Energy efficiency and ventilation in Swedish industries
barriers, simulation and control strategy

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This thesis is based on work conducted within the interdisciplinary graduate school Energy Systems. The national Energy Systems Programme aims at creating competence in solving complex energy problems by combining technical and social sciences. The research programme analyses processes for the conversion, transmission and utilisation of energy, combined together in order to fulfil specific needs.

The research groups that participate in the Energy Systems Programme are the Department of Engineering Sciences at Uppsala University, the Division of Energy Systems at Linköping Institute of Technology, the Department of Technology and Social Change at Linköping University, the Division of Heat and Power Technology at Chalmers University of Technology in Göteborg as well as the Division of Energy Processes at the Royal Institute of Technology in Stockholm.

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Abstract

The energy issue is presently in focus worldwide. This is not only due to increasing environmental concern regarding energy related emissions, but also due to the trend of increasing energy prices. Energy usage in the industrial sector in Sweden today represents about one third of the national energy use. A substantial part of that is related to support processes such as heating, ventilation and cooling systems. These systems are important as they are related both to energy cost and indoor climate management as well as to the health of the occupants.

The purpose of this thesis is to reach a more comprehensive view on industrial energy efficiency and indoor environment issues related to industrial ventilation. This has been studied in three themes where the first part addresses barriers to energy efficiency in Swedish industries, the second theme discuss simulation as decision support, and the third studies the variable air volume system in industrial facilities.

In the first theme three different studies were made: the first studies non-energy intensive companies in Oskarshamn in Sweden, the second studies the energy intensive foundry industry and the third study was part of an evaluation of a large energy efficiency program called Project Highland. These studies had several findings in common, such as the importance of a strategic view on the energy issue and the presence of a person with real ambition with power over investment decisions related to energy issues at the company. The studies also show that several information related barriers are important for decision makers at the studied companies. This shows that information related barriers are one reason in why energy efficient equipment is not implemented.

In the second theme the use of simulation in the form of Computational Fluid Dynamics (CFD) and Building Energy Simulation (BES) are used as decision support for industrial ventilation related studies at two different industries, one foundry is investigated and one dairy. BES has mainly been used to simulate energy and power related parameters while CFD was used to give a detailed description of the indoor and product environment. Together these methods can be used to better evaluate the energy, indoor and product environment and
thus enable the implementation of more efficient heating, ventilation and air-conditioning systems.

In the third theme the use of Variable Air Volume (VAV) systems was evaluated, and was found to be an efficient way to reduce energy use at the studied sites. At the studied foundry the VAV system is predicted to reduce space heating and electricity use by fans by about 30%, and in the dairy case by about 60% for space heating and 20% for electricity.
Sammanfattning

Energifrågan är idag högaktuell, dels beroende på kopplingen till hotet om global uppvärmning, dels beroende på stigande energipriser. Den industriella energianvändningen i Sverige står för ca en tredjedel av den totala energianvändningen och en betydande del av denna användning är relaterad till stödprocesser som till exempel luftkonditionering, värming, kylning och ventilation. Dessa processer är viktiga då de är kopplade till såväl energianvändning som hälsa och inomhusmiljö.

Syftet med denna avhandling är att ge en mångsidig beskrivning av industriell energieffektivisering och industriventilation. Detta har studerats i tre teman där det första temat tar upp frågan om hinder mot energieffektivisering, det andra temat simulering som beslutsstöd och det tredje temat variabelflödessystem för industriell ventilation.

I det första temat har tre studier genomförts, en studie av icke energiintensiva företag i Oskarshamn, en studie av den energiintensiva gjuteriindustrin i Sverige och en studie i samband med en utvärdering av Projekt högland. Dessa studier har flera gemensamma nämnare som exempelvis behovet av en långsiktig energistrategi samt behovet av en eldsjäl med makt över investeringsbeslut. Dessa studier visar också på flera informationsrelaterade hinder som är viktiga för beslutsfattarna på företagen. Det andra temat undersöker hur simulering, i form av Computational Fluid Dynamics (CFD) och byggnadssimulering (BES) kan användas som beslutsstöd. Två detaljerade studier har genomförts inom detta tema, ett lättmetallgjuteri och ett mejeri har studerats. Byggnadssimulering har främst använts för att studera effekt och energirelaterade parametrar medan CFD har använts för att ge en detaljerad beskrivning av termisk- och produktmiljö. Tillsammans ger dessa båda metoder bättre möjligheter att utvärdera energi, produkt och inomhusmiljörelaterade aspekter, vilket ger bättre möjligheter att dimensionera effektivare system. I det tredje temat har potentialen för att använda variabelflödessystem undersökts, och för de studerade anläggningarna finns en stor potential för tekniken. För den studerade gjuterilokalen visar simuleringarna på en reducering av värme och fläktel med ca 30% och för den studerade mejerianläggningen en reducerad varmeanvändning med ca 60% och elanvändning med ca 20%.
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First, I would like to thank my supervisor, Professor Bahram Moshfegh, both for introducing me to the world of research and for all the help, encouragement and valuable input on this thesis. I would also like to express my gratitude to him for encouraging me to do so many different projects and studies, as this has made my time as a PhD student both interesting and rewarding. I would also like to thank my assistant supervisor, Professor Hazim Awbi, at Reading University, U.K. for the support and comments on drafts of this thesis and valuable comments in the early parts of my PhD project. Furthermore, I would like to thank my assistant supervisor at the Division, Dr. Magnus Karlsson, for valuable comments on drafts as well as fruitful collaboration on several projects, and Dr. Jenny Palm for all the help with the interview guide and for reading drafts of this thesis.

A special thanks also to the co-authors with whom I have had the privilege to work. Ph.D. student Patrik Thollander for all the work we did together during the first years of our PhD studies, not to mention for showing me that you can actually fish even though Linköping is far from the ocean. Dr. Fredrik Karlsson for all the work we did together on various projects as well as all the sometimes very long discussions. Our collaboration has meant a lot to me. Ph.D. student Maria Danestig, Dr. Marie-Louise Persson and Mr Petter Solding for all the work we did together and Tekn. Lic. Ulf Larsson and Dr. Mathias Cehlin at the University of Gävle, for the CFD discussions. The representatives at the companies I have worked with are also gratefully acknowledged. Mr Sten-Erik Lindhe, Mr Lars-Erik Stöllman, Mr Kjell Lunden-Pettersson, Mr Hans Nycander and Mr Hans-Olov Appelgren at Arla Foods AB and Mr Gunnar Göransson, Mr Anders Gustafsson and Mr Ola Ring at Husqvarna AB to name a few. Thank you.

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Finally, I would like to thank my friends and family, and especially my fiancée Johanna, for the things in life that matter the most.
Appended papers

**Theme 1**


**Theme 2**


**Theme 3**

Nomenclature

\( C \)  Concentration (ppm)
\( c_p \)  Specific heat, (J/kg K)
\( f_{cl} \)  Clothing surface factor (-)
\( g_i \)  Component of the gravitational vector in the \( i \)th direction (m/s\(^2\))
\( h_c \)  Convective heat transfer coefficient (W/m\(^2\)K)
\( I_{cl} \)  Clothing insulation (m\(^2\)K/W)
\( k \)  Turbulent kinetic energy, (m\(^2\)/s\(^2\))
\( l \)  Length scale (m)
\( M \)  Metabolic rate (W)
\( P_{fans} \)  Power used by fans (kW)
\( P_a \)  Water vapor partial pressure (N/m\(^2\))
\( Pr \)  Prandtl number (-)
\( p \)  Pressure, (N/m\(^2\))
\( q \)  Airflow (m\(^3\)/s)
\( S_{ij} \)  Magnitude of rate of strain (1/s)
\( TI \)  Turbulence intensity, (-)
\( t \)  Temperature (°C)
\( t_a \)  Air temperature (°C)
\( t_{cl} \)  Clothing surface temperature (°C)
\( t_r \)  Mean radiant temperature (°C)
\( U \)  Mean velocity, (m/s)
\( \bar{u} \)  Instantaneous velocity, (m/s)
\( u \)  Velocity fluctuation, (m/s)
\( V \)  Volume (m\(^3\))
\( v_{air} \)  Relative air velocity (m/s)
\( \dot{v} \)  Ventilation rate (ls\(^{-1}\)olf\(^{-1}\))
\( W \)  Effective mechanical power (W)
\( y \)  Distance to wall (m)
\( y^+ \)  Dimensionless wall distance (-)
\( x, y, z \)  Coordinate, (m)
Greek symbols

$\beta$  Volumetric thermal expansion coefficient (1/K)
$\delta$  Kronecker delta, (-)
$\varepsilon$  Dissipation of turbulent kinetic energy, (m$^2$/s$^3$)
$\lambda$  Thermal conductivity, (W/mK)
$\mu$  Dynamic viscosity, (kg/m s)
$\mu_r$  Eddy viscosity (kg/m s)
$\nu$  Kinematic viscosity, (m$^2$/s)
$\nu_t$  Eddy viscosity, (m$^2$/s)
$\rho$  Density, (kg/m$^3$)
$\tilde{\theta}$  Instantaneous temperature (°C), $\tilde{\theta} = \Theta + \theta$
$\Theta$  Average temperature, (°C, K)
$\Theta_0$  Reference temperature (°C, K)
$\theta$  Temperature fluctuation (°C, K)
$\sigma_i$  Turbulent Prandtl number (-)
$\sigma_k, \sigma_\varepsilon$  Constants
$\tau_i$  Mean age of air (s)
$\tau_n$  Nominal time constant (s)
$\tau_{ij}$  Stress components (N/m$^2$)

Subscript

oz  occupied zone
i  inlet
o  outlet
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1 Introduction

This introduction outlines the background of this thesis followed by the purpose, aim and scope. The co-author statement as well as a short description of the appended papers are also included in this chapter.

The threat of global warming as a result of the use of fossil fuels and other energy-related emissions are forcing politicians on all levels are to try to influence energy use, and as a result different policy instruments have been implemented such as CO₂ emissions trading. These and other future policy instruments will in all probability result in higher energy prices to decrease the use of fossil fuels, and thus further increase the demand for industrial energy efficiency. From a Swedish perspective the increased globalization and opening up of domestic markets within the European Union will also make the implementation of cost-efficient energy efficiency measures within industry even more necessary, due to among other things the historically low prices of electricity. This highlights the need for an increase in energy efficiency investments for Swedish industrial companies.

Energy usage in the industrial sector in Sweden today represents a large part of the national energy use, but is still considered by many Swedish companies to be a non-strategic factor. The structure of industrial energy use is complex, due to a high degree of interdependency among processes, technology development affecting e.g. energy efficiency and energy conservation, and various dynamics coming into play through production schedules, energy prices, raw materials, labor force and other management issues. From a corporate perspective this introduces multiple problems when working with energy-efficiency issues.
Support processes in industrial energy systems, such as ventilation, heating and cooling systems, are important issues in industrial premises as they are related both to energy cost and indoor climate management as well as to the health of the occupants. Heating, cooling and ventilation of industrial premises account for a large part of the total industrial energy usage in manufacturing. Poor indoor environment conditions in industries also cost large amounts of money in health care, administration, and lost productivity. This underscores the importance of well functioning Heating, Ventilation and Air-Conditioning (HVAC) systems.

1.1 Purpose

The aim of this thesis is to reach a more comprehensive view on energy performance and indoor environmental issues related to industrial ventilation.

The structure of the thesis is summarized in five research questions:

1. Is there a potential for cost-efficient energy efficiency measures in Swedish industry?
2. What barriers inhibit the implementation of cost-efficient energy efficiency measures?
3. What barriers are specific to Heating, Ventilation and Air-Conditioning (HVAC) in industrial ventilation?
4. How can Building Energy Simulation (BES) and Computational Fluid Dynamics (CFD) be used to reduce these barriers to energy efficiency for HVAC in industrial premises?
5. Is there potential for using Variable Air Volume (VAV) systems in industrial premises?

There are three main themes within this thesis. The first theme focuses on barriers and drivers affecting the adoption of energy efficiency measures and is connected to the first three research questions. The second theme picks up issues derived from the first theme and focuses on Building Energy Simulation and Computational Fluid Dynamics as decision support. The third theme focuses on the effects of Variable Air Volume (VAV) control in industrial premises.
1.2 Scope of the thesis

This thesis primarily treats energy efficiency issues in industries with focus on decision support for industrial ventilation applications. All the studies are made mainly from a company perspective and the barriers to energy efficiency presented reflect the respondents’ at the studied companies view of the importance of the different barriers. The same perspective has been used in detailed studies at two large industrial companies where the energy efficiency potential reflects possible reductions at the facility or site. No studies of how these measures would affect the surrounding energy system have been made. This also includes the fact that no explicit studies of environmental performance have been made. Furthermore, when studying the indoor environment, secondary parameters such as sound, lighting, etc. have not been studied. The focus has been on air quality and thermal comfort and to some degree the product environment. The studies are made exclusively in a Swedish context.

1.3 Outline of the thesis

This thesis includes 11 chapters. Chapter 1 contains background, purpose, scope and brief description of the appended papers. Chapter 2 summarizes some aspects of Swedish industrial energy use and also shows some recent studies of the energy efficiency potential within the Swedish industrial sector. In Chapter 3 some industrial management aspects related to decision-making in industrial firms are also discussed and the concept of barriers to energy efficiency is presented. Chapter 4 describes some requirements and overall measures of performance used for industrial ventilation and HVAC in industrial premises, such as indoor air quality, thermal comfort, product environment and energy use aspects. Chapter 5 treats industrial ventilation and its aspects such as control systems, air supply issues, local ventilation and the measures of performance used. Chapter 6 treats the methods used in the appended papers including measurements, Computational Fluid Dynamics (CFD), Building Energy Simulation (BES) and qualitative case studies, including interviews and questionnaires. In Chapter 7, results from the studies of barriers and drivers to energy efficiency are presented. This chapter includes a presentation of the findings in the first three appended papers as well as a discussion of these barriers in relation to industrial ventilation. Chapter 8
contains a description of two detailed studies at one foundry and two dairy processing plants. The production processes, energy use structure as well as CFD and BES are presented. Chapter 9 sums up and discusses the main ideas and Chapter 10 concludes the thesis. In Chapter 11 further work is presented.

1.4 Co-author statement

The first two papers were planned, executed and written in co-operation with PhD student Patrik Thollander. The third paper was written in collaboration with Patrik Thollander and PhD student Maria Danestig, where the author mainly contributed with issues related to the barrier study as well as writing parts of the paper. Paper four was written mainly by the author, but professor Bahram Moshfegh wrote parts of the section about computational fluid dynamics in addition to making valuable comments on drafts of the paper. Paper five was written entirely by the author while Professor Bahram Moshfegh contributed with valuable input and comments on drafts. Paper six was written in collaboration with Dr. Fredrik Karlsson at Linköping University and Dr. Mari-Louise Persson at Ångström, Uppsala University. The author made simulations and exclusively wrote the part about one of the three software programs and was also responsible for the sensitivity analysis. The rest of the paper was co-written with the other authors. Papers seven and eight were written by the author of this thesis but Professor Bahram Moshfegh contributed with many important comments on drafts and ideas as well as made valuable contributions when the measuring strategy for the papers was formulated.
1.5 Appended papers in brief


This paper treats barriers to energy efficiency in the non-energy intensive industry in Oskarshamn. The aim of the paper was to investigate the existence and importance of these barriers. The results highlight barriers inhibiting the diffusion of energy-efficient technology such as risk, cost of production disruptions, lack of time and other priorities, and lack of sub-metering. The study also found a number of drivers such as people with real ambition and the need for long-term strategy. This article was a result of a project within the National Energy Systems Programme.


This paper evolved from the first study presented in paper one. In this paper the barriers to and drivers for energy efficiency within the energy-intensive foundry industry were studied. This project was made in collaboration with the Swedish Foundry Association. The results show that barriers within group-owned companies were more related to organizational problems and barriers within private foundries more related to information. The study also found that consultants and other actors working within the sector were considered more credible and thereby preferred before for instance governmentally funded energy audits. The most important drivers by far were found to be people with real ambition and long-term strategy.

This paper is an evaluation of Project Highland, which was one of the largest local energy programs targeting small and medium-sized industry in Sweden. The study shows an adoption rate of approximately 40% for low- or no-cost measures within the studied industries. The paper also compares this energy efficiency program with another ongoing program targeting energy-intensive industry, and indications are that the approach used is effective. The paper also studies barriers to and drivers for energy efficiency. Lack of time and other priorities are shown to be the most important barriers followed by other priorities for capital investment. The main drivers found were long-term strategy followed by people with real ambition.


This paper explores the benefits of using computational fluid dynamics as a method by which to predict indoor environment parameters in a complex industrial packaging facility. The paper also presents a comparison between three eddy-viscosity turbulence models: the standard $k$-$\varepsilon$ model, the renormalized group (RNG) $k$-$\varepsilon$ model and the realizable $k$-$\varepsilon$. The RNG model gave the results with least deviation compared with measured values. The paper also explored the potential energy savings of changing supply airflows and what consequences this would have on the indoor environment.

This paper focuses on numerical simulation of indoor parameters and energy use using computational fluid dynamics and energy simulation. The main purpose is to evaluate the potential use of CFD when designing industrial ventilation systems in a foundry. The turbulence model used was the renormalized group $k$-$\varepsilon$ model, and the results were compared with measurements. The paper shows a good agreement between simulated and measured values for both temperature and velocity in the 104 points measured. The paper also explores the impact of reducing supply airflow in the facility.


This paper compares the use of three different energy simulation models. The simulated object was an empirically well-known low-energy building in Lindås in Sweden. The focus of the paper was on the choice of simulation software, the impact of the habits of the tenants, and the impact of the uncertainties in supply airflow, heat exchanger efficiency and internal loads. The paper shows small variation in predicted energy use for the different software programs. The most important parameters are shown to be the habits of the tenants when comparing the results with measured values. This underscores the importance of accurate design parameters during the design phase.

This paper focuses on the combination of building energy simulation and computational fluid dynamics as a trustworthy and accurate method of obtaining detailed information when studying industrial ventilation and its control. The study includes predictions of the impact of implementing a Variable Air Volume (VAV) system in a light alloy casting facility. The paper shows that a VAV system is predicted to decrease energy and electricity use for industrial ventilation by about 30%.

The paper was awarded an honorary mention for best poster.


This paper explores the use of building energy simulations in predicting energy use and thermal comfort in the dairy industry. The focus is on industrial ventilation and an entire site is simultaneously simulated. The study includes a benchmark of two large dairy production sites built at three different stages and it is shown that the energy use per square meter increases with time, as does the electricity used for ventilation.

The use of a Variable Air Volume system with heat recovery is explored and shown to be an effective way to reduce both energy and electricity use. The main potential is in the reduction of heat used for space heating.
2 Swedish industrial energy use and some recent studies of the efficiency potential

This chapter contains a short description of the Swedish energy system followed by an introduction to some large or recent studies of the energy efficiency potential in the Swedish industry.

The Swedish electricity generation system is based on a large amount of hydropower and nuclear power, and since the deregulation of the Swedish electricity market in 1996 the Swedish market has become more and more interconnected with the rest of Europe. This became even more so as the European Union accepted the EU Electricity Directive, which includes rules for the internal electricity market in the EU. The European system also has a different structure compared with the Swedish system. The European electricity system has a high degree of coal, natural gas and nuclear power.

Swedish industry accounts for 39% of the total energy use and 43% of the electricity use (SEA, 2005), and the energy use per energy carrier is presented in Figure 2.1, both for the total Swedish system and for the industrial sector.
Figure 2.1. Total Swedish energy use and industrial energy use per energy carrier [TWh] (SEA, 2004).

The historical structure of energy use has changed even though the total industrial energy use has not increased very much in absolute terms despite significant increases in production. The main change is a drastic decrease in oil use since the 1970s, which has been compensated for by an increase in biofuels and electricity (SEA, 2004). Electricity, in contrast to oil, natural gas and coal, is not a primary fuel, and since primary fuels are used in the process of generating electricity, it will in all probability follow the general trend of the underlying fuels. The trend of increasing energy prices and other environmental policy instruments such as emissions trading systems and CO₂ taxes raising the price of energy will change the conditions for industrial companies from what they are today. One way to reduce the risk of these increasing energy prices is to increase energy efficiency within the Swedish industrial sector. The question is then “How large is this potential for Swedish industry?”

There are a large number of publications on the potential for energy efficiency both international and domestic. However, the differences in market conditions, location, energy prices, legislation and environmental aspects make it hard to compare these studies. For this reason only more recent or large studies and programs are discussed, and for Swedish conditions only.

Perhaps the largest Swedish energy program, called “Uppdrag 2000” (Commission 2000), was reported in four parts, with one part treating the industrial sector. The study targets Swedish industries with more than four employees, thus including the food industry, wood industry, graphical industry, textile industry, manufacturing industry, and parts of the chemical and
quarrying industry. The general conclusions of this large program include issues such as: (1) Electricity conservation can be achieved through more efficient utilization of existing technology and modifications of equipment to the actual requirements; (2) Oversizing is common, especially for electric motors; (3) The importance of a whole system perspective together with careful operation and maintenance instructions are important in reducing energy use; (4) The greatest potential to reduce electricity use is found in connection with constructing new buildings, repair and renovation; (5) Measures that simultaneously result in other positive spin-off effects are more likely to be implemented, such as better working conditions, improved indoor climate and improved operational reliability. The final report from Uppdrag 2000 was published in November 1991.

In January 2005, a program called Program for Energy Efficiency (PFE) was initiated by the Swedish Energy Agency. The PFE is a program targeting electricity use in energy-intensive industry, and presently more than a hundred companies are active in the program. The companies participating in the program receive a tax reduction, provided that they work strategically with the energy issue and implement efficiency measures within their companies (SEA, 2007). During the first two years 98 companies participated, representing an electricity use of 29 TWh/year, and about 900 efficiency measures with an annual potential of 1 TWh have been generated. The program includes energy audits in the initial phase and also the implementation of an energy management system. For these energy-intensive industries, 48% of the measures were related to the production process, leaving 52% of the measures to support processes. Among the support processes, compressed air, pumps and fans are the processes with most measures suggested (SEA, 2007). It is important to note that this program's main goal is to target electricity. Results from this program are also presented in Ottosson and Petersson (2007).

A large energy auditing program in Sweden called Project Highland, covering about 340 companies of which 139 are industrial companies is currently being undertaken. This program targets small and medium-sized industrial companies in the Highland region in Sweden. A large portion of the potential cited is related to heating ventilation and air-conditioning of the industrial premises, as nearly all of the possible heat conservation is related to space heating and additional electricity used by cooling compressors and fans. An evaluation has
been made of the first part of the program and is found in Thollander et al. (2007).

In several other recent Swedish studies such as Trygg and Karlsson, 2005; Nord-Ågren, 2002; Dag, 2000; Thollander et al., 2005; Karlsson et al., 2004; Henning, 2005, the technical potential for reducing the energy use in Swedish industrial companies have been studied. In Trygg and Karlsson (2005), a 40% reduction in energy use and 48% reduction in electricity use are possible for the 11 industries studied. In Thollander et al. (2005), the potential reduction was assessed at 33% for energy and 23% for electricity at a foundry. In Karlsson et al. (2004), two large dairy processing plants were studied, and the potential for reducing energy use was 8% of these measures; 32% was related to HVAC, which indicated a large potential for reducing energy and electricity use in HVAC. In a summary of energy auditing projects in Sweden by Henning (2005) the potential for 10 industrial sectors based on 40 energy audits is presented. The average potential for these sectors is about 40% for energy and 45% for electricity. The main potential for reducing the energy use is found in support processes such as space heating (and cooling), ventilation, lighting and compressed air. In another industrial study of a large car manufacturing plant by Trygg et al. (2006) focusing on the efficiency potential for electricity, the total amount of energy used by support processes is 59.1 GWh (of which 34.5 GWh is electricity) and of that space heating and ventilation represents 55%. The potential for reducing the electricity used by fans by more efficient control including using a variable air volume systems is found to be about 35%. The impact on heat demand was not assessed.

The variation in energy efficiency potential in the studies presented above ranges from about 10% to 50% for the different cases. There are several factors making the audits hard to compare, such as different rates of return on invested capital, different structure of energy use at the sites, different goals as some of the studies or programs only focus on electricity while others have a broader approach and target energy, some have environmental focus and target CO$_2$-effective measures while others target cost-effective measures. However, whatever the focus, the studies all find substantial potential for implementing effective measures and the studies result in an increase in implementation at the firms studied. The studies have another aspect in common: they indicate that the diffusion of investment in efficient HVAC installations seems to be slow.
and thus a large potential for cost-efficient investments in this area is currently being overlooked. Mechanisms inhibiting this potential from being implemented are discussed in Chapter 3 where some industrial management issues related to energy management are briefly covered.
3 Industrial Management Issues

Industrial management issues and issues related to decision making are important when studying reasons to why energy efficiency measures are or are not undertaken. In this chapter the used theory of barriers to energy efficiency as well as a short description of rational decision making is included.

3.1 Rational decision making

The management of an industrial company requires decisions related to e.g. management of production, maintenance, facilities, energy and labor issues. Within each of these categories there are multiple dimensions to deal with, such as risk evaluation, what information on which to base the decision, how to finance different measures, education and the hiring of personnel (Sandberg, 2004). Management and its strategy are strongly related to the investment decision the organization has to make in order to be profitable, which is the overall goal of a company. This company strategy includes being alert to changing market conditions and other competitors and suppliers as well as issues like environmental concerns. The ability to make the “correct” decision, in relation to the overall goal, is often stated as what separates a successful business from an unsuccessful one. When making these decisions, if not made by rule of thumb, resources have to be allocated to the process of evaluating competing alternative investments. These resources, in the form of personnel, information, audits, simulation tools and consultants, are needed to build a sound foundation for decision making (Sandberg, 2004).

An investment decision usually involves choosing between a number of alternative solutions, each of which has consequences for the future. In many
corporate and technical models, the theory of rational decision making is used. In this theory the rational decision maker has the ability to choose the optimal solution to the problem, based on a decision process where:

1. The problem is explicitly defined and the goal is unambiguously stated
2. All possible alternatives are gathered and examined
3. All the consequences of all these alternatives are established
4. The consequences are compared with the overall goal
5. The alternative with the highest degree of fulfillment in relation to the goal is chosen

When using this procedure of rationality the decision maker is confronted with several problems. All the alternatives have to be known, it must be possible to know the consequences of all these alternatives, there must be an unambiguous goal and the different alternatives must be comparable in all aspects. The decision maker is faced with an impossible task, which is why investment decisions in all probability are not made strictly in this fashion (Andersson, 1997). This is elegantly put by James G. March (1998) as: “Rational choices involve two kinds of guesses: guesses about future consequences of current actions and guesses about future preferences for those consequences.”

Theories of choice often assume that future preferences are stable and known with sufficient precision to make decisions unambiguous (March, 1998), which in some cases is a rather large simplification. Another problem with models of individual choice, such as the “economic man”, is that the model doesn’t predict the behavior of any individual. This problem can however be avoided to a large degree with the use of aggregation of a large number of persons or organizations (March, 1998).

The concept of rationality is not connected only to the economic field but also to other fields such as psychology, sociology and political science (March, 1988). The concept of bounded rationality is introduced by H. Simon where he argues that decisions are made with bounded rationality, where decision makers are only able to recognize a limited number of alternatives, and are aware of only a number of the consequences. He argues that human abilities are fallible and limited, information is never perfect, and that among other things, time
and capital are limited. As a result it is thus impossible to maximize benefits in decision making; instead a satisfying decision is to be sought (Torsi et al., 1994).

In addition to the economic considerations the final decision should include additional aspects such as work environment issues, labor security issues and liquidity aspects, as these are hard if not impossible to include in a strict economic model (Andersson, 1997).

3.2 Barriers to energy efficiency

There are numerous studies stating the existence of a gap between potentially cost-effective energy efficiency measures from a technical perspective and the measures actually implemented (DeCanio, 1993; DeCanio, 1998; Hirst and Brown, 1990; Howart and Andersson, 1993; Jaffe and Stavins 1994a-b; Ramirez et al., 2005; Sanstad and Howarth, 1994, Sorrell et al., 2004 and Weber, 1997). This gap has been referred to as the “energy efficiency gap”, and is argued to exist due to the presence of a number of barriers to energy efficiency preventing cost-efficient energy efficiency measures to be implemented. The energy barrier framework is mostly derived from mainstream economic theory and a deviation from this theory is thus explained in terms of a barrier.

One purpose of introducing a concept of barriers is to assign explanatory variables to why the companies/decision makers act as they do and thus give policy makers means to efficiently target their behavior. These theories are thus argued to result in better understanding of the internal function of the firm and consequently allow better modeling. However, it is important to note that the barriers are not unambiguous and that an empirical find may be related to more than one barrier.

According to Sorrell et al. (2000), a barrier is defined as:

“A postulated mechanism that inhibits investments in technologies that are both energy efficient and economically efficient.”

The barrier theory, used in Papers I, II and III, uses the distinctions of Sorrell et al. (2000) where the barriers are divided into two economic, one organizational, and one behavioral category. The barriers are explained in more detail below.
Furthermore, it’s worth noting that the theory has a “company perspective” and the barriers are used to explain the corporate view on energy efficiency measures, not the policy makers’ view of the company. Outside the company there may exist other explanatory variables for not adopting a measure.

The theoretical barriers in the framework used are hidden cost, limited access to capital, risk, heterogeneity, adverse selection, principal agent relationship, split incentives, imperfect information, form of information, credibility and trust, value, inertia, bounded rationality, power and culture. A more comprehensive description of the theoretical barriers used in the appended papers is found in below.

**Hidden costs**
Hidden costs are defined as costs associated with information seeking, meeting with sellers, writing contracts, etc. These costs are often used to explain large parts of the energy efficiency gap (DeCanio, 1998). The argument is that when included, the otherwise cost-efficient measure is no longer cost efficient since the hidden costs stand for a significant part of the actual profit of an implementation. Hidden costs are a frequently used argument against the existence of an energy efficiency gap, by arguing that engineering-economic studies often fail to see the full cost of an energy efficiency measure (Sorrell et al., 2000).

**Limited access to capital**
Energy-efficient equipment often has a higher initial cost than less efficient equipment. This may have multiple reasons and some are discussed in Almeida (1998), which we will refer to later when discussing results from the studies. Limited access to capital is a barrier when the additional capital needed to make an energy-efficient investment is hard to obtain, even though the investment is cost efficient in terms of the company’s investment criteria (Hirst and Brown, 1990).

**Heterogeneity**
A population of firms is most likely heterogeneous with respect to their energy use, which is why a technology that appears cost efficient on average will be cost inefficient for some portion of the population (Jaffe and Stavins, 1994).
This barrier is arguably larger for industrial companies where the processes and plants are to a large degree site specific. This is one strong argument for providing site-specific information to increase adoption of energy-efficient equipment, such as on-site energy audits and investigations instead of general information.

**Risk**

In Sorrell *et al.* (2000) risk is divided into three categories: external risks such as overall economic trends and expected reductions in fuel prices; business risk, including sector-specific economic trends; and technical risks, such as reliability and technical performance of a specific technology. Risk is also often used to explain shorter pay-back periods or high discount rates when investing in energy-efficient equipment compared to other production related investments. In Hirst and Brown (1990), it is explained that even though managers know the cost of an energy-efficiency investment, uncertainty about the long-term savings in operating costs means the investment is a risk as future energy prices are not known. The uncertainties in future energy prices and availability are argued in Stern and Aronson (1984) to be an important aspect increasing the risk of investments in energy efficient equipment. This and the irreversibility of the investment, also discussed in March (1988), in energy efficiency technology are argued to be an explanation for applying relatively high discount rates for investments whose return is uncertain (Jaffe and Stavins, 1994). In the concept of risk, the risk of trying new equipment which may lead to an increased amount of production disruptions is also included and has been cited in Hirst and Brown (1990) to be very important to decision makers.

**Adverse selection**

When the two parties in a transaction have had access to different levels of information, the problem of asymmetric information arises. The problem is extremely common in the real world, and Sanstad and Howarth (1994) argue that this is more common than not. Manufacturers and retailers of energy-efficient equipment are often much better informed about the performance than the buyer which represents an adverse selection.

**Principal-agent relationship**

The principal-agent relationship problem is another form of asymmetric information which is due to lack of trust between parties in different levels
within an organization. The manager, who may not be as well informed about energy efficiency investments, may demand extra short pay-back rates on energy efficiency investments due to distrust in the ability of the organization/department to make such an investment, inhibiting cost-efficient energy efficiency investments (DeCanio 1993; Jaffe and Stavins, 1994).

**Split incentives**
In Jaffe and Stavins (1994) the barrier of split incentives is argued to be important when the party receiving or discovering an energy efficiency investment is not the party that pays the energy bill. Then a cost-efficient measure may not be sufficient for adoption. The adoption will only occur if the adopter can recover the investment from the party that has the incentive to save energy (Jaffe and Stavins, 1994). In Hirst and Brown (1990), it is argued that this is a problem for energy-efficient technologies, which often have higher initial costs but lower life-cycle costs than conventional technologies. A common type of split incentive is the landlord-tenant relationship. Lack of sub-metering within multidivisional organizations may also be classified as a split incentive.

**Imperfect information**
That consumers are poorly informed about market conditions, technology characteristics and their own energy use is often cited. In Sanstad and Howarth (1994) the authors argue that lack of adequate information about potential energy-efficient technologies inhibits investments. Imperfect information may be divided into lack of information, where information of energy performance may not be available to the buyer; cost of information, when there are costs associated with searching and acquiring information about energy performance; and accuracy of information, where the information provider may not always be transparent or truthful about the energy performance. In Sorrell et al. (2000) it is argued that imperfect information is likely to be more common for adoption of products purchased infrequently. Problems related to imperfect information are often countered with information campaigns.

**Form of information**
There is a relation between the form of information and the degree of adoption of suggested measures. When information is provided in an inefficient form it is thus argued to constitute a barrier. In Stern and Aronson (1984) as well as in
other sources it is shown that people are more likely to remember information if it is specific and presented in a vivid and personalized manner coming from a person that is similar to the receiver. This has implications for how policy instruments such as an energy audit or a complex investment assessment should be performed, indicating increased adoption for site-specific, vivid information such as a presentation of detailed results from measurements or simulations.

**Credibility and trust**
A prerequisite for efficient adoption is the adopters’ perceived trust in the information provider. In Stern and Aronson (1984), it is argued that efficiently spread information and trust in the information provider is essential.

**Values**
Our values influence our behavior and in studies of households it is cited that value a have strong impact on cost-free conservation measures, but a weaker impact on low-cost conservation measures. The behavior of surrounding people also has great impact on the behavior of a person, as friends and colleagues implementing energy efficiency equipment or with conservation behavior act as good examples (Stern and Aronson, 1984).

**Inertia**
This concept states that individuals and organizations are, to some degree, “beings” with habits and tend to establish routines and stick to them. This is argued in Stern and Aronson (1984) to be a way for decision makers to reduce perceived uncertainty and change in their surrounding by avoiding or ignoring problems. Stern and Aronson (1984) also show that a person who has made an important decision seeks to justify and rationalize this by convincing themselves and those around them that the decision was the correct one. Inertia becomes a barrier when energy users and decision makers fail to take economically justifiable action to save energy as a result of not reevaluating routines and procedures (Stern and Aronson, 1984).

**Bounded rationality**
Bounded rationality is connected to problems related with multiple objectives for individuals as well as organizations and imperfect information etc. when making decisions. In Sanstad and Howarth (1994) this concept is applied to
energy-related decisions and it is found that this is an important explanatory variable, as the assumption of rational decision makers would require individuals and firms to solve extremely complex optimization problems in order to obtain the optimal energy service. Furthermore, a company does not consist of one person with one view, but multiple individuals with their own views and the interests of one individual or department may conflict with other departments’ or individuals’ interests. Also, organizations or individuals do not act on the basis of complete information but rather make decisions to some degree by rule of thumb (Stern and Aronson, 1984).

**Power**
In many organizations energy management has low status compared to for instance the production process. This is argued to be a barrier to energy efficiency when this low status leads to constraints when striving to implement energy efficiency measures Sorrell *et al.* (2000).

**Culture**
In Sorrell *et al.* (2000) culture is explained as the sum of each individual’s values where the values of executives or other workers have influence within the organization. Culture is not by definition a barrier, and it is closely connected to value. But even though culture is not a true barrier it has been shown to have significant impact on the adoption of energy efficiency measures (Sorrell *et al.*, 2000).
4 Indoor environment and energy use in industrial buildings

In this chapter Indoor Air Quality, Thermal Comfort, Product environment issues and Energy use for HVAC are described, and used measures of performance are also included.

The indoor environment, product environment and energy use in industrial facilities are closely linked. The term “indoor environment” includes both the thermal environment and the indoor air quality (IAQ). For industrial facilities it is also common to treat the product environment separately. At the end of this chapter energy issues related to HVAC will be discussed.

4.1 Indoor air quality (IAQ)

The quality of air in indoor areas occupied by humans is often referred to as the Indoor Air Quality (IAQ). Fanger (2006) defined IAQ as “The extent to which human requirements are met” (in terms of air quality). This expresses whether the air is perceived as fresh and pleasant, that it doesn’t have a negative effect on human health, or that the air doesn’t negatively affect the ability to work or think. Fanger (2006) argues that when examining IAQ for non-industrial buildings, controlling the quality of the air by assigning target values for all known chemicals reducing the IAQ is not possible, as there are typically thousands of compounds in the air in very low concentrations which affect the IAQ. However, when controlling IAQ for industrial buildings, the concept of target values for emissions is an often-used design tool, as often only a few compounds are substantially more important and can thereby be used as design criteria (Goodfellow and Tähti, 2001). Target values for numerous common compounds are found in ASF 2005:17 – Occupational exposure limit values
and measures against air contaminants (AFS, 2005) issued by the Swedish Work Environment Authority. The hygienic target values are usually divided in three categories, a Level limit value, a Ceiling limit value and a Short-term value. The Level limit value refers to the average exposure during a work day. The Ceiling limit value refers to an average value of exposure during a specific amount of time, often either five minutes or 15 minutes. The short-term value is a recommended value which is based on a reference period of 15 minutes. The difference between the ceiling value and the short-term value is that the short-term value is more of a guideline than the ceiling limit value (Hedlund, 2005).

In international literature such as ACGIH (2004) the health hazard of an airborne compound is categorized by the Threshold Limit value (TLV) which, according to (ACGHI, 2004), “is defined as that airborne concentration of a substance which it is believed that nearly all workers may be exposed to day after day without developing adverse health effects.” If multiple compounds with similar effects are simultaneously present, the effect of these should be evaluated together when designing the ventilation. In AFS (2000) it is stated that the concentration of contaminants in the air should be as low as possible when considering the specific production process. This means that even if the concentration is below the level limit it is to be decreased if that can be done using reasonable economic means (Goodfellow and Tähti, 2001). There are, however, some important limitations to this concept, as all the contaminants need to be known and new toxicological aspects when mixing different contaminants must also be known. This is not always treated specifically by a target level assessment in its common form.

4.1.1 Measures of performance

The performance in terms of IAQ for polluted production facilities is recommended to use target level assessments, and they are to be evaluated in terms of measured concentration, or when appropriate or necessary with calculations of the emission concentration. In non-industrial facilities the concept of using human sensory response is suggested to determine the perceived IAQ, measured in decipol or percentage dissatisfied (PD) (Fanger, 2006). This concept is argued to also be a workable measure of performance for non-production contaminated industrial facilities which are similar to
facilities such as residential buildings or offices. The PD index for non-production contaminated industrial premises may then be defined as:

\[
PD = 395 \cdot \exp(-1.83 \cdot \nu^{0.25})
\]  

(4.1)

where \( \nu \) is the outdoor airflow rate in \( \text{ls}^{-1}\text{olf}^{-1} \), see Awbi (2003).

### 4.1.2 Requirements

The requirement for Swedish companies is to fulfill the regulations issued by the Swedish Work Environment Authority, by providing an indoor air quality not exceeding any of the emissions cited in the target levels in AFS (2005). The requirements should also fulfill other forms of legislation and GMPs (Good Manufacturing Procedures) of specific sectors. As an example, for the dairy studied in Papers IV and VIII, the requirements stated in the Food and Drug Administration's regulations should also be taken into consideration (NFA, 1996) and, if found applicable, recommendations such as those issued by Brown (1996). Extended site-specific requirements are sometimes used to improve indoor air quality to promote a comfortable and healthy working environment.

### 4.2 Thermal comfort

Humans want and seek thermal comfort wherever they are, whether at work or at home. The term thermal comfort may be defined as: “that condition of mind that expresses satisfaction with the thermal environment” (ASHRAE, 2003). Clothing, activities, posture, location and shelter are chosen, altered and adjusted to minimize discomfort both consciously and unconsciously. Discomfort is related to human health, number of mistakes, productivity and industrial accidents, as discomfort is a form of physiological strain. This strain can be in the form of sweating, muscle tension, stiffness, shivering and loss of dexterity (Goodfellow and Tähti, 2001). Thus, thermal climate is an important factor and it is desirable to minimize thermal discomfort. In general it is often cited that a facility that provides a satisfactory environment will be financially more successful as well as more desirable for the people working there, as it contributes to a safer and more comfortable environment with less loss of productivity and better comfort (Goodfellow and Tähti, 2001).
When making statistical correlations of comfort in the thermal environment one may distinguish some reproducible primary factors and some secondary factors of less importance. The lesser factors are factors such as age, local climate, physical fitness, food and illness. These secondary factors have a lesser effect on the perceived thermal climate and are not discussed further in this thesis. The primary factors directly affect the heat transfer of the person, where the objective of a person’s thermoregulation is to maintain the body core temperature vital for the internal organs to function properly (Goodfellow and Tähti, 2001).

One way to quantify comfort and discomfort is through empirical environmental indices. These studies are based on a model of the heat exchange between the body and its surroundings, which is made by subjecting a large population to different known activities and clothing to a range of environmental conditions, and recording the response to these conditions. Probably the most used model is the Predicted Percentage Dissatisfied (PPD) index created by Fanger and his co-workers in Denmark (Fanger, 1972). This work as well as other more zone-specific indices is included in the ISO 7730 standard of “Ergonomics of the thermal environment” (ISO, 7730). To compare the comfort sensation of different thermal climates in this thesis, the concept of empirical environmental indices will be used. In Papers IV and V, the concept of Predicted dissatisfied due to draught was used as this was considered to be a problem in the studied facility. In Paper VIII several of the indices presented below were used to predict comfort. The indices that have been used as measures of performance related to comfort are summarized below.

4.2.1 Measures of performance

To quantify the consequences in terms of comfort in this thesis three major indices are used, the PD\textsubscript{Draught} (Predicted Dissatisfied due to draught), PMV (Predicted Mean Vote), and its related PPD index.

To relate the physical parameters such as temperature, velocity, and turbulence intensity to the predicted comfort of the personnel, the PD\textsubscript{Draught} index has been used. The PD\textsubscript{Draught} index is defined as:
\[ PD_{\text{draught}} = (34 - t_a)(U_{oz} - 0.05)^{0.6223}(3.143 + 0.3696U_{oz} \cdot T_{I_{oz}}) \]  

(4.2)

where \( PD_{\text{draught}} \) represents the percentage of dissatisfied people due to draught in the head region. This has been used in several of the appended papers and has been implemented in the CFD code (FLUENT) using a custom field functions. For \( PD_{\text{draught}} < 0 \), which occurs when \( V_{oz} < 0.05 \text{ m/s} \) the \( PD_{\text{draught}} \) has been set to zero to avoid undefined nodes.

In Fanger (1970) human thermal comfort has been described by the predicted mean vote (PMV) index. The PMV index represents the mean votes of a large group of individuals describing their thermal sensation using a seven-point thermal scale that ranges from hot to cold, with neutral at zero (ISO, 1994; ISO, 2005). The equation for the PMV index is defined by:

\[
\begin{align*}
\text{PMV} &= \left( 0.303e^{-0.036M} + 0.028 \right) \\
&\times \left[ (M - W) - 3.05 \times 10^{-3} \times [5733 - 6.99(M - W) - p_a] \right] \\
&- 0.42 \times [(M - W) - 58.15] \\
&- 1.7 \times 10^{-5} M(5867 - p_a) - 0.001 \cdot 4M(34 - t_a) \\
&- 3.96 \times 10^{-8} f_{cl} \times \left[ (t_{cl} + 273)^4 - (t_r + 273)^4 \right] - f_{cl} h_c (t_{cl} - t_a)
\end{align*}
\]

(4.3)

where,

\[
t_{cl} = 35.7 - 0.028(M - W) - I_{cl} \left\{ 3.96 \times 10^{-8} f_{cl} \left[ (t_{cl} + 273)^4 - (t_r + 273)^4 \right] + f_{cl} h_c (t_{cl} - t_a) \right\}
\]

\[
h_c = \begin{cases} 
2.38(t_{cl} - t_a)^{0.25} & \text{for } 2.38(t_{cl} - t_a)^{0.25} > 12.1\sqrt{V_{ar}} \\
12.1\sqrt{V_{ar}} & \text{for } 2.38(t_{cl} - t_a)^{0.25} < 12.1\sqrt{V_{ar}}
\end{cases}
\]

\[
f_{cl} = \begin{cases} 
1.00 + 1.290I_{cl} & \text{for } I_{cl} \leq 0.078 \text{ m}^2 \cdot \text{oC} / \text{W} \\
1.05 + 0.645I_{cl} & \text{for } I_{cl} > 0.078 \text{ m}^2 \cdot \text{oC} / \text{W}
\end{cases}
\]

It is also possible to transform the PMV index into a statistical expression for the Predicted Percentage of Dissatisfied (PPD) people. The expression for the PPD index is based on empirical correlations and the equation reflects the fact that in large groups of people there will be at least about 5% dissatisfied no matter how the overall thermal climate is arranged. The expression for the PPD index contains only the PMV of the group and is given by:

\[
\text{PPD} = 100 - 95 \cdot e^{-\left(0.03353 \times \text{PMV}^4 + 0.2179 \times \text{PMV}^2 \right)}
\]

(4.4)
4.2.2 Requirements

In the standard for the PMV and PPD index (ISO 7730, 1994; ISO 7730, 2005) it is suggested that the requirements for the physical variables: temperature, mean radiant temperature, relative air velocity, and partial water vapor pressure should be solved for PMV=0. This is because this is when most people are predicted to be neutral in terms of their climate sensation, neither too hot nor too cold. The use of this concept may however result in large installations and high energy use. However, in the newer standard (ISO 7730, 2005), this concept is less in focus.

The use of the controlled indices instead of more adaptive models for free running buildings in this thesis is due to the occupants’ inability to control their climate. For the industrial cases studied in this thesis the occupants have been entitled to wear certain types of clothing, special clean clothing and hairnets in the dairy case and boiler suits in the foundry case. Furthermore, the occupants don’t have any way to control the indoor temperature or airflows in the premises.

4.3 Product environment

The product environment is defined as the surrounding environment that the product requires in order to be of sufficient quality, and is specific for each process and may need to be investigated for each individual case. However, many manufacturing and storage processes don’t have any extended product requirement. In Papers IV and VIII, a dairy processing plant has been studied and for these types of plants there are several extended requirements in order to produce products of high quality. For instance, it is recommended that the airflow between different product facilities should be in the direction from clean to less clean areas. The air filters should also be easy to reach and procedures for changing them are required. Guidelines on air quality for the food industry may be found in publications such as Brown (1996). Here issues such as internal condensation are discussed and it is recommended that ventilation and process equipment be designed to avoid condensation since this leads to extended microbiological growth. For the foundries such as those discussed in Papers V and VII the issue of condensation on the metal to be
melted may be of interest. In addition it is also recommended to have a under pressure in this type of facility, to avoid unnecessary transport of contaminants into the ambient facilities.

4.4 Energy use in HVAC

There are different ways in which to categorize and present energy use and energy efficiency indicators. In Jaegemar (1996) energy efficiency is defined as: “Energy efficiency is a measure of the balance between the energy gained and the sacrifice necessary to bring about this gain”. An energy-efficient system is thus a system that provides its function with the lowest possible energy use at reasonable cost. This definition is useful when discussing indoor environment aspects as when Abel and Ekberg (2002) stress the importance of two aspects when implementing efficiency measures:

1. The implementation of an energy efficiency measure should not have a negative effect on the building and its function.
2. The primary use of resources when implementing an energy efficiency measure should be related to the total energy reduction due to the measure.

These two requirements are to be fulfilled in order for the measure to be categorized as an efficiency measure. This sorts out measures where the function of the building, such as IAQ issued, is reduced or when the measure results in a use of resources not in proportion to the reduction of energy use (Abel & Ekberg, 2002). Another aspect in defining an energy efficiency measure could be to establish an energy pay-back criteria, where the energy pay-back index represents the potential saving per year divided by the embodied energy, and thus results in a relation of how long it will take for the measure to save as much energy as it has required in production.

In Jagemar (1996) a thesis on designing energy-efficient HVAC installations targeting the explicit energy performance indices of commercial buildings is presented for individual components in the HVAC system. Here the energy performance ratios are defined in terms of kWh/(m² and year), kWh/(m³ and year), kWh/(m³/s) and kW/(m³/s) at different levels in a building.
For industrial companies additional indices are often of interest, such as the amount of energy used per employee, kWh/person, and the index of energy use per unit of product, e.g. kWh/kg, kWh/volume or kWh/number of produced goods. In economic terms an energy cost/unit such as EUR/m² or EUR/person is used, or energy cost in relation to turn-over, often referred to as energy intensity. All these indices are easy to use and have their individual advantages and disadvantages depending on how the energy use at a site is composed and what information is requested. It is important to note that aspects such as an increase in production will decrease the specific energy use in kWh/produced ton if generic processes represent a substantial part of the energy use. These indices also often make comparisons between different industrial sites difficult, as there are multiple processes that differ between industrial buildings at different locations, etc.

One way to solve parts of this problem for industrial companies, and allow both easier benchmarking and a more effective structure, is to use the concept of unit-processes, see Söderström (1996). The concept is used, for example by Nord-Ågren (2002) and Trygg (2006) and has been used in Project Highland and the two detailed studies appended to this thesis. The concept and the categorization of unit-processes are shown in Table 4.1.

Table 4.1. Structure of unit processes according to Nord-Ågren (2002) and Söderström (1996).

<table>
<thead>
<tr>
<th>Production Process</th>
<th>Support Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disintegrating</td>
<td>Ventilation</td>
</tr>
<tr>
<td>Disjointing</td>
<td>Space heating</td>
</tr>
<tr>
<td>Mixing</td>
<td>Compressed air</td>
</tr>
<tr>
<td>Jointing</td>
<td>Lighting</td>
</tr>
<tr>
<td>Coating</td>
<td>Pumping</td>
</tr>
<tr>
<td>Molding</td>
<td>Tap water heating</td>
</tr>
<tr>
<td>Heating</td>
<td>Internal transport</td>
</tr>
<tr>
<td>Melting</td>
<td></td>
</tr>
<tr>
<td>Drying/concentrating</td>
<td></td>
</tr>
<tr>
<td>Cooling/freezing</td>
<td></td>
</tr>
<tr>
<td>Packaging</td>
<td></td>
</tr>
</tbody>
</table>
This concept enables comparison between individual processes for different sites and with different production. For a more detailed description of the concept see Nord-Ågren (2002).

4.4.1 Measures of performance

As previously discussed there are many ways in which to monitor or measure performance in terms of energy use. Different measures are used for the different unit processes and for individual facilities. In general, indices like kWh/m² and kWh/kg have been used. To evaluate the electric efficiency of fans, the Specific Fan Power (SFP) has been used. The SFP is defined as:

\[
SFP = \frac{P_{\text{fans}}}{q}
\]

Where \(P_{\text{fans}}\) is the total fan power (supply and exhaust) [kW] and \(q\) airflow (the largest of supply or exhaust flow) in m³/s.

The degree of using heat exchangers and their average efficiency is also of interest as a measure of a site’s energy efficiency for ventilation and space heating.

When discussing energy use and energy efficiency another important aspect is the quality of the energy used, for example if it is electricity or heat. Abel and Ekberg (2002) consider a ratio between electricity and heat of about 1.5, while a ratio of 3 is argued to be reasonable if coal-fired power plants without district heating are the marginal production. From a company perspective, where the price of the energy carrier reflects all its costs and is constant over time, the ratio is given by the ratio of the different energy carriers. However, as previously discussed, uncertainties of e.g. future fuel prices, supply limitation, technological progress and negative externalities not presently fully included in the price makes this issue complex.
5 Industrial Ventilation

In this chapter industrial ventilation is described, including issues related to HVAC control, air supply, local ventilation and process ventilation.

In Goodfellow and Tähti (2001) industrial air technologies are defined as:

“Air flow technologies that control workplace indoor environment and emissions”.

In this definition air flow technologies encompass efforts to achieve a safe, healthy, productive and comfortable indoor environment for the persons working as well as a functioning product environment.

The term Air flow technologies can be divided into Industrial Ventilation, treating air conditioning systems, general ventilation, local ventilation and process ventilation, and Process Air Technology, treating cleaning systems, pneumatic conveying systems, drying systems and safety air technology systems (Goodfellow and Tähti, 2001). In this thesis the focus is primarily on industrial ventilation.

The purpose of process ventilation, also referred to as local ventilation when relating to work space measures, is to ventilate the process by efficiently capturing heat and contaminants before they are dispersed to the surrounding air (Goodfellow and Tähti, 2001; Hedlund, 2005). The process ventilation is thus a key feature in attaining a functioning IAQ in the premises.

When designing industrial ventilation, it is recommended to start by designing the process ventilation and local ventilation to optimize performance. For effective operation most industrial plants then require makeup air to replace the
air exhausted by the local and process ventilation in creating a functioning indoor environment (AHRAE, 2003). This makeup air is often categorized as general ventilation. However, if it is difficult to obtain the desired indoor environment using process ventilation and local ventilation, an increase in the requirements on the general ventilation may be a feasible way to solve the problem. The down-side of using the concept of increased requirements on the general ventilation is the risk of large increases of supply airflows resulting in an increase in energy use. In applications where the process ventilation demands large amounts of exhaust air, the general ventilation may be limited to supplying air just to obtain balanced ventilation in the facility. The process and industrial ventilation is highly dependent on the actual process, and should be treated as such (Goodfellow and Tähti, 2001; Hedlund, 2005). This makes general airflow recommendations difficult if not impossible to give.

When discussing industrial ventilation, one of the main publications is the Industrial Ventilation Manual issued by the American Conference of Governmental Industrial Hygienists (ACGIH). This manual of recommended practice is accepted by industry and governmental agencies and as a world-wide reference book (Goodfellow and Smith, 1984). This design guidebook provides a compilation of research data and focuses on design, maintenance, operation and evaluation of industrial ventilation (ACGIH, 2004).

In a review by Goodfellow and Smith (1984), the literature on industrial ventilation is divided into ten different categories: general aspects of industrial ventilation, natural ventilation, local ventilation, specialized ventilation techniques, dilution ventilation, air jets, recirculation, exhausts of open tanks, tracers for ventilation studies and mine ventilation. Furthermore, the Center for the Analysis and Dissemination of Demonstrated Energy Technologies (CADDET) published an analysis report in 1993 (Aro, 1993), which focuses on practical application and includes case studies of 17 different demonstration projects. The report contains technology descriptions, component descriptions and field studies and focuses on energy use in industrial premises. The report concludes, among other things, that heat recovery is important but not without problems in industrial premises as the environment may be corrosive and exhaust air may contain particles and gaseous matter that destroy the recovery systems and filtration. The biggest problem, according to Aro (1993), is maintenance, because the staff’s main aim is to maintain production, while
everything else is secondary—a conclusion which is in line with the results presented in theme 1 and the appended Papers I and II. The report also stresses the heterogeneity of industry in terms of industrial ventilation, and that it is thus difficult to give general design criteria for industrial ventilation. Instead the report stresses that “It is more a question of ‘system-thinking’ and ‘know-how’,” as no two facilities are alike (Aro, 1993).

The topics in the above-referenced publications covered by this thesis are discussed in each subsection below. Goodfellow and Smith (1984) argue that ventilation is one of the most important engineering techniques available to industrial hygienists in maintaining or improving the workplace environment, but states that the field has been badly neglected for a long period of time. Industrial ventilation applications and local exhaust systems and design criteria are covered in design guidebooks such ASHRAE Application (2003), Goodfellow and Täthi (2001) and ACGIH (2004).

5.1 Some aspects of HVAC control

Buildings in general, and thereby industrial buildings too, exist, for among other purposes, to provide a controlled environment for people and their activities. Since the ambient conditions of a building are dynamic and change continuously, it is reasonable to assume that the system to provide this environment will be more efficient if it is provided with continuous control (Nilsson, 2003). In NUTEK (1997), four different flow control methods (damper control, inlet vane control, blade pitch control and variable speed control) are compared. The relative power needed for the different systems differ greatly where the variable speed control requires least power.

In many industrial facilities Constant Air Volume systems (CAV) are still used, implying that no flow control exists. There are several articles citing the potential for saving energy by replacing a CAV system with a demand-controlled Variable Air Volume (VAV) system (using variable speed controlled fans), such as Aktacir et al. (2006) and Burd et al. (2006). In Burd et al. (2006), a study was made of a large manufacturing plant where a constant air volume system was compared with a variable air volume system. They experienced savings in HVAC of about 40% for electricity used by fans and 35% in space
heating energy. The main savings in energy were the reduced flows during times when only part of the production was active. The plant also had a 70% reduction in maximum power for HVAC installations (only electricity used by fans and air-conditioning and not for the entire site). Aktacir et al. (2006) investigates a VAV system for a school and an office building in Turkey, and finds that the net-present cost of a VAV system is lower due to lower fan operating costs during the systems lifespan. In addition to reducing annual energy use, the VAV system use in Swedish applications has another advantage since the electrical power and energy will decrease during the cold season when the need for both heat for space heating and electricity is the largest.

5.2 Air supply issues

Effective diffusion of clean air in industrial facilities as well as in other rooms and the proper amount of conditioned air are essential for creating acceptable working conditions, for removing contaminants, and for minimizing the initial and operation cost of a ventilation system. Generally speaking the air supply system must supply air of proper temperature, velocity, turbulence intensity, humidity and with contaminant concentration within the desired limits (AHSRE, 2003). However, in ASHRAE Application (2003) the object in most cases is referred to as “to provide tolerable (acceptable) working conditions rather than comfort (optimal) conditions”. An industrial ventilation supply system can serve several different purposes. The most common purposes are to serve as exhaust air replacement, plant ventilation, building pressurization, space heating, cooling and humidification, and to attain space cleanliness (ACGIH, 2004). In the foundry case discussed in appended papers the main purposes of the supply system has been to replace exhausted air as well as controlling the pressure to inhibit contaminants from spreading into the surrounding facilities. For the cleaner dairy production applications covered in the appended papers, the main purpose of the supply air has been to control the cleanliness of the facility and to secure the flow direction (pressurization) between zones with different requirements on cleanliness. In both applications the facilities are heated or cooled using the supply air system. In the dairy case the system was also used to control air moisture to prevent condensation which could lead to undesired biological growth in the facilities.
In ASHRAE Applications (2003) the air supply methods are divided into localized ventilation, mixing air distribution and displacement ventilation. The localized ventilation may be designed as e.g. a piston flow which is sometimes cited to be a separate ventilation principle. In mixing ventilation systems, the air is generally supplied with velocities far greater than accepted in the occupied zone, but the air is blended with the room air by entrainment before it reaches the occupied zone. The system can handle both over-heated air as well as air cooler than room temperature depending on the heating or cooling load in the occupied zone. In displacement ventilation which is based on stratified flow, air with lower temperature than room temperature is supplied with a low velocity directly into the occupied zone from a supply device located at floor level. The cooled air rises as it meets heat sources in the rooms, thus creating temperature and density stratification, see Mundt (1994) and Mundt (1990). In localized ventilation air is supplied locally in the occupied region or at specific work stations. The conditioned air is supplied directly to the breathing zone, making these zones much less contaminated than the surrounding parts of the facility. The piston flow principle may be used.

Displacement and mixing ventilation have been compared in several publications such as Lin et al. (2005a), Lin et al. (2005b) and Brum and Orhede (1994), and different aspects are discussed such as ventilation efficiency and thermal climate. All these supply systems have their advantages and disadvantages: mixing ventilation with its poor ventilation efficiency; displacement ventilation with the inability to effectively supply heated air during the cold season and to supply air to the occupied zone in facilities with high thermal loads and in a multiple buoyancy source environment; and the piston flow system with its susceptibility to disturbance with low airflows or high energy use for large flows. However, they also have their advantages. Mixing ventilation offers even temperature distribution, flexibility and the ability to be used for both heated and cooled air. Displacement ventilation has the advantage of its stratification characteristics enabling low pollution concentrations in the occupied zone and its ability to use less active cooling than the mixing system. It also has low air velocities in the occupied zone and low turbulence intensity, enabling high comfort. The piston flow principle has the advantages of high efficiency in terms of pollution transports and is mainly used in pharmaceutical and other critical applications.
5.3 Local and process ventilation

In ASHRAE (2003) four different strategies of controlling the air quality in a building are outlined. The strategies are eliminating the source, local hooding or screening with exhaust or recirculated air cleaning, dilution by increasing the general ventilation, and when none of the above is feasible general ventilation air cleaning with or without increased flows. The fourth option is generally difficult as the contaminant is fully dispersed in the facility (AHRAE, 2003). The most important aspects when designing process ventilation may be considered trivial but are still very important (Hedlund, 2005; Goodfellow and Smith, 1984):

(1) Proximity to the contaminant’s source. This is because the concentration of the contaminant decreases with increasing distance from the source and thereby a larger air volume must be captured to capture the contaminant. It is perhaps most important to minimize the capture distance (Goodfellow and Smith, 1984).

(2) Using gravitational force as contaminated air moves in the same manner as clean air. It is a common belief that contaminated air falls to the floor. This is however only true for large air containing particles which deposit on the floor (ACGIH, 2004, Goodfellow and Smith, 1984).

(3) Air jets move large quantities of air. The airflow in the jet increases with increasing distance from the supply point and at the same time the volume increases and the concentration of contaminants decreases.

(4) Air movement is created by ventilation, moving objects and buoyancy effects from heat sources such as machines and persons. Persons moving in close proximity to a contaminant source may affect the airflow pattern and make contaminants move in proximity to the head region if the process ventilation is poorly designed (Hedlund, 2005).

(5) Contaminants are ejected from machines such as blasting or grinding equipment. This implies a need for specially designed local exhaust units to capture these contaminants (ACGIH, 2004). In Goodfellow and Smith (1984) it is also recommended that a static pressure gauge and testing system be
installed and that the fan be the last component to be chosen. In Cascetta and Rosano (2001) an assessment of the velocity field in the vicinity of the rectangular exhaust hood is made and several empirical formulas are presented. In Rueegg et al. (2004) the local capture of contaminants is outlined for different exhaust systems and a reinforced exhaust system is shown to give higher capture efficiency than conventional exhaust systems.

Goodfellow and Täthi (2001) outline three factors that govern the process of designing industrial ventilation in general and local exhausts in particular. (1) The toxic target levels and the amount in the working environment, which states how effective the ventilation needs to be. (2) The occupied zone and how the personnel move in the facility, this to know if they are constantly by the contaminant source or only temporarily. (3) Whether the source is widely spread or dispersed from a small area (Goodfellow and Tähti, 2001; Hedlund, 2005). The design principles stated above may seem easy to implement but several problems still exist in solving the problem. The efficiency of different processes are possible to predict or measure but how the overall systems function together requires either full-scale measurements or as suggested in this thesis predictions in the form of validated Computational Fluid Dynamic simulations (CFD). The use of CFD for complex industrial ventilation projects are recommended in ASHRAE (2003) as well as Goodfellow and Täti (2001).

The measures of performance used for industrial ventilation are summarized below.

### 5.4 Measures of performance

The measures of performance for industrial ventilation are numerous. The presented indices are selected as they are commonly used indices and used in the appended papers. The general indices used are ventilation efficiency, air exchange efficiency, mean age of air and ventilation effectiveness for heat distribution or heat removal.

The relative ventilation efficiency may be defined as in Sandberg (1981) as:

\[
\varepsilon_c = \frac{C_o - C_i}{C_m - C_i}
\]  

(5.1)
where $C$ represents the concentration of the contaminant and subscripts $o$, $i$ and $m$ denote outlet, inlet and mean value for the occupied zone. For ideal mixing ventilation $\varepsilon_c = 1$, if the facility has a short-circuit between supply and exhaust $\varepsilon_c < 1$ and for a contaminant source in the proximity of e.g. a local exhaust $\varepsilon_c > 1$. In Sandberg (1981) the index is defined locally in the facility where $C_m$ indicates a point or a zone.

The capture efficiency of a local exhaust system, i.e. the percentage of released contaminants extracted by a local exhaust system, is also a key measure of performance for local ventilation systems.

The Air Exchange efficiency is defined as, see Etheridge and Sandberg (1996)

$$\eta_a = \frac{\tau_n}{2 \cdot \tau_i}$$

(5.2)

where $\tau_n = \frac{V}{q}$ represents the nominal time constant of the facility, $V$ is the volume and $q$ is the airflow, and $\tau_i$ represents the mean age of the air in the facility.

The local mean age of the air or the mean age of air can be used to describe the freshness of the air. These indices can be found either by measurements such as using tracer gas or by calculation using e.g CFD.

The ventilation’s effectiveness for heat distribution or heat removal ($\varepsilon_t$) is a measure of how effective the ventilation system is in removing the heat produced internally in the occupied zone and is defined as:

$$\varepsilon_t = \frac{t_o - t_i}{t_{oz} - t_i}$$

(5.3)

In Equation (5.3), $t_i$ and $t_o$ are the supply and exhaust air temperatures respectively and $t_{oz}$ represents a mean value in the occupied zone. The value of $\varepsilon_t$ is dependent on the method of room air distribution, room characteristics, heat and sources, etc.
5.5 Requirements

The requirements for industrial ventilation are mainly based on the requirements for indoor air quality, thermal comfort and energy use. The measures of performance used are commonly used indices to measure or compare performance in terms of air quality, comfort of energy use. Several of the measures of performance presented here are also used in guidelines or legislation.
6 Methods

Several methods have been used in this thesis and in this chapter they are presented. The methods used are related to three groups, measurements and audits, simulations or qualitative studies.

The methods used in this study depend on the theme in which the study was made. In theme one, where the corporate views on energy issues and barriers to energy efficiency were studied, qualitative case studies with interviews and questionnaires were used. In themes two and three energy audits, measurements or simulations of physical behavior were used. The measurements consist of temperature, air velocity, turbulence intensity, humidity, contaminants, electricity and airflow. These measurements and other research tools are followed by the two main simulation methods used, Computational Fluid Dynamics (CFD) and Building Energy Simulation (BES).

6.1 Measurements and other research tools

Several ways of gathering information have been used in the studies included in this thesis, such as measurements of temperature, humidity, etc., as well as interviews and questionnaires. The measurements of velocity, temperature, humidity, contaminants, electricity and air-flow are mainly used to validate or use as boundary conditions or inputs in the simulations presented later. The questionnaires and interviews were used to gather information on some aspects of how decision makers in industrial companies perceive problems related to energy efficiency investments. The energy audit procedure is used to gather initial data on energy and indoor performance.
6.1.1 Energy and indoor environment auditing

Energy audits are a key feature in successful management of the energy issue, as this is a starting point for implementing energy issues in management procedures. An audit aims at assessing the present energy situation at a plant. In ASHRAE (2003) a classification of energy audits is made. This classification involve three levels, defined in Mazzucchi (1992), and is similar to the audit procedure presented in Nilsson (2003). The three levels presented in ASHRAE (2003) are Level I (Walk-through assessment), Level II (Energy survey and analysis), and Level III (Detailed analysis of capital-intensive modifications). The Level I walk-through assessment involves an assessment of the energy cost and efficiency by analyzing energy bills and a brief survey of the site. This first level assessment targets low- or no-cost measures and presents a listing of capital improvements that need to be studied further. The survey also gives an initial judgment of the potential for further cost and energy savings (ASHRAE, 2003). This level, based on historical data of energy use, often include a brief walk-through where representatives at the firm audited are interviewed (Nilsson, 2003). In addition to this a coarse break down of energy use on different processes may be done. The second level, energy survey and analysis, includes a more detailed survey and analysis of the plant studied. This is usually done by some form of detailed break-down of energy use, either by activities and energy carriers or, as in this thesis, the previously discussed unit processes. In this level, potential savings are derived in relation to the owner’s constraints and economic criteria. This is accompanied by a discussion of how these measures affect maintenance procedures and operation. An energy survey analysis should also include a listing of potential capital-intensive measures that require more detailed data and measurements along with a study of their potential costs and savings (ASHRAE, 2003). In some Level II studies, where measures affecting for instance indoor climate or indoor air quality are studied, complaints may be gathered. More extensive long-term measurements may be preformed, and suitable measures suggested (Nilsson, 2003). The third level focuses on capital intensive measures found in the level II analysis. This level provides detailed costs and savings sufficient to be used as decision support for a major capital investment (ASHRAE, 2003). This generally involves a detailed study of the effects of specific measures by using specialized software and simulations and extensive measurements. In the third phase aspects such as
indoor environment are often included next to economic considerations and other management issues (Nilsson, 2003).

The audits performed related to Papers I, III can for the most part be categorized as level I audits if the above categorization is used. Historical data were gathered by the auditors, a break-down on unit-processes were made and short-term measurements on a few highly interesting end-using equipments were performed, after which suitable suggestions were given. Many of the suggested measures in Project Highland were low- or no-cost measures.

This approach also summarizes large parts of the initial energy audits for both the dairy case studied later and the foundry case. Initial energy audits were performed and overall characteristics were gathered, after which an extensive measuring program distributed energy use on the unit processes previously discussed. In addition to this efficiency measures were generated and studied from multiple perspectives using simulation and even more measurements. Other aspects such as indoor environment, consequences on global emissions were also included in the dairy case (Karlsson et al., 2004). The overall perspective was holistic in nature, and based on a top-down approach. Specialized software was used to simulate effects on indoor climate, and in the dairy case the production was also analyzed by optimization (Karlsson et al., 2004).

6.1.2 Velocity and turbulence intensity measurements

Velocity measurements have been made with three different measuring devices: vane anemometers, hot-wire anemometers and an orifice plate.

The vane anemometer, a Kimo LV110 with a diameter of 106.1 mm, has been used mainly in the foundry case due to high levels of contaminants in the exhaust and conveying system. The vane anemometer was then used to measure mean velocity at fan exhaust and to assess the air velocity of plumes above furnaces to compare with CFD. The velocity error given by the manufacturer is about 3% or ±0.2 m/s of the measured value with a resolution of 0.1 m/s.
A SwemaAir 300 hot-wire anemometer with a SWA 10 probe, was used during the field measurements. The Swema was calibrated using a calibration rig at the University of Gävle. The instrument error of the Swema was 0.04 m/s or 3% of the measured value depending on which is larger. According to Johansson and Svensson (1999) the methodological error is 8% when measuring supply airflow and 5% for exhaust airflow measurements if the specified requirements are met. The resolution of the SwemaAir 300 is 0.01 m/s.

### 6.1.3 Temperature and humidity measurements

To minimize the methodological error when measuring temperature it is important to avoid a number of potential pitfalls. In Awbi (2003), four important parameters to keep in mind are summarized:

1. Heat conduction from probe to a surface not of the same temperature as the fluid measured.
2. Velocity pressure of the moving fluid instead of static temperature
3. Radiant heat exchange between the probe and surrounding surfaces (if not of same temperature as fluid)
4. Dynamic response of the measuring device.

The first two are argued not to be a problem due to low velocity in the occupied zone and it was made certain that the probe was not in contact with any surface. The latter two however are relevant to discuss further.

For the foundry case the measured surrounding wall temperatures were on average 27.9°C. The air temperature was in an interval ranging between 18 to 24°C. The probes were shielded from direct radiation from the furnaces and other hot production equipment. The error due to surface radiation was found to be about 0.12°C for this case. The uncorrected difference is thus of the order of about 0.1 degree. For the dairy packaging facility this term is even smaller even though the air velocity was lower. The error due to surface radiation for this case was less than 0.05°C.

To handle the dynamic term during the measurements, the measurements have been made over a long enough duration for the probes to attain a steady-state.
The manufacturer-calibrated Tinytag loggers have a measuring error of 0.35°C according to the manufacturer. When adding the deviation due to radiation differences the total error is of the order of 0.5°C. In addition to the temperature loggers, Infrared Thermography (IR) has been used. This kind of system, an Agema 570, has a specified accuracy of ±2°C. However, Cehlin (2006) shows that this figure may be considerably improved if, among other things, the surfaces have high emissivity and the measurements are averaged over time. The deviation from measurements with thermocouples at 17-25°C was about 0.6°C (Cehlin, 2006).

The humidity is also measured using a manufacturer-calibrated logger, with an error of 3%. The methodological error is hard to assess but in Karlsson (2006) the total error of the Tinytag logger used is found to be about 6%.

6.1.4 Electricity measurements

The electricity used by different machine groups and other equipment has been measured with an instrument from Fluke with an error of ±2.5%. No methodological error has been used due to the character of the measuring procedure. In Karlsson (2006) the total uncertainty is found to be about 5%.

6.2 Computational fluid dynamics

6.2.1 Introduction

Computational fluid dynamics (CFD) has been extensively used as a scientific tool in many industrial application and research situations since the 1950s. Use is widespread in a range of fields such as aerodynamics, hydraulics, meteorology, combustion engineering, electronic cooling, bio-medical engineering and in predicting internal and external environment of buildings.

In Versteeg and Malalasekera (1995) the authors give a broad definition of CFD and state that:

“Computational fluid dynamics (CFD) is the analysis of systems involving fluid flow, heat transfer or associated phenomena such as chemical reactions by means of computer based simulation.”
The use of CFD to simulate ventilation and air movements in rooms is not uncommon. One of the earliest publications simulating air flow in rooms was made by Nielsen in 1974. In Awbi (1998) CFD was used to compare mixing and displacement ventilation by using a newly proposed index namely the thermal air quality index. For the studied test cell, the displacement ventilation was concluded to be a more energy-efficient supply strategy. Karlsson and Moshfegh (2006) use CFD to simulate and visualize the indoor climate in a low-energy building. In Lau and Chen (2007) CFD is used to evaluate the performance of a workshop. The CFD results are compared to temperatures and tracer gas measurements. In Liu et al. (2003) CFD has been used to model the particle transport in an hospital operating room. The result of the study pointed out several critical parameters that govern the particle distribution in the room.

Due to the increase in computer resources the use of the CFD as a scientific tool has been increased and continues to increase as it is possible to solve more complex and challenging problems. CFD is a user friendly design and analysis tool for the food industry when designing process equipment. In two review publication, Xia and Sun (2002) and Norton and Sun (2006), the use of CFD in the food industry was reviewed. The main use of CFD has been in studying heat transfer–related problems for process equipment and not HVAC-related aspects, but in recent time some aspects of ventilation and cold storages have been simulated.

Due to the cost and time needed to perform real experiments, CFD has been extensively used, and this method is of special interest for cases where it is not possible to obtain measurements. To ensure the validity and reliability of numerical methods such as CFD measurements though are still needed. An often-used approach is to compare results from numerical simulations with measurements; if the results coincide, a numerical approach in predicting similar situations may be used.

In Freitas (2002) and Sørensen and Nielsen (2003) numerical uncertainties of CFD simulations are discussed. In Freitas (2002) a list of ten important aspects is summarized derived from requirements by the International Journal of Fluid
Dynamics for published papers. For steady-state simulations like the ones in this thesis, six of these aspects are applicable:

- the basic features of the method should be described
- methods should be at least second-order in space
- grid independence or convergence should be established
- accuracy and implementation of boundary and initial conditions should be explained
- existing codes should also be fully cited
- reliable experimental results should be used to validate a solution.

These six criteria are used to allow transparency and reduce the uncertainty of issues such as modeling error (inaccuracies in the mathematical modeling of a physical phenomenon), domain dependency error (errors due to finite representation of a domain), boundary and initial condition error, multiple steady-state solution errors (from using different relaxation factors), iterative errors (incomplete convergence), and truncation convergence errors (due to insufficient grid refinement) (Karimipanah, 1996). In Nielsen (2004), related aspects of CFD quality such as “false diffusion” and the importance of using higher schemes when possible are discussed.

The governing equations and turbulence models used in the papers in this thesis are described in the section “Governing equations”, and the boundary conditions, schemes and grid independency studies are presented in the chapter “Numerical accuracy and boundary conditions”.

6.2.2 Governing equations

Fluid flow and energy transport are governed by the conservation laws of mass, momentum and energy. These equations are complemented by some relations between fluid properties like the equation of state and the linear pressure strain relation for a Newtonian fluid. By assuming the flow is steady state, three-dimensional and incompressible and for Newtonian fluid, the equations for conservation of mass, momentum and energy can be written as:
\[ \frac{\partial (\vec{u})}{\partial x_i} = 0 \quad (6.1) \]

\[ \frac{\partial (\vec{u}, \vec{u}_j)}{\partial x_j} = -\frac{1}{\rho} \frac{\partial \rho}{\partial x_i} + \frac{1}{\rho} \frac{\tau_{ij}}{\partial x_j} + S_M \quad (6.2) \]

\[ \frac{\partial (\vec{u}, \vec{\theta})}{\partial x_j} = \alpha \frac{\partial^2 \vec{\theta}}{\partial x_j^2} + S_T \quad (6.3) \]

Where \( \tau_{ij} \) is defined as:

\[ \tau_{ij} = \mu \left( \frac{\partial \vec{u}_i}{\partial x_j} + \frac{\partial \vec{u}_j}{\partial x_i} \right) \]

### 6.2.3 Turbulence

Turbulence is a flow regime that is characterized by three-dimensionally irregular properties both in time and space. The regime is also highly dissipative and diffusive: dissipative as viscous forces continuously transfer kinetic energy into heat, and diffusive as it has high rates of mixing and is efficient in diffusing heat and momentum within the flow. Turbulent flow is categorized by a large spectrum of length, velocity and time scales (or eddies), where the larger eddies extract turbulent energy from the mean flow. The larger eddies form smaller eddies which in turn form even smaller eddies and so on through a process known as energy cascading. There is however a limit to the length scales of the eddies at which the energy is dissipated to the flow, known as the Kolmogorov scale.

When studying practical problems of fluid flow the flows are often turbulent and it has been shown to be convenient to rewrite the instantaneous scalar, such as velocity, pressure or temperature, as a mean part and one fluctuating part, to allow us to study the average values and the fluctuating parts separately. This is referred to as the Reynolds decomposition.

In the CFD investigations in this study the flow has been assumed to be steady-state, three-dimensional, incompressible and turbulent. The buoyancy effect is
invoked in the momentum equation to include influence of density variations. The use of radiation models varies between the papers, but in general the models have used constant surface temperatures on all surfaces, which is why no radiation model has been used. Based on the above-mentioned assumptions the equations (6.1)-(6.3) can be re-written in time–averaged form as:

\[
\frac{\partial (U_i)}{\partial x_i} = 0
\]  

(6.4)

\[
\frac{\partial (U_i U_j)}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + v \left( \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) + \frac{\partial}{\partial x_j} \left( -u_i u_j \right) + g_i \beta (\Theta_0 - \Theta)
\]  

(6.5)

\[
\frac{\partial (U_i \Theta)}{\partial x_j} = \alpha \frac{\partial^2 \Theta}{\partial x_j^2} + \frac{\partial}{\partial x_j} \left( -u_i \theta \right)
\]  

(6.6)

The unknowns, \( u_i u_j \) and \( u_i \theta \) constitute the second-moment statistical correlation or so-called Reynolds stresses and turbulent heat fluxes. These terms must be modeled to close the system of equations.

6.2.4 Turbulence modeling

There are a wide range of different turbulence models, from Direct Numerical Simulation (DNS) where the instantaneous Navier-Stokes equations are resolved without modeling to zero-equation models where the turbulent length scales and turbulent viscosity are calculated from the local mean flow quantities. However, the most widely used group of turbulence models for practical engineering problems are the two equation models using the eddy viscosity turbulence approach. In this thesis different two-equation models have been used. To approximate the two terms, presented in eq. 6.5 and 6.6, the Boussinesq eddy-viscosity hypothesis is used. The Boussinesq eddy-viscosity hypothesis for the two terms is given by

\[
\overline{u_i u_j} = -2 \nu_i S_{ij} + \frac{2}{3} \delta_{ij} k \quad \text{and} \quad \overline{u_i \theta} = -\frac{\nu_i}{\sigma_i} \frac{\partial \Theta}{\partial x_j}
\]  

(6.7)
where \( \nu_t \) is the turbulent eddy viscosity, \( \sigma_t \) is the turbulent Prandtl number, \( k \) is turbulent kinetic energy and \( S_{ij} = 0.5(\partial U_i / \partial x_j + \partial U_j / \partial x_i) \).

The two equation models imply that the length scale, \( l \), and velocity scales, \( \bar{u} \), of the mean flow and the turbulence are proportional and can be related to the turbulent kinetic energy, \( k \), and its dissipation rate, \( \varepsilon \), \( \bar{u}^t = k^{0.5} \), \( l = k^{1.5} \varepsilon^{-1} \). The turbulent eddy viscosity can then be derived as \( \nu_t = C_t k^2 / \varepsilon \). This model is valid only when local isotropy in the turbulence field is assumed. The dissipation rate of turbulent kinetic energy, \( \varepsilon \), is given by:

\[
\varepsilon = \nu \frac{\partial u_i}{\partial x_j} \frac{\partial u_i}{\partial x_j}
\]

Thus two-equation eddy-viscosity models require two additional transport equations for \( k \) and \( \varepsilon \) to solve the spatial and temporal variation of the local velocity scale and the length scale.

The models used in this thesis are the standard \( k-\varepsilon \), the renormalized group \( k-\varepsilon \) and the realizable \( k-\varepsilon \) model. A brief description of the models follows below.

**The Standard \( k-\varepsilon \) Model (SKE)**

The standard \( k-\varepsilon \) model is often referred to as the workhorse of turbulence models for practical engineering purposes due to its robustness, economy and reasonable accuracy. The model is a semi-empirical model as the expression for the kinetic energy, \( k \), is derived from the exact equations while the transport model for the dissipation rate, \( \varepsilon \), is empirical and has little in common with its mathematically exact counterpart (FLUENT, 2003). The transport equation for \( k \) and \( \varepsilon \) may be expressed as:

\[
\frac{\partial (\rho U_j k)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + \mu_t S^2 - \rho \varepsilon
\]
\[
\frac{\partial (\rho U_j \varepsilon)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_s} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{\varepsilon 1} \frac{\varepsilon}{k} \mu_s S^2 - C_{\varepsilon 2} \rho \frac{\varepsilon^2}{k} \tag{6.10}
\]

The coefficients are \((C_{\mu}, \sigma_k, \sigma_\mu, C_{\varepsilon 1}, C_{\varepsilon 2})=(0.09, 1.00, 1.44, 1.44)\) and \(S = \sqrt{2S_j S_y}\).

**The Renormalization Group \(k-\varepsilon\) model (RNG)**

The coefficients of the SKE model are determined from a number of case studies of simple turbulent flows. The SKE model has a limited scope of applicability, which may yield poor performance in cases with complex flows. The Renormalization Group \(k-\varepsilon\) model introduces an additional term in the \(\varepsilon\)-equation to improve its performance. The idea is to systematically filter out the small-scale turbulence to a degree that the remaining scales can be resolved. This is done by a parameter which is the ratio between the time scales of the turbulence and the mean flow. The Renormalization Group \(k-\varepsilon\) model will hereafter be referred to as the RNG model.

**The Realizable \(k-\varepsilon\) Model (RKE)**

The term realizable for this model means that non-physical values of variables, such as negative normal stresses, can be removed from the predictions by numerical clipping. To achieve the realizability effect the \(C_\mu\) is no longer constant but a function of the turbulence fields, mean strain and rotation rates. The \(k\) equation is identical with the standard \(k-\varepsilon\) while the \(\varepsilon\) equation is based on the dynamic equation of mean square vorticity fluctuation for high Reynolds numbers (Remírez, 2006).

**Wall treatment**

The presence of walls highly affects turbulent flows, which makes the treatment of walls important for large-scale CFD simulations of rooms. The walls have been modeled with a no-slip condition. The models used in the appended papers are primarily valid for turbulent flow, which is why the wall zone needs to be modeled.
The near wall region is often described as having three zones. The zone closest
to the surface, the viscous sublayer, has a flow that is almost laminar and the
molecular viscosity plays a dominant role in momentum and heat transfer.
Above this viscous sublayer is a transition zone, buffer layer or blending region,
where the molecular viscosity and the turbulence are of the same magnitude. In
the third and outer zone, the fully turbulent layer, turbulence is dominant in
affecting the momentum and heat transfer (FLUENT, 2003).

To model the innermost layers the standard wall function has been used. The
standard wall function was proposed by Launder and Spalding in (1974). When
constructing the computational meshes another function has also been used,
$y^+$, which is defined as:

$$y^+ = y \frac{\rho u_t}{\mu}$$  \hspace{1cm} (6.11)

Where $y$ is the distance to the wall, $u_t$ the friction velocity. In the papers the aim
has been to construct mesh with $y^+$ around 10 close to the wall boundaries, as
recommended by Chen (1995).

**Comments on the turbulence models used**

In this thesis three different turbulence models have been used: the SKE, RNG
and RKE models. For simulations of large industrial facilities the three $k$-$\varepsilon$
turbulence models were compared in the appended Paper IV and the RNG
model gave the results most concurrent with the measurements. However,
differences in computational time were apparent and the RNG model was also
much slower in reaching a converged solution.

**6.2.5 Numerical accuracy and boundary conditions**

The numerical accuracy of a CFD simulation depends on a number of issues
such as numerical schemes, grid independence and boundary conditions. The
finite-volume code Fluent 6.2. was used to numerically solve the governing
equations with a segregated scheme and the SIMPLE algorithm solved the
pressure-velocity coupling. The discretization scheme for the non-linear terms
and viscous terms are second-order upwind scheme and second-order central
scheme, respectively. This is in accordance with Nielsen (2004), where it is
stated that “It is always recommended to use a scheme of second order
accuracy if it is available and if convergence can be obtained”.

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The quality of the grid (or mesh) also affects the accuracy of the solution. A finer grid will therefore reduce these inaccuracies by reducing the errors related to interpolations between the grid nodes. However, since the number of nodes are strongly related to the time needed to iterate and the memory capacity there is a need to use mesh effectively to achieve a solution with sufficient quality. One frequently used approach is to start from a coarse mesh and gradually refine it. A grid-independent solution is found when the difference between two consecutive grids is within the used tolerance.

The importance of boundary conditions is also discussed and several useful methods are suggested to enable prediction of complex diffusers in large rooms. One way is to replace the actual diffuser with a less complex geometry supplying the same momentum flow, thus enabling less mesh. This method is referred to as Simplified Boundary Conditions (SBC) in Nielsen (2004). Another method is the box method, using a box in the room on which the boundary conditions are set. The flow in the intermediate vicinity of the boundary condition is thus ignored, resulting in less mesh as it doesn’t need to predict the zone closest to the diffuser. The third method, the prescribed velocity method, uses the concept of prescribed velocities on a boundary within the volume but all other variables are predicted. The velocities are predicted outside the prescribed volume.

In Paper IV the SBC has been used for a hanging supply diffuser. The momentum and mass flow were measured and implemented. The study compares physical variables in the occupied zone, several meters away from the device, with predicted values to establish that the model gives reasonable predictions. In Papers V and VII the same procedure was used for the supply devices but with a measured velocity distribution. The exhaust devices and process ventilation used a fixed mass flow. The CFD predictions were compared to measured values in the nearby occupies zone. In the studied cases in Papers IV, V and VII a number of meshes were tested with increasing refinement until the changes in the key parameters were small.

The wall temperatures in Papers IV, V and VII have been modeled with constant temperatures. These temperatures were measured both using an IR-camera and using surface temperature probes. The machine groups in the
simulations have also been modeled using constant temperature boundary conditions. These temperatures were attained using both infrared camera and a surface probe. The overall heat transferred to the facility was also compared with measurements of electricity use.

The outlets are generally modeled as pressure outlets with reference pressure. The walls have been modeled using a non-slip condition.

### 6.3 Building energy and indoor climate simulation

#### 6.3.1 Introduction

Building Energy Simulation (BES) is an often-used tool in predicting energy use of buildings both within the academic sphere and in the design process in the construction industry, mainly related to residential or commercial buildings. Similar to other types of simulations, BES is a numerical experiment using a mathematical model. The aim is to be able to predict or forecast a future or otherwise presently unknown situation or in research projects to study effects of a phenomenon. For energy simulation programs, issues such as predicting energy use, either in a future building not yet built, or after a change in a system has been made in a present building, is of interest. In Bergsten (2001) a comparison of different energy simulation software is presented, and a classification of the software is made depending on whether it is a general simulation program, it has multi-zone capabilities or if it is static or dynamic. The main categorization however is made depending on whether it is a general BES software or specific for residential buildings. The issue of code validation is also addressed. The software compared, which were considered the most important energy simulation software used in Sweden, Norway and Denmark, were Bsim 2000, BV2, EiB, IDA ICE, Energikiosken, Enorm 2000, Huset, OPERA, Villaenergi, VIP+ and Värmeenergi (Bergsten, 2001). In Crawley et al. (2005) a more extensive review of the performance and capabilities of building energy simulation programs are presented. The report includes BLAST, BSim, DeST, DOE-2. IE, ECOTECT, Energy-10, Energy Express, Ener-Win, EnergyPlus, eQUEST, ESP-r, IDA ICE, IES<VE>, HAP, HEED, PowerDomus, SUNREL, Tas, TRACE and TRNSYS. The choice of simulation
software for the simulations related to the appended papers was based mainly on a list of requirements including:

- The software should be validated in international journals or research programs
- The software should be able to handle energy and power as well as indoor climate
- The software should be dynamic (time-stepping)
- The software should include the ability to simulate multiple zones
- It should be possible to construct new components if the need arises.

IDA ICE meets all these requirements and has been widely used by many other researchers.

6.3.2 General description of IDA ICE

IDA ICE (Indoor Climate and Energy) is a simulation tool for modeling building performance (Equa, 2000, Bring et al, 1999, Björsell et al., 1999, Sahlin, 1998, Kurnitski and Vuolle, 2000, Pavolas, 2004). The software development was financed by both governmental research means as well as by a consortium of approximately 30 construction and consultant companies (Bergsten, 2001). It is entirely implemented in a general purpose environment, IDA Simulation Environment (SE), where models are available as NMF (Neutral Modeling Format) source code (Sahlin, 1996). NMF, first introduced as a draft standard in 1989 is a tool-independent modeling language, making it possible to re-use source code from other applications (Sahlin, 1996). In IEA SHC Task 22 (Bring, 1999), a NMF model library was developed, which is implemented in IDA ICE. This model has been developed especially for indoor climate and energy design tasks, and enables the user to simulate operating temperatures, comfort indices and daylight levels in the zone. The model has balance equations for CO2, humidity and energy. The library also contains components for both primary and secondary systems, i.e. coils, heat exchangers, dampers, fans, boilers and valves to name a few (Bring, 1999).

The IDA solver simulates a dynamic system consisting of interconnected modules. The modules are based on a system of differential algebraic equations
and connection equations, describing how the variables are connected, and a set of boundary equations assigning input values to specific variables. A description of standard link types (connection equations) is found in (Bring, 1999).

Validation of IDA ICE has been carried out throughout the development where a large number of inter-model comparisons have been made against other software and measurements over the years. An extensive empirical validation exercise based on test cell measurements has also been carried out within IEA SH&C Task 22 (Bring, 1999).

6.3.3 Numerical accuracy

Issues of uncertainty are highly relevant when performing building energy simulations. In Reddy (2006) a review of uncertainties and calibration classifies uncertainties in four categories: improper input, improper model assumptions, lack of robust and accurate algorithms, and errors in writing the code. The first category, improper input, is related to lack of user experience or neglect, improper specifications of building materials, control values or other system parameters. The class of improper model assumptions includes simplifications such as the underlying physics of the problem or the use of semi-empirical coefficients (Reddy, 2006). The last three categories can to a large degree be avoided by choosing software that is well trusted, frequently used both in research projects and in the construction industry, and thoroughly validated. However, the first category, which affects the results of a simulation to a large degree, is not directly software related. A usual, and necessary, way to tackle this problem is to calibrate simulation models when simulating existing plants or facilities. This technique involves four parts: collection of data, input of data, execution of the simulation software to compare output from simulation with measured whole-building data, and finally a decision on whether desired accuracy has been achieved. In Reddy (2006) one formalized requirement on the accuracy for a calibrated building simulations is made and that is that it can be considered calibrated if the normalized mean deviation is less than ±10% when using hourly data. This value is 6.6% and 7.4% for the model used in Paper VIII and Paper VII respectively. No calibration was made of the model in Paper VI as the object was to compare the uncorrected difference between the three software programs used when trying to model the same low-energy
building. Another important aspect of modeling accuracy is the models used for tenants or industrial processes. This is addressed in Paper VI.

6.4 Qualitative case studies, interviews and questionnaires

Case study is a frequently used concept, but depending on tradition the term may have somewhat different meanings. Some disciplines equate case studies with field work, ethnographical methods, qualitative interviews and pilot studies (Merriam, 1994). Within marketing literature such as Lekvall and Wahlbin (1993), case studies are explained as studies where the interest is a detailed and explorative analysis of single cases. In Merrian (1994) the term is defined in a broader sense as “a systematic investigation or questioning” and that a case study is a method which can be used to systematically study a phenomenon (Merriam, 1994). According to Yin (1994) the concept of case studies are suitable for studies with questions such as “how” or “why” where the investigators have little or no control. In Merriam (1994) a categorization is made of the different parts of the concept of case studies; see Figure 6.1.

![Figure 6.1. Categorization of different types of case studies based on Merriam (1994).](image)

An experimental case study requires the ability to manipulate or control the variables studied. This is for the purpose of making predictions based on an “action-reaction” perspective. The experimental case study can be divided into two subgroups, a “quasi-experimental” where all important variables can be controlled and the variables are known, and an ”ex post facto” group where correlations or relations are made between different phenomenon (Merriam, 1994). The non-experimental group includes surveys, case research and
historical surveys. This form of study may be used when it is not possible to control the object studied and when it is hard to identify all important parameters and when the investigator is part of the phenomenon being studied (Merriam, 1994). Surveys are represented by for example surveys of public opinion and often use large quantities of statistical data. Historical studies are similar to case research with the distinction of studying past time. Case research, according to Merriam (1994), can be descriptive, interpretive or evaluative and is used to explore a specific phenomenon and describe the connections and interplay with other factors or components. Merriam (1994) and Yin (1994) both argue that the investigators' skills are very important when making a case study as many features of the case study method are not routine work and as the reality when studying people and organizations is more in need of interpretation than measurements. In that sense the qualitative investigator is the foremost instrument (Merriam, 1994).

In Papers I-III (Rohdin and Thollander, 2006; Rohdin et al., 2007; Thollander et al., 2007), one of the questions asked was “Why don’t companies implement what seem to be cost-efficient energy efficiency measures from a technical perspective?”. The case study approach was used to study this “why” question, also due to the exploratory nature of the study. Since the actions of the company are outside the control of the investigators the aim was mainly to explore, describe and increase the understanding of the company's actions. Based on the categorization presented above this is classified as a non-experimental case study with a primarily non-descriptive approach, since some initial theories were used and the aim was an understanding of aspects related to investments in energy efficiency measures.

In Yin (1994) several types of sources of information are cited: documentation, including letters, articles and mass media; archival records, such as maps, name lists, and charts; interviews, either unstructured, structured or even using a predefined questioner; direct observations; participant observations; and physical artifacts. In Kvale (1996) three types of interviews are defined unstructured, semi-structured and structured depending on how much of the content is pre-defined. During a unstructured interview the respondent is to have freedom to speak more freely about the topic at hand if compared to a structured interview, where the questions are planned before the interview and discussed in a predefined order (Bryman, 2002). A semi-structured interview
may be seen as a mix between these two types. In Paper I semi-structured interviews were used. These interviews were used to explore barriers to and drivers for energy efficiency and the interview was rounded off with a questionnaire based on the theory of barriers to energy efficiency. In Paper II and III, the collection of information was based on a questionnaire sent out to the studied companies. The process of creating the questionnaire follow the process described in Trost (1996), where the research questions and the purpose of the study was describes in detail, and the population of the study were specified as well as delimitations such as how many questions to use was set. In Yin (1994) some general criteria during the design of a case study are presented. The criteria or tests are to construct validity, internal validity, external validity and reliability. Construct validity is achieved using tactics such as using multiple sources of evidence and to establish a chain of evidence. Internal validity can be achieved through pattern-matching, explanation-building, addressing rival explanations and by the use of logic models. The external validity is achieved by the use of theories in single-case studies. And finally reliability can be obtained by the use of case study protocols and the development of case study databases (Yin, 2003).

In Paper I all companies within a previously conducted auditing project were targeted, while in Paper II all member companies of the Swedish Foundry Association were asked to participate. In Paper III all companies which were active in the first part of Project Highland and had received energy audits were sent the questionnaire. In the study related to Paper I a protocol was used even during the more open-ended or unstructured part of the interview. Results from these Swedish studies were also compared with other international studies. In all the studies the respondents at the companies were selected because they were in charge of the energy issue at their company, site or department.
7 Barriers to and drivers for energy efficiency

In this chapter some of the results from the barrier studies in Paper I-III, are presented. These results are also discussed in relation to other studies and the chapter ends with a discussion of barriers to energy efficiency specific to HVAC.

This first theme, related to barriers to energy efficiency, is connected mainly to three studies which are appended as Papers I-III in this thesis. In the first section some general comments on the results from these studies are made. In section 7.2 the appended papers will be discussed in relation to some international barrier studies, and in section 7.3 the barriers are discussed in relation to HVAC or industrial ventilation.

7.1 Results of barriers to energy efficiency in the appended papers

In Paper I non-energy intensive manufacturing industries were targeted. The study showed that the participating companies rated risks and costs associated with production disruptions, lack of time and other priorities and lack of sub-metering high.

This study rated three barriers related to the theoretical barrier imperfect information high, which were cost of obtaining information about energy usage of purchased equipment, poor information quality regarding energy efficiency opportunities, and cost of indentifying opportunities, analyzing cost effectiveness and tendering. Technical risks were also shown to be an important barrier to energy efficiency investments. The study presented in Paper I also found two main drivers, even though this was not the aim of the study. They were long-term strategy and people with real ambition with power of investment decisions related to the energy issue.
The second barrier study, presented in Paper II, reported 23 barriers to energy efficiency in the energy-intensive foundry industry. Here the top ranked barriers of most importance in hindering energy efficiency investments were access to capital, technical risks, and lack of budget funding. Several information-related barriers are ranked high such as difficulties in obtaining information, poor information quality, and lack of sub-metering. It should be noted that this study was made during a financially difficult time for the foundry industry in Sweden, and several of the companies participating hadn’t shown profit during the previous years. This is clearly seen in what is by far the most important barrier, access to capital. This study also showed a ranking for drivers to energy efficiency and here, like in the study of the non-energy intensive industry, long-term strategy and people with real ambition with power to influence investment decisions are ranked high.

In Paper II, targeting the energy-intensive foundry industry, different sources of information were also ranked by the respondents. The purpose was to investigate how information that leads to implementation is transferred and how credible and trustworthy different sources of information are to the respondents. Here colleagues within the sector, along with the Swedish Foundry Association and consultants performing energy audits, are top ranked. At the bottom are information from power companies, product information, and government-sponsored energy audits, as the respondents regard them as less trustworthy.

In the third barrier study, Paper III, targeting small and medium-sized enterprises (SMEs) in the highland region of Sweden, 20 barriers to energy efficiency were investigated. Here lack of time and other priorities, other priorities for capital investment and access to capital are the top ranked barriers inhibiting energy efficiency investments. It should be noted that this study was made during a time of clear economic upswing, which is reflected in the barriers. However, several information-related barriers rank high, such as difficulties in obtaining information, lack of sub-metering, and poor information quality. This study also included a study of drivers, and long-term strategy and people with real ambition were top ranked.
7.2 Results from some important barrier studies in relation to the appended papers

In an article by Nagesha and Balachandra (2006), about 100 companies in the foundry and brick industry in India were studied. Both in the brick and foundry industry the financial barriers were found to be largest, followed by the behavioral barrier. This is in good agreement with what was found in Paper II investigating the Swedish foundry industry. In Schleich (2004) the German service sector is treated with an econometric approach. The study found a correlation between lack of time and organizational size, indicating long decision chains. This was also found in paper II. Regarding information, there is an expected difference depending on energy intensity, and it is shown that lack of information about possible measures is great in small organizations. The study found no correlation for lack of capital and organizational size. However, information provided, initially in the form of site-specific energy audits, reduced all barriers studied (Schleich, 2004). In Paper I and III it was shown that even though the companies had received energy audits they still rated barriers related to imperfect information, such as costs of or difficulties in obtaining information about energy usage of purchased equipment and poor information quality regarding energy efficiency opportunities, high. The authors argue that this implies a need for more detailed information. When the adoption is compared to national programs in other countries where the information was more detailed and included investment assessments the adoption was higher. In Paper III it was suggested to include investment assessments and promote more detailed information. In Almeida (1998) the implementation of high performance motors used in compressors, fans and other production-related equipment in France is studied. Almeida (1998) identifies a number of problems in this market. The competition in the motor market is made primarily on initial cost, which means that the retailer has no incentive to sell energy-efficient motors since in general they have equal margins for those products. Energy cost is not a department issue at the site buying the motor, as the cost is allocated to their maintenance department and buyers choose motors on price, brand, reputation, reliability, and delivery time and not energy performance. To overcome these barriers Almeida (1998) argues that information campaigns should be conducted to visualize the problem, using computer software solutions, workshops, training programs, and conferences to educate the retailers at the manufacturing companies. In
Lawrence *et al.* (2005), some of the same issues cited by Almeida (1998) are found when the authors investigate barriers to installation of high-performance HVAC equipment in the US. They divide the barriers into ownership structure, technical, baseline information cost, technology information cost, capital constraint, interest of uncertainty, bounded rationality, energy price volatility, cost amortization, planning horizon and negative externalities. In this article the barriers are not explicitly rated in the publication but indicate a large potential for measures in HVAC as well as the fact that there are major barriers related to technology information, such as obtaining relevant information in relation to efficient HVAC equipment, and attaining accurate and dynamic information about energy use.

### 7.3 Barriers to energy efficient HVAC

If the question previously posed “Why aren’t those measures that seem to be cost-effective from a technical perspective implemented?” is analysed from a perspective of barriers some issues may be extracted. Both in the Swedish and the Indian foundry industry, barriers related to financial and behavioral barriers were found. For the Swedish foundry industry, information and risk issues such as technical risks for production disruptions, possible poor performance of equipment and lack of sub-metering were found. For the companies studied in the non-energy intensive industry in Sweden, risk of production disruptions, lack of time or other priorities, and cost of information about energy usage for purchased equipment were found to be significant even though the companies had already gotten energy audits. The stated barriers related to risk of production disruptions are not a strong factor, as HVAC is not as strongly connected to the production process, indicating a lower adversity to these measures. The evaluation of barriers to energy efficiency for Project Highland was also made after they had gotten energy audits, but information issues were still ranked high indicating a need for more detailed information to close the information gap in certain areas. The issues of lack of sub-metering, information on how purchased equipment will work and how to implement the equipment is related to the need to visualize the energy use, which was also suggested by Almeida (1998). The barriers relating to costs of or problems in attaining technology information, such as obtaining accurate and dynamic information on energy use, may also be reduced using visualization or simulation. This is argued to be especially important for complex processes.
such as HVAC. When the need for more detailed and dynamic information as well as ways to visualize the problem are summarized, different types of simulations are feasible and may be a practical way to achieve this.

In Chapter 8 this is exemplified in two industrial cases of somewhat different character, one semi-clean environment with low temperature gradients at normal room temperatures and a foundry with large temperature gradients as well as a need to control airborne toxic compounds.
8  Applied studies at two industries

Results from two industrial studies are presented in this chapter and the use of simulation is exemplified.

Two different field studies were made related to theme two and three, which is made to exemplify the use of CFD and BES as decision support and to make predictions of the energy efficiency potential for a variable air volume system. First a dairy corporation, presented in 8.1, and then a light alloy casting facility presented in 8.2. The dairy study included two plants, one in the city of Linköping and one in city of Gothenburg.

8.1  Dairy production plants

The processes using most energy at the studied plants are the production-related processes pasteurization, evaporation, drying of milk, and direct product cooling. However, in a dairy large quantities of energy are also used by processes such as cold storage and cleaning of production equipment, as well as support processes such as ventilation, space heating, space cooling, compressed air, pumps and lighting.

8.1.1  Auditing energy use at the dairies

Two dairy sites was investigated and both are considered energy intensive. When comparing energy and electricity use for production and support processes it is shown that about 55% of the electricity at both sites is used by the support processes and about 25% and 17% respectively of the heat. The overall site statistics such as energy use per ton and electricity use per produced ton differ only slightly, but the newer site is a somewhat more efficient plant in
terms of energy use per produced ton. A substantial part of the energy and electricity used for support processes are used by ventilation and space heating and cooling. For the Linköping plant this was about 49% of the electricity use and 23% of the heat, while for the Gothenburg plant the corresponding figures were 38% of the electricity and 25% of the heat. A more detailed description of the audits are found in Karlsson et al. (2004).

8.1.2 Auditing HVAC energy use and indoor climate

The structure of the energy use related to HVAC at the two sites differs widely where the Linköping site uses district heating and the Gothenburg site natural gas. The use of energy for space heating is twice as high at the Gothenburg site compared to the Linköping site. This can be explained by the fact that the more recently built Linköping site uses more heat exchangers between supply and exhaust air. At the Gothenburg site, heat exchangers are rare. The overall heat exchanger efficiency for the Linköping site is about 55% and for the Gothenburg site 35%. This can also be seen in the lower electricity use to run fans at the Gothenburg site, whereas the Linköping site uses over 60% more electricity to run fans in the HVAC installations.

When comparing the overall HVAC energy costs per produced ton the difference was about 7% at current energy prices during the project. The fact that the cost of energy use by HVAC differs only slightly does not in any way indicate that the function, in this case the indoor climate, was equal. It was therefore of interest to study the indoor climate further. The study of the thermal climate at the sites is presented in Paper VIII.

8.1.3 Whole site energy simulation

As previously discussed, energy simulation is a method by which energy use and power are computed. The method used also includes the possibility of calculating average indoor temperatures in the studied zones. In Paper VIII this method was used to assess the consequences of using a temperature-controlled Variable Air Volume (VAV) system. The model was calibrated using several sources and measurements. Energy use for the site was gathered continuously during one year and temperatures were measured in all modeled facilities.
Other sources of information such as construction materials in walls, measurements of supply and exhaust airflows, electricity use of individual machines, electricity used by fans, compressors, and heat-exchanger efficiencies were gathered. Together these formed the basis for the model. To measure the performance of the model it was compared with measured values of energy use and indoor temperature. The model was accepted as calibrated when the energy use and temperatures were within the limits of a maximum of 10%, after which the VAV control system was simulated.

The result from the studied whole-site simulation presented in Paper VIII showed the model to be both robust and that it had the ability to predict energy and power use as well as average temperatures in the individual facilities. However, the lack of detailed information on the indoor environment important to this type of industry, such as product environment, indoor air quality and comfort, makes it hard to assess the performance of these parameters using energy simulations alone. The predicted energy use and the average temperatures resulting from this simulation indicate that a VAV system has the potential of being an effective way to reduce energy use in HVAC installations within similar industries. The dynamics of the process, where large differences in heat transferred to the room air over time, as well as the surplus of heat in some rooms, makes this measure effective in terms of energy. The use of a VAV system was predicted to decrease the electricity use (by fans) by about 21% and heat used for space heating by about 60%.

The output of this type of simulation enables prediction of energy use for a suggested method and the possibility to test dynamic controlling, which ordinary degree-days or similar methods are unable to predict. This enables the decision maker to better assess the energy reduction, and thus cost reduction, of a suggested measure. However, the issue of indoor environment still needs to be assessed separately.

8.1.4 Computational fluid dynamics

There are as previously discussed several ways in which to assess indoor climate, such as field measurements in different forms or by using computational fluid dynamics. For large industrial premises, whole field measurements are very time consuming to perform. Therefore the CFD
approach was chosen, and measurements were used to assess the accuracy of the simulation.

In Paper IV, this method was used to study the impact of different airflow rates in a packaging facility at the studied dairy. At the time of the study, several complaints of draught were made, which is why the draught index (PD_{Draught}) was chosen to assess the comfort in the facility. In Figure 8.1 a plot of the PD_{Draught} index is visualized for the winter case with full flow and is an intuitive and effective way to visualize draught.

![Figure 8.1. PD_{Draught} prediction for full flow case to the left and half flow case right. A decrease of PD_{Draught} in the occupied zone is predicted for the half flow case](image)

For this dairy packaging facility another important aspect was to predict the air flow patterns to make sure that the supply air reached the front of the packaging machines and “showered” them with fresh filtered air. One way to show this is using path lines. Path lines for the winter case are shown in Figure 8.2.
Another effective option is to be able to predict zones with air velocities above a certain values, so called iso-surfaces. Because draughts are highly velocity dependent, this can be an easy to use guideline to attain mean velocities under 0.15 m/s in winter and about 0.25 m/s in summer for certain facilities. This has been used and is shown in Figure 8.3, here in a perspective view of the facility.

![Machine group and Supply](image)

**Figure 8.2.** Path lines above packaging machines in the dairy case for full flow case. The plots allows a study of the flow field in proximity of the front of the machine groups.

![Figure 8.3](image)

**Figure 8.3.** Perspective view of the constant velocity magnitude in the occupied zone. Summer case, iso-velocity 0.25 m/s (left) and Winter case, iso-velocity 0.15 m/s (right).

From this overview the risk of draught is evident in the region close to the machine groups in the front part of the facility, especially as the supply temperature was about 19.5°C.
8.2 Light alloy foundry

The light alloy facility, in contrast with the previously discussed clean and relatively cool dairy production facilities, has high thermal loads and the process ventilation is important in securing the indoor air quality and meeting the required target levels for contaminants.

8.2.1 Energy use at a light alloy casting facility

The relative proportions of energy use for some Swedish non-iron or steel foundries are presented in Svensson and Svensson (2004), stating that melting and holding is estimated to be 40% of total energy use, molding about 20% and support processes about 40%. The light alloy casting facility presented in this paper has 44% melting/holding, 19% molding and about 37% support processes.

8.2.2 Energy simulation

For the foundry case, studied in Papers V and VII, energy simulation was used to calculate the heat demand in terms of energy used by this individual facility. In Paper VII, the model was also used to predict the consequences of using a temperature-controlled variable air volume system. The simulations predict a decrease in both electricity (used by fans) and space heating by approximately 30% if a VAV system is implemented.

8.2.3 Computational fluid dynamics

The supply air is distributed from a low-impulse displacement system. The supply system which is used to supply make up air for the process ventilation exhausts, in the form of hoods and local exhausts, had an inlet temperature of approximately 16.5°C during the heating season. During the summer the supply temperature follow the outdoor temperature as no active cooling is used. Due to complaints of draught during the heating season, the PD_{Draught} index as well as the more commonly used predicted percentage dissatisfied (PPD) index were
used to predict the comfort under different situations, see Figure 8.4. In Figure 8.5 an overview of air movements are presented as path-lines.

![Figure 8.4.](image1)

Figure 8.4. The PPD index shows significant predicted dissatisfaction during the heating season in the proximity of the supply devices. In the central part of the facility the predicted comfort suggests a more comfortable situation.

![Figure 8.5.](image2)

Figure 8.5. Path lines for supply air. The cool air supplied hits the heated production machinery and furnaces and rises leaving the center corridor of the foundry with only a small amount of fresh air as the momentum of the supplied air isn’t enough to reach this region.

The ventilation efficiency has been measured at four points in the facility and at two heights and has been compared with the model predictions. In Figure 8.6 this is shown in a cross-section of the facility. The view shows high values of $\varepsilon_c$ in the supply region, but much lower values in terms of ventilation efficiency, especially between the machine groups. This indicates that supply air doesn’t reach the occupied zones between the machine groups. This has later been confirmed by measuring particle concentrations in the facility. Several options
for improvements exist, where one is to use higher supply momentum such as with an impinging jet system.

![Diagram](image)

**Figure 8.6. Prediction of $\varepsilon_c$ in the studied facility. The view shows high values of $\varepsilon_c$ in the supply region, but low values between the machine groups.**

This concludes the chapter where some of the results from the studied papers were presented. In this chapter the general results for the thesis were presented, for the more specific results see the appended papers.
9 Discussion

This thesis deals with energy and indoor-related issues of industrial ventilation from a company perspective. The thesis was divided into three themes due to the differences in perspective. The first theme treated barriers to energy efficiency, the second simulation of the indoor environment and energy use and the third Variable Air Volume systems in industrial premises. The starting point of this thesis has been to study methods and technologies that aid in reducing energy use, and it is important to point out the need both for new technology and methods and for understanding the diffusion process of energy-efficiency, and its methods and equipment. From a technology perspective this thesis focuses on industrial ventilation.

The starting point of this thesis was the question about if there is a potential for improving the energy efficiency in industrial companies. There are two strong ways to argue that this is so, first of all that there are several studies showing a large potential, especially for HVAC and other support processes. The other argument for the existence of a energy efficiency potential at the studied companies is that it is the general view of the respondents. In the first study, presented in Paper I, only one of the respondents disagreed, while during the second study targeting the foundry industry there were two who disagreed. From the evaluation of Project Highland it was seen that only four companies had not implemented any of the suggested efficiency measures, and none of those stated that this was due to there not being a potential. Instead the respondents stated that there were other reasons.
However, to be successful with energy management in the long run the issue must be treated strategically and with the full support of senior members of the staff with power to make or at least influence investment decisions. The issue of long-term strategy was found to be one of the most important driving forces to energy efficiency presented in Papers I, II and III. The need for people with real ambition and with power over investment decision was found to be another major driver. This identifies an important human dimension of the energy efficiency process, which implies that to efficiently manage the energy issue the employees must be part of the energy efficiency work. In Caffall (1995) it is suggested that the employees should have energy objectives to motivate them. This was however not found to be important by the respondents in the foundry industry in Paper II or in the non-energy intensive companies in Paper I. Another way to work strategically with the energy issue may be to include energy indicators in financial reports to ensure that the energy issue is properly managed and to treat energy as another “raw material” and not as an overhead cost at the companies.

The issue of outsourcing of energy services in the non-energy intensive sector reported in Paper I was found by some respondents to be a problem as there appeared to be a split incentive, as one part owned the installations and another part paid the energy bill, thus making investments in energy efficiency hard if not impossible. However, with proper contracting different types of energy services can be an effective way to manage energy services of support systems such as ventilation, compressed air, lighting, etc. The non-energy intensive sector in Paper I as well as the SMEs in Paper III report lack of time and other priorities as the second largest and largest barriers respectively, indicating that the companies don’t have time to manage issues other than core processes such as production. Furthermore, lack of technical skills is reported to be important when facing implementation of energy-efficient equipment in all three studies.

In all three studies (Papers I-III) the energy issue is to some degree regarded as not sufficiently managed or given low priority. As might be expected, this issue is less of a problem in the energy-intensive foundry sector compared to the small and medium sized and non-energy intensive companies. However, in a context with environmental concerns and supply side limitations, this poses a problem.
Any strategic work with energy issues must however start with some form of energy audit to assess the current situation. The audit is the first essential tool in distributing energy use on different processes and facilities. This activity is important in identifying the areas to investigate further. During this process the energy efficiency potential is weighted against risk of production disruption, other priorities for capital investment, and other management issues. Following the first audit the energy use is analyzed and measures are suggested. For measures with high complexity, such as measures involving multiple objectives, more detailed and trustworthy information is often needed. This may be reflected in the relatively high ranking of information-related barriers even after a completed energy audit in the appended Papers I and III. In the appended papers I-III problems related to insufficient information, lack of trust in the information, and in some cases even incorrect information are presented. In Paper I as well as in the study of the SMEs within Project Highland (Paper III), lack of sub-metering was reported to be important. This is an important part of energy management as it enables follow-ups of energy efficiency measures and gives the ability to assess the real cost effectiveness. The need for sub-metering in industrial premises is also important to monitor processes and to detect insufficient maintenance.

Energy used by ventilation and air conditioning in industrial premises represents a large portion of the total energy use by support processes, and the potential to increase the efficiency for these processes is large. The area of industrial ventilation is complex as it relates to multiple objectives such as work environment (IAQ and comfort), product environment and energy use, thus making it hard to design well-functioning systems with respect to all of these parameters. In the study of barriers to energy efficiency appended to this thesis this is shown to be a general problem as the respondents referred to difficulties in obtaining information on energy usage of purchased equipment and poor information quality regarding energy efficiency opportunities. The problem of poor information quality thus reflects an inability to make accurate investment assessments when it comes to more complex measures. Furthermore, studies of barriers relating to the design of HVAC installations shows need of detailed and dynamic information and ways to visualize these problems. Another indication of the need for more detailed information is the fact that even companies that have received energy audits and implemented some of those low-cost or no-cost measures rank information as a major barrier.
Another barrier which is arguably larger for industrial ventilation than for office or residential ventilation is heterogeneity, as the differences between different sites with unique processes are larger and it is even harder to produce general solutions for multiple sites.

In this thesis it is argued that simulation in the form of computational fluid dynamics (CFD) and building energy simulation (BES) together is one means to reduce this heterogeneity and the problems related to imperfect and insufficient information. The method using CFD enables the decision maker to gain information on how an HVAC measure affects both the product environment and the work environment, making it visual during the design process. The BES makes it possible to simulate the energy and power performance of various measures, thus giving the decision maker the information needed to make accurate investment assessments of HVAC equipment and making the study more likely to be implemented. When used together these methods capture large portions of the energy and indoor environment issues that need to be addressed when implementing energy efficiency measures.

The CFD method gives the advantage of being able to predict complex flows and their properties, enabling the modeling of important aspects such as air quality and comfort. In Paper IV a large packaging facility for dairy products is simulated and compared with measured values. The average deviations between measured values and the simulation, especially for the RNG model used, is of the same order as the error related to the measurements. These small differences indicate that CFD is an effective way to predict indoor climate for large industrial facilities. In Paper V a similar approach is used for a large foundry facility. The predictions in this environment were also of the same order as the errors related to the measurements. In Papers IV and V a series of indices of performance are used to predict comfort and the performance of the industrial ventilation systems. The papers illustrate the potential use of CFD in simulating industrial ventilation system and thereby achieving more effective systems.

The other simulation method used is building energy simulation. This method is used to predict energy and power use by different energy carriers. In Paper
VI three different building energy simulation programs were compared when predicting the energy demand for a low-energy house. The differences when predicting the energy demand for this type of house were small, only about 2%. The small difference in energy use may be explained by the simplicity of the building and the relative low use of space heating, as most heat is a result of using appliances and other equipment indoors. However, when discussing uncertainties and accuracy, it was shown that the uncertainty in occupant behavior (internal gains), and accuracy of the actual airflows as well as uncertainties in heat exchanger efficiency had much greater impact. This indicates that it is important to focus on the input data and that these factors may be more important than the code used in practical applications. This can be related to the barriers of poor information quality, possible poor performance of equipment, and to issues of trust in the companies supplying the systems. In Papers IV, V and VII, energy simulation programs were used to predict energy use in addition to the CFD predictions of the indoor environment.

The above discussion has focused on barriers to energy efficiency, which is one of two important aspects. Another aspect is technology. This thesis also includes studies of a technique to achieve more energy-efficient industrial ventilation, the variable air volume (VAV) systems. In Paper VIII the VAV system has been simulated for an entire production site and the results indicate that this system can be an effective energy efficiency measure for this type of industry with relatively high internal gains. The large reductions in energy use are mainly a result of the fact that most facilities were designed for the maximum heat load without any control, which is why airflows in winter were very large in relation to the demand. In the foundry case presented in Paper VII the VAV system is also predicted to perform well, though not as well as in the dairy case. This is due to problems with implementing heat exchangers on the exhaust air from the process ventilation due to corrosion, oil fog and dust and due to the very large internal gains. However, in both cases the VAV system is predicted to reduce space heating and fan electricity use. The VAV system in Swedish applications has another advantage since the electrical power and energy use will decrease during the cold season when the need for both heat for space heating and electricity is the largest.
To conclude the discussion some final remarks are to be made. In the above discussion of barriers one focus has been on information which may be seen as a market failures and thus imply a need for public interventions. The main reason that energy efficiency is a public issue is that it creates environmental externalities. It is therefore important to stress the need for governments to address the issue of energy efficiency and conservation and one way to achieve this is to strive to include the cost of these externalities. This as companies will react to changes in prices and the availability of efficient technologies and information related to these technologies.
10 Conclusions

This thesis has the aim of reaching a more comprehensive view of energy efficiency and indoor environmental issues related to industrial ventilation in industrial premises. This has been studied in three themes. The first part addresses barriers to energy efficiency in Swedish industries, the second is applying simulation as decision support, and the third studies the variable air volume system in industrial facilities. In this chapter the general conclusions for the thesis are presented, for the more specific conclusions see the appended papers.

From the studies made in the first theme it can be concluded that there is a need for a long-term strategy to succeed with the transition to a more energy-efficient company. The other main component found is to have people with real ambition who have power over decisions related to the energy issue. This also shows that the diffusion of energy-efficient technology has a behavioral and organizational dimension. In this theme it is also concluded that information-related barriers are one component in why energy-efficient equipment is not implemented.

In theme two, two types of simulations for industrial ventilation are used as decision support for industrial ventilation. In this theme it is shown that, when used together, computational fluid dynamics and building energy simulation are efficient in acquiring the information needed when investigating energy-efficient measures related to industrial ventilation. It is shown that this information may be one way to reduce information-related barriers. It was also found that the impact of different building energy simulation models was small in comparison with other factors such as user behavior and the accuracy of
equipment specification, such as efficiencies, and the ability to control airflows for the studied case.

In the third theme variable air volume systems were studied. It was shown that the variable air volume system is an effective way of reducing energy used by industrial ventilation in the studied cases. This was especially so in the facilities with large and highly dynamic load profiles.
11 Further work

The issues studied within this thesis have spawned many interesting questions that would be of interest to study further. In addition to the studies of barriers and drivers in SMEs, foundries and some non-energy intensive companies, it would be of great interest to study other sectors such as the service and building sector. Another topic of great interest is to study the policy implication of these studies.

The academic research activities in the field of industrial ventilation have had relatively low activity when compared to other related fields. However, the need for energy efficiency measures to be implemented within the industry and the previously discussed high potential for ventilation and space heating (and cooling) stresses the need for increased work in this field. In relation to this, studies of specific technologies and their practical application is of interest. It is also of interest to study the indoor environment in many more industries, especially in relation to their energy use.

Another aspect that has come up during these studies is the importance of supply systems for special environments, such as foundries and clean or semi-clean production. One system of interest is the impinging jet system which supplies air with high momentum downwards towards the floor, causing the supplied air to spread over the floor and reach larger areas or withstand higher thermal loads without breaking up. This may be of interest in special environments such as industrial premises with large floor areas and warm production-related equipment, and could be a way to overcome some of the shortcomings of the conventional systems in these environments.
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