Mapping of Heat Distribution Networks at Sawmills and Modeling of their Heat Losses and Pressure Drops

Master's Thesis within the Innovative and Sustainable Chemical Engineering programme

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Department of Energy and Environment
Division of Heat and Power Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2013

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Cover:
The sawmill Norra Skogsägarna Sävar, which is one of the sawmills analyzed for improvement potential in regards of their heat distribution networks in this thesis work. © Pernilla Gervind

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ABSTRACT

Through years of research and new investments in boilers and dryers at sawmills, the heat distribution networks (HDNs) have been neglected. Very little literature on HDNs at sawmills is available. More extensive research has been performed on district heating networks. Due to its similarities to an HDN, some of the performed research is of relevance, but a more thorough analysis of HDNs is required. Through interviews with employees at sawmills, the current situation of Swedish sawmills has been mapped. The sawmills are different in some ways, but they also have important similarities. In particular, both investigated sawmills lack of proper documentation of their HDNs. There is also evidence of outdated sections of the pipe systems, which indicates potential for improvements in performance of the HDN. A mathematical model has been developed with available information from the interviews and analysis of relevant literature as a background. The model is used to illustrate improvement potential for an HDN by comparing current heat losses and pressure drops of an actual HDN with estimates using Matlab as a simulation tool. The Matlab programme is flexible with many user defined parameters and is capable of handling many variations in the investigated HDN. The simulation results show a theoretical potential for the investigated sawmill at Mörlunda to decrease their heat losses from circa 970kW to 91kW. The model is very sensitive and requires detailed input data to make accurate estimates. However, the simulations illustrate several useful trends for factors affecting the performance of an HDN at a sawmill.

Key words: heat distribution network, heat transfer, pressure drop, mathematical modeling, pipe network, sawmills

Kartläggning av värmeledningsnät på sågverk och modellering av deras värmeförluster och tryckfall

Examensarbete inom masterprogrammet *Innovative and Sustainable Chemical Engineering*

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SAMMANFATTNING

Under år av forskning på, och investeringar i, pannor och torkar på sågverk har värmeledningsnätet försummats. Mycket lite litteratur om värmeledningsnät (HDN) på sågverk finns tillgänglig. Mer omfattande forskning har utförts på fjärrvärmenät. Eftersom värmeledningsnäten och fjärrvärmenät har ett flertal likheter är en del av den utförda forskningen relevant för sågverk, men en mer grundlig analys av värmeledningsnät krävs. Genom intervjuer med anställda på sågverken har den nuvarande situationen för svenska sågverk kartlagts. Sågverken har vissa skillnader, men också viktiga likheter. I synnerhet saknar båda undersökta sågverken korrekt dokumentation av sina värmeledningsnät. Det finns också bevis på föråldrade delar av rörsystemen, vilket indikerar potential för förbättringar i prestanda för värmeledningsnäten. En matematisk modell har utvecklats med tillänglig information från intervjuer och analys av relevant litteratur som bakgrund. Modellen har använts för att illustrera förbättringspotential för ett HDN genom att jämföra nuvarande värmeförluster och tryckfall i ett HDN med värden som har uppskattats med Matlab som ett simuleringsverktyg. Matlabprogrammet är flexibelt med många användardefinierade parametrar och kan därför hantera många variationer i det undersökta systemet. Simuleringsresultaten visar på en teoretisk potential för att minskade värmeförlusterna från det undersökta sågverket i Mörlunda från cirka 970kW till 91kW. Modellen är mycket känslig och kräver mer detaljerade indata för att göra korrekta uppskattningar av tryckförluster. Dock påvisar simuleringarna flera användbara trender för faktorer som påverkar prestandan för ett värmeledningsnät på ett sågverk.

Nyckelord: värmeledningssnät, värmeöverföring, tryckfall, matematisk modellering, rörsystem, sågverk

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Preface

This thesis work has been conducted for SP Swedish Technical Research Institute, as a contribution to an ongoing larger project, where the aim is to show that the Swedish sawmill industry can reduce its energy consumption by 20% by 2020.

I would like to express my sincere appreciation to all employees at the department of Energy Technology at SP, where I have spent much time during this thesis work. The group made me feel welcome and included, and many have been very helpful in answering my questions. A special thanks to my supervisors at Roger Nordman and Pernilla Gervind, for taking time from their other duties to guide me and for helping me get in touch with the sawmills I have investigated. I would also like to thank Elin Svensson and Mathias Gourdon, supervisor and examiner at Chalmers University of Technology, for detailed feedback and help in time planning.

Finally, a big thank you to the employees at Bergs Timber AB Mörlunda and Norra Skogsägarna Sävar, Anders Johansson, Göran Karlsson and Fredrik Samuelsson, for allowing me to ask them numerous questions, and taking time for several follow up interviews.

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Notations

This section is a compilation of all notations used in the report.

Roman upper case letters

A	Heat transfer area [m^2]
A_{cross}	Cross-sectional flow area [m^2]
B	Coefficient for correlation for external forced convection [ ]
BAT	Best available technology
D	Outer diameter of pipe [m]
D_s	Outer diameter of “surroundings insulation” [m]
HDN	Heat distribution network
L	Pipe length [m]
Nu	Nusselt number [ ]
P	Power consumption of pump [W]
Pr	Prandtl number [ ]
Q_{actual}	Current heat losses of actual system [W]
Q_{BAT}	Inevitable heat losses with best available technology [W]
Q_{cond}	Conductive heat losses [W]
Q_f	Heat losses from feed pipe [W]
Q_s	Potential reduction in heat supply [W]
R_i	Convective heat transfer resistance, pipe and insulation [W^{-1} K]
R_m	Convective heat transfer resistance, surroundings [W^{-1} K]
R_s	Convective heat transfer resistance, joint temperature field [W^{-1} K]
Re	Reynolds number [ ]
T	Temperature [K]
$T_{b,in}$	Temperature entering heat supplier, actual system [K]
$T_{b,out}$	Temperature leaving heat supplier, actual system [K]
T_f	Temperature of feed pipe [K]
$T_{f,i}$	Calculated best available technology (BAT) temperature entering the heat supplier [K]
T_f'	Calculated BAT temperature of next subsection of feed pipe [K]
T_r	Temperature of return pipe [K]
$T_{r,i}$	Calculated BAT temperature leaving the heat supplier [K]
T_s	Temperature of surroundings [K]
T_{tube}	Temperature at outer surface of pipe [K]

Roman lower case letters

c_p	Specific heat capacity [J kg^{-1} K^{-1}]
d	Inner diameter of pipe [m]
e	Roughness of pipe [m]
f_f	Friction factor [ ]
h	Buried depth of pipes [m]
h	Convective heat transfer coefficient [W m^{-2} K^{-1}]
h_e	External convective heat transfer coefficient [W m^{-2} K^{-1}]
n	Coefficient for correlation for external forced convection [ ]
Δp_{tot}	Total pressure difference [Pa]
Δp_c	Continuous pressure difference [Pa]
Δp_{inst}	Instantaneous pressure difference [Pa]
q	Volumetric flow rate [m^3 s^{-1}]
s	Distance between feed and return pipe [m]
v	Flow velocity [m s^{-1}]

Greek lower case letters

λ	Thermal conductivity [W m^{-1} K^{-1}]
λ_i	Thermal conductivity of soil and insulation [W m^{-1} K^{-1}]
λ_m	Thermal conductivity of surroundings [W m^{-1} K^{-1}]
ξ	Fitting coefficient [ ]
μ	Viscosity [Pa s]
ρ	Density [kg m^{-3}]

1 Introduction

This section will give an introduction to the thesis work performed, by providing relevant background information on the Swedish sawmill industry, heat distribution networks (HDNs) and a larger project about energy efficiency in sawmills, which this thesis is a part of. At the end of this section, related work and the aim of the project will be presented.

1.1 Sawmill industry in Sweden

Renewable resources are becoming increasingly important and sought after on a global scale. Different areas of the world have access to different resources. In Sweden, one of the largest available resources is forests. The forest and wood processing industries constitute substantial parts of Sweden's welfare and make out 10-12% of the Swedish industry's total employment, turnover and export value. Furthermore, the forest and wood processing industries are not only financially important; the forests themselves are also natural carbon capturers. Through the process of photosynthesis, the trees take up carbon dioxide from the atmosphere to grow (Skogsindustrierna 2010). Thus, forests fill both a financial and an environmental purpose.

There are about 2000 sawmills in Sweden that process the trees, and they are spread all over Sweden. A majority of them are small with a yearly production of less than 5000 m^3 sawn timber, but there are a number of larger sawmills as well (Andersson et al. 2011). The location of the largest sawmills in Sweden and their yearly productions are displayed in the following figure.

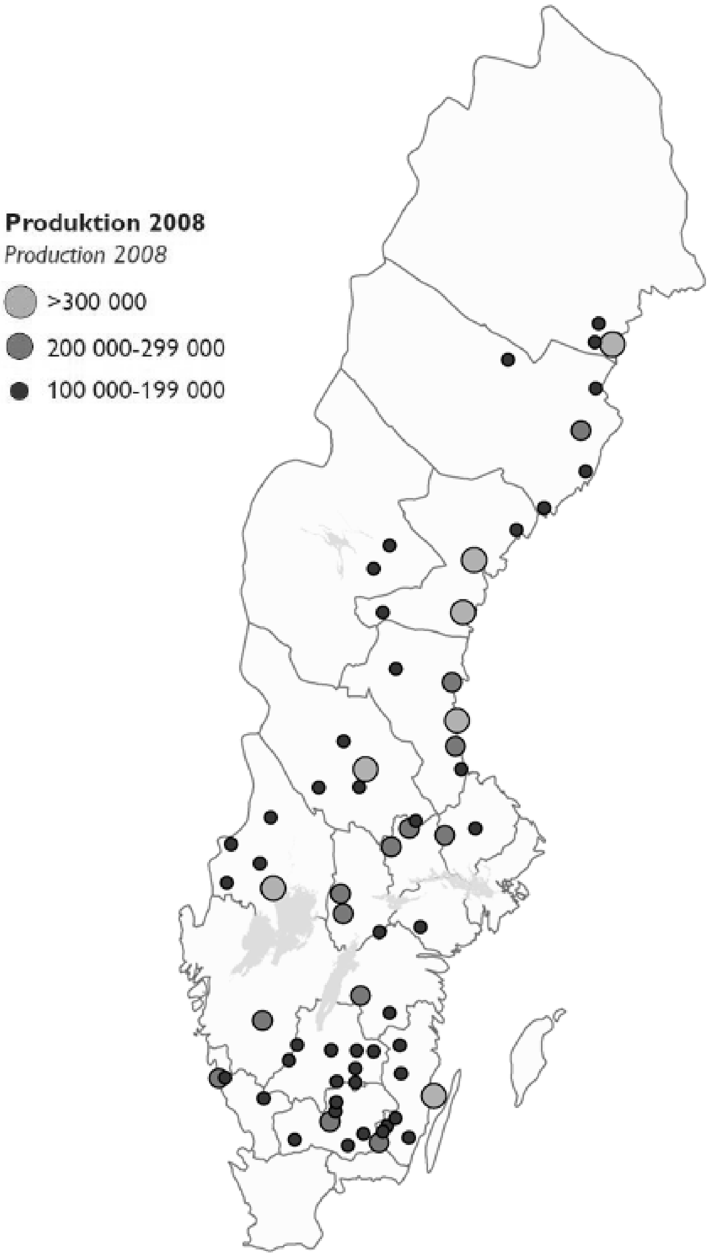

Figure 1. The distribution of large sawmills in Sweden (Andersson et al. 2011).

By ensuring that the processes in the sawmill industry are as energy efficient as possible, there is potential to save substantial amounts of energy resources, as well as increasing the profits for the industry. In general, sawmills today require much energy. Due to the naturally high water content in softwood, the industrial wood drying in Sweden year 2006 consumed about 5 TWh. This is comparable to the total heating requirement for 200 000 small houses (Valutec 2007). The drying process is an important part of the wood processing industry, since wood with moisture content of more than 20% are prone to be exposed to wood-degrading fungi, bugs and bacteria. It is also necessary to dry the wood before any surface treatment such as varnishing and gluing (Valutec 2007). Moreover, the drying process is very energy demanding. Thus, the dryers and surrounding technology play a central role in order to minimize the energy use of modern Swedish sawmills.

1.2 Heat distribution networks

The heat distribution network (HDN) of a sawmill has many similarities with a district heating network. In a district heating network, more than 10% of the supplied heat can be lost to the surroundings from the distribution pipes (Comakli et al. 2004). Because of the similarities between the heat distribution network of a sawmill and district heating networks, it is relevant to consider the heat losses for the sawmill system as well. Consequently, it is of great importance to have an accurate and profound understanding of the heat transfer in such systems. Furthermore, it is interesting to investigate to which degree pressure drops in a heat distribution network contribute to the energy consumption. Through this knowledge it is possible to analyze how a system can be improved in order to decrease the losses to the surroundings.

Due to technological advances over the years it is now possible to better control the drying process. In addition, the sawmills' dryers as well as the boilers have been developed to be more efficient. However, the heat distribution network between the boiler and the dryers have been somewhat set aside, in spite of the fact that dryer operators claim that much energy is lost here if the system is not functioning properly. Although this problem is known, it is not known what its causes are, and if these are of similar character at different sawmills. Obtaining a clear idea of the problems and possible solutions is therefore relevant for the entire sawmill industry.

1.3 EESI Project

This thesis work is performed in collaboration with SP Technical Research Institute of Sweden (SP). One of the projects at SP concerns the energy efficiency of sawmills in Sweden and is called the EESI-project (Energy Efficiency in the Sawmill Industry). It is as a part of this EESI project that this thesis work is performed.

One benefit of making the Swedish sawmills more energy efficient is that the increased profitability will increase their ability to compete on an international market. If the sawmills are able to expand it will create more job opportunities, especially in the rural parts of Sweden. With this as premise, a large project has been initiated involving SP and a number of sawmills all over Sweden. The main aim for the research project is to show that it is possible to reduce the energy use of sawmills by 20% per produced cubic meter of timber before 2020. If successful, this reduction of energy consumption could save Swedish sawmills about 22 SEK/m^3 (Andersson et al. 2011). In order to do this, the project has assessed the current technologies of sawmills to find where energy can be saved, and thus where further research should be focused. This master thesis focuses on the heat distribution networks.

1.4 Related work

In order to gain an understanding of the current research situation, a study of related work was performed. This contains analysis of studies on different types of heat transfer and pressure drops in similar systems, as well as an investigation of existing software performing estimates of these phenomena. The results of this analysis are briefly laid out below.

A general conclusion to be made is that few studies have been made about the exact type of HDN that are present at sawmills. On the other hand, these systems have some similarities with district heating networks, on which numerous studies of heat losses and pressure drops have been performed. The similarities include the type and dimensions of pipes used, as well as the heating media used; water or glycol. However, the differences are not negligible, and include different temperature intervals, larger flow rates and substantially longer pipe distances in district heating networks (Comakli et al. 2004). Instead, more focus in this work was placed on studies of heat transfer and pressure drops on more simple systems.

The studies performed on simpler systems enable analysis of more complex phenomenon. As Bau (1982) points out, many studies resulting in expressions for calculations of heat losses assume isothermal surfaces or constant heat fluxes. He continues by arguing that this is not usually the case in real life systems, and these idealizations must be processed. As a consequence, he proposes a system in which the interaction between the pipes and the media they are buried in is taken into consideration. The expressions derived show that the temperature profiles of the pipes are in fact affected by the buried depth of the pipes (Bau 1982). Although these results are interesting, the mathematical procedures used are considered too complicated for the scope of this thesis work. Another study of importance for the mathematical simulations in this work was performed by Abbas et al. (2010). They found that a mathematical simulation of forced convective heat transfer of air though a heated pipe using the Dittus Boelter correlation, the same as used in this project, gave results that coincided within a range of 25% of the measured results from experiments. They conclude that the correlation is validated for most industrial applications (Abbas et al. 2010). Thus, the Dittus Boelter correlation is used in the simulations performed in this thesis work.

Regarding available software, it was found that there are a few that can perform the desired estimates of heat losses and/or pressure drops for district heating networks. Depending on the degree of flexibility in terms of temperatures and pipe lengths, for instance, these types of software can be useful to estimate heat losses and pressure drops for heat distribution networks at sawmills as well. However, many of the interesting programs are expensive and were thus unavailable for this thesis work. The review resulted in software from two different manufacturers. One manufacturer of pipes provides a free program for download combined with an online calculator tool for calculation of heat losses and pressure drops of pipes used in district heating networks. Since it offers a number of user inputs it can be used to simulate parts of an HDN at a sawmill. Available input includes (but is not limited to) pipe configuration (single or double pipes), flow rate, feed and return temperature and pipe dimensions (LOGSTOR 2012). The expressions and correlations used for this calculation tool are not available, but the tool can be used to validate some parts of the mathematical model developed in this thesis work. The other available software is more basic, and focuses on the degradation of the materials used for the insulation over several years, with the option of an economic evaluation (Jarfelt 2002). Since this thesis work does not include financial aspects and the program was not flexible enough to be applicable to a HDN, this program was discarded.

1.5 Aim of project

The purpose of this project is to map the heat distribution networks of two sawmills, and to identify and discuss the current problems in heat distribution networks. Moreover, with the results as a basis, a model describing a general HDN will be developed and used to suggest possible improvements for the sawmill industry. A partial aim is to obtain an in-depth understanding of the heat transfer and pressure drops in such systems.

1.6 Scope and delimitations

Due to restricted time resources, the number of investigated sawmills is limited to two. Interviews were performed with both sawmills and data acquired from one of them. The selection of investigated sawmills was based on location and previously expressed interest in this project. Since only two sawmills are analyzed, more time was available for development of an accurate model for a general heat distribution network.

The model is limited to describing steady state systems, due to the lack of time. Thus, actions such as startup of the process and changes in load are regarded as instantaneous steps. In order to generalize the model, a standard choice of materials for the pipes and insulation in the HDN is assumed. The choice of materials is based on common practice in the industry.

The project is also limited to only investigate the system between the boiler and the dryer and does not take into account any losses or other mechanisms outside of this system, which means that the boiler and dryers will be regarded as “black boxes”. Furthermore, all calculations and simulations are performed using MATLAB, due to availability and prior knowledge of the program.

2 Theoretical descriptions

The necessary theoretical knowledge concerning sawmills, heat distribution networks as well as heat transfer and pressure drops in pipes has been obtained by evaluating available literature. The information relevant for this thesis work is explained in this chapter.

2.1 Energy use of sawmills and its processes

As in many industries, the energy use of sawmills is of central importance. In brief, sawmills are supplied with energy from the waste products from sawing, and they consume energy when drying wood and heating the buildings on site. When sawing the logs, a lot of bark and other imperfections are removed from the timber in order to get high quality boards. In year 2000, wood chips and sawdust constituted 44.7% of the production. The production yield for an average sawmill in Sweden is illustrated below (Skogsindustrierna 2010).

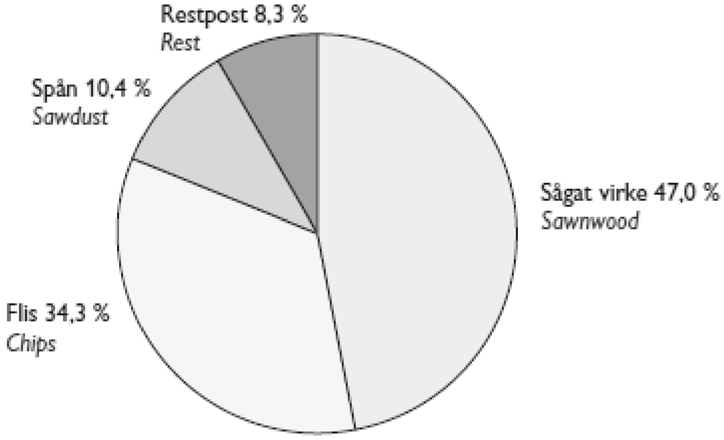

Figure 2. Production yield for Swedish sawmills in 2000 (Skogsindustrierna 2010).

In order to minimize energy and resource usage, the waste products from the production of boards (such as wood chips and sawdust) are used as a heat source (Esping 1996). A majority of sawmills today have their own boiler where the waste from the production is incinerated, and the heating value of the waste products easily cover the heating demand of the dryers. The heat generated is consequently distributed to the dryers and other parts of sawmills with a heat demand (Valutec 2007). However, it is sometimes beneficial for sawmills to sell the waste products to industries that produce paper pulp. If that is the case, it is of great importance to limit the amount of incinerated waste products, and consequently the energy demand of the dryers (Esping 1996). It is also possible for sawmills with a higher energy production than usage to sell heat to a district heating system, but this requires a nearby municipality which can use the heat. Moreover, as the market price of biomass increases, so does the profitability of selling the waste products instead of burning them. This provides yet another incentive for low internal energy use (Nordman et al. 2011; Valutec 2007).

2.2 Heat distribution networks

As mentioned in Section 2.1 above, a boiler use waste products to supply heat to the dryers and other heat consumers. The heat released in the boiler is used to heat water or, less commonly, to produce steam (Esping 1996). The heating media then enters what is referred to as the *heat distribution network*, HDN, which connects the boiler to the dryers. In direct connection to the boiler there is commonly a large central pump that transports the heating media into the HDN. The heating media is then divided into separate streams to continue to the individual dryers. The flow of the heating media to each dryer is regulated with a shunt regulator and, if necessary, supplementary pumps. These work by allowing a certain amount of the flow to be recirculated through the dryer, and thus controlling the amount of heat delivered to the dryer at any given time. Once inside the dryers, the warm water or steam passes through a heat exchanger which in turn heats the drying air. These heat exchangers use high temperature differences as a driving force, about 40°C (Nordman et al. 2011). It is common to recirculate a part of the cold flow through the dryer, and the rest is returned to the boiler to be reheated, thus closing the system. A basic sketch of such a heat distribution system is displayed below in Figure 3.

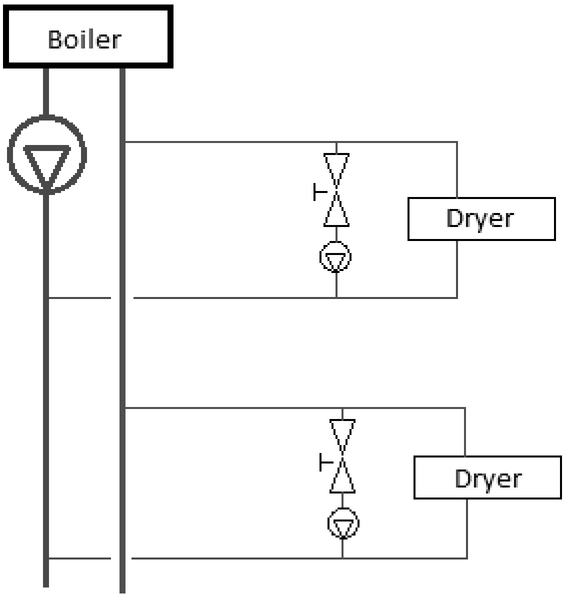

Figure 3. Basic illustration of a heat distribution network to dryers at a sawmill.

The pipes that form an HDN can be dimensioned and structured in different manners. Their design is similar to those used in district heating, which means that modern pipes are covered by a relatively thick insulating layer to decrease the heat losses, and the pipes are buried in the ground. They can be either a pair of single pipes with individual insulation or double pipes, where two pipes are placed in the same insulating casing. Double pipes are normally only used for pipes of smaller flows, and consequently relatively small dimensions (Johansson 2012). If the pipes are single it is common to have the feed and return pipes placed close to each other. This is mainly done for practical reasons. A schematic figure of a feed and return pipe in cross section is displayed in Figure 4.

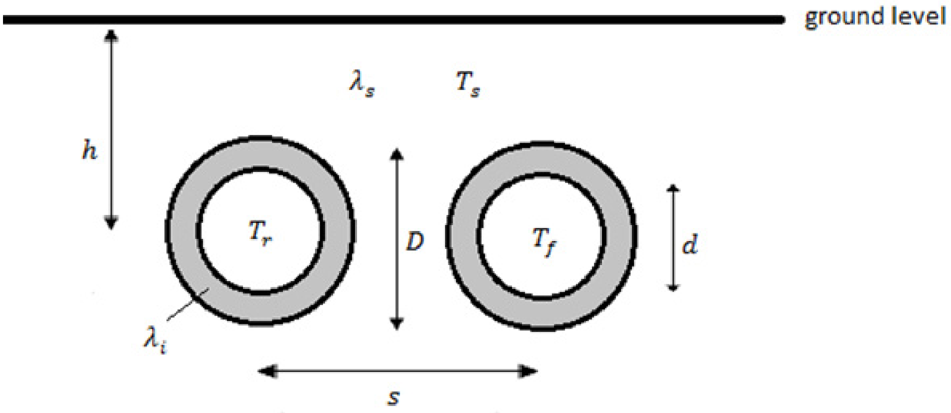

Figure 4. Schematic cross section of feed and return pipes in a heat distribution network.

The figure illustrates a standard piping configuration in a heat distribution network. The pipe to the right is the feed pipe (containing warm water) and the pipe to the left is the return pipe (containing cold water). The notations used in this figure and the remainder of this report are as follows: D is the outer diameter of the insulation around the pipes, d is the inner diameter of the pipes (also referred to as flow diameter), λ_i is the thermal conductivity of the insulating material, s is the distance between the centers of the feed and return pipes, h is the buried depth of the pipes and λ_s is the thermal conductivity of the soil surrounding the pipes (Frederiksen et al. 1993).

2.3 Heat transfer in closed pipe systems

When analyzing the heat losses of a pipe system such as a heat distribution network, it is crucial to understand how the heat is transferred from the pipes and to which degree the different mechanisms occur. In brief, heat is transferred through the pipe walls by convection, and the same amount of heat that reaches the outer surface of the pipes can be transferred to the surrounding by convection, conduction or radiation. Thus, the effect of conductive, convective and radiative heat transfer is examined. Moreover, it is important to recognize that the materials involved and the dimensions of the pipes will affect the heat transfer. The basic expressions for convective, conductive and radiative heat transfer are as follows:

$$\frac{Q}{A} = h\Delta T \tag{1}$$

$$\frac{\mathbf{Q}}{A} = -\lambda\boldsymbol{\nabla}\mathrm{T} \tag{2}$$

$$\frac{Q}{A} = \sigma T^4 \tag{3}$$

where Q is the heat transfer [W], A is the heat transfer area [m^2], h is the convective heat transfer coefficient [W m^{-2} K^{-1}], λ is the thermal conductivity [W m^{-1} K^{-1}], T is the temperature [K], and σ is the Stefan Boltzmann constant ($5.676 \cdot 10^{-8}$W m^{-2} K^4) . These expressions are adjusted to include the dimensions of the pipes, as well as the interaction with the surrounding environment.

Convective heat transfer occurs in fluids in motion, which in this case corresponds to heat being transferred from the fluid to the inner walls of the pipe. If the pipes are not buried underground, convection will also take place from the outer surface of the pipes to the surrounding air. Through extensive experiments, the following empirical correlations for the internal and external forced convective heat transfer respectively have been developed (Abbas et al. 2010; Welty et al. 2008):

$$\mathrm{Nu}_i = 0.023\mathrm{Re}_i^{0.8}\mathrm{Pr}_i^{0.3} \tag{4}$$

$$\mathrm{Nu}_e = B\mathrm{Re}_e^{n}\mathrm{Pr}_e^{1/3} \tag{5}$$

Table 1. Values of B and n for calculation of the external Nusselt number (Welty et al. 2008).

Re_e	B	n
0.4 – 4	0.989	0.330
4 – 40	0.911	0.385
40 – 4000	0.683	0.466
4000 – 40’0000	0.193	0.618
40’000 – 400’000	0.027	0.805

In these expressions, Nu represents the Nusselt number, which is the ratio for the convective heat transfer resistance to the conductive heat transfer resistance. Re stands for the Reynolds number, representing the ratio of inertial to viscous forces, and Pr stands for the Prandtl number which represents the ratio of the molecular diffusivity to the thermal diffusivity. These dimensionless numbers can be expressed as (Welty et al. 2008):

$$\mathrm{Nu} = \frac{hL}{\lambda}, \mathrm{Re} = \frac{Lv\rho}{\mu}, \mathrm{Pr} = \frac{\mu c_p}{\lambda} \tag{6}$$

$L = \text{characteristic lenght [m]}$

$v = \text{flow velocity [m s}^{-1}\text{]}$

$\rho = \text{fluid density [kg m}^{-3}\text{]}$

$\mu = \text{fluid viscosity [Pa s]}$

$c_p = \text{specific heat capacity [kg}^{-1}\text{ K}^{-1}\text{]}$

These correlations are used to calculate the convective heat transfer coefficients h_i and h_e for internal and external heat transfer (Welty et al. 2008). The calculations performed during the mathematical simulations are presented in more detail in Section 4.3.

The heat transferred to the inner wall of the pipe will pass through the pipe into the surroundings through the process of conduction. By modifying the expression for conduction to be applicable for a cylinder, the following equation is derived:

$$\mathrm{Q} = \frac{2\pi\lambda L}{\ln\left(\frac{D}{d}\right)}\Delta T \tag{7}$$

where L is the length of the cylinder [m], D is the outer diameter of the cylinder [m], d is the inner diameter of the cylinder and ΔT is the temperature difference between the inner and outer surfaces of the cylinder [K]. The conduction process can be represented as heat transferred through composite layers, namely the pipe and the surroundings. Since the feed and return pipes usually are placed together the rate of conduction will be affected by the adjacent pipe as well, due to their joint temperature field. For calculation purposes, the heat can be said to pass through a set of resistances; the resistance of the pipe with insulation R_i [K W^{-1}], the resistance of the surroundings (ground or air) R_m [K W^{-1}], and the resistance formed by the joint temperature field R_s [K W^{-1}]. Consequently, the total heat transferred by conduction through a tube and its surroundings can be expressed as:

$$Q = \frac{\Delta T}{\sum R} = \frac{\Delta T}{(R_i + R_m + R_s)} \tag{8}$$

These resistances are based on an averaged heat transfer area between the inner and outer surfaces. These resistances are expressed mathematically as follows (Frederiksen et al. 1993; Welty et al. 2008):

$$R_i = \frac{1}{2\pi L\lambda_i}\ln\left(\frac{D}{d}\right) \tag{9}$$

$$R_m = \frac{1}{2\pi L\lambda_m}\ln\left(\frac{D_s}{D}\right) \tag{10}$$

$$R_s = \frac{1}{2\pi L\lambda_m}\ln\left(\sqrt{\left(\frac{2h}{s}\right)^2 + 1}\right) \tag{11}$$

$$\lambda_i = \text{thermal conductivity of pipe with insulation [W m}^{-1}\text{K}^{-1}]$$

$$\lambda_m = \text{thermal conductivity of surroundings [W m}^{-1}\text{K}^{-1}]$$

$$h = \text{buried depth [m]}$$

$$s = \text{distance between pipes [m]}$$

In these expressions, the volume of the surroundings closest to the pipe is regarded as an additional insulating layer. This is done for simplicity in the calculations, and explains the similarities in the expressions of R_i and R_m. Moreover, since an HDN consists of both feed and the return pipes, the heat losses expressed in Equation (8) must be calculated for both the feed and the return pipes. The final expression for the total heat conducted from a section of pipes is therefore as follows:

$$Q_{cond} = \frac{\left(T_f + T_r - 2T_s\right)}{R_i + R_m + R_s} \tag{12}$$

These general expressions are based on the assumption that the temperatures of the feed and return pipes are constant. It has however been shown that the heat losses at sawmills are large enough to cause temperature differences between the inlet and the outlet of the piping system. This effect has been taken into account in the mathematical model, and is explained further in Section 4.3. In addition, the resistances above are only valid when steady state can be assumed, which is in accordance with the delimitation made for this project (Frederiksen et al. 1993).

Finally, heat can be transferred from the pipes through radiation. The impact of radiation on the total heat transfer is greatly dependent on the temperature, since $Q \propto T^4$. In practice, the degree of radiation is also closely correlated to the emissivity of a certain material. The emissivity contributes to the radiated heat with a factor between 0 and 1. However, since the temperatures are relatively low in HDNs (circa 100°C), radiation will constitute a negligible amount of the total heat losses form the pipe system, and is thus not included in the mathematical model.

2.4 Pressure drop in closed pipe systems

When analyzing the pressure drop of a pipe system, there are two different effects that must be considered. These are the pressure drop that originates from frictional losses of the fluid and roughness of the pipe (continuous pressure drop) and pressure drop which can be considered instantaneous. The latter include changes in height of the pipe, flow through pressure valves, pumps, pipe bends et cetera. Simply put, the pumps of a system must be able to supply a pressure difference that equals the pressure drops, or

$$\sum_k \Delta p_{pump,k} = \sum \Delta p_c + \sum_i \Delta p_{inst,i} \tag{13}$$

where k represents the number of pumps, Δp_c represents the continuous pressure drop, $\Delta p_{inst,i}$ represents each instantaneous pressure drop of the system.

The continuous pressure drop of a system depends on the friction of the fluid, its density and its flow velocity, as well as the pipe dimensions. Abbas expresses the pressure drop as (Abbas et al. 2010):

$$\Delta p_c = f_f \frac{\rho v^2}{d} L \tag{14}$$

$$f_f = \text{friction factor}$$

$$L = \text{length of pipe [m]}$$

To be able to calculate the continuous pressure drop of the system, it is vital to determine the friction factor of the flow. This is not an elementary task, and different empirical correlations must be used. The magnitude of the friction factor is affected by the dimensions of the pipe and whether the flow is turbulent, laminar or in the transition region. However, since HDNs are required to meet a large heat demand, the flow rates in the network are usually relatively high. In practice, no laminar flows are used. As a result, the mathematical model developed in this thesis work is designed to handle fully turbulent flows and flows in the transition region. The transition region represents flows where the friction between the fluid and the pipe depends on both roughness of the pipe and the Reynolds number, Re. The exact line separating the turbulent region from the transition region is difficult to pinpoint, and thus different values are given by different authors. Abbas et al. (2010) and Welty et al. (2008) chose $\mathrm{Re} > 3000$ as a limit for description of turbulent flow. Moreover, the roughness of the pipes affects the continuous pressure drop, and thus the empirical expressions are limited by this as well. The correlation and its limitations proposed by Welty et al. is given by (Welty et al. 2008):

$$\frac{1}{\sqrt{f_f}} = 4.0\log_{10}\left(\frac{d}{e}\right) + 2.28 - 4\log_{10}\left(4.67\frac{d/e}{\mathrm{Re}\sqrt{\mathrm{f_f}}} + 1\right) \qquad (15)$$

$$\mathrm{Re} > 3000 \qquad \frac{d/e}{\mathrm{Re}\sqrt{f_f}} < 0.01$$

If, on the other hand, the flow is found to be fully turbulent, the expression for the friction factor is quite different. For flows in this regime, the friction factor is independent of the Re number, and expressed as (Welty et al. 2008):

$$\frac{1}{\sqrt{f_f}} = 4.0\log_{10}\left(\frac{d}{e}\right) + 2.28 \qquad (16)$$

After the friction factor is determined, the continuous pressure drop is calculated according to Equation (15) above. Determination of the instantaneous pressure drop is relatively straight forward, but similar to the continuous pressure drop. As it is instantaneous, the expression does not incorporate any length of the pipes. Instead using a friction factor, a fitting coefficient ξ, is included to take into account pipe bends, gate valves and similar fittings. It is expressed as (Welty et al. 2008):

$$\Delta p_f = \frac{\xi\rho v^2}{2} \qquad (17)$$

$$\xi = \text{fitting coefficient}$$

Table 2. Table of fitting coefficients for instantaneous pressure drops (Welty et al. 2008).

Fitting	ξ
Gate valve, wide open	0.15
Gate valve, 3/4 open	0.85
Gate valve, 1/2 open	4.4
Gate valve, 1/4 open	20
Standard 90° elbow	0.7
Standard 45° elbow	0.35
180° bend	1.6
Tee, through side outlet	1.5
Tee, straight through	0.4

Finally, the contributions from each type of pressure drop are added and a total pressure drop for the system can be calculated. When compared to the raise in pressure from the pumps of the real system, a potential for improvement can be determined.

3 Method

In order to achieve the aims of this thesis work, as stated in Section 1.5, three different methods have been combined; interviews at sawmills, data collection and model development. Interviews have been performed with employees at the two sawmills, giving both a general overview of sawmills in Sweden as well as detailed information on the operation and design of their heat distribution networks. These interviews were supplemented by collection of data such as water temperatures at Bergs Timber AB Mörlunda. Based on the acquired knowledge from these previous steps, a mathematical model describing the heat losses and pressure drops of a HDN was developed. This chapter deals with the first two methods, and the mathematical model is described in the next chapter.

3.1 Interviews

As this thesis work stems from an ongoing project between SP and representatives from the Swedish sawmill industry, contact with a number of interested persons at different sawmills was already established before the start. From the group of sawmills that were considered, a few had expressed that they had problems with the HDN in particular, which made them interesting for this project. The final choice was to a high degree a result of geographical availability (for interviews in person) and available time and interest on the behalf of employees at the sawmills. As a result, Bergs Timber AB Mörlunda and Norra Skogsägarna Sävar were the two sawmills chosen to be analyzed. For simplicity, these sawmills will be referred to as Mörlunda and Sävar for the remainder of this report. Additional information concerning the interviews conducted is presented in Table 3.

Table 3. Compilation the performed interviews by type of interview, interviewee, sawmill, position and date of interview.

Type of interview (in person or over telephone)	Interviewee	Sawmill	Position	Date of interview (follow up interview)
In person	Anders Johansson	Bergs Timber AB Mörlunda	Production Manager (dryers and saw)	2012-08-28 (2012-10-16, 2012-11-20)
In person	Göran Karlsson	Bergs Timber AB Mörlunda	Boiler Operator	2012-08-28
In person and telephone	Fredrik Samuelsson	Norra Skogsägarna Sävar	Project Engineer	2012-08-24 (2012-10-16)

This setup of interviews represents one sawmill in southern Sweden (Mörlunda) and one in the north of Sweden (Sävar). Furthermore, the sawmills are fairly similar in size. The yearly production of Mörlunda is circa 150 000 m^3 sawn timber, and the corresponding production at Sävar is about 170 000 m^3 (Bergs Timber 2012; Norra Skogsägarna 2012). This places these sawmills in a category of medium sized sawmills in Sweden (Skogsindustrierna 2010).

3.1.1 Interview preparation

In order to ensure that as much useful information as possible was obtained from the interviews they were carefully prepared. This includes a literature study of books and articles treating interviews and what to consider when conducting an interview. Furthermore, the preparations include analyzing what the desired outcome information from the interviews was and how this information could be obtained. Based on this analysis, the questions for the interviews were developed. Since the interviews were performed with Swedish sawmills, the questionnaire and interviews were held in Swedish. A copy of the questions asked can be found in Appendix A.

Another important step of the preparatory stage was to decide which people to interview. It was considered interesting to investigate whether people with different positions within the same sawmill would hold the same perspective of the current situation and any problems they may have with the HDN. Interviews were held with two employees at Bergs Timber AB Mörlunda and one employee at Norra Skogsägarna Sävar.

3.1.2 Conduction of interviews

From the literature study about interview conduction, several useful tips were acquired about how to conduct interviews. One of the stressed points is to ensure that the interviewee feels comfortable and safe in the situation (Kvale 1997; Trost 2001). This was facilitated by the fact that all interviews were performed with the interviewee in their usual environment, at their workplace.

Another aspect of importance is how to maintain attentive during the interview in order to be able to be in control of the interview and lead it in the desired direction with follow up questions (Kvale 1997). By recording the interview instead of taking notes during the interview, this was achieved. The recording was used later on to make a transcript of the interview in question.

When the interviews were complete, the results were analyzed in terms of if the desired information was. In order to clear out any uncertainties and fill in blanks, follow-up interviews were conducted over telephone with both Mörlunda and Sävar.

3.2 Data collection

In order to have a basis for the mathematical simulations, data from the HDN was collected from Mörlunda in addition to the interview data. This data was used to estimate the current heat losses and pressure drops of the HDN. The available data was recorded by the sawmill several times a day for control purposes, and then stored electronically. As much data of different physical magnitudes as possible was collected, with the intention of creating a model that is as accurate as possible. The different available magnitudes are listed below:

- Heat supplied by boiler to the HDN
- Volumetric flow of heating media
- Pumping power
- Temperature of heating media supplied by, and returning to, the boiler
- Heat consumed by individual dryers
- Temperature of heating media entering and leaving individual dryers
- Dimensions of pipes in the HDN
- Distance between boiler and individual dryers

Attempting to develop a model which takes seasonal differences into account, boiler data and temperatures were taken at one typical winter day and one typical summer day in 2011. Furthermore, monthly averages of these magnitudes were collected for 2011.

4 Description of Mathematical Model

During this thesis work a mathematical model has been developed to describe and analyze the heat losses and pressure drops of HDNs at sawmills. The model has been developed in Matlab and is meant to be used for evaluation of which factors have the greatest influence over the performance of the HDN and to show important trends in performance behavior. This chapter will explain what assumptions and simplifications are made in the model, which input information is required, an explanation of how the calculations are executed, as well as what the available output results are.

In brief, the task of the program is to compare the current heat losses from the system as well as the required pressure lifts from the pumps to inevitable losses of a similar system, in order to be able to present areas of possible improvement. The inevitable losses are calculated based on a system with modern pipes, minimal pipe length, minimum number of pipe bends and fittings, and simplified branching.

4.1 Assumptions and simplifications of the model

The mathematical model developed requires a number of reasonable assumptions and simplifications. Firstly, the model is only designed to handle steady state operations. As a consequence, any changes in the system (such as temperature changes) are considered instantaneous and piecewise constant. The distance of pipe over which this is reasonable is determined through test runs of the program. If was found that a distance of 1m generated a sufficiently low temperature drop, without requiring an unnecessary computational demand. Another effect of the steady state assumption is that the variations in heat flow that occurs at start-up of dryers or boilers are not treated. The start-up effects can be quite substantial, and the implications of the steady state assumption are discussed further in Section 7.3.

Another mathematical simplification made is that the network is completely branched as it leaves the boiler, due to the fact that there is little or no available documentation concerning the branching of the HDN (see Section 5.2). This would mean that each dryer is connected to the dryer with an individual set of pipes of lesser dimension (for example DN65). In reality, there is usually a main pipe connected to the boiler (usually DN200), which is branched progressively to reach all ends of the network. However, since there is little information available from the sawmills regarding the details of the branching (see Section 5.1), this simplification is deemed necessary. In addition, it will sometimes be necessary to make assumptions about the bends and length of the pipe network as another result of the poor documentation. Since one aim of the model is to illustrate potentials for improvement in the system, if no information is available about the actual number of bends and length of the pipes, these are chosen to be a minimum for an ideal reference system. The same conditions apply to the number of pipe bends and fittings of the system. This ideal system is then used as a reference for comparison with the real system.

Regarding the materials used for piping, insulation and heating media for the reference system simulating the inevitable losses, these are all assumed to be constant and of best available technology (BAT) type in the entire system. All interviewed sawmills use water in their system, thus the heating media assumption is considered valid. Concerning the materials used for piping and insulation, it is known from the interviews that these are not the same in an entire HDN. In fact, some parts of the pipe network might date back as far as 1970. This is explained in more detail in Chapter 5. Similarly to the number of pipe bends, the assumption of modern materials for the reference system is reasonable to illustrate improvement potential of the actual system. Furthermore, the physical data of the piping and heating media are considered constant in the standard temperature interval for HDNs and taken at 373K. Although many properties vary with temperature, the effect of the variations is negligible in the small temperature interval of HDNs.

A number of other assumptions made were all analyzed and found reasonable. They are as follows:

- Heat suppliers and consumers considered as “black boxes.”
- Incompressible flow, which means that the density of the flow is assumed constant.
- Effects of radiation and internal convection are neglected, as well as impacts of external convection for buried pipes.
- Heat exchangers and other equipment assumed adiabatic (no heat losses).
- Surrounding soil or air, pipes, insulation and other equipment materials are assumed isotropic, i.e. identical in all directions.
- Constant temperature of soil and air at a given distance from the pipe (but season dependent).

4.2 Required input information

In order to be able to make use of the model, information about the system to be modeled is required. As a result of presenting a flexible model in terms of dimensions and structure of the HDN, there are many options for user inputs. It is possible to use standard material data and pipe dimensions, as well as user defined inputs to analyze specific systems. Some of the parameters are correlated, and as a consequence they can be calculated if certain other data are specified. More specifically, if three of the magnitudes below are known, the last one can be calculated from the others.

- Amount of heat supplied by each boiler [MW]
- Total flow of heating media [m^3 h^{-1}]
- Temperature of heating media leaving boiler [°C]
- Temperature of heating media returning to boiler [°C]

A list of the remaining required input information, along with some additional requirements, are presented in Table 4 below.

Table 4. Required known information about the system to be modeled.

Physical description	Additional information
Which season is simulated	Winter, spring, summer or autumn
Standard or user defined materials and dimensions of equipment	
Heating media used	Water or glycol
Number of heat consumers	Dryers, district heating, house heating etc.
Heat consumption for each consumer	
Total pipe length from boiler to each consumer	If unknown, enter distance from boiler to consumer
Pipes burier or suspended in air	If buried, buried depth is required
Temperature of heating media entering dryer(s)	
Temperature of heating media leaving dryer(s)	
If a shunt group is used (for each consumer)	If used, recirculation ratio, R, is also required
Number of gate valves per section	If unknown, enter 2 wide open for system with shunt group, and 1 for system without (minimum)
Number of bends per section	If unknown, enter 10 for system with shunt group, and 8 for system without (minimum)
Number of tees per section	If unknown, enter 2 for system with shunt group and 0 without (minimum)

These variables are all necessary in order to correctly perform the calculations explained in the following section.

4.3 Structure of program and performed calculations

As mentioned above, the necessary calculations to estimate the potential for improvement of the HDNs are performed using Matlab. Simply put, the model consists of a main program calling on function files, which perform most of the calculations, and then compile and display the results. The structure of the program is illustrated in Figure 5 below.

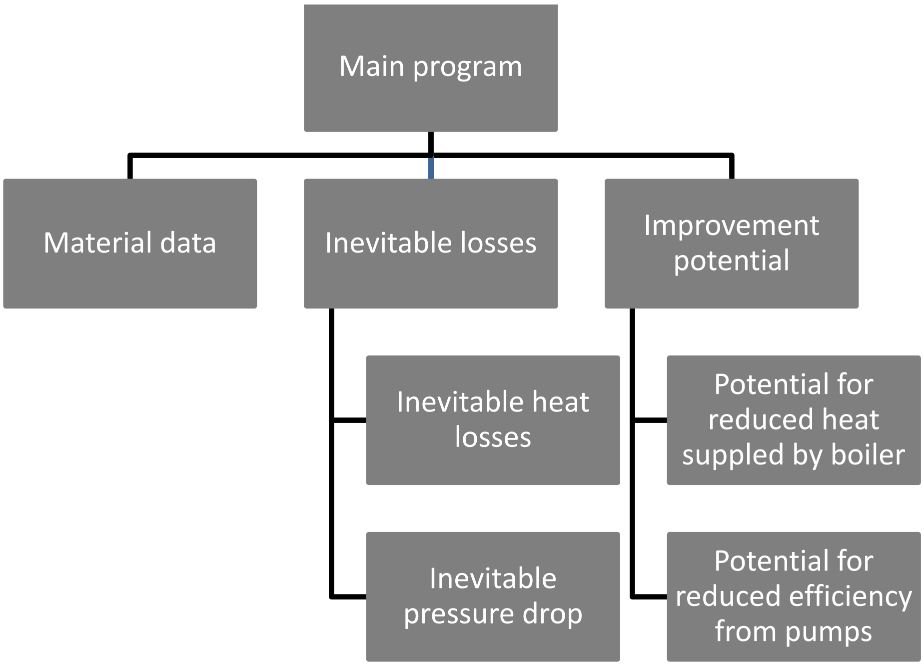

Figure 5 - Hierarchical structure of the Matlab program

As can be seen above, the program calculates the inevitable heat losses and pressure drops of the HDN (with modern pipes, minimal pipe length, minimal number of pipe bends and simplified branching) and compares these to the actual losses of the system. This is done by accessing the material data from a separate function file where the user chooses which heating media to use, as well as whether they wish to use standard material data or user defined. The actual losses are calculated from the measured difference between the temperature drops over the feed and return pipes and power consumed by the pumps. The difference is then expressed as potentials for improvements of the HDN in terms of reduced heat supplied by the boiler and pressure lift by the pumps.

The system with best available technology (BAT) shares many features with the actual system. The calculations of the inevitable heat losses use the actual temperatures entering and leaving the consumers as starting values and the flow rate in each subsystem is calculated from the heat consumed by each dryer. Moreover, the heat supplied by the boiler and the total flow rate of the actual system and the BAT system are equal, as well as the buried depth and type of heating media used. Essentially, the systems only differ in terms of the pipes used, that is dimensions, length and material. Where the actual system consists of a combination of different types of pipes of different age, the BAT system has state of the art materials and dimensions. An actual system at Bergs Timber AB Mörlunda is described in detail in Chapter 5.

4.3.1 Heat loss calculations

Calculations of both heat losses and pressure drops are executed iteratively as the HDN is divided into one section per heat consumer (usually dryers). Moreover, each section is divided into shorter distances over which the temperature can be assumed constant. This is done to simplify the mathematical expressions used for calculations of heat transfer to the surroundings. As explained in Section 2.3, internal convection and radiation can be neglected in this system. The final expression for the heat losses from the feed pipe will be different depending on whether the pipes are buried or suspended in air. If the pipes are buried, the reasoning from Section 2.3 applies, and a general expression for the total heat loss from the feed pipe to the surroundings can be expressed as:

$$Q_f = \frac{\left(T_f - T_s\right)}{R_i + R_m + R_s} \tag{18}$$

where Q_f is the heat loss [W], T_f is the temperature of the feed pipe [K], T_s is the temperature of the surroundings [K], $R_i, R_m,$ and R_s are the resistances for heat transfer of the pipe with insulation, surroundings, and the joint temperature field respectively [W^{-1} K]. If the pipes are suspended in air, the external convection from the wind contribute to the heat losses from the system and must be taken into account. The conduction of heat in air is very low in comparison to the convection, and as a result it is neglected. The final expression for the heat losses of the feed pipe in air is consequently:

$$Q_f = \frac{\left(T_f - T_{tube}\right)}{R_i} = h_e \pi D L \left(T_{tube} - T_s\right) \tag{19}$$

Here, T_{tube} is the temperature at the outer surface of the insulating layer [K], h_e is the external convective heat transfer coefficient [W m^{-2} K^{-1}], D is the outer diameter of the insulating layer [m], L is the length of the pipe section with constant temperature, and T_s is the temperature of the surroundings [K]. The expression for heat transfer from the return pipe is obtained by simply substituting T_f with T_r. For details of the heat resistances, see Section 2.3. The value of T_{tube} is usually not measured, but it can be calculated from the other parameters in the expression:

$$T_{tube} = \frac{T_f + T_s h_e \pi D L R_i}{h_e \pi D L R_i + 1} \tag{20}$$

In order to perform this calculation, the program requires the temperature of the feed and return pipes at this point, plus the length of pipe over which the assumption of constant temperature is valid. For each section of the HDN, the starting values of the feed and return temperatures are the temperature entering and leaving the dryer respectively. This means that the feed and return temperatures for the first iteration are the temperatures entering and leaving the dryers. After the heat transfer is found, the temperatures for the next section of pipe is calculated using the flow rate of the subsection q [m^3 s^{-1}], density ρ [kg m^{-3}] and specific heat capacity of the flow c_p[J kg^{-1} K^{-1}]. For the feed pipe, the expression is:

$$T_f' = T_f + \frac{Q_f}{\rho q c_p} \tag{21}$$

The calculation for the return temperature is done in the same way, apart from a sign change of the temperature change, due to falling temperature of the return pipe further away from the dryer. These two calculations are continued iteratively until the total pipe length between the boiler and dryer is covered. The calculated final temperatures of the feed and return pipes are then compared to the input values of temperatures leaving end entering the boiler, given by the actual system. Any difference between these temperatures can be a result of defects in the real system. There are a number of possible explanations for the discrepancies. The materials used for the pipes and insulation may differ from the BAT system, with greater heat losses as a consequence. Possible cracks in the insulating layer means that water can leak into the insulation, and severely damage its insulating capacity. It is also likely that the actual total pipe length is longer than the minimum distance. The consequences of these factors are discussed further in Chapter 5 and 6.

Consequently, the program displays the inevitable heat losses for the section [kW] and the heat losses per meter for the section [W m^{-1}]. The difference between the calculated final feed and return temperatures for each section, i, gives an indication of the inevitable heat losses for the BAT system. The program then continues to the next section with another heat consumer and performs the same calculations. When all sections are completed the heat losses for each section is added to find the total losses for the entire BAT system. Comparing the inevitable heat losses to the actual gives a measure of a potential decrease in supplied heat to the HDN according to:

$$Q_s = Q_{actual} - Q_{BAT} = \rho q c_p \left(\left(T_{b,out} - T_{b,in}\right) - \sum_i \left(T_{f,i} - T_{r,i}\right) \right) \tag{22}$$

4.3.2 Pressure drop calculations

Parallel to the heat transfer calculations, the program estimates the pressure drops for each section of the HDN. As mentioned in Section 2.4, there are two types of pressure drops that are relevant to this type of system, the continuous and the instantaneous pressure drops. The instantaneous pressure drops are quite simple to determine. For each section, the program requires the number of pipe fittings, such as gate valves, bends and tees, through which the flow passes. This number is then multiplied with the corresponding fitting factor ξ according to Section 2.4 and summed to a joint pressure drop according to:

$$\Delta p_{inst} = \sum_{pipe\ fittings} \frac{\xi \rho v^2}{2} \tag{23}$$

In contrast, the continuous pressure drops are difficult to describe analytically, and the available expressions are based on empirical studies. The difficulty lies in determining an accurate friction factor f_f to be used in the expression:

$$\Delta p_c = f_f \frac{\rho v^2}{2d} L \tag{24}$$

Section 2.4 explains that f_f depends on both the Reynolds number and the relative roughness of the pipes. Thus, the program needs both of them to find the suitable expression for the current section. The relative roughness is an input variable, and Re is calculated from the flow and inner diameter of the pipe. Depending on the resulting variable, the program calculates the appropriate value of the friction factor f_f and consequently the continuous pressure drop of the section. If the flow is found to be in the turbulent transition region, Equation (15) is usually solved using a Moody chart. However, in this model, a function file is used to determine the friction factor based on relative roughness and Re number (Recktenwald 2007). In contrast to the heat transfer expressions, this calculation is performed over the entire distance of the pipe section (feed and return) at once. The pressure drops are then presented separately and as a combination. Similarly to the heat transferred, the results for the pressure drop simulations are presented both per section and in total.

For comparison with the actual HDN, the power consumed by the pumps is expressed as a raise in pressure. It is assumed that the pressure losses of the actual system correspond to the pressure raise from the pumps. This correlation is expressed as

$$P = vA_{cross}\Delta p_{tot} \tag{25}$$

where P represents the power consumed by the pumps [kW], A_{cross} is the cross-sectional flow area of the pipes [m^2].

4.4 Available output information

As explained above, the main aim of the model is to show in which part of the HDN the largest heat losses and pressure drops take place, in order to point to areas of interest for possible improvement. Thus, the output information from the Matlab program for a BAT system is:

- Inevitable temperature drop over feed and return pipes for each section [K]
- Inevitable heat losses for each section [kW]
- Inevitable heat losses per meter for each section [W m^{-1}]
- Inevitable total heat losses for the entire HDN [kW]
- Potential for decrease in supplied heat for the entire HDN [kW]
- Instantaneous pressure drop for each section [kPa]
- Continuous pressure drop for each section [kPa]
- Combined pressure drop for each section [kPa]
- Total combined pressure drop for the entire HDN [kPa]
- Potential for decrease in supplied pressure lift [kPa]

Based on the numbers derived from the mathematical model, it is possible to analyze the magnitude of each type of loss for the BAT system and difference between the BAT system and the actual HDN. These results might then give an indication of whether it is useful to continue to investigate if actions ought to be taken.

5 Mapping of heat distribution networks at sawmills

The heat distribution networks of sawmills in Sweden have been mapped based on information acquired from a visit with interviews to Bergs Timber AB in Mörlunda and from telephone interviews with Norra Skogsägarna Sävar. The gathered raw data has been compiled and analyzed, and is presented below as similarities and differences between the sawmills, as well as explaining current perceived problems.

5.1 Similarities and differences

From the interviews, it was found that that the results from the mapping of the HDNs of the sawmills could be divided into two separate categories for comparison. These categories are *General heat distribution network design* and *Operation of the heat distribution network*.

5.1.1 General heat distribution network design

The design of the HDN includes geographic design or structure as well as the dimensions of the piping and equipment used in the network. An early observation regarding both sawmills is that there is a lack of proper documentation of the HDN, which hamper the mapping of the HDNs. This is discussed further in the next section.

Although they did not have any up-to-date plans of the HDN, a simple sketch of the structure of the HDN at Mörlunda and its components can be constructed. Such a sketch of the HDN and its branching is displayed in Figure 6 below.

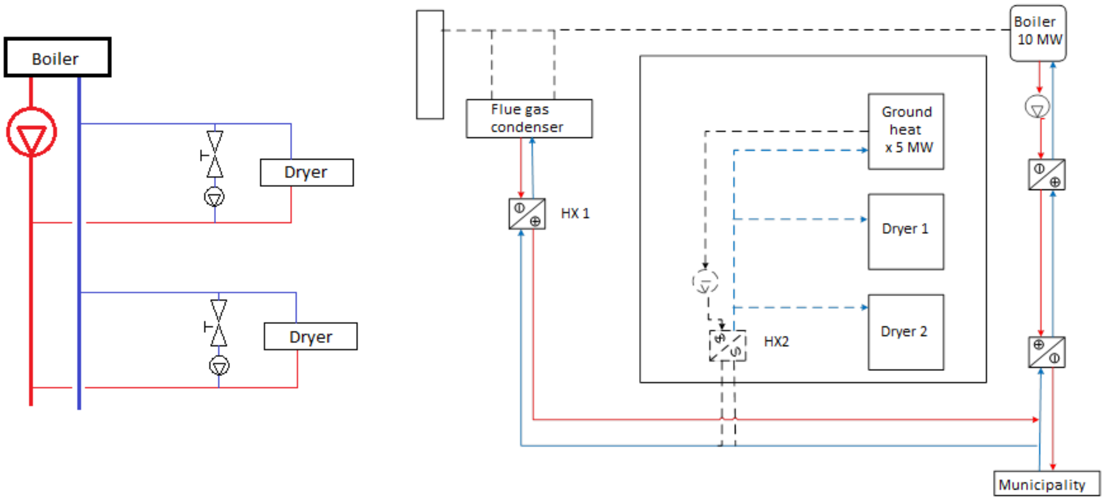

Figure 6. Basic sketch of the structure of two types of HDNs. The system at Mörlunda is displayed on the left-hand side, and the system at Sävar is displayed on the right-hand side.

The sketches above show many of the typical aspects of HDNs at sawmills, but also some important differences between the sawmills. A boiler supplies the network with hot water at both sawmills, usually at circa 105-110°C (Johansson 2012; Samuelsson 2012). A main pipe is then divided into smaller branches carrying the water near the dryers, where additional branching provides each dryer with a single feed and return pipe. The water is then returned to the boiler and reheated. However, if the sawmill in question supplies heat to the district heating network, the HDN differs slightly in structure. For instance, at Sävar, there is an additional closed system from the boiler to a heat exchanger, from which the water is then used for district heating. Sävar has also included a heat exchanger between the boiler and the rest of the system, resulting in a total of three different closed loops. In comparison, Mörlunda operates their system as a single closed system. It is also notable that all interviewed sawmills have included the heating of office spaces and other staff areas in their HDN. This is a consequence of the fact that all sawmills have an excess of residual biomass from the sawing process, which at both sawmills is sold to other industries (Johansson 2012; Samuelsson 2012).

Another parallel between the sawmills is that parts of the piping of the HDN date back to the 70's. Thus few current employees were present when - or remember how - the pipes were placed in the ground(Johansson 2012; Samuelsson 2012). In spite of the fact that the sawmills have different manufacturers for their pipes, the newer pipes are similar in dimensions and insulation qualities. Standard pipe sizes are used (DN200 & DN65), with a thick insulation layer (Johansson 2012; Samuelsson 2012). Since the oldest pipes have virtually no insulation, it is assumed that relatively much of the heat losses from the HDN take place at sections with outdated piping (Johansson 2012). This hypothesis is investigated further through mathematical simulations, and the results are presented in Section 6.3.2.

One of the most important differences between the designs of the HDNs at the two sawmills concerns the placement of the pipes. At Mörlunda, the entire HDN is placed underground, which is not the case at Sävar. Although a majority of the total network is buried, the sawmill at Sävar exhibit some exceptions. At this sawmill there are culverts surrounded by air between dryers (Samuelsson 2012). This is a remarkable difference, as Sävar is situated in the northern part of Sweden where the mean air temperature in year 2011 was as low as 4°C (and considerably lower during the winter) (SMHI 2012). However, when dryers are placed close to each other, it is possible to save pipe length and thus potentially decrease pressure drops by not leading them underground. Nonetheless, in this case it is likely that the saving of pipe length occurs at the cost of increased heat losses to the surroundings. However, both sawmills share the inevitable lift of the heating media up to the height of the dryers. The required height varies between sawmills as the height of the dryers varies; 8m at Mörlunda and circa 4-5m at Sävar. This means that even at Mörlunda, short segments of the pipes are surrounded by air. The effect of buried depth of the pipes on the heat losses of a HDN is analyzed using mathematical simulations and is presented in Section 6.3.3.

Finally, it is common for the flow of the heating media to a certain dryer (based on the heat demand of the dryer at the time) to be regulated by the use of shunt groups. The temperature of the flow leaving the dryer is lower than the flow entering the dryer (usually around 10-15°C (Johansson 2012)). As a result, the temperature of the feed to the dryer can be lowered by increasing the recirculation ratio. This recirculation requires an additional small pump and some extra piping.

5.1.2 Operation of the heat distribution network

Although a majority of the HDN at Mörlunda is buried in the ground, there is certain available data on temperatures and heat used or supplied at the dryers and boilers at the sawmills. Consequently, it is possible to determine the size of the heat losses of the system when being operated under steady state conditions even though the details of where and how the losses occur are unknown. With these data as a reference, mathematical simulations were performed to analyze the current heat losses and pressure drops of Mörlunda, and the potential improvement were highlighted. The results from the simulations are presented in Section 6. However, both sawmills use a number of batch kilns, which means that they have a heat demand that varies substantially over time. During start-up of the dryer, the heat demand is quite large, and it gradually decreases during the drying cycle until the timber is dried. This must be kept in mind when analyzing the simulation results.

Conventionally there are two commonly used heating media for heat distribution networks, namely water or ethylene glycol. Ethylene glycol freezes at a lower temperature than water, -17°C (Mörstedt et al. 1987), and can thus be useful as a heating media in colder climates such as here in Sweden. When there is a risk of freezing, a mixture of the two fluids is used. In spite of occasionally low temperatures, both investigated sawmills use water only as heating media (Johansson 2012; Samuelsson 2012). This is probably due to the easy access to water, and the fact that water is a better conductor of heat ($\lambda_{H_2O} = 0.60\,\mathrm{Wm^{-1}K^{-1}}$, $\lambda_{glycol} = 0.26\,\mathrm{Wm^{-1}K^{-1}}$ at 18°C) (Mörstedt et al. 1987).

5.2 Identified problems at investigated sawmills

When analyzing the interviews with employees at the different sawmills, it was apparent that they did in fact have problems with the transfer of heat from the boiler to the dryers and the heat distribution networks. These problems will be discussed further in this section.

As mentioned in the previous section, it is undeniable that there are gaps in the knowledge at the sawmills about the structure of their networks. This problem is visible from the fact that none of the interviewed sawmills have available drawings or plans of the network showing exact branching or placement of the pipes. At Mörlunda, there were some old sketches, but nothing that was kept updated (Johansson 2012). Naturally, this is a result of a majority of the pipes being buried in the ground to decrease heat losses, inevitably impeding a simple overview of the system. This means that it is difficult for a particular sawmill to determine a detailed position of a detected flaw in the system. If, for instance, there is a crack in the insulation of one of the pipes, allowing for surrounding water to leak in and decrease the insulation property, it will only be possible to determine between which two temperature measurements it has taken place. This may also explain the fact that there are few points of measurements of temperatures. It is simply difficult to access the pipes if they are buried.

Since both sawmills display a temperature drop of the heating media over both feed and return pipes, (circa 5°C) there is potential for improvements in the insulation capacity of the pipes and/or the equipment used. Another direct disadvantage of a buried HDN, combined with the poor documentation of changes, is that the age and materials of different pipe sections is unknown. The visit to Mörlunda clearly illustrated this. They were in the process of exchanging an old pipe section (dating back to the 70's) that was leaking, and did not know whether there were any more as old pipes still in use. In fact, one section of old piping has such large losses that it melts the snow covering the ground 1.5m above them (Johansson 2012).

Sävar share the issue of sections with old pipes, but they have recently struggled with another problem, namely the heat exchangers used in the HDN. As the sawmill has expanded, the heating demand has increased. In order to cope with the increased demand, the flow of the subsections was increased. However, the required flow finally put too much strain on the pumps of the systems. After analyzing the problem, Sävar invested in new heat exchangers between the subsections a few years ago, allowing a decreased flow. Since then the heat transfer is much more efficient, and as a result the flow through the heat exchangers could be decreased. This means less strain on the pumps and that less electricity is required to power the pumps (Samuelsson 2012).

Although the sawmill in Mörlunda exhibit issues with their HDN, they are currently struggling with another, more serious, problem. Similarly to sections of their pipes, their boilers are in need of improvement, and during the visit were not able to heat the water to a satisfactory level of circa 105°C. A restoration was being performed, and in the meantime a temporary boiler was being used. Before the restoration, the boiler had to be stopped every second day to be emptied of ashes, since this waste leads to reduced heat transfer capacity. With the inevitable periods of cooling and start-up of the boiler, this problem generates a large loss of income. This issue is in turn likely to have contributed to the neglect of the HDN.

6 Simulation results

In order to illustrate the current situation at sawmills in Sweden, mathematical simulations of an HDN have been performed with Matlab. The simulations are meant to represent a typical HDN with particular focus on the problems and issues that were presented during interviews with employees at Mörlunda and Sävar. These results are presented below as a case study of Bergs Timber Mörlunda, a comparison of general factors that affect the performance of the HDN and finally a proposed improved design of a HDN.

6.1 Fixed material data

Although the simulations are meant to illustrate the impacts of different factors on the performance of an HDN, certain material data are kept constant for all simulations. These variables and their values are presented in Table 5.

Table 5. Material data used during simulations of HDN.

Parameter	Value
Thermal conductivity of soil [W m^{-1} K^{-1}] (Powerpipe Systems 2011)	1.5
Inner diameter of DN65 pipes [m] (Powerpipe Systems 2011)	$73.03 \cdot 10^{-3}$
Insulation thickness [m] (Powerpipe Systems 2011)	$31.95 \cdot 10^{-3}$
Standard relative roughness of pipes [ ] (Powerpipe Systems 2011)	$68.465 \cdot 10^{-3}$
Conductivity of pipe with insulation [W m^{-1} K^{-1}] (Powerpipe Systems 2011)	0.026
Specific heat capacity of water [J kg^{-1} K^{-1}] taken at 373K (Mörstedt 1987)	4211
Viscosity of water [Pa s] taken at 373K (Mörstedt 1987)	$278 \cdot 10^{-6}$
Thermal conductivity of water [W m^{-1} K^{-1}] taken at 373K (Mörstedt 1987)	0.682
Density of water [kg m^{-3}] taken at 373K (Mörstedt 1987)	958.4

Even though the data above are held constant, most other variables are adaptable. The impact of changes in a number of variables is presented in the following sections.

6.2 Reference case study Bergs Timber AB Mörlunda

The sawmill in this study from which the most information is available is Bergs Timber AB Mörlunda. As such, this sawmill is appropriate for simulations of a reference case to which alternative HDN designs can be compared. As mentioned in Section 5.1, the pipes of the HDN at Mörlunda are buried underground, with the feed and return pipes placed separately but close together. The system directly connects the dryers to the boiler. All dryers have shunt groups for flow regulation, but the dryers are placed in groups at different distances from the boiler. The closest groups is at a distance of about 50m, the second circa 100m away, and the furthest is nearly 250m from the boiler. The simulation used as reference illustrates the HDN at a standard autumn day with two dryers in operation. One of the dryers is 250m from the boiler and one of them is 50m from the boiler.

Using the simplifications explained in Section 4.1, the input data for the simulated reference case are derived and are available in Table 6 below.

Table 6. Input data for simulation of reference case Bergs Timber AB Mörlunda

Physical description	Input for reference case
Flow media used, water or glycol	Water
Season	Autumn
Number of heat suppliers (usually boilers) to the system	1
Amount of heat supplied heat supplier [MW]	3.8
Total flow of heating media [m^3 h^{-1}]	241.1
Temperature of heating media returning to boiler(s) [°C]	82.7
Temperature of heating media leaving boiler(s) [°C]	96.3
Number of heat consumers, i.e. dryers, district heating, house heating etc.	2
Heat consumption for each consumer [MW]	1.5
Pipes in ground or above	In ground
Buried depth [m]	1.5
Temperature of heating media entering dryer(s) [°C]	94.5

Temperature of heating media leaving dryer(s) [°C]	84.5
Use of shunt group, yes or no, for each consumer	Yes
Recirculation ratio	0.5
Height increase up to consumer [m]	8
Double or single pipes	Single
Number of gate valves, wide open	2
Number of standard 90° bends	10
Number of tees, through side outlet	2
Number of tees, straight through	2

The HDN at Bergs Timber AB Mörlunda consists of pipes of pipe dimension DN200 for the large flow rates, and DN65 pipes for the smaller flows. However, there is no available data of the lengths of each pipe dimension and therefore a simplification is made in the model. As explained in Section 4.1. Since one aim of the model is to calculate the smallest inevitable losses for a network similar to that at Mörlunda, for simulations of heat losses of the system, the pipe dimension DN65 is used, since it generates the least losses. For the same reason, the pressure drops are analysed using DN200 pipes.

When investigating the effect of a specific factor of the performance of the HDN, all other input variables will be kept constant in order to obtain unambiguous results. The results of simulations of specific factors are presented in Section 6.3. Regarding the reference case, the simulations show that there is indeed a potential for improvement of the HDN. The results from the simulation of the operating conditions at Bergs Timber AB Mörlunda, but with best available technology (BAT) pipes are presented in Table 7 below.

Table 7. Heat losses for Bergs Timber AB Mörlunda operating conditions with BAT pipes.

	Section 1 (250m)	Section 2 (50m)
Heat loss per section [kW]	76	15
Heat loss per meter [W m^{-1}]	150	150
Total heat loss [kW]	91	

A BAT design for the system with two dryers in operation will have a total heat loss of 91 kW with a temperature drop of 0.13°C over the pipes of Section 1, and 0.03°C over the pipes of Section 2. These values should be compared to those corresponding to the current design. A temperature drop of 1.8°C for both feed and return pipes renders current total heat losses of 970kW for Mörlunda. This means that there is potential to substantially decrease the temperature drop over both sections, which is equivalent to a reduced heat demand of 880 kW. As a result, more waste products from the sawing process could be sold instead of incinerated, rendering an increased profit for the sawmill. In both the current design and the BAT, the heat losses and the continuous pressure drop increase with an increased distance from the boiler to the dryer. This effect is unavoidable, but the BAT design show relatively low losses of 150W m^{-1} for each of the two sections. These results confirm the suspicions of the employees at Mörlunda that the current temperature drops are unnecessarily large (Johansson 2012).

In terms of pressure drops, the case study further highlights the importance of obtaining accurate data for the HDN and its piping dimensions. As explained in Section 4.1 and 5.1, the sawmills today lack specific information about the branching of the system, which means that simplifications had to be made when calculating the BAT heat losses and pressure drops. The choice of pipe diameter has a great influence of the calculated pressure drops, since smaller inner diameter of the pipes means that the flow velocity will increase. In turn, both the instantaneous and continuous pressure drops are proportional to the velocity squared (see Equations (14) and (17)). Table 8 summarizes the findings of the analysis of pressure drops at Mörlunda.

Table 8. Current and BAT pressure drops at Bergs Timber AB Mörlunda.

Physical description	DN65		DN200	
Instantaneous pressure drop per section [kPa]	220	220	3	3
Continuous pressure drop per section [kPa]	2600	510	10	2
Maximum pressure drop [kPa]	2820		13	

The drastic difference in the maximum pressure drop between the two different pipe dimensions is as much as 2800kPa, which reinforces the importance of having access to accurate data concerning the dimensions of the pipes in the HDN. In reality the system is made up of a combination of the two different dimensions, with the larger DN200 pipes used for the parts with large flow rates and DN65 used for smaller flows when the network is branched off to reach the individual dryers. This is supported by the fact that the two 20kW pumps currently in use at Mörlunda supply the system with a raise in pressure of 1600kPa, which is an intermediate value between the pressure drops of DN65 and DN200 pipes. Although this makes it difficult to pin point any specific improvement potential for Mörlunda, the results illustrate important trends. As expected, longer pipe distances will give larger continuous pressure drops, and as a consequence it can be preferable to place the dryers as close to the boiler or boilers as possible. Larger pipes will result in lower flow velocities and thus lower continuous pressure drops, which is illustrated by a continuous pressure drop of 10kPa for Section 1 with DN200 pipes compared to 2600kPa with DN65 pipes. This indicates that larger pipes are beneficial for low pressure drops, but in reality it is not reasonable to use DN200 pipes for the entire system since it would give rise to laminar flows and increased heat losses for the system. Moreover, as there is no available data about the bends, exact lengths or the roughness of the pipes for the actual HDN it is not possible to compare instantaneous and continuous pressure drops between the systems.

These results are quite drastic. The BAT design has a very low temperature drop between the boiler and dryer, enabling large savings potentials. There are also possibly potential for savings for the pumping power. Important differences between the two designs are that the pipes in the BAT design have a very low conductivity (0.026 W m^{-1} K^{-1}) and low relative roughness ($68.465 \cdot 10^{-3}$). It is more difficult to make any certain conclusions about reductions of the pressure drops, but the simulation results illustrate the importance of accurate input data. In addition, the assumptions and simplifications of the model must be considered. These are evaluated further in Section 7.3.

6.3 Factors affecting the performance of the HDN

Section 4.2 describes the flexibility of the model used. The reason for this is partly to enable simulation of many different types of HDNs, but also to simplify a comparative analysis of the effect of the different input variables on the performance of the HDN. The comparative analysis is done to put focus on the areas of the HDN where the largest improvements could be made. However, some factors that have a large impact are not within control of the sawmills, such as the variations in outdoor temperature over the year. These factors are still presented here, since they help bring an understanding of the challenges of running a sawmill, and ought to be taken into consideration.

6.3.1 Impact of climate

The climate in Sweden varies quite much during the year. In 2011, the coldest month at Mörlunda in southern Sweden was February with an average temperature of -3°C and the warmest months, June and July, had an average temperature of 17°C. For Sävar, the corresponding values were -12°C and 18°C in February and July (SMHI 2012). The changes in season also affect the soil temperature, although these variations are not as drastic (Trafikverket 2012). From this knowledge, it is natural to assume that colder surroundings might lead to greater heat losses from the pipes, and thus the system will increase its heating demand. Figure 7 below shows how the supplied heat from the boiler varies with the outside air temperature at Bergs Timber AB Mörlunda in 2011.

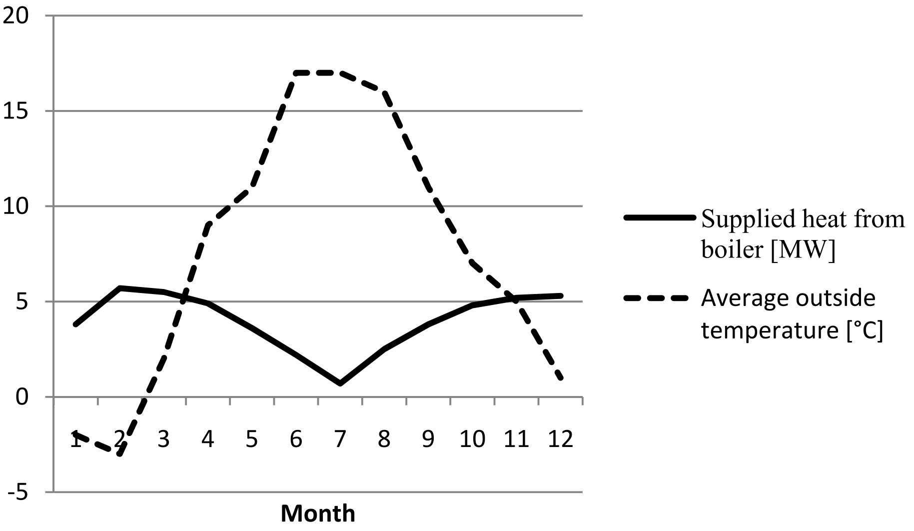

Figure 7. Correlation between the average surrounding air temperature and heat supplied by boiler at Mörlunda (2011)

The chart clearly illustrates the expected behavior; the supplied heat from the boiler peaks in February when the outside temperature is at its lowest, and the supplied heat exhibit a distinct minimum in July with the highest outside temperature. It is reasonable to assume that this effect is even more distinct at Sävar Norra, since they have sections with airborne pipes and larger variations in average air temperature. However, it is likely that some of the additional required heat can be attributed to the fact that the timber itself holds a lower temperature in the winter. This effect is important to consider when estimating the heat demand for a sawmill, and it is more appropriate to consider monthly or seasonal averages rather than a yearly equivalent.

6.3.2 Insulation properties

As presented in Section 5.1, the interviews with employees at the sawmills showed that they both have sections of pipes with obsolete insulation qualities. It is also suggested by Frederiksen et al. (1993) that the dominant factor determining the heat losses for a district heating network is the insulation. Therefore, it is interesting to analyze how the insulation qualities affect an HDN. In order to analyze the importance of the quality of the insulation, simulations were performed with different thermal conductivity of the insulating layer, as well as with different insulation thicknesses. The diagram below shows how the heat losses of the system vary with the conductivity of the insulation.

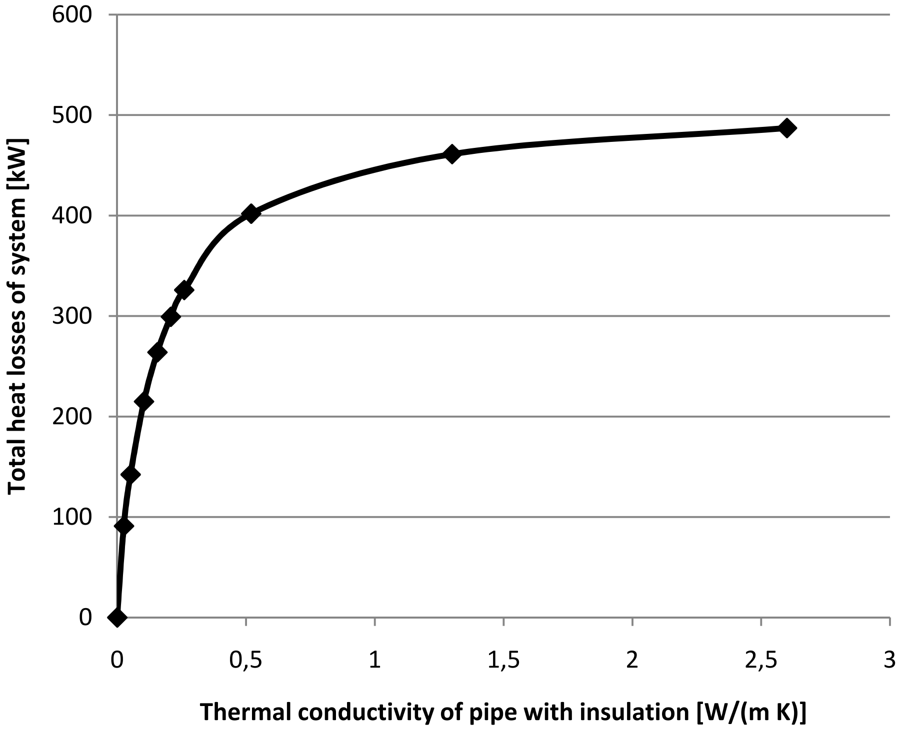

Figure 8. Correlation between the heat loss from the system and the conductivity of the insulation.

The figure shows a clear general increase in the total heat losses from the system with increasing conductivity of the insulating layer. At low values of the conductivity, a small increase will lead to a large increase in the total heat losses. At higher values, there is a planing effect. The modern pipes used at sawmills have a thermal conductivity of 0.026W m^{-1} K^{-1}, which corresponds to a total heat loss of 91kW. As a comparison, the oldest pipes at Mörlunda and Sävar were made of iron with a conductivity of 68W$m^{-1}K^{-1}$, or more than 2600 times higher conductivity that the BAT pipes. If all pipes were made of iron, the total heat loss of the system would be 515kW. Thus, the thermal conductivity of the pipes and insulation used are indeed an important factor when attempting to reduce heat losses for an HDN.

In addition to the conductivity, the thickness of the insulation also affects the heat losses from the system. Modern pipes have an insulation thickness of 35.2 mm for DN65 pipes (Powerpipe Systems 2011), which is what is used for the reference case above. Older pipes are likely to have thinner layers of insulation, leading to greater heat losses. Figure 9 below illustrates how the total heat losses for the system decrease with increasing insulation thickness.

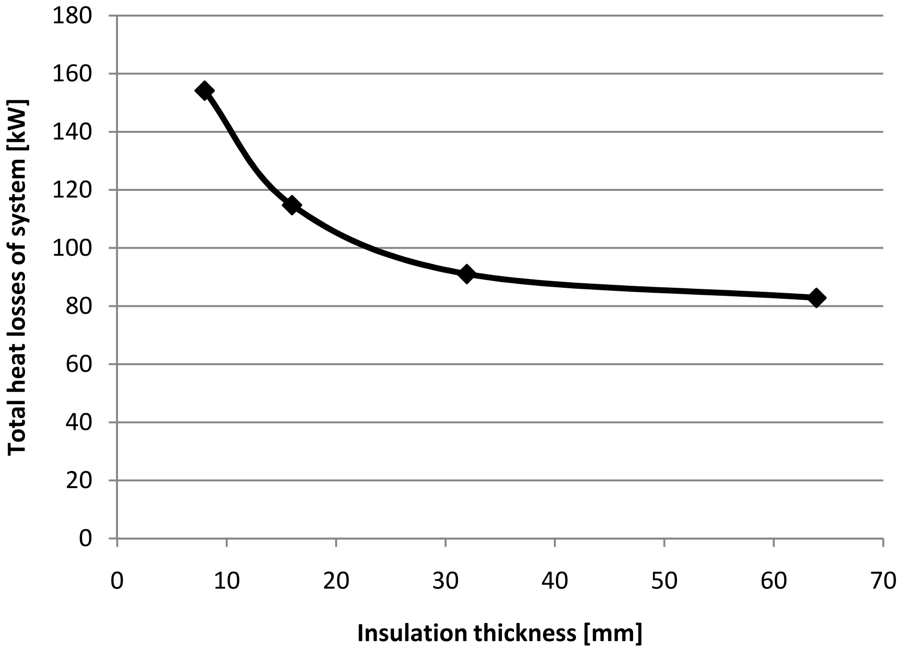

Figure 9. Heat loss of the HDN at varying insulation thicknesses.

From the simulation results, it is clear that an increased insulation thickness will result in decreased heat losses of the systems. These results are reasonable and follow the same trend as the results obtained by Comakli and colleagues (Comakli et al 2004). Figure 9 illustrates that if the thickness of the insulation decreased from 31.95mm, the heat losses will increase quite a bit. In comparison, a large increase of the insulation thickness is required to obtain noticeable reductions in heat losses. The fact that the current HDN design has a total heat loss of 970kW indicates that the average insulating layer performs substantially worse than BAT insulation. In reality, both Bergs Timber AB Mörlunda and Sävar Norra have sections of modern pipes in their HDN, as well as sections of old pipes made of iron with no additional insulating layer. These simulations illustrates the importance of having modern pipes when attempting to reduce the heat demand of the HDN at a sawmill. However, insulation thickness alone cannot explain the large heat losses of the actual system. For instance, it is possible that there are cracks in the insulating layer, which would greatly damage its insulating properties.

6.3.3 Influence of external forced convection

Since Sävar Norra has some shorter distances of piping suspended in air instead of underground, it is relevant to investigate how the heat loss of the system is affected by the surroundings of the pipes. When the pipes are surrounded by air, the influence of forced convective heat transfer on the outer surface of the pipes must be accounted for. This effect largely depends on the wind velocity. Therefore, the average wind velocity at Mörlunda for the season in question is used when simulating the heat losses of a system. As explained in Section 4.3.1, the influence of conduction in the air is negligible compared to the convection. Consequently, the simulation of a system with pipes surrounded by air account for conduction in the pipes and external convection The results on the heat losses from the system are displayed below.

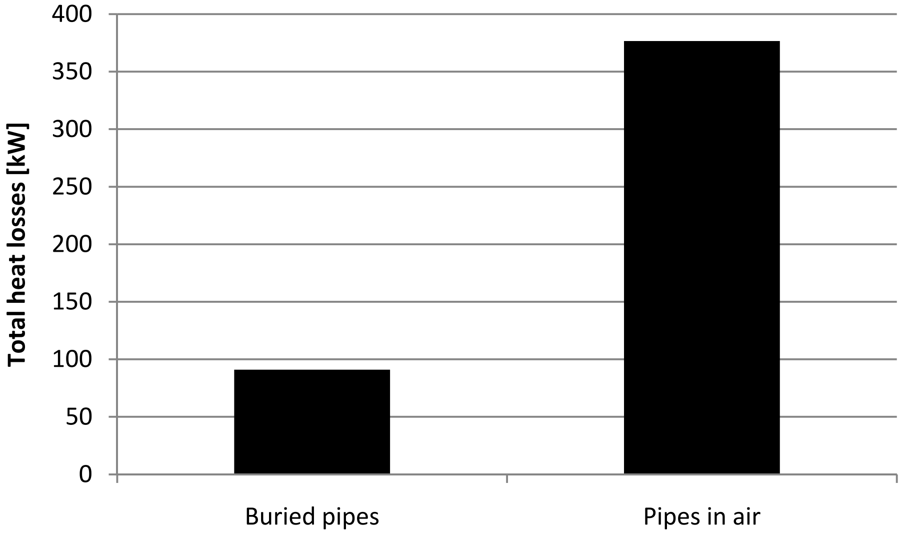

Figure 10. Comparison of total heat losses for the system if the pipes are buried or suspended in air.

As expected, the addition of forced external convective heat transfer from wind will increase the heat transfer from the outer surface of the pipes, and consequently the total heat losses.The figure shows that a system completely suspended in air instead of buried underground will increase its heat losses from 91kW to 130kW, or by roughly 43%. However, the mapping of the sawmills only shows evidence of short distances with pipes suspended in air. In reality the increased heat losses will not be as large, but the simulations illustrate the increased heat losses if the pipes are not buried. It is also important to take note of the importance of the air temperature in this situation. This means that the difference in heat losses in the two systems will be greatest during colder periods of the year. The outside temperature and wind velocity are beyond the control of the sawmills, but as described in Section 6.3.1, this behavior cannot be neglected when dimensioning an HDN.

6.3.4 Roughness of the pipes

As shown by the case study in Section 6.2, the pressure drops of the current design of the HDN are 1.61MPa. The continuous pressure drop of a pipe system with a flow in the turbulent transition region depends on the roughness of the pipes. According to a pipe manufacturer, the roughness of new pipes is 0.05 mm, whereas the roughness of older pipes is about 3-5 times higher (Johansson 2012). Hence it is interesting to investigate to which degree the roughness of the pipes affects the total pressure drops of the system. The results of an analysis of the continuous pressure drop depending on the roughness of the pipe are shown Figure 11 below.

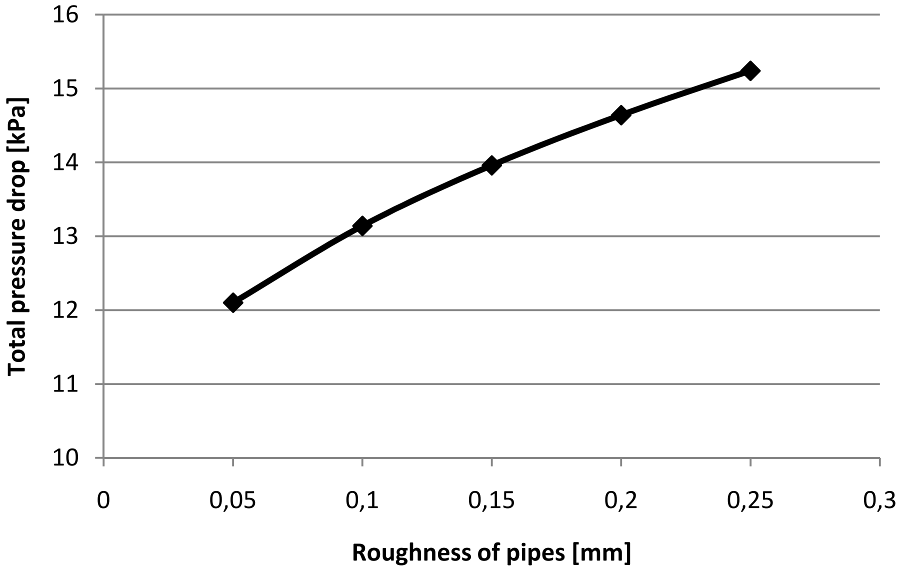

Figure 11. Continuous pressure drop depending on the roughness of the pipes

The figure shows that a factor five increase in the roughness of the pipes increased the continuous pressure drop of Section 1 from 12kPa to 15kPa, or by 25%. If the roughness is increased by a factor of three the total pressure drop is 14kPa or an increase of 17%. Consequently, newer pipes are likely to contribute to a reduction in the continuous pressure drop.

6.4 Suggested BAT-design of HDN

Based on the interviews with employees at two sawmills and simulations using a mathematical model, an improved BAT design of an HDN design is determined. The design is chosen with the intention of keeping the heat losses and pressure drops as low as possible. The recommendations based on this thesis work are stated below:

- Use a direct system connecting the boiler to the dryers without intermediate heat exchangers. This will avoid inevitable losses at the heat transfer in the heat exchanger.
- Invest in new pipes, with low conductivity, low relative roughness and a thickness of at least 30 mm.
- Keep the number of bends of the pipes as well as the distance between the boiler and the dryers as low as possible.
- Keep the pipes underground to avoid heat losses related to convection of wind and the sharp drop in air temperature during the colder months of the year

These factors are only selected based on their impact on the heat losses and pressure drops of the HDN. It is possible that a financial analysis of the suggested HDN design would give a different result, but this thesis does not handle economic results.

7 Discussion

Throughout this chapter, the findings of this thesis work will be discussed in terms of current situations at Swedish sawmills, interviews as a source of information, reliability and reproducibility of the obtained results, implications of the mathematical assumptions and simplifications and suggestions for suitable future research.

7.1 Interviews

Since a large part of the raw data for this investigation stems from interviews with employees at the sawmills, it is crucial to consider the advantages and risks of this method. As with many other ways to obtain information about a process with a limited time resource, one can choose to make a few in depth analyses or to analyze many more shallow sources. In this case, only two interviews were performed, with follow up interviews to further develop answers or to fill in blanks. The obvious drawback here is that there is not enough data to draw conclusions about the Swedish sawmill industry in general, only for the two sawmills Bergs Timber AB Mörlunda and Norra Skogsägarna Sävar in particular. Nonetheless, few interviews conducted in person might present more honest and relative information than a number of written surveys (Kvale 1997).

Another important aspect of using interviews as a method is that the information given is always the subjective opinion of the interviewee. For many of the questions, this is not a limitation as they were related to specific measurements et cetera. However, parts of the interviews concerned their opinions as to where the largest problems with the HDN lay. This can be interpreted in different ways (such as financial aspects, working conditions, and so on), and it is not unlikely that employees with different tasks might perceive different problems with the HDN. Thus, it would have been interesting to perform more interviews with additional employees.

7.2 Current situation at studied sawmills

As made apparent in both Sections 5 and 6, there are many aspects of sawmills in Sweden today that can be improved. The heat distribution network is only one of these aspects, and it has often been neglected when new investments have been made. One of the reasons for this neglect might be the fact that the losses connected to the HDN are relatively small to those which can appear in other parts of the sawmill. For instance, at Mörlunda, the boiler had to be stopped to remove ashes in order to reach the required heat demand. This caused much greater losses for the sawmill than the fact that there was a temperature drop of up to 5°C between the boiler and the dryer. Another apparent explanation for the neglect or lack of interest could be that the pipes often are buried, therefore it is difficult to discover any problems before they become rather serious. When the snow over the oldest pipes at Mörlunda melted because of the heat losses from the pipes, the issue was more difficult to ignore. The two investigated sawmills – as well as many other – were constructed at a time when heating and electrical costs were very low, and thus it has only lately become economically reasonable to consider matters such as heat losses and pressure drops. The financial benefits of investments which lead to reduced resource use is however increasing each year.

The lack of interest in the HDN was also reflected in the fact that none of the sawmills had any complete or up to date drawing of the network, and had relatively few points were control measurements were made. Again, this behavior is undoubtedly a result of a majority of the pipes being placed underground, making them difficult to reach. However, it would be beneficiary for the sawmills to document their HDN more carefully, since it would increase the chance of a reduced reaction time to any problems as well as facilitate any repairs or replacements of pipes.

7.3 Implications of assumptions in the mathematical model

The lacking documentation has had a direct impact on the mathematical model developed. Since one of the purposes of the model is to illustrate which parts of the HDN that have the greatest potential for improvement and presenting reliable values of the heat losses and pressure drops in the system, it is vital to have access to accurate data on temperatures and dimensions from the sawmills in question. Since data such as exact lengths of the pipes and insulation thickness were unavailable, they had to be estimated in the model. As a result, it has not been possible to locate exact locations and magnitudes of the current losses of the HDN. Instead, an HDN with best available technology and minimized distances and interferences with the flow is presented, and with it potentials of improvement for the current system. Section 6.2 illustrates the importance of having access to plans or data from the system to be simulated, as the pressure drops vary significantly based on which pipe dimensions are used. Although the values of heat losses and pressure drops might differ from reality, the simulation results have been successful in illustrating several important trends. In addition to the required idealizations, a number of simplifications are made to the model. These are explained in Section 4.1. The implications of these simplifications have been evaluated and deemed negligible and thus valid.

In spite of the necessary assumptions and simplifications made, the model is a useful and flexible tool to estimate heat losses and pressure drops of an HDN. The fact that many different factors are user defined means that the model is applicable to many different types of heat distribution networks. For instance, the model includes parameters for the different seasons of the year with varying temperature of the surroundings. Similarly, the model can handle systems with pipes buried in the ground or suspended in air. It is also possible to simulate systems with different numbers of both heat suppliers and consumers, placed at various distances from each other.

7.4 Reliability and reproducibility

In terms of the mapping of the heat distribution networks at sawmills, the results presented here correspond well to the analysis of available literature . The structures of the HDNs and the dimensions of the pipes are of standard type, even though they vary from each other in certain aspects. As far as the heat losses and pressure drops of the current designs are concerned, few studies have been made. A number of articles have been analyzed in order to find which factors affect heat transfer through pipes, as well as pressure drops over pipes. When evaluating relevant effects in the model, the ones which had a noticeable effect on the heat transfer and pressure drop were included in the model, and the rest discarded.

As explained in Section 7.3, the model is affected by the limited availability of data from the process that is modeled. This has naturally also made is more difficult to find appropriate methods to validate the mathematical model. It is also important to remember that any measurement errors that may have occurred when the sawmills gather data from their processes will affect the calculated heat losses and pressure drops of the system. For instance, a measurement error of 0.1°C in the temperature measurements would affect the current heat losses with approximately 10% increase or decrease. Naturally, other parameters are affected by measurement errors. Thus, it is not only important to have proper documentation of the system, but accurately calibrated measurement equipment as well.

7.5 Further research

During the thesis work, many interesting results have been illuminated, but perhaps more interesting is the possibility to further develop the study and to continue the research in question. Firstly, a larger number of sawmills ought to be analyzed with interviews, and preferably visits. Additional data from several sawmills might make it possible to draw more universal conclusions about sawmills in Sweden in general and make the results statistically significant. Similarly, interviews should be held with multiple employees at these sawmills, to ensure that a complete documentation of the perceived situation is acquired. If possible, this analysis ought to generate more detailed documentation of the HDN and its components during different operating conditions. This would in particular include details of how and where the HDN is branched off from the main pipe. If this information is known, it would be possible to further develop the model by taking into account the splitting and mixing of streams and the individual flow rates in each section of the HDN. This would enable more accurate simulations.

Concerning the model developed, there are several further developments that could be of interest. One of them is to adapt the model to handle unsteady situations, such as start-ups of a dryer in the system. Since the heat requirement for a dryer varies during a drying cycle, there are aspects which are of interest for a more complete simulation of the performance of the sawmills. Such a model could be fed with operating data for a year and show the variations in heat demand over time. Moreover, a model that combines all parts of the heating network of a sawmill could be developed, including more details of the boiler and the different heat consumers of the system.

Finally, it would be most relevant to perform an economic evaluation of current HDNs and possible future investments. As financial aspects are the driving force behind most decisions of investments or repairs, there is reason for a thorough analysis.

8 Conclusion

The possibly most significant conclusion from this thesis work is that the investigated sawmills, and probably several other, lack proper documentation and information of their heat distribution networks. This is a consequence of buried pipes and the fact that some sections are up to 40 years old. A thorough investigation, resulting in an accurate sketch of the HDN, might facilitate future maintenance and analysis of the system. Combined with the pipes usually being buried, the fact that the losses of the HDNs are relatively small compared to other parts of the sawmills makes it easy to ignore the HDN.

The model developed is a functional and useful tool to estimate the heat losses and pressure drops of heat distribution systems at sawmills. Since it is flexible, it can model many different setups and structures. The heat losses that occur are to an extent a consequence of old pipes with poor insulation, and an investment in BAT pipes could reduce the heat losses at Bergs Timber AB Mörlunda by up to 0.9MW. However, the thermal conductivity and insulation thickness cannot alone account for the current heat losses at Mörlunda. Another factor that greatly affects the heat losses is the temperature of the surroundings, which results in that the heating demand is more than doubled in the winter compared to the summer. Although this effect is out of the control of the sawmills, it must be considered in all analyses of heat losses of HDNs. The investigated sawmills have kept the losses down by placing most of the pipes underground.

Potential reductions in pressure drops are more difficult to determine with the poor documentation available. The results vary greatly with the dimensions of the pipes, and thus it is crucial to acquire more detailed information about the HDN in order to supply the model with correct input data. It was found that smooth pipes help to reduce the pressure drops, but more importantly, the pressure drop is heavily dependent on the flow velocity.

Further research ought to be performed, especially including more sawmills to enable statistically significant results. Such research is preferably combined with an economic evaluation of the HDNs.

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9.1 Personal Communication

Johansson, A., and Karlsson, G. (Production Manager & Boiler Operator, Bergs Timber Mörlunda AB) Interviewed by author 28 Aug. 2012.

Fredrik Samuelsson (Project Engineer, Norra Skogsägarna Sävar) Interviewed by author 24 Aug. 2012.

Appendix A – Interview questionnaire

The appendix gives additional details concerning the interviews performed at the sawmills. Moreover, the Matlab files developed for calculation of the heat losses and pressure drops of a heat distribution network at sawmills are presented in the following appendices.

Allmänt

- Vad heter du och vad är din roll på sågverket?
- Hur länge har du jobbat här?
- Har du jobbat med liknande uppgifter tidigare?
- Ungefär hur stor (årlig) produktion har sågverket?

Mätningar och reglering

- Vad mäter ni för storheter för kontroll och reglering av driften? *Temperatur på värmeflödet eller marken ovanför rören, volymsflödet effekt (elförbrukning) på pumpar, temperatur och fuktighet på luften som lämnar torkarna, tid för virket att torka.*
- Var mäter ni de storheterna? *Temperatur direkt efter pannan/direkt innan flödet ska in i torkarna/på flera ställen där mellan (gärna visa på P&ID)*
    - Vet ni hur stor temperaturskillnad det är mellan pannan till torkarna?
    - Vet ni hur stor stryckskillnad det är mellan pannan till torkarna?
- Är det möjligt att mäta fler storheter? *Absolut tryck?*
- Är det möjligt med fler mätpunkter? *Innan och efter varje komponent (pumpar, förgreningar & sammanslagningar av rör, ventiler etc), temperatur utanför isoleringen, mellan isolering och rör, i rör.*
- Hur stora är osäkerheterna vid mätningarna? *5%? Intervall?*
- Hur regleras värmebehovet till torkarna?
    - Håller pannan samma last hela tiden? (värmen till torkarna regleras med minskat flöde till dem, shuntventiler) Eller ändras bränslemängden?
    - Hur lång tid tar det att uppnå steady state efter en flödesreglering?
    - Hur lång tid tar det att uppnå steady state efter en bränsleändring?

Rörsystemet

- Vilken leverantör använder ni er av för rören och kopplingar?
    - Powerpipe?
- Hur gamla är era rör?
    - Är alla rör i systemet lika gamla?
    - Hur gammalt är systemet?
    - Har ni gjort utbyten eller utbyggningar av systemet? I så fall när?
    - Har ni planer på att göra nyinvesteringar av rör?

- Hur ser systemen ut?
    - Finns det ritningar på hur rören förgrenas och kan jag i så fall få tillgång till dem?
    - Hur många olika slutna system har ni? (dvs hur många gånger värmeväxlar ni innan värmen når torken?) vad är det för värmemedium i varje system?
    - Hur många förgreningar har ni?
    - Är nätet maskat? Dvs finns det flera inmatningsställen? *Relaterat till antalet pannor gissar jag.*
- Är det enkel- eller dubbelrör?
    - En kombination?
    - Om dubbelt, är de horisontellt eller vertikalt parade?
- Vilket material används till rören? *Rostfritt stål?*
- Vilka dimensioner har rören? (intervall om det är flera olika)
    - Inner- & ytterdiameter
    - Längd?
    - Finns det några max eller min-tillstånd rören klarar av (eg tryck, temperatur)
- Vad för typ av isolering används och hur tjock är den?
    - PUR-skum?
    - Har alla rör likadan isolering? (Finns det äldre rör med annan/tunnare isolering? I så fall, vilken typ och hur tjock?)
    - Vet ni vad den har för värmeledningskapacitet λ?
- Skiljer sig rören på något sätt från standard fjärrvärmerör?
    - Hur djupt ner ligger rören? (finns det något genomsnittligt värde eller tumregel som används)
    - Hur högt lyfts rören när de ska kopplas till torkarna?
- Vilken eller vilka flödesämnen använder ni?
    - Använder ni vatten och glykol? Något annat? Innehåller det några tillsatser (tensider för att minska friktion)? *Glykol har lägre värmekapacitet, så det kräver högre flöden. Glykol används för att förhindra att det fryser (sänker fryspunkten i blandningar)*
    - Är det olika rör till olika ämnen?
    - Är det alltid samma ämne som leds in i torken?
        - Dvs är värmebatterierna specifika för vatten eller glykol? Kan det vara olika i olika torkar?
    - Hur stora flöden har ni? Vet ni om det är turbulent eller laminära flöden?

Utrustning

- Vilken typ av pannor har ni?
    - Är det varmvatten eller vattenånga som lämnar pannan? Glykol?
    - Vad är temperaturen och trycket på mediet som lämnar pannan?
    - Vad är temperaturen och trycket på mediet som kommer in i pannan?
    - Finns det några max eller min-tillstånd pannan klarar av (eg tryck, temperatur)

- Hur många pannor har ni?
- Vilken typ av torkar har ni?
    - Kontinuerliga eller satstorkar (vandringstork eller kammartork)?
    - Vilken temperatur har mediet som kommer in i torkarna?
    - Vilken temperatur har mediet som lämnar torkarna?
    - Finns det några max eller min-tillstånd torkarna klarar av (eg tryck, temperatur)
- Hur många torkar har ni?
    - Hur många är i drift samtidigt?
    - Har de samma driftvillkor (operating conditions) vad gäller temperatur och flöde?
    - Hur reglerar ni flödena till varje tork? Är systemen parallellkopplade?
- Hur fungerar era pumpar?
    - En centralpump efter pannan? Fler mindre pumpar ute i nätet kopplade till varje tork? Extra pumpar till eventuellt fjärrvärmenät?
    - Har ni någon uppskattning på vilken verkningsgrad de olika pumparna har?
    - Använder ni er av shuntar? I så fall var? Hur regleras de? Används de som enda reglering av flöde till individuella torkar?

Energi

- Säljer ni flis och sågspån till företag som omvandlar det till biobränsle?
- Var upplever ni att förluster sker?
- Upplever ni andra problem relaterade till värmebehov eller tryck i ledningsnäten?
- Hur mycket varierar värmebehovet med årstider och yttre temperatur?
    - Beror det på att mer värme förbrukas i själva torkarna?
    - Hur mycket större blir förlusterna i värmeledningsnätet?
    - Varierar samtidigt hur mycket värme ni säljer till fjärrvärmenätet?
- Säljer ni värme till fjärrvärmenätet?
    - Hur mycket? Är det samma för olika laster?
    - Var tas den värmen ut? Direkt efter pannan eller efter värmevaxlingar eller tork?
    - Vilken temperatur har vattnet som lämnar sågverket? (40-65 C?)
    - Hur regleras hur mycket värme som kan säljas?
    - Vilket medium är det i fjärrvärmenätet? Vatten?
    - Har ni ökat hur mycket ni säljer de senaste 5 åren?
    - Hur mycket vinst gör ni per MWh?

Appendix B – Matlab files developed for simulations

B.1. main.m

```
% Main file for calculation of steady state heat losses and pressure drops
in pipe
% systems.
%Assumptions: incompressible flow, cp is assumed constant, inner and outer
%diameter of pipe assumed constant, temperature of surrounding constant
%heat suppliers and consumers regarded as black boxes (i.e. heat consumtion
%means heat consumed from heating flow)
%pipe material:(stainless?) steel and PUR-foam insulation.

clc
clear all
clear variable
close all
profile on
global season cp mu k rho sigma v D matdata qtot nconsume H double h



%% Material data
season=input('Winter = 1, spring = 2, summer = 3, autumn = 4: ');
matdata=mat_data(); %Calls on function file setting material data for the
heating media

cp=matdata(8);      %Defining the specific heat capacity for the heating
media [J kg^-1 K^-1]
mu=matdata(9);      %Defining the viscocity for the heating media [Pa s]
k=matdata(10);      %Defining the thermal conductivity for the heating
media [J m^-1 K^-1]
rho=matdata(11);    %Defining the density for the heating media [kg m^-3]

D=matdata(4)+2*matdata(5);          %Outer diamter of pipe + insulation
[m]
sigma=5.76e-8;      %Stefan-Boltzmann constant [W m^-2 K^-4]

%% Heat suppliers
nsupply=input('Number of heat sources, eg boilers: ');
Pb=zeros(nsupply,1);      %Setting empty matrix
Pbadd=zeros(nsupply,1);   %Setting empty matrix

for i=1:nsupply
    Pb(i)=input('Heat delivered from heat source [MW]: ')*1e6;
end
Pbadd=sum(Pb(i));         %calculates the total heat added from heat
supplies [W] GÖR OM TILL (i) IFALL DET FINNS FLER SUPPLIERS
qtot=input('Total flow of heating media [m^3/h] (if unknown, enter 0):
')*1/3600;   %flow rate through heat source [m^3 s^-1]
Tbin=input('Temperature in to heat source(s) [C] (if unknown, enter 0):
')+273.15;
Tbout=input('Temperature out from heat source(s) [C] (if unknown, enter 0):
')+273.15;
dTb=Tbout-Tbin;     %Temperature difference over heat source [K]
```

```
if qtot==0
    qtot=Pbadd/(rho*cp*dTb);   %Calculates the total volumetric flow rate
[m^3 s^-1] from the added heat and temperature difference
    fprintf('The total flow in the piping system is %2.2f m^3 s^-1.
\n',qtot)
end
if dTb==0
    dTb=Pbadd/(rho*cp*qtot);   %Calculates the temperature difference over
the heat source [K] from the heat source's  added heat and the flow rate
    fprintf('The temperature difference over the heat source is %2.2f K.
\n',dTb)
end
if Pbadd==0
    Pbadd=qtot*rho*cp*dTb;     %Calculates the added heat from the heat
source [W] from the flow rate and temperature difference
    fprintf('The heat added from the heat source is %2.2f MW. \n
\n',Pbadd*1e-6)
end

%% Heat consumers

fprintf('\n The HDN will be divided into one section for each heat
consumer, \n and heat losses and pressure drops calculated over each
section. \n')
nconsume=input('Number of heat consumers, eg dryers or district heating:
');
L=zeros(nconsume,1);          %Setting empty matrix
Pd=zeros(nconsume,1);         %Setting empty matrix
etad=zeros(nconsume,1);       %Setting empty matrix
dTd=zeros(nconsume,1);        %Setting empty matrix
qsys=zeros(nconsume,1);       %Setting empty matrix
Qcomb1=zeros(nconsume,1);     %Setting empty matrix
Qr1=zeros(nconsume,1);        %Setting empty matrix
Qtot=zeros(nconsume,1);       %Setting empty matrix
P_onetime=zeros(nconsume,1);  %Setting empty matrix
P_flow=zeros(nconsume,1);     %Setting empty matrix
Ptot=zeros(nconsume,1);       %Setting empty matrix

for j=1:nconsume        %performing calculations for each separate system
    fprintf('\n Section %2.0f: \n',j)
    Pd(j)=input('Heat supplied to consumer [MW]: ')*1e6;
    fprintf('Total pipe lenght of section from heat supplier to consumer
\n')
    L(j)=input('(If unknown enter distance between supplier and consumer)
[m]: ');
    Pdused=Pd(j);       %Heat removed from stream [W]

    Tdin(j)=input('Temperature of heating media in to consumer [C]:
')+273.15;
    Tdout(j)=input('Temperature of heating media leaving consumer [C]:
')+273.15;
    dTd(j)=Tdin(j)-Tdout(j);

    shunt=input('0 = no shunt used, 1 = shunt is used: ');
    if shunt==1
        R=input('Reculculation ratio: ');       %Setting the recirulation
ratio over the consumer []
        qsys(j)=Pd(j)/(cp*rho*dTd(j))*(1-R);   %Calculates the partial
flow rate in section [m^3 s^-1]
```

```
        v=4*qsys(j)/(pi*matdata(4)^2);  %flow velocity in each separate
system [m s^-1]
        Tdfeed(j)=(Tdin(j)-R*Tdout(j))/(1-R);  %Calculates temeprature of
feed pipe before mixing with recirculated flow

[Qcombf(j),Qcombr(j),Toutf(j),Toutr(j)]=comb(L(j),Tdfeed(j),Tdout(j));
%Calculates the combined convective and conductive heat transfer of feed
pipe of the section [W]
    else
        qsys(j)=Pd(j)/(cp*rho*dTd(j));          %Calculates the partial
flow rate in section [m^3 s^-1] ASSUMES ONE MIXING POINT
        v=4*qsys(j)/(pi*matdata(4)^2);  %flow velocity in each separate
system [m s^-1]

[Qcombf(j),Qcombr(j),Toutf(j),Toutr(j)]=comb(L(j),Tdin(j),Tdout(j));
%Calculates the combined convective and conductive heat transfer of feed
pipe of the section [W]
    end

    Qtot(j)=Qcombf(j)+Qcombr(j);
    P_onetime(j)=Ponetime();         %Calculated the one time pressure
drops of the section [Pa]
    P_flow(j)=Pflow(L(j));           %Calculates the flow pressure drops of
the section [Pa]
    Ptot(j)=P_onetime(j)+P_flow(j);   %Calculates the total pressure drop
of the section [Pa]
    fprintf('The total heat losses for section %2.0u is %4.2f kW.
\n',j,Qtot(j)*1e-3)
    fprintf('The heat loss per meter for section %2.0u is %4.2f W/m.
\n',j,Qtot(j)/(2*L(j)))
    fprintf('The intantaneous pressure drops for section %2.0u is %4.2f
kPa. \n',j,P_onetime(j)*1e-3)
    fprintf('The continuous pressure drops for section %2.0u is %4.2f kPa.
\n',j,P_flow(j)*1e-3)
end

Qactual=qtot*rho*cp*3.6;       %3.6 only for Mörlunda system
Qlosses=sum(Qtot);              %Calculates the total heat losses in the
system [W]
Qsave=Qactual-Qlosses;                 %Calculates the total potential for
reduction of supplied heat in the system [W]
Pdrop_onetime=sum(P_onetime);   %Calculates the total one-time pressure
drops in the system [Pa]
Pdrop_flow=sum(P_flow);         %Calculates the total continuous pressure
drops in the system [Pa]
Pdrop=sum(Ptot);                %Calculates the total pressure drop over
the system [Pa]

%% Display
fprintf('\n The total heat losses of the HDN is %2.2f kW.',Qlosses*1e-3)
fprintf('\n The total potential savings on supplied heat is %2.2f kW.
\n',Qsave*1e-3)
fprintf('\n The total pressure losses of the HDN is %2.2f kPa.
\n',Pdrop*1e-3)

stats=profile('INFO');      %shows calculation time and time used for each
function
```

B.2. comb.m

```
function [Qfeed,Qreturn,T_tubeoutf,T_tubeoutr]=comb(L1,Tf,Tr)
global matdata D qtot v H double h buried
%Calculates the convective heat transfer from pipe section [W].

buried=input('Pipes buried in ground = 1, pipes suspended in air = 2: ');
ds=5;                                  %outer diameter of "soil
insulation" [m] ("tillräckligt långt")
s=0.3;  %distance between double pipes [m]
hi=0.023*matdata(10)/(matdata(4))*(matdata(11)*v*matdata(4)/matdata(9))^0.8
*(matdata(9)*matdata(8)/matdata(10))^0.3;
const=1;                                            %Section of pipe for
which temperature is assumed constant [m]

Qfeed=0;    %Setting empty starting value for heat transferred
Qreturn=0;  %Setting empty starting value for heat transferred
Qconvf=0;   %Setting empty starting value for heat transferred
Qconvr=0;   %Setting empty starting value for heat transferred
l=0;        %Setting empty starting value for distance along pipe



    if buried==1
        disp('buried')
        h=input('Buried depth of pipe [m]: ');  %Setting the buried depth
of the pipes [m]
        R_tube=log(D/matdata(4))/(2*pi*const*matdata(7));       %Heat
transfer resistance of pipe [K W^-1]
        R_soil=log(ds/D)/(2*pi*const*matdata(1));               %Heat
transfer resistance of "soil insulation" [K W^-1]
        R_joint=log(sqrt((2*h/s)^2+1))/(2*pi*const*matdata(1)); %Heat
transfer resistant from joint temperature field [K W^-1]

        while l<L1
            Qf=1/(R_tube+R_soil+R_joint)*(Tf-matdata(3));           %Heat
transferred from feed pipe [W]
            Qr=1/(R_tube+R_soil+R_joint)*(Tr-matdata(3));           %Heat
transferred from return pipe [W]
            Tf=Tf+(Qf)/(matdata(11)*qtot*matdata(8));    %Temperature of
fluid leaving feed pipe section [K]
            Tr=Tr-(Qr)/(matdata(11)*qtot*matdata(8));    %Temperature of
fluid entering return pipe section [K]

            l=l+const;                               %Next section of pipe
            Qfeed=Qfeed+Qf;
            Qreturn=Qreturn+Qr;

        end

    else
        Re_e=D*matdata(17)*matdata(16)/matdata(18); %Reynolds number for
air
        if Re_e>4 && Re_e<40
            B=0.911;
            n=0.385;
        elseif Re_e>40 && Re_e<4000
            B=0.683;
            n=0.466;
        elseif Re_e>4000 && Re_e<40000
```

```
            B=0.193;
            n=0.618;
        elseif Re_e>40000 && Re_e<400000
            B=0.027;
            n=0.805;
        end

        Pr_e=matdata(17)*matdata(19)/matdata(13);   %Prandtl number for air
        Nu_e=B*Re_e^n*Pr_e^(1/3);                   %Nusselt number for air
        ho=Nu_e*matdata(13)/D;      %Convective heat transfer coefficient
[W m^-1 K^-1]
        R_tube=log(D/matdata(4))/(2*pi*const*matdata(7));           %Heat
transfer resistance of pipe [K W^-1]

        while l<L1

T_tubef=(Tf+ho*pi*D*const*R_tube*matdata(3))/(ho*pi*D*const*R_tube+1);
%Temperature at outside surface of feed tubes [K]

T_tuber=(Tr+ho*pi*D*const*R_tube*matdata(3))/(ho*pi*D*const*R_tube+1);
%Temperature at outside surface of return tubes [K]

            Qf=(Tf-T_tubef)/R_tube;     %Heat transferred from feed pipe
[W]
            Qr=(Tr-T_tuber)/R_tube;     %Heat transferred from return pipe
[W]

            Tf=Tf+(Qf)/(matdata(11)*qtot*matdata(8));    %Temperature of
fluid leaving feed pipe section [K]
            Tr=Tr-(Qr)/(matdata(11)*qtot*matdata(8));    %Temperature of
fluid entering return pipe section [K]

            l=l+const;                              %Next section of pipe
            Qfeed=Qfeed+Qf;
            Qreturn=Qreturn+Qr;
        end
    end

T_tubeoutf=Tf;                          %Set new inlet feed temperature for
next section [K]
T_tubeoutr=Tr;                          %Set new outlet return temperature
for next section [K]

fprintf('The temperature of the feed stream leaving the section is %4.2fC.
\n',Tf-273.15)
fprintf('The temperature of the return stream entering the section is
%4.2fC. \n',Tr-273.15)
```

B.3. matdata.m

```
function matdata=mat_data()
global matdata season
matdata=zeros(18,1);      %Defining empty matrix for material data
fprintf('Would you like to use standard materials and dimensions or user
specified? \n')
standard=input('Standard = 1, user specified = 2: ');

if standard==1

    matdata(1)=1.5;         %Thermal conductivity of surrounding soil [W
m^-1 K^-1] Powerpipe
    matdata(2)=0.9;         %Emissivity of outer surface of pipes, between
0 and 1 (perfect black body) [ ]

    if season==1
        matdata(3)=273;                         %Temperature of surrounding
soil in winter [K] http://www3.vv.se/tjaldjup/
        matdata(12)=270;                        %Temperature of surroining
air in winter [K]
        matdata(13)=(2.26+(2.42-2.26))*1e-2/20*17;%Thermal conductivity for
air in winter [W m^-1 K^-1] (taken at 270K)
        matdata(16)=1.276+(1.38-1.276)/20*3;    %Density of surrounding air
in winter [kg m^-3] (taken at 270K)
        matdata(17)=3.311580735;                %Wind velocity in winter [m
s^-1]
        matdata(18)=(16.0+(17.1-16.0)/20*17)*1e-6;%Viscosity of air in
winter [Pa s] (taken at 270K)
    elseif season==2
        matdata(3)=278;                         %Temperature of surrounding
soil in spring [K]
        matdata(12)=284;                        %Temperature of surronding
air in spring[K]
        matdata(13)=(2.42+(2.54-2.42))*1e-2/20*11;%Thermal conductivity for
air in spring [W m^-1 K^-1] (taken at 284K)
        matdata(16)=1.189+(1.276-1.189)/20*9;   %Density of surrounding air
in spring [kg m^-3] (taken at 284K)
        matdata(17)=3.259310183;                %Wind velocity in spring [m
s^-1]
        matdata(18)=(17.1+(18.1-17.1)/20*11)*1e-6;%Viscosity of air in
winter [Pa s] (taken at 270K)
    elseif season==3
        matdata(3)=278;                         %Temperature of surrounding
soil in summer [K]
        matdata(12)=290;                        %Temperature of surroining
air in summer [K]
        matdata(13)=(2.42+(2.54-2.42))*1e-2/20*17;%Thermal conductivity for
air in summer [W m^-1 K^-1] (taken at 290K)
        matdata(16)=1.189+(1.276-1.189)/20*3;   %Density of surrounding air
in summer [kg m^-3] (taken at 290K)
        matdata(17)=2.452356631;                %Wind velocity in summer [m
s^-1]
        matdata(18)=(17.1+(18.1-17.1)/20*17)*1e-6;%Viscosity of air in
winter [Pa s] (taken at 270K)
    elseif season==4
        matdata(3)=278;         %Temperature of surrounding soil in autumn
[K]
        matdata(12)=273;        %Temperature of surroining air in autumn
[K]
```

```
        matdata(13)=2.42*1e-2;  %Thermal conductivity for air in autumn [W
m^-1 K^-1] (taken at 273K)
        matdata(16)=1.276;      %Density of surrounding air in autumn [kg
m^-3] (taken at 273K)
        matdata(17)=2.728444702;%Wind velocity in autumn [m s^-1]
        matdata(18)=17.1*1e-6   ;%Viscosity of air in winter [Pa s] (taken
at 270K)
    end

%     matdata(4)=(76.1-2.9*2)*1e-3;    %Standard inner diameter of pipes
DN65 [m]
    matdata(4)=(219.1-4.9*2)*1e-3;  %Standard inner diameter of pipes DN200
[m]
%     matdata(5)=(140-76.1)/2*1e-3;   %Standard insulation thickness [m]
31.95e-3
    matdata(5)=0.25*(315-219.1)/2*1e-3;  %Standard insulation thickness [m]
31.95e-3
    matdata(6)=0.05e-3;                %Standard roughness of pipes e/D
    matdata(7)=0.026;               %Conductivity of pipe + insulation
0.026 [W m^-1 K^-1]

    matdata(8)=4211;        %Specific heat capacity of water [J kg^-1 K^-1]
(assumed constant, taken at 373K)
    matdata(9)=278e-6;      %Viscosity of water [Pa s] (assumed constant,
taken at 373K)
    matdata(10)=0.682;      %Thermal conductivity of water [W m^-1 K^-1]
(assumed constant, taken at 373K)
    matdata(11)=958.4;      %Density of water [kg/m^3] (assumed constant,
taken at 373K)
    matdata(14)=0.1;                %Emissivity of air []
    matdata(15)=0.05e-3/matdata(4)*5; %Relative rougness of pipes (För
äldre rör kan man räkna med ett 3-5 gånger så högt tal.) Powerpipe
    matdata(19)=1.0035*1e-3;        %Specific heat capacity of air [J kg^-1
K^-1] (taken at 273K)

else

    matdata(1)=input('Thermal conductivity of surrounding soil [W m^-1 K^-
1]: ');
    matdata(2)=input('Emissivity of surrounding soil, value should be
between 0 and 1: ');
    matdata(3)=input('Temperature of surrounding soil [K]: ');
    matdata(4)=input('Standard inner diameter of pipes [m]: ');
    matdata(5)=input('Standard insulation thickness [m]: ');
    matdata(6)=input('Standard roughness of pipes [m]: ');
    matdata(7)=input('Thermal conductivity of pipe + insulation [w m^-1 K^-
1]: ');

    matdata(8)=input('Specific heat capacity of water [J kg^-1 K^-1]: ');
    matdata(9)=input('Viscosity of water [Pa s]: ');
    matdata(10)=input('Conductivity of water [W m^-1 K^-1]: ');
    matdata(11)=input('Density of water [kg/m^3]: ');

    matdata(12)=input('Temperature of air [K]: ');
    matdata(13)=input('Thermal conductivity of air [W m^-1 K^-1]');
    matdata(14)=input('Emissivity of air [ ]: ');
    matdata(15)=input('Relative roughness of pipes [ ]: ');
    matdata(16)=input('Density of surrounding air in summer [kg m^-3]');
    matdata(17)=input('Wind velocity in autumn [m s^-1]');
```

```
    matdata(18)=input('Viscosity of air in winter [Pa s]');
    matdata(19)=input('Specific heat capacity of air [J kg^-1 K^-1]');
end
```

B.4. Ponetime.m

```
function P=Ponetime()
global v matdata H

%% Calculates one time pressure losses in pipes due to curvatures etc
fprintf('\n Choose number of components in the piping section from the list
below (feed plus return pipe): \n')
fprintf(' Gate valve, wide open \n Gate valve, 3/4 open \n Gate valve, 1/2
open \n Gate valve, 1/4 open \n')
fprintf(' Standard 90 degree elbow \n Standard 45 degree elbow \n Standard
180 degree bend \n')
fprintf(' Tee, through side outlet \n Tee, straight through \n')

xi(1)=input('Number of gate valves, wide open: ')*0.15;     %coefficient
for increased losses from gate valves, wide open
xi(2)=input('Number of gate valves, 3/4 open: ')*0.85;      %coefficient
for increased losses from gate valves, 3/4 open
xi(3)=input('Number of gate valves, 1/2 open: ')*4.4;       %coefficient
for increased losses from gate valves, 1/2 open
xi(4)=input('Number of gate valves, 1/4 open: ')*20;        %coefficient
for increased losses from gate valves, 1/4 open
xi(5)=input('Number of standard 90 degree elbows: ')*0.7;   %coefficient
for increased losses from standard 90 degree elbows
xi(6)=input('Number of standard 45 degree elbows: ')*0.35;  %coefficient
for increased losses from standard 45 degree elbows
xi(7)=input('Number of standard 180 degree bends: ')*1.6;   %coefficient
for increased losses from standard 180 degree bends
xi(8)=input('Number of tees, through side outlet: ')*1.5;   %coefficient
for increased losses from tees, through side outlet
xi(9)=input('Number of tees, straight through: ')*0.4;      %coefficient
for increased losses from tees, straight through

P=sum(xi*matdata(11)*v^2/2);
```

B.5. Pflow.m

```
function P=Pflow(L)
global matdata rho v mu epsilon_pipe

%% Calculates the Fanning friction factor
epsilon_pipe=matdata(15);   %Roughness of pipe [m] (Götan Johansson
Powerpipe)
Re=rho*v*matdata(4)/mu;     %Reynolds number for the pipe section
ff=moody(epsilon_pipe,Re);

P=ff*rho*v^2/(matdata(4))*L;      %Pressure loss due to flow, Abbas (2010)
& Ekroth&Granryd (1994)
```

B.6. moody.m

```
function f = moody(ed,Re)
%Find friction factor by solving the Colebrook equation (Moody Chart)
% Input: ed = relative roughness = epsilon/diameter
% Re = Reynolds number
% Output: f = friction factor

if Re<0
    error(sprintf('Reynolds number = %f cannot be negative',Re));
elseif Re<2300
    f = 64/Re; return % laminar flow
end
if ed>0.05
    warning(sprintf('epsilon/diameter ratio = %f is not on Moody
chart',ed));
end
if 2300<Re && Re<3000, warning('Re = %f in transition range',Re);

coleFun = inline('1./sqrt(f)-4*log10(ed)-
2.28+4*log10(4.67*ed./(Re*sqrt(f))+1)',...
'f','ed','Re');
fi = 1/(1.8*log10(6.9/Re + (ed/3.7)^1.11))^2; % initial guess at f
dfTol = 5e-6;
f = fzero(coleFun,fi,optimset('TolX',dfTol,'Display','off'),ed,Re);
end

% --- Use fzero to find f from Colebrook equation.
% coleFun is an inline function object to evaluate F(f,e/d,Re)
coleFun = inline('1.0/sqrt(f) + 2.0*log10( ed/3.7 + 2.51/( Re*sqrt(f))
)',...
'f','ed','Re');
fi = 1/(1.8*log10(6.9/Re + (ed/3.7)^1.11))^2; % initial guess at f
dfTol = 5e-6;
f = fzero(coleFun,fi,optimset('TolX',dfTol,'Display','off'),ed,Re);

if f<0, error(sprintf('Friction factor = %2.0f, but cannot be
negative',f));
end
```

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