usage phase was the most interesting no manufacturing methods were examined. No conclusion of the percentage of the product's total energy impact can be drawn, but the actual figures for energy use and CO_2 footprint are correct, see table 16.

Table 16: Energy use and CO2 footprint in the different phases

Phase	Energy (MJ)	Energy (%)	CO_2 (kg)	CO_2 (%)
Material	2.01×10^6	1.9	1.29×10^5	17.5
Manufacture	0	0.0	0	0.0
Transport	1.13×10^4	0.0	803	0.1
Use	1.06×10^8	98.1	6.01×10^5	81.8
Disposal	5.2×10^4	0.0	3.64×10^3	0.5
Total (for first life)	**1.08×10^8**	**100**	**7.34×10^5**	**100**
End of life potential	-1.33×10^6		-8.44×10^4	

CBC WITH FINISHING

It turns out that manufacturing does not significantly impact the environment in comparison with the usage phase if it was to be taken into consideration. Note that manufacturing in this case only includes the finishing method, and that no other manufacturing methods were examined. According to Halton only the visible parts of the beams are powder coated, which amounts to totally 4,8×10^3 m^2 for the 1667 CBC beams in the system, and thereby stands for 0,3% of the energy use and 2,6% of the CO_2 footprint in the system, see table 17.

Table 17: Energy use and CO2 footprint in the different phases

Phase	Energy (MJ)	Energy (%)	CO_2 (kg)	CO_2 (%)
Material	2.01×10^6	1.9	1.29×10^5	17.1
Manufacture	3.65×10^5	0.3	1.97×10^4	2.6
Transport	1.13×10^4	0.0	803	0.0
Use	1.06×10^8	97.8	6.01×10^5	79.7
Disposal	5.2×10^4	0.0	3.64×10^3	0.0
Total (for first life)	**1.08×10^8**	**100**	**7.54×10^7**	**100**
End of life potential	-1.33×10^6		-8.44×10^4	

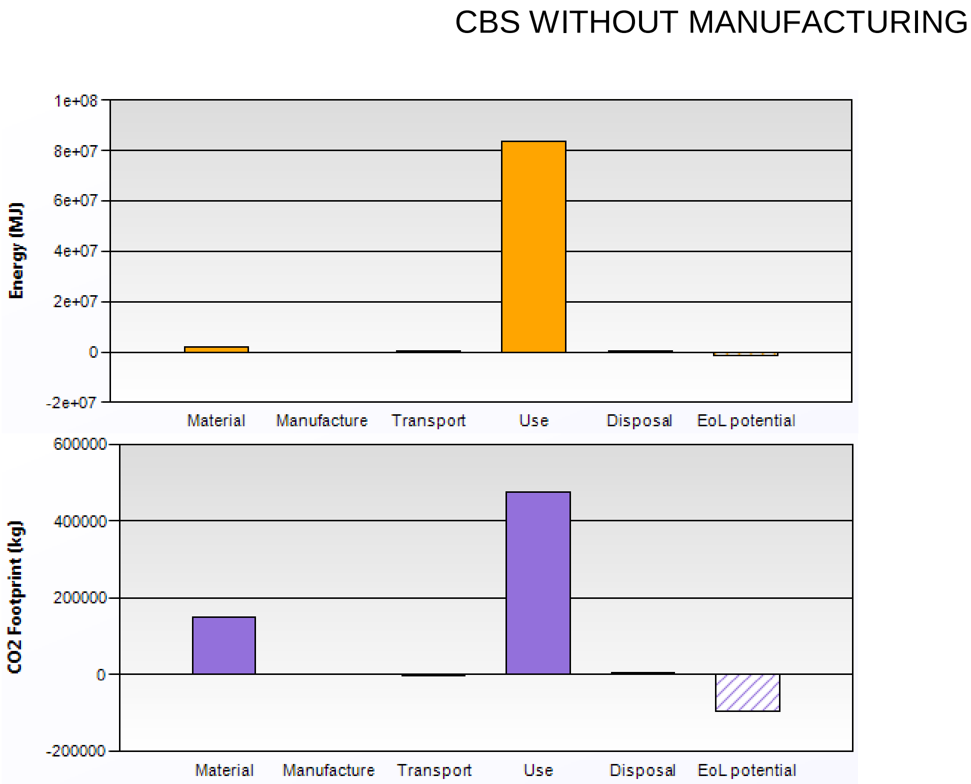


Figure 40: Energy and CO2 footprint allocation diagrams

Figure 40 shows the energy and CO_2 footprint allocation in the system, not including any manufacturing methods. The energy use and CO_2 footprint are listed in table 18 and use stands out as the heaviest phase in both categories. The end of life potential amounts to -1,53×10^6 MJ and -9.66×10^4 kg CO_2.

Table 18: Energy use and CO2 footprint in the different phases

Phase	Energy (MJ)	Energy (%)	CO_2 (kg)	CO_2 (%)
Material	2.3×10^6	2.7	1.47×10^5	23.6
Manufacture	0	0.0	0	0.0
Transport	1.3×10^4	0.0	920	0.1
Use	8.36×10^7	97.2	4.73×10^5	75.6
Disposal	5.96×10^4	0.1	4.17×10^3	0.7
Total (for first life)	**8.59×10^7**	**100**	**6.26×10^5**	**100**
End of life potential	-1.53×10^6		-9.66×10^4	

CBS WITH FINISHING

As for the CBC beams it was interesting to compare the manufacturing impact for the CBS beams. Note that manufacturing in this case only includes the finishing method and that no other manufacturing methods were taken into consideration. The area which is powder coated amounts to totally $5,4\times10^3$ m^2 for the 1525 CBS beams in the system, which thereby stands for 0,5% of the energy use and 3,4% of the CO_2 footprint in the system, see table 19.

Table 19: Energy use and CO2 footprint in the different phases

Phase	Energy (MJ)	Energy (%)	CO_2 (kg)	CO_2 (%)
Material	2.3×10^6	2.7	1.47×10^5	22.7
Manufacture	4.11×10^5	0.5	2.22×10^4	3.4
Transport	1.29×10^4	0.0	919	0.0
Use	8.36×10^7	96.8	4.73×10^5	73.1
Disposal	5.95×10^4	0.0	4.17×10^3	0.6
Total (for first life)	**8.63×10^7**	**100**	**6.5×10^5**	**100**
End of life potential	-1.52×10^6		-9.65×10^4	

8.6.3 Interpretation

The life cycle assessment was aimed to *compare* the cooling beams CBC and CBS to evaluate their respective environmental impact from a life cycle perspective, as the overall goal was to strive for a system with low environmental impact, combined with low life cycle costs, flexibility and simplicity. By weighting the different characteristics a final result will be discussed considering all affecting factors in choosing the most optimal system, though, life cycle costs, flexibility and simplicity are discussed in other chapters whereas solely the environmental impact is considered here.

Based on this life cycle assessment the CBS beam system is considered more environmentally friendly than the CBC beam system as fewer beams are needed to provide the same indoor climate, which minimizes their environmental impact. The use phase is the phase with highest burden, and Figure 41 shows that the energy burden from the use of the CBS beams is $2,21\times10^7$ MJ lower than from the CBC beams.

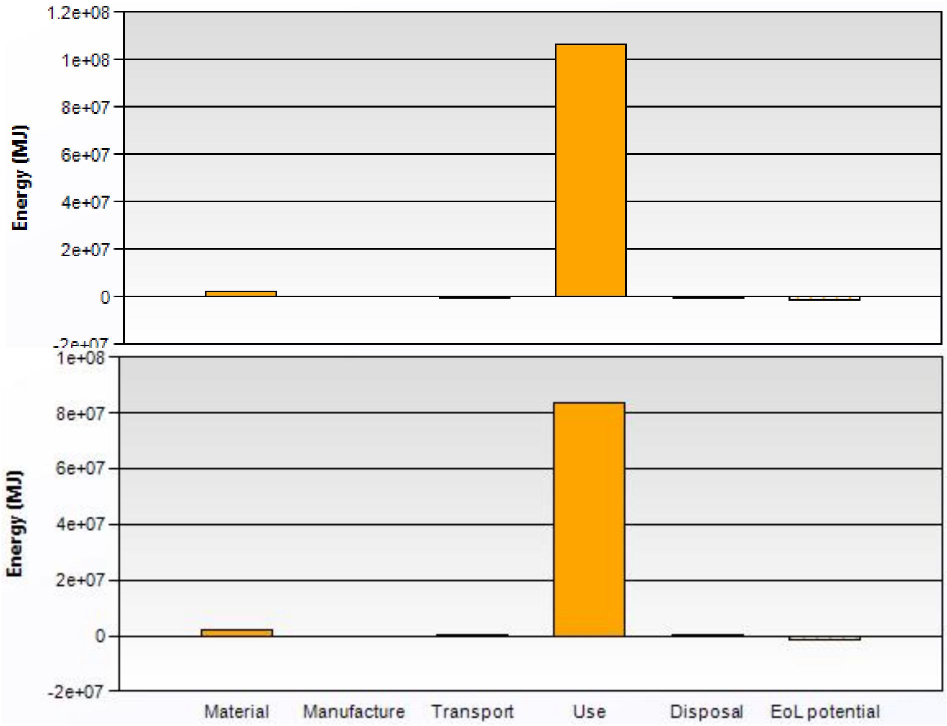


Figure 41: Comparing energy allocation diagrams for the CBC and CBS beams

The corresponding difference of carbon dioxide footprint is 1,08×10^5 kg, see Figure 42. Also visible in the figure is that the burden from the material is higher for the CBS beams, but that also means that the end of life potential is higher.

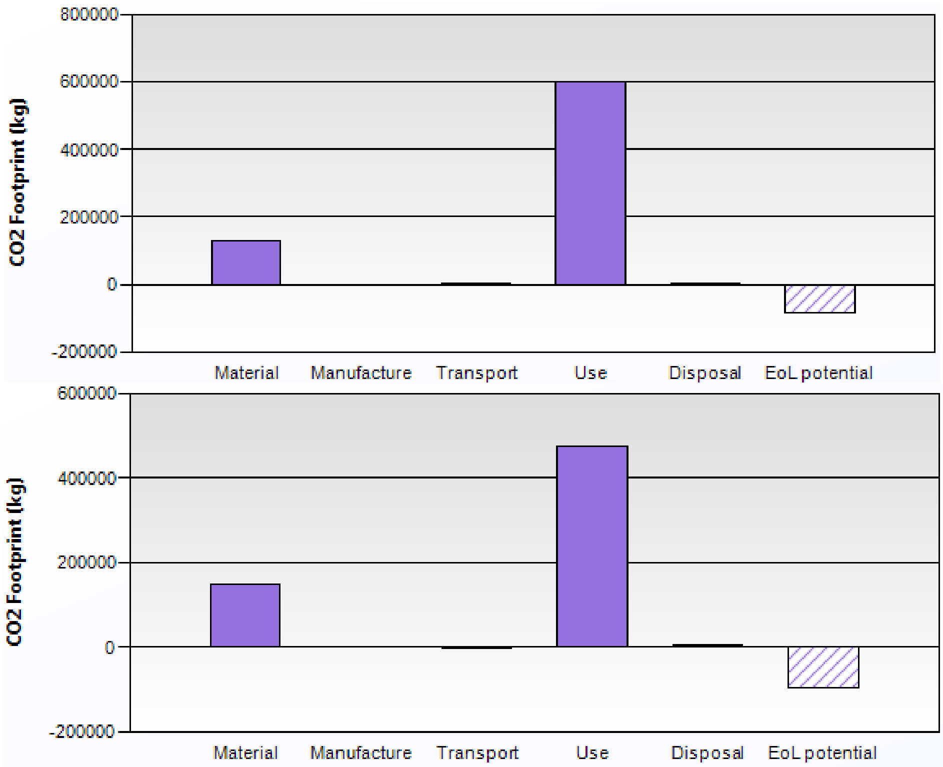


Figure 42: Comparing CO2 footprint allocation diagram for the CBC and CBS beams

The price difference of the carbon dioxide emission amounts to 16 965 SEK, calculated in accordance with the EU ETS directives, thus making the CBS beam system in theory about 17 000 SEK cheaper regarding carbon dioxide emission.

8.6.4 **Critical review**

The used methods are considered to correspond to the international standards as the assessment was executed with support from extensive literature on the subject, including ISO 14040.2 Draft: Life Cycle Assessment - Principles and Guidelines, LCA, which also acts as a base for several other studies. The methods are thereby also considered scientific, and the tool used for performing the calculations, CES EduPack, is the tool commonly used at KTH Royal IT for these types of works. Some assumptions and limitations were made in the study, which can be discussed regarding the result's accuracy. This includes choice of specific materials, as this information was not based on facts from the manufacturer but assumptions with engineering accuracy. This also applies to the modes of transport and route, as well as the use profile. The usage profile was developed from the energy calculations, but also the less accurate weather information from various weather stations in Solna, which might mean that the most critical impact category depends on however small but still loose assumptions. This was a concern early in the process which led to that the use profile, giving the operational energy consumption, was based on an extensive amount of research to minimize the risk for misleading results and error sources. That included both literature on weather and solar radiation history, earlier theses on the subject, as well as in-house information and the energy calculations performed and presented in this thesis. Consequently, it was assumed accurate enough for the assessment. The interpretation is considered to reflect the goal and limitations of the LCA.

9 CONCLUSIONS & DISCUSSION

This chapter provides the conclusions, recommendations based on the results, and suggestions for future work and includes a critical review of the thesis where the methods, delimitations and results are discussed.

"The purpose is to find the system that best corresponds to the energy and cost related requirements and preferences and by that also propose a workflow for procurements that covers the life cycle perspective", 1.2 Purpose.

As stated in the introduction the purpose was to find the system that would best correspond to the energy and cost related requirements and preferences, and also propose a workflow for procurements that covers the life cycle perspective, which should be well-founded and broken down into easy to follow steps. The work was based on a series of actions all connected to each other, where the result of one action acted as input information for another action. The workflow covers energy calculations, climate measurements, life cycle cost calculations, life cycle assessments regarding environmental impact, and an analysis of the results. Also, the climate conditions were connected to performance level, which itself motivates conducting such an extensive evaluation and a possibly more expensive cooling system as it in the long run could be paid back by a high performance level. All methods were motivated in their respective theory section, but it should be questioned if the background research was extensive and resulted in the choice of the alternative system to examine; the automatic CBS beam system, which is the base for the work and therefore affects the whole project. Due to lack of basic knowledge on cooling systems, characteristics in the systems that to an HVAC designer are obviously good or bad took more time to evaluate. The work could possibly have been wider otherwise, covered a greater part of the system or provided more exact results, if the background research did not have to be as extensive. Further on, the information used as base for this decision was mostly secondary information of which no control of the error sources was possible. In detail, the work was divided into an extensive background research to examine the systems currently on the market, their respective pros and cons, to state a recommended new cooling system. Thereafter, their performance was examined through calculations and measurements and the two systems were modeled in accordance with existing architecture plans on the building. The modeling was done in Revit MEP which for ÅF meant a sought-after analysis of the program. The two systems were then examined through a life cycle perspective including both economical and environmental aspects, to investigate the differences between them and thereby establish the optimal system. An important part of the primary data used to evaluate the systems was the climate measurements. These were conducted late and after a marquis problem that might have affected the indoor temperature and there by the measurement results. The work was limited by the 20 week time frame given for master thesis but the work was aimed towards presenting a complete and well-founded evaluation, as far as possible. Some delimitations were necessary, to make it possible to reach this goal. The most significant delimitation is therefore the decision to only suggest changes to the cooling system and only to analyze the distribution part of the cooling system, even though obtaining a complete view of the climate system of the building requires understanding and analyzing the heat and ventilation systems too. Only two alternatives were compared after an extensive research to find the most appropriate systems. The modeling was based on one dimensioning floor which was multiplied by the number of office floors in the building, to limit the work put on modeling but still get an adequate model for the purpose. Regarding the energy use analysis the model was limited to specific areas in the building acting as dimensional areas. When determining the limits of this section, it should fulfill the requirements to acquire satisfying results from the simulation, but not being unnecessary large. The outcome, calculated in percent, was assumed to apply to the whole system.

The climate measuring and modeling is a part of this work that works as a foundation for the suggestions of how to build the new system and evaluate it. As in usual cases when experiments of any kind are used to represent reality it is of great importance to discuss sources of error that occurs between the complex environments that the simplified model is supposed to symbolize, this is no exception. Possibly the most obvious of these sources of errors is the fact that the measuring took place in two different locations. How exactly this effects the results is difficult to quantify, and could probably be a decent setup for a thesis of similar magnitude to this. It is assumed for this thesis however, that the main problem with comparing two different buildings is that the setup (interior design, location of furniture etc), occupation degree and exposure to sun radiation through windows differ. In defense of the choice of method used here; the cooling system used in both offices are build up by beams from the same supplier, designed for similar conditions and are generally regarded as comparable when setting up climate systems in offices like these, regardless of exact location and layout of the office floors. The extent of the measuring, meaning number of measuring, time for logging temperature etc can also be mentioned as a source of error. It is safe to assume that more loggers, more temperature velocity nodes and in other ways a more extensive measuring would result in a safer and more accurate result. However, the intention of the measuring in this thesis was to get an indication of the climate that would act as an important but limited part of this thesis, and not the main purpose of it itself. Therefore, since the thesis, as any other project, is done over a limited amount of time, an extended measuring session wasn't prioritized, especially since the results were needed for further work.

The climate models were simplified especially in the sense that a limited area of the building would act as an indicator for the rest. It can be assumed here as well, that a larger model would improve the results. The reason for this limitation was obviously time related, it can also be mentioned that since the objective of both measurements and modeling is to conclude how the beams work in any office environment, and not Hagaporten in particular, therefore, limitations have to be drawn somewhere.

9.1 Recommendations

Revit MEP is a warmly recommended program for projects of this type. It is a forward looking program for BIM work, designed after the normal workflow which makes it very easy to use even for someone without many years of experience. It is possible to work in one file simultaneously with other involved instances, as linked files automatically updates when changes are made, and all information follows with the parts. This is not possible in for example AutoCAD, where one HVAC designer explained that the architects had to put text pictures on the walls so that the information on wall properties got through to the next person in the design process. On the downside the files quickly get large which affects the time it takes to perform certain actions.

The recommended *workflow* for evaluations during procurements or when designing a new system covers, besides modeling, the following steps:

- Energy calculations
- Climate measurements
- LCC, life cycle cost calculations
- LCA, life cycle assessments
- Analysis of the results, as a high LCC might be motivated by a low LCA

IDA ICE was used for the energy calculations and simulations, which is a program that covers all possible input information. Another positive aspect is that it is possible to directly import CAD files into IDA, minimizing the work load and the time needed. As a comparison ProClim Web from Swegon was tried, which does not cover as many aspects as IDA and it is not possible to directly import CAD files, but for being a free online program it is fairly good and could act as an indicative evaluation method.

The directives for life cycle cost analyses from *ENEU*, more specifically ENEU 2000, were used as a base for the LCC. There are many methods for calculating these costs, but ENEU stood as one of the more trustworthy by being developed by qualified people, in use since 1994 and updated with experience. It provides concrete examples on how to calculate the life cycle costs and the present values are quite high compared to many other sources, which means that the calculations do not present a dream scenario but the worst case scenario. *CES EduPack* was used for the life cycle environmental assessment. It is a highly recommended program for environmental impact analyses which provides a clear presentation and visualization of the results, and also presents extensive material and process information to simplify possible changes.

To summarize, to perform the evaluation stated by the recommended workflow the programs Revit MEP, IDA ICE, and CES EduPack should be used and the calculations are recommended to be based on the ENEU directives.

9.2 Suggestions on future work

Interesting would be to further examine Revit MEP by comparing its built in calculation tools with IDA ICE, which would be recommended for someone with knowledge in programming to evaluate the detail level of the calculations. Is Revit MEP exact enough and would it be possible to completely move over to using it without having to perform calculations in another program, or even manually?

Do blockages or deposits in the piping affect the flow and thereby the performance, energy use and costs? In that case it would be interesting to develop a simple cleaning method, or product, that does not require a lot of time or skilled personnel. It should not interfere with the flow in the pipes, but is should also not require shutting down or opening up a closed part of the system as the downtime costs are high. This would be recommended for someone with a product development or machine design background for example.

REFERENCES

CHAPTER 2

Data collection

1. Energieffektiva upphandlingar, The Association of Swedish Engineering Industries and Bengt Dahlgren AB, 2000

Current system

1. *DWG*: V50-P05.dwg
2. *DWG*: Rör_flödesschema_model.dwg
3. Interview HVAC engineer ÅF 2012

Programs

1. usa.autodesk.com/revit/mep-engineering-software/
2. www.equa.se/eng.ice.htm

Functional unit

1. Arbetsmiljöverket, AFS 2009:2, www.av.se/dokument/afs/afs2009_02.pdf, accessed 2012-02-21
2. Gagge, Burton and Bazett, *A practical system of units for the description of heat exchange of man with his environment*, 1941
3. International Organization of Standardization, 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*, 2005
4. Ramsey, Burford, Beshir and Jensen, *Effects of workplace thermal conditions on safe work behavior*, National Institute for Occupational Safety and Health, 1983
5. Seppänen, Fisk and Faulkner, *Cost benefit analysis of the night-time ventilative cooling in office buildings*, Lawrence Berkeley National Laboratory, www.osti.gov/bridge/servlets/purl/813396-hZB8LT/native/813396.pdf, 2003

Alternative system

1. Interview HVAC engineer ÅF 2012

CHAPTER 3

Workplace ergonomics

1. International Ergonomics Association, iea.cc, *Home – What is ergonomics*, 2012-05-30
2. Office Ergonomics Handbook, 5th Edition, *Occupational Health Clinics for Ontario Workers Inc.*, www.ohcow.on.ca/resources/workbooks/ergonomics.pdf, 2011, accessed 2012-05-30
3. Jonas Högberg & Mats Isaksson, *Dose rate from gamma radiation in dwellings – a modelling approach*, Department of radiation physics University of Gothenburg www.nsfs.org/filer/Gammaradiation_Hogberg_Iskasson.pdf, accessed 2012-05-26

4. The Swedish National Board of Housing, Building and Planning, BFS 1998:38, www.boverket.se – Webbokhandel, 2012-05-26
5. Arbetsmiljöverket, www.av.se – Klimat, 2012-05-30
6. Hans Gullberg and Karl-Ingvar Rundqvist, *The Work Environment Act (AML)*, 1 January 2010, 15th Edition, Joint publication with Arbetsmiljöforum, Norstedt Juridik.
7. Interview with Per Fahlén, www.afconsult.com%2Fsv%2Fmarketing-web-sites%2Fmagazines%2Ffunktion%2Ffunktion-oktober-2006%2Fprofilen%2F&ei=bLrET8TJDsKh4gTm4JmLCg&usg=AFQjCNHgmdznKwkNvTMitiO6GTX0IKRXWg&sig2=_6QGlImtkxThI7dVXCUaxw, 2006, 2012-05-28
8. Prevent, Ventilation i arbetsmiljön, www.prevent.se – Ämnesområde – Fysiska risker – Ventilation 2012-05-30
9. grokcode.com/655/how-to-increase-productivity-by-reordering-your-office/
10. June Pilcher, Eric Nadler and Caroline Busch, *EVects of hot and cold temperature exposure on performance: a meta-analytic review*, 45:10, Taylor & Francis Group 2002, www.fra.dot.gov/downloads/Research/temp_effects_on_perf.pdf, accessed 2012-05-30
11. Olli Seppänen, William J. Fisk and David Faulkner, *Cost benefit analysis of the night-time ventilative cooling in office building*, Lawrence Berkeley National Laboratory: Lawrence Berkeley National Laboratory, 2003. *LBNL Paper LBNL-53191.*
12. Clifford Federspiel, Rodney Martin and Hannah Yan, *Thermal comfort models and complaint frequencies*, Center for the Built Environment, University of California, Berkeley, 2003
13. Sven Setterlind, *Den hälsosamma arbetsplatsen: Från analys till åtgärd*, Stress Management Center AB, Karlstad, 2004
14. Seppänen and Fisk, *Summary of human responses to ventilation*, HUT and LBL, escholarship.org/uc/item/64k2p4dc, 2004

CHAPTER 4

Climate measurements

1. BFS Boverkets Författarsamling, 1998:38 BBR 7, from OVK, ISBN 1998
2. Setterlind, *Den hälsosamma arbetsplatsen. Från analys till åtgärd*, Stress Management Center AB, 2004
3. Boverkets Nybyggnadsregler BFS 1988:18, ISBN 91-38-09758-3, 1989
4. Boverkets Byggregler BFS 1993:57 BBR 94:1, 1993
5. Roger Taesler, *Klimatdata för Sverige*, ISBN 91-540-2012-3, 1972
6. International Orgganization for Standardization, 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*,
7. Federspiel, Liu, Lahiff, Faulkner, Dibartolomeo, Fisk, Price and Sullivan, *Worker performance and ventilation – analyses of individual data for cell-center workers*, 2002

CHAPTER 5

Energy calculations

1. http://www.wbdg.org/resources/energyanalysis.php, accessed 2012-07-20

CHAPTER 7

LCC

1. Energimyndigheten, *Krav på kylaggregat*, ISO 15930-1, 2006
2. IEC 60300-3-3:2004 Dependability management - Part 3-3: *Application guide - Life cycle costing*, www.elstandard.se/standarder/visa.asp?IDnr=880701, accessed 2012-05-18
3. WBDG, National Institute if Building Sciences, www.wbdg.org/resources/lcca.php, accessed 2012-05-18
4. Association of the Swedish Engineering Industries and Bengt Dahlgren AB, *Energieffektiva Upphandlingar 94/94 K/2000 - Directives for the procurement of energy efficient equipment and machines in industry*, 1994/1996/2000
5. Public Procurement Act, SFS 1995:704
6. The Swedish Board of Housing, Building and Planning recommendations, *No. 6006 Annual Cost Estimates*, 1991-12
7. Svensk Byggtjänst, *Svensk AMA Standard*, ama.byggtjanst.se/Default.aspx#VadArAma, accessed 2012-05-21
8. Olsson and Skärvad, *Företagsekonomi från* början, ISBN 9789147062430, 2001
9. VVS Special, 1:1980 Profitability Calculations
10. The Swedish Board of Housing, Building and Planning recommendations, *No. 6006 Annual Cost Estimates*, 1991-12
11. Energimyndigheten, *Löpande kommersiella energipriser i Sverige 1970-2007 (inkl. skatt), öre/kWh statistiskt underlag,* 2009. *(*SCB och Energimyndigheten)
12. Hessam Tabrizi, *Energieffektivisering – integrerat värmesystem mellan bostäder och livsmedelsbutik*, Examensarbete inom Institutionen för bygg- och miljöteknik, Chalmers Tekniska Högskola, 2009
13. Sveriges Riksbank, *Reporänta,* tabell, www.riksbank.se/sv/Rantor-och-valutakurser/Reporantan-tabell/, collected 2012-06-11
14. Energimyndigheten, *Table of present value factor: constant yearly expenditures,* energimyndigheten.se/Global/Företag/df.pdf, 2006
15. Halton Oy, *Environmental specification: Ventilated cooled beams*, www.halton.se/halton/se/cms.nsf/files/456A45B144496F1BC22572B2002A75BA/$file/kylbafflar.pdf, collected 2012-06-11
16. Grundfos Prislista 2011 www.grundfos.se/web/homese.nsf/Grafikopslag/prislista_2011/$file/ATTM8TXH.pdf, collected 2012-06-11
17. Energimyndigheten, *Krav på kylaggregat*, www.swerea.se/DocumentsEnig/Krav%20p%C3%A5%20kylaggregat.pdf, ISO 15930-1, 2006
18. Expowera, *startsida – ekonomi – kalkylering – investeringskalkyl*, www.expowera.se/mentor/ekonomi/kalkylering_investering_berakning.htm
19. Norrenergi, *Miljöprestanda för Norrenergis fjärrvärme och fjärrkyla 2011,* www.norrenergi.se/NE_hemsida/_down/Miljoprestanda%202011.pdf, accessed 2012-06-13

20. Halton, *Halton – kylbafflar*, www.halton.se/halton/images.nsf/files/0294FE91FD68E241C22573D200682D48/$file/Chilled%20Beam%20product%20category%20brochure_SE.pdf, acessed 2012-06-13

CHAPTER 8

LCA

1. UN Conference on Environment and Development, *Agenda 21*, www.hu2.se/agenda21/innehall.htm, 1992
2. Climate Committee, UNCCC, *Kyoto Protocol*, Unfccc.int/kyoto_protocol/items/2830.php, 1997
3. The Swedish National Energy Administration, *Building Sustainable Energy Systems*, ISBN 91-7332-961-4, 2001
4. ÅF AB, www.afconsult.com/en/Sustainability/, accessed 2012-06-04
5. Rydh, Lindahl and Tingström, *Livscykelanalys – en metod för miljöbedömning av produkter och* tjänster, ISBN 91-44-02447-9, 2002
6. Moberg, Finnveden, Johansson and Steen, M*iljösystemanalytiska verktyg – en introduction med koppling till beslutssituationer Kartläggning*, AFN, Naturvårdsverket, 1999
7. NVF, *Miniseminar om livscyklusanalyser*, 1996
8. Stripple, *Livscykelanalys på väg*, IVL Svenska Miljöinstitutet, 1995
9. International Organization for Standardization, ISO 14040:2006, *Environmental management – Life Cycle Assessment – Principles and framework*, www.iso.org/iso/catalogue_detail?csnumber=37456
10. Baumann and Tillman, *The Hitch Hiker's guide to LCA – an orientation in life cycle assessment methodology and application*, ISBN 91-44-02364-2, 2004
11. DNV Det Norske Veritas, *Livsløpsvurderinger I* transportsektoren, 1996
12. Granta Design, www.grantadesign.com/education/software.htm, accessed 2012-05-21
13. Halton, www.halton.com, accessed 2012-05-21
14. Energimyndigheten, www.energimyndiheten.se, accessed 2012-05-21
15. Pålsson and Carlsson, *Livscykelanalys – ringar på vattnet*, 2008
16. International Organization for Standardization, ISO 14044:2006, *Environmental management – Life Cycle Assessment – Requirements and guidelines*, www. iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=38498, accessed 2012-05-25

APPENDIX A: LCC calculations, excel

Economical evaluation of cooling systems

Life cykle cost analysis according to guidelines from Statens Energimyndighet

2012-05-03

PROJECT: HAGAPORTEN III

DATE/ADMINISTRATOR: 2012-05-03/MRH

Conditions			
Time the calculation covers	years	20	
Annual rate of interest (%)		7%	
Annual energy price increases above inflation (%)		5%	
Annual inflation for maintenance above inflation (%)		5%	
Number of intervals during the calculation period	**No.**	13	13

INVESTMENT COST			
System		**Befintligt**	**Ersättande**
Beam type		CBC	CBS
Manufacturer		Halton AB	Halton AB
Beams 1,8 m	No.	89	0
Beams 2,1 m	No.	9	0
Beams 2,4 m	No.	1465	0
Beams 3,0 m	No.	29	1525
Beams 3,6 m	No.	45	0
Price per unit	SEK/m	1700	2000
Beam cost total	SEK	6 704 970	9 150 000

PIPING			
Copper pipes	m	11 655	11 655
Price per unit	SEK/m	99	99
Steel pipes	m	1295	1295
Price per unit	SEK/m	72	72
Stainless steel pipes	m	121	121
Price per unit	SEK/m	152	152
Pipe cost total	SEK	1247085	1247085

Valves in system			
AV51 ball valves Armatec	No.	287	287
Price per unit	SEK/No.	157	157

AL51 security valves Durgo	No.	24	24
Price per unit	SEK/No.	2245	2245
AVL51 deaerator Armatec AT 3602	No.	22	22
Price per unit	SEK/No.	78	78
RV51 control valves	No.	42	42
Price per unit	SEK/No.	144	144
BV51 check valves	No.	3	3
Price per unit	SEK/No.	120	120
Valves by beams			
AV53 mini ball valves Beulco Armatur	No.	3274	3274
Price per unit	SEK/No.	144	144
SV71 two-way + M check valves Armatec	No.	1637	1637
Price per unit	SEK/No.	77	77
Valve sost total	SEK	647461	647461

Insulation			
Armaflex NH 13 mm KB01	m	655	0
Price per unit	SEK/m	74	0
Paroc Section Alucoat T 20 mm KB21-22	m	22655	0
Price per unit	SEK/m	39	0
Paroc Section Alucoat T 30 mm KB21-22	m	1416	0
Price per unit	SEK/m	96	0
Insulation cost total	SEK	1063230	0

Installation			
Delivery- and work costs	SEK	1134787	1134787
Flow meter	SEK	15858	15858
Control equipment	SEK	9911	0
Thermometres	SEK	10707	10707
Pressure gauge equipment	SEK	612	612
Other	SEK	0	0
Installation costs	SEK	1 171 874	1 161 963

SUM INVESTMENT COSTS	SEK	**10 834 620**	**12 206 509**

OPERATION COSTS		**Befintligt**	**Ersättande**
Energy costs			
Subscription power	kW	1 100	850
Connection fee	SEK	2750000	2125000
Subscription fee annual	SEK	211200	163200
Flow fee annual	SEK	385119,36	233098,56
Energy fee annual	SEK	218400	176400
Operation time	h/year	3 648	2 928

Use factor		1,0	1,0
Energy use / year	MWh/year	728,00	588,00
Electricity price	SEK/kWh	0,90	0,90
Operation cost / year	SEK/year	1 469 919	1 101 899
Calculation factor 1		16,35	16,35
Present value energy costs	**SEK**	**26 783 182**	**20 766 041**
Maintenance costs			
Hourly wage maintenance workers, SÖ	SEK/h	970	970
Time spent training	SEK/h	20	20
Cost maintenance training	SEK/h	19400	19400
Hourly wage maintenance personnel	SEK /h	700	700
Maintenance time beams	h	16	16
Maintenance cost beams	SEK	11200	11200
Operation time before maintenance	h	2 000	2 000
Maintenance interval	times/year	2	1
Maintenance time installations	h	16	0
Maintenance cost installations	SEK	11200	0
Operation time before maintenance	h	1 000	10 000
Maintenance interval	year	4	0
Maintenance cost / year	SEK /year	67200	11200
Calculation factor 2		16,35	16,35
Present value maintenance costs	SEK	**1 118 120**	**202 520**
SUM OPERATION COSTS		**27 901 302**	**20 968 561**

TOTAL COST	**SEK**	**38 735 922**	**33 175 071**
Difference to existing			**5 560 851**

Environmental affection			
CO2 emission	kg	728	588
Difference to existing	kg		140

Cost through EU ETS	SEK	146	118

APPENDIX B: Energy costs and fees, Norrenergi

Valid from 2012-01-01 until further notice, VAT will be added to all charges. Norrenergi's price list for district cooling is based on three elements:

- A fixed part that depends on the customer's subscription power in kW
- A variable part that depends on the customer's energy usage in MWh
- A flow-related part that depends on how much district cooling water that is circulating through the customer's central during May through September

Connection fee

For connecting to the district cooling system a one-time connection fee incurs, which in this case amounts to 2 500 SEK per kW subscribed effect excluding VAT. It should be noted that this is only an estimate.

- Connection fee existing system: 2500 SEK * 1100 kW = **2 750 000 SEK**
- Connection fee replacing system: 2500 SEK * 850 kW = **2 125 000 SEK**

Subscription fee

The subscription effect is determined each year as the average of the three highest hourly average effects from three different days that Norrenergi measured during May through September. The annual subscribed effect amounts to 1 100 kW with the existing system and corresponds to 850 kW for the replacing system.

- Fixed annual subscription fee existing system: 1100 kW * 192 SEK = **211 200 SEK**
- Fixed annual subscription fee replacing system: 850 kW * 192 SEK = **163 200 SEK**

Flow fee

The flow fee is calculated from the amount of district cooling water that circulated through the customer's district cooling central. The fee is 0,85 SEK/m^3 and starts from May 1 to September 30, during other times there will be no charge of flow. Elapsed time with district cooling, i.e. when the temperature exceeds 15°C and 19°C, was examined through temperature graphs over the last couple of years. It applies to the periods May 1 – September 30 and May 15 – August 15.

- Flow district cooling water existing system: 34,5 l/s = 0,0345 m^3/s
- Elapsed time May 1 – September 30: 152 days = 13 132 800 s
- Passed flow May 1 – September 30: 0,0345 * 13 132 800 = 453 081,6 m^3

Flow fee existing system: **385 119 SEK**

- Flow district cooling water replacing system: 34,5 l/s = 0,0345 m^3/s
- Elapsed time May 15 – August 15: 92 days = 7 948 800 s
- Passed flow May 15 – August 15: 0,0345 * 7 948 800 = m^3

Flow fee replacing system: **SEK**

Energy fee

The energy fee is calculated from the current energy price in SEK / MWh as shown below, multiplied with the amount of energy in MWh extracted during the period.

Period	Days	Extracted energy	Energy price	Fee
May 1 – September 30	152	728 MWh	300 SEK/ MWh	218 400 SEK
May 15 – August 15	92	560 MWh	300 SEK/ MWh	168 000 SEK

Free cooling during the period October 1 to April 30 means that no district cooling is used during that period in the calculations, however, it is expected that the district cooling yet is added sporadically during the period.

- Energy fee existing system: **218 400 SEK**
- Energy fee replacing system: **168 000 SEK**

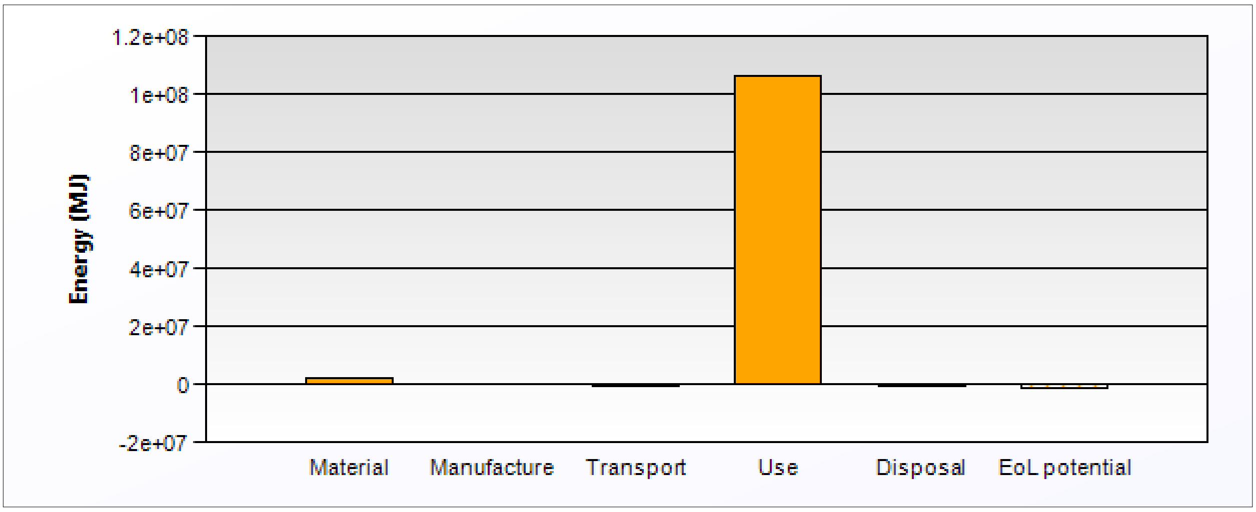
APPENDIX C: ECO Audit Report, results CBC and CBS

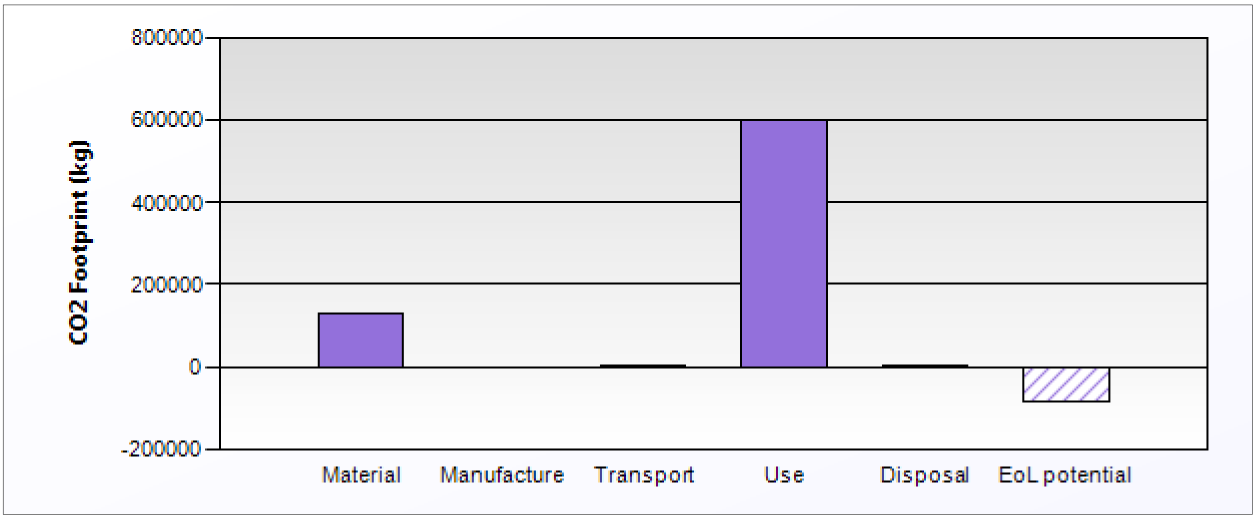
Eco Audit Report

Product Name CBC

Product Life (years) 20

Energy and CO2 Footprint Summary:





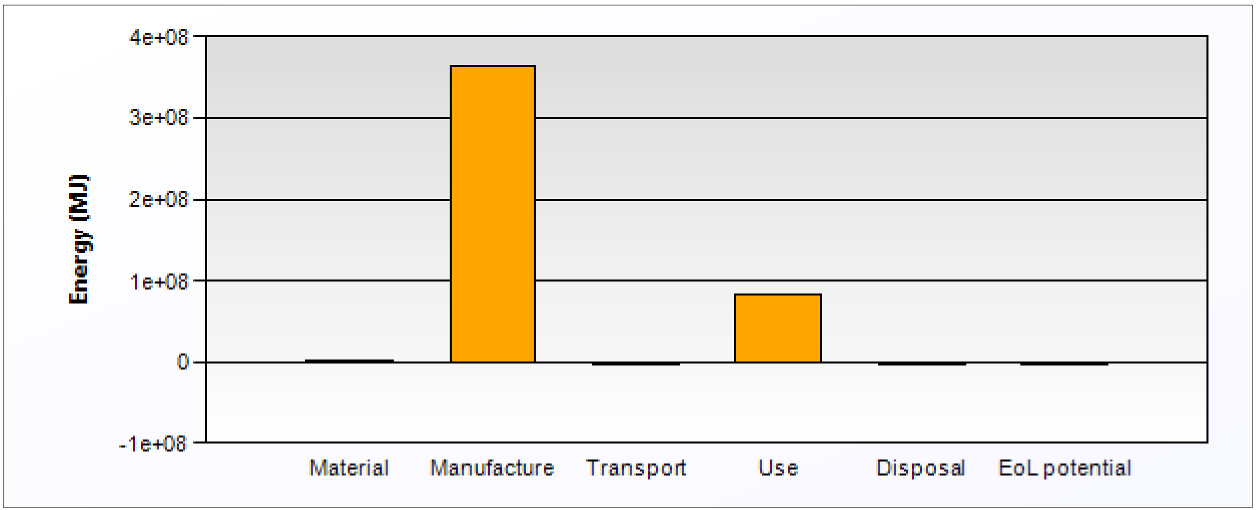
Phase	Energy (MJ)	Energy (%)	CO2 (kg)	CO2 (%)
Material	2.01e+06	1.9	1.29e+05	17.5
Manufacture	0	0.0	0	0.0
Transport	1.13e+04	0.0	803	0.1
Use	1.06e+08	98.1	6.01e+05	81.8
Disposal	5.2e+04	0.0	3.64e+03	0.5
Total (for first life)	1.08e+08	100	7.34e+05	100
End of life potential	-1.33e+06		-8.44e+04	

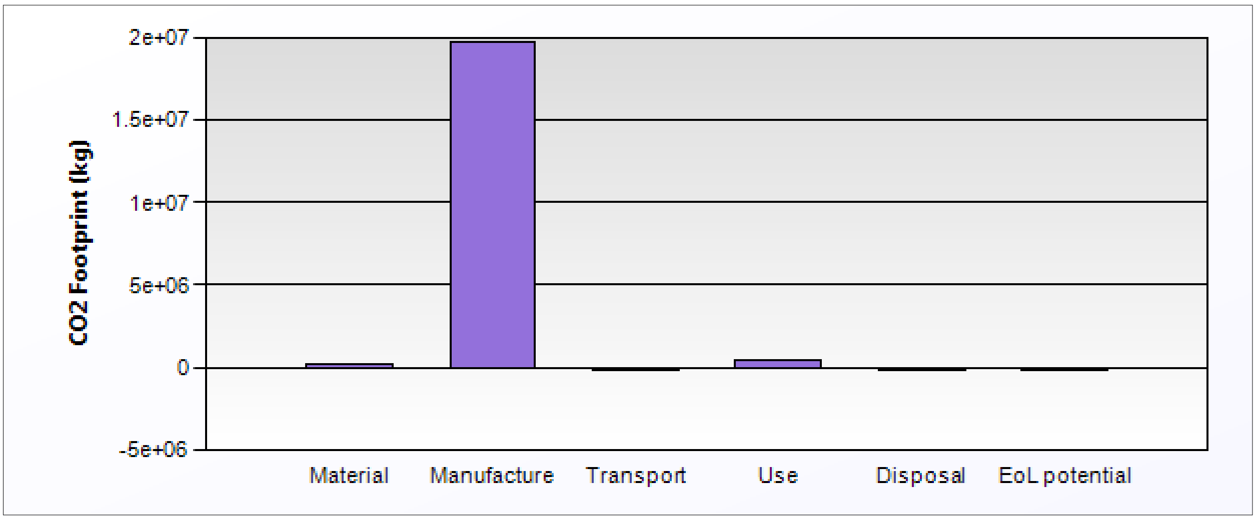
EcoAudit Report

Product Name CBS

Product Life (years) 20

Energy and CO2 Footprint Summary:





Phase	Energy (MJ)	Energy (%)	CO2 (kg)	CO2 (%)
Material	2.3e+06	0.5	1.47e+05	0.7
Manufacture	3.65e+08	80.9	1.97e+07	96.9
Transport	1.29e+04	0.0	919	0.0
Use	8.36e+07	18.5	4.73e+05	2.3
Disposal	5.95e+04	0.0	4.17e+03	0.0
Total (for first life)	4.51e+08	100	2.03e+07	100
End of life potential	-1.52e+06		-9.65e+04	