CHALMERS
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# Investigation and evaluation of energy efficiency measures in a textile industry

## A case study at AB Ludvig Svensson

Master's thesis within the Sustainable Energy Systems programme

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Department of Space, Earth and Environment
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Gothenburg, Sweden 2018

Master's thesis 2018

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Cover: Photo of AB Ludvig Svensson in Kinna. Photo taken by authors.

Typeset in LaTeX
Printed by Chalmers Reproservice
Gothenburg, Sweden 2018

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# Abstract

As a result of increased awareness of climate change, several global measures have been presented in recent years. Within the EU, energy efficiency has been highlighted as a priority issue, which in Sweden partially resulted in a law on energy audits of large companies. These audits, in addition to mapping the company's energy consumption, are intended to present different energy-saving measures for the company.

Following the implementation of energy audits, AB Ludvig Svensson has been announced several potential energy saving measures. In order to proceed with these, a deeper evaluation has been requested where the size of the savings is required to enable an economic analysis for payback period of investments. In addition, an analysis of the production processes is also desired to identify additional saving potentials that are not highlighted in the energy audit. As AB Ludvig Svensson process large amounts of water in its yarn and fabric dyeing areas, these parts of the production will be the focus of the project. There, the main heat carrier is steam, which in turn is produced by LPG-fired steam boilers.

In order to evaluate how different parameters affect the energy consumption, mathematical models of the different processes were created. These intended partly to imitate the actual processes and partly of evaluating different proposals for energy savings. In addition, site visits was conducted to improve the general picture and contribute to a better understanding of the different processes. To assist and verify the models, temperature measurements was carried out in different parts of the production processes.

Through different changes of the current operation the energy saving potentials have shown promising results without the need of investments; decreased steam consumption of over 20% and decreased drain losses of almost 26% in the dyeing processes. Further other measures, in need of additional equipment, have shown to be profitable from a slightly longer time perspective. Also some suggestions of energy savings measures have been ruled out after more careful evaluation.

The report is written in English.

**Keywords:** energy efficiency, textile industry, heat recovery, flue gas heat recovery, heat pump integration, accumulation system.

# Acknowledgements

We would like to express our gratitude to the division Energy Management at ÅF Infrastructure, especially to our supervisors Viktor Arvidsson and Olle Wedin. They have been of great support in both theoretical and practical details throughout the project. Furthermore we would like to thank our supervisor and examiner at Chalmers, Stavros Papadokonstantakis, who have supplied useful feedback and has shown a great and valuable commitment for the project. We would also like to thank the personnel at AB Ludvig Svensson for valuable inputs and interesting discussions. Also, gratitude is directed to the division of Energy Technology for a friendly working environment and for lending of relevant measuring equipment.

Christoffer Alm & Viktor Persson, Gothenburg, June 2018

# Contents

# List of Figures

# List of Tables

# 1

# Introduction

In 2012 the European Union decided to establish a set of measures, known as the Energy Efficiency Directive (2012/27/EU), as a step to meet a target of 20% energy efficiency increase within the union. The directive requires all member countries to use energy in a more efficient way, including all steps from production to final consumption [1].

In Sweden, a measure to accomplish this was through the legislation of energy audits in larger companies that was implemented during 2014 [2]. This means that larger companies, that are enclosed by this legislation, actively need to chart their energy consumption and are responsible to report this to the Swedish Energy Agency. A part of this audit includes recommendations of future improvements, which AB Ludvig Svensson (denoted from now on as AB LS) has wished for to be evaluated further. Energy costs have been identified as a substantial part of the total expenses for AB LS. They have therefore, since a few years back, started an energy cooperation with ÅF Infrastructure AB (from now on denoted as ÅF) to investigate significant improvements for their production processes.

## 1.1 Background

AB LS is a fourth generation family-owned textile manufacturer located in Kinna, 60 km south east of Gothenburg. The company is a manufacturer of different textiles that are delivered all over the world. When the production facilities were built, larger quantities were manufactured and the production capacity in these facilities were consequently dimensioned for this. However, during the last years a restructuring regarding the production of textiles has been carried out. One new type of product, climate screens, is a large produce while the textile production is now mainly characterised by smaller batches. Since 2015, AB LS has established an energy cooperation with ÅF to consult with energy saving matters for the whole site. ÅF has also performed two energy audits at AB LS in 2015 respectively 2017. As a result of the energy saving collaboration, redundant parts of the production have been closed down. Yet, some parts of the production is in need of an investigation to achieve a long-term solution to satisfy the energy need in a more efficient way.

Steam has historically been the primary source of heat for the production process. Today some of the processes are still dependent on steam while other processes are not anymore. The steam has been locally produced in steam boilers with Liquefied

Petroleum Gas (LPG) as the base fuel. This steam is used in various equipment within the industry, for instance heating water used for dyeing or drying of yarn and fabric. Some parts of the production need specific air temperature and moisture content. To achieve the required conditions, steam is also used to satisfy this.

The current two steam boilers are old and on the advice of ÅF, as a step in the energy cooperation, AB LS is currently only using one of the steam boilers. However, the age and increased need for maintenance mean that AB LS is facing the decision to either renovate these or investigate in other alternatives for the steam production in the future. AB LS are thus interested in an investigation to find a more efficient way to supply energy to their whole production.

## 1.2 Aim

One expected outcome of this thesis is to map and analyse the flows of LPG and steam at AB LS. A detailed analysis is expected to show energy saving potentials within the textile production processes, in which the steam and gas supply is involved. This will further evolve in the estimation of costs and savings associated with proposed solutions. Implementation of design proposals shall be able to satisfy the expected variations in the production loads at AB LS. The goal is to also present energy saving potentials that do not require investment in new equipment, i.e. savings by only changing operation parameters. The project will not intervene with the established process requirements within the production and will only include the surrounding equipment.

The working procedure can be divided in the following steps:

- Map and evaluate the energy flows within the studied area of the production.
- Identify and analyse parts of the production where the steam usage is possible to be reduced.
- Identify and evaluate parts of the production with energy saving potential.

## 1.3 Limitations

The duration of the project was 20 weeks, from calendar week 4 throughout 23. Primarily, the investigation was focused on the current production schedule of the industry. However, the project intended to identify possible drawbacks with the current production planning, that would be beneficial to consider in a new production plan.

The thesis was also limited to only investigate and evaluate design setups that possibly would be realisable for AB LS, taking production planning and payback period into account. Consequently, the methods and the results used may not be valid for other textile industries.

## 1.4 Specification of issue under investigation

The project intended to analyse the energy conversion processes within the industry. Beyond this, possible retrofitting setups and heat recovery was investigated. Also some investment analysis was performed in order to decide the relevance of the investment alternatives for AB LS.

# 2

# Theoretical background

In this chapter relevant theoretical background for the thesis is presented. It starts with a general introduction of industrial steam systems and continues with a theoretical background of recovery of flue gases and waste water. In addition the significance of production planning will be discussed followed by essential theory about heat exchangers and heat pumps. Finally the basic theory behind investment cost analyses will be explained.

## 2.1 Steam systems in industrial processes

The most prominent application of steam is in steam electric power plants [3]. However, steam is also used in many industrial applications for different purposes. The most common applications among producing industries are for instance petroleum refining, paper, chemical and textile industries [4, 5]. The reason for this is likely the flexible nature of steam, as it is a rather efficient way to generate and transport heat which in turn can be used in various processes such as sterilising, drying and cooking or simply provide space heating [3]. More specifically, regarding to [6], the characteristics of steam that has made it successful for industry applications are:

- High specific and latent heat
- High heat transfer coefficient
- Easy to control and distribute
- Cheap and inert

When steam is flowing in a system it will loose energy to the surrounding equipment, which will turn some of the steam into condensate. This condensate contains around 25% of the useful energy in the original steam [7]. Recovery of the condensate back into the boiler reduces fuel cost and water consumption as well as brings down chemical treatment costs and effluent charges. Thus it is vital to have some kind of condensate recovery system to keep a high efficiency in a steam system, both for environmental and economical reasons [7]. In general it is advantageous to keep as high pressure as possible in the steam system, taking heat losses and investments in the pipes into account. However, where the steam is consumed the pressure preferably should be reduced to maximise heat transfer. The velocity of the steam also needs to be considered when dimensioning steam pipes to avoid noise [8].

The boiler efficiency is one of the most important parameters for the overall performance of a steam system. Furthermore, the boiler efficiency is strongly dependent on incomplete combustion, excess air, thermal loss due to water vapour in flue gas, fuel type, lower heating value of fuel, burners, boiler load, thermal loss from boiler surface and dirtiness of the heater surface [9].

When it comes to the steam characteristics the moisture content is of significant importance. If the steam is wet it reduces the total heat in the steam. Water also tends to form wet films on heat transfer surfaces and condense on equipment [6]. Consequently it is dry saturated steam that is desired for industrial process steam to keep the thermal efficiency high.

## 2.2 Flue gas recovery

As mentioned above, flue gases is one of the major contributing factor for a lower boiler efficiency. Thus, the heat from the outgoing flue gases is often recycled and used to for example space heating or preheating of the boiler fuel or the feed water.

In most modern steam boilers the flue gases have a temperature of around 200°C, which is a promising potential for heat recovery. However, due to the acidic particles in the flue gases the temperature may need to be maintained above a certain level to prevent condensation of acid [10]. This leads into one of the main challenges when investigating in an application of flue gas recovery in an industry; to map the content of the flue gas. Usually some kind of knowledge about the content of the flue gases are already known, since an industry need to follow the Swedish legislation of what gas content that is allowed and not allowed to emit to the surroundings. For example there are strict legislation of the release of $NO_x$ [11]. The content of the flue gases also becomes important for the heat transfer in the flue gas recovery. If the flue gases contain significant amounts of for example soot or tar the heat transfer surfaces may be covered by these mediums which consequently would decrease the heat transfer significantly.

Except the content of the flue gases, the temperature and the volume flow of the flue gases are the most significant parameters to determine and evaluate the potential of flue gas heat recovery. The volume flow of the flue gases can either be physically measured or theoretically calculated.

In the process that will be investigated in this thesis, the main generation of flue gases comes from the drying and heat treatment of the fabric in machines called stenters, which will be further described in Section 3.3.4. Flue gases from stenters are usually cooler than flue gases in general, due to the cooling effect of the wet fabric and the prevention of fire in the machine.

## 2.3 Heat recovery of waste water

In most industrial steam systems the heat from waste water is not fully utilised. Even though the temperatures of these streams usually are relatively low, it can still be of valuable use. The heat from the waste water can be applied in many different ways to decrease or replace the consumption of fossil fuels. The most common way to utilise waste water heat is to apply some kind of heat exchanger or a heat pump. It is also possible to apply a heat exchanger together with a heat pump to recover waste heat [12]. In some cases it is also possible to simply reuse the waste water without further utilisation of any equipment.

In general the optimal solution to recover waste heat is unique, since the layout of the industries often varies significantly. For example, Wu et al. [13] designed a waste heat recovery system for a dyeing industry, that consisted of a high temperature heat pump and a twin-screw compressor, that could rise the temperature of the waste dyeing water to 95°C. When investigating in what equipment to use to recover as much heat as possible, it is important to consider the temperatures of the waste water. The composition and cleanliness of the water are other factors significant for the heat recovery.

## 2.4 Production planning and environmental impacts

In all industrial processes some kind of production planning is needed. The aim of the production planning is however varying dependant on what is considered to be the most important factor for the production. It is common that it is of highest prioritisation that the end user will receive the product as fast as possible. If the production is producing customer specific goods this prioritisation turns the production into small batches and usually no storage of goods. This means that no production takes place before there is a demand for that specific kind of goods, which is a philosophy known as *just in time* [14]. Except the fast delivery time it is economically profitable to avoid binding capital into stored goods.

However, the just in time philosophy has some drawbacks as well. To divide the production into smaller batches may lead to a less efficient production from both an economical and an environmental perspective in some cases. The alternative would be larger batches and consequently consume less energy and less money per produced item. Economically this would then have to be compared with an estimation of the storage costs. However, from an energy saving perspective larger batches would be preferred.

## 2.5 Heat exchanger calculations

Heat exchangers are commonly used to transfer heat between two or more fluids without mixing the fluids. Their field of application is wide but examples are space heating, power plants, chemical plants and sewage treatment [15]. Heat exchangers can be designed for a variety of setups but the main two types are shell-and-tube exchangers and plate-and-frame exchangers. The plate-and-frame exchanger is the most essential type for the project as these will be further investigated. Plate-and-frame exchangers offers prominent benefits such as high heat transfer rates, flexibility as the heat transfer area easily can be modified, compactness and favourable cleaning possibilities [15].

The operating parameters of a heat exchanger are often expressed through the heat balance equations [16]:

$$Q_{hot} = CP_H * (T_{hot,in} - T_{hot,out}) \tag{2.1}$$

$$Q_{cold} = CP_C * (T_{cold,out} - T_{cold,in}) \tag{2.2}$$

For heat exchangers operated with counter-flow of the heat exchanging fluids, the heat transfer rate can also be expressed through the design equation [17]:

$$Q = UA * \Delta T_{lm} \quad [\mathbf{kW}] \tag{2.3}$$

The overall conductance, $UA$, is defined as the product of the overall heat transfer coefficient and the total heat transfer area. The logarithmic mean temperature difference, $\Delta T_{lm}$ is defined in Equation 2.4 [17]:

$$\Delta T_{lm} = \frac{(T_{hot,in} - T_{cold,out}) - (T_{hot,out} - T_{cold,in})}{\log \frac{T_{hot,in} - T_{cold,out}}{T_{hot,out} - T_{cold,in}}} \tag{2.4}$$

Given the conditions for the heat exchanger, it is possible to transform these relations to find the outgoing temperatures of each stream. The heat balance equations for both the hot and cold stream, Equation 2.1 and Equation 2.2, could be used with the design equation, Equation 2.3, to compose the following expressions [16]:

$$Eq1 = (1 - R * B) * T_{hot,out} + (B - 1) * R * T_{cold,in} + (R - 1) * T_{hot,in} = 0 \tag{2.5}$$

$$Eq2 = R*(1-R*B)*T_{cold,out} + (B-1)*R*T_{hot,in} + (R-1)*B*R*T_{cold,in} = 0 \tag{2.6}$$

where $R$ is the ratio of the heat capacity flow rates defined according to Equation 2.7.

$$R = \frac{CP_C}{CP_H} = \frac{\dot{m}_{cold} * c_{p,cold}}{\dot{m}_{hot} * c_{p,hot}} \tag{2.7}$$

and $B$ is an exponential relation of the overall conductance, heat capacity flow rate and $R$, defined in Equation 2.8.

$$B = \exp[(UA/CP_C)(R - 1)] \tag{2.8}$$

Solving Equation 2.5 and Equation 2.6, the exit temperatures of the two stream, $T_{hot,out}$ and $T_{cold,out}$, could be determined. Equation 2.5 and 2.6 are linear regarding the temperatures but have a non-linear relation with respect to heat capacity flow rates and the overall conductance ($UA$) [16].

## 2.6 Different types of heat pumps

Heat pumps for heat recovery purposes uses the energy from a waste-heat source and increases its temperature to a level where the waste heat can be used. This means that energy that otherwise would be wasted can be used to reduce energy that would have been purchased instead. The energy transfer is of course associated with a cost, where the aim is to design a system that benefits of using the waste-heat from the heat pump including the costs for driving the pump.

### 2.6.1 Mechanically driven heat pump

The schematic of a simple mechanically driven heat pump is shown i Figure 2.1. There are several types of heat pumps and they can be designed and applicable for a large variety of medias and capacity intervals [18]. It is for example common with heat pump configurations with several pressure levels, i.e multistage heat pumps, because of the more flexible operation and lower operating cost [19].

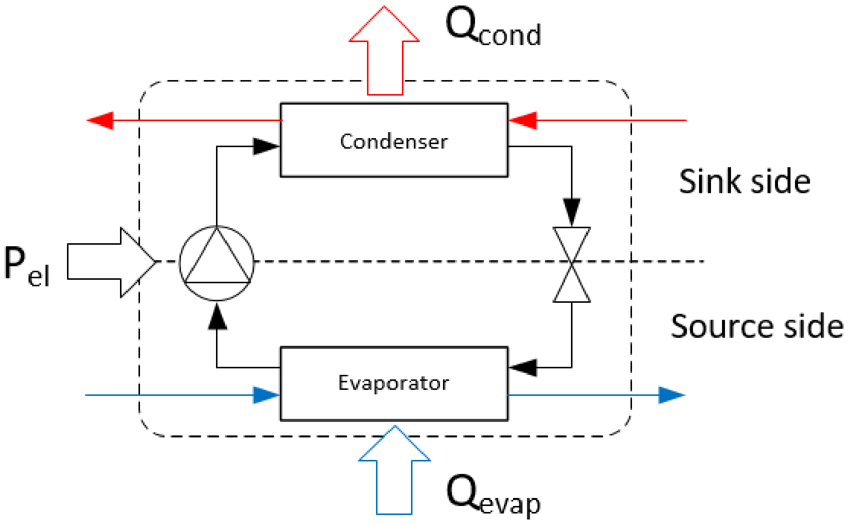

**Figure 2.1:** Overview of main components in a regular heat pump

When evaluating the performance of a heat pump a significant parameter is the coefficient of performance (COP) which determines the relationship between work input and heat output, shown in Equation 2.9 [18].

$$COP = \frac{rejected\ energy}{electrical\ energy\ needed} = \frac{Q_{cond}}{P_{el}} \tag{2.9}$$

The rejected heat, $Q_{cond}$, is the useful heat that is supplied on the sink side. It can be expressed as the summation of the extracted heat from the heat source, $Q_{evap}$, and the work input to the compressor, $P_{el}$, according to Equation 2.10.

$$Q_{cond} = P_{el} + Q_{evap} \tag{2.10}$$

Consequently the extracted heat from the waste-heat source can be expressed as Equation 2.11.

$$Q_{evap} = Q_{cond} - P_{el} \tag{2.11}$$

The working principle of a mechanically driven heat pump is dependent of the working fluid which controls the working interval of the heat pump. Heat from the waste water source is delivered to the evaporator in which the working fluid is vaporised. The working fluid is then passing the compressor which increases the pressure. As the pressure of the working fluid is increased, the condensing temperature is increased. The working fluid is then directed to the condenser in which it condenses and rejects heat to the process stream intended to be heated. The working fluid passes through an expansion and is then led back to the evaporator to complete the cycle [18].

When dimensioning and investing in a heat pump it is in general beneficial to use a smaller heat pump with a higher work load than a heat pump with higher capacity that only runs part time [18]. This means, when sizing such equipment, the aim is to find a heat pump that can be operated for a maximum amount of time without the risk of exceeding capacity requirements, as a measure to minimise investment costs.

### 2.6.2 Hybrid heat pump

The hybrid heat pump is an interesting alternative to the traditional mechanically driven heat pump that has emerged the last year. The main principle of a hybrid heat pump is similar to the mechanical heat pump. One of the main differences is that the refrigerant in the hybrid heat pump is a mixture of medias, usually water and ammonia. Then as the refrigerant mixture enters the evaporator and heat is extracted, the ammonia boils and can be separated in a separator, see Figure 2.2.

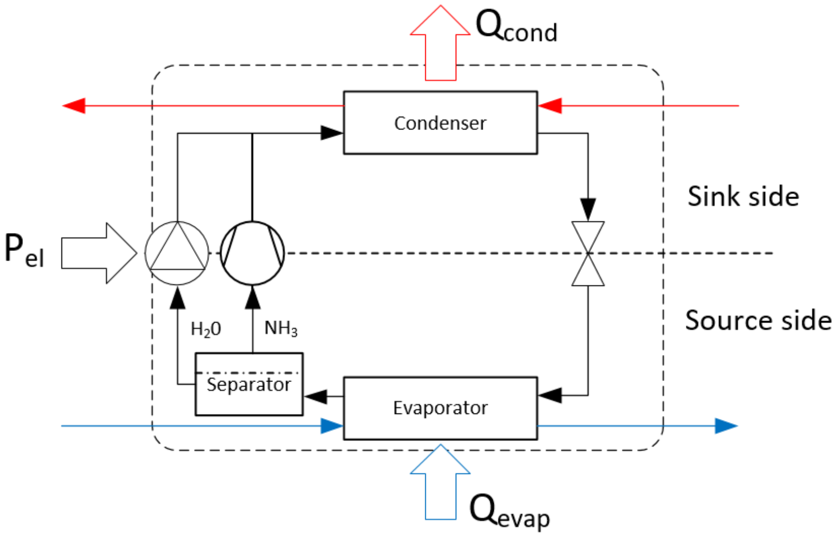

**Figure 2.2:** Overview of main components in a hybrid heat pump

The mixture of ammonia and water is a non-azeotrope medium, which means that evaporation and condensation will take place at gliding temperatures. The temperature glides in the hybrid heat pump can be adjusted to the temperature glide of the heat sink and the heat source [20]. This makes the hybrid heat pump more flexible, which would be beneficial in this study where the temperatures may be varying. Furthermore, compared to a heat pump with a pure refrigerant, where the temperature stays constant during evaporation and condensation, the compression ratio in a hybrid heat pump can be lower for an equal temperature lift. A lower compression ratio demands less electricity, which consequently increases the COP of the cycle.

Among the most prominent advantages with the hybrid heat pump is the high COP and the higher condensation temperatures. On the downside the hybrid pump in general is an expensive investment that might be challenging to justify economically on a short sight [21].

## 2.7 Investment cost analysis

Capital expenditures, *CAPEX*, is a common concept within investment analysis of equipment for a company. In general, the term refers to the capital that a company uses to purchase or upgrade physical assets, such as a new roof, property or industrial equipment [22]. From an accounting perspective, an expense is a capital expenditure if the expense is for a newly purchased capital asset or an upgrade of an existing capital asset that improves its useful lifetime [22]. For companies, capital expenditures need to be capitalised, which means that the cost for the investment needs to be spread over the useful lifetime of the asset. A common way of translating the investment to an annual cost is the calculation of the annuity factor, *AF*, that is the annual share of the total investment over the depreciation time. Equation

2.12 shows how the annual cost of investment is estimated. With Equation 2.13, the annuity factor is estimated, which considers the annual cost for an investment based on the technical lifetime of the equipment and the internal rate of return. At AB LS an internal rate of return of 5% is commonly used.

$$C_a = C_i * AF \tag{2.12}$$

$$AF = \frac{R}{1-(1+R)^{-DT}} \tag{2.13}$$

$C_a$=Annual cost of investment [SEK/year]
$C_i$=Investment cost [SEK]
AF=Annuity factor [$year^{-1}$]
DT=Depreciation time [year]
R=Internal rate of return [$year^{-1}$]

With a known cost of an investment together with the actual savings of that same investment, the *payback period* can be calculated. In other words, the time it takes for the revenues to cover for the associated expenses. Given that the revenues are of a constant size, the payback period can be easily estimated with Equation 2.14.

$$\text{Payback period} = \frac{\text{Investment [SEK]}}{\text{Annual savings [SEK/year]}} \quad \textbf{[year]} \tag{2.14}$$

The annual savings includes the actual savings associated with the the investment but is also considering the annual cost of investment, shown in Equation 2.15.

$$\text{Annual savings} = \text{Actual savings} - AF * C_i \tag{2.15}$$

# 3

# Process description

As previously stated in Section 1.2, the project mainly focuses on the areas of the production that uses liquefied petroleum gas (LPG) and steam. Equipment in the remaining part of the industry is mainly powered by electricity. In Figure 3.1 below, the production processes dependant of LPG and steam are displayed. These streams and essential equipment will be explained in the following subsections.

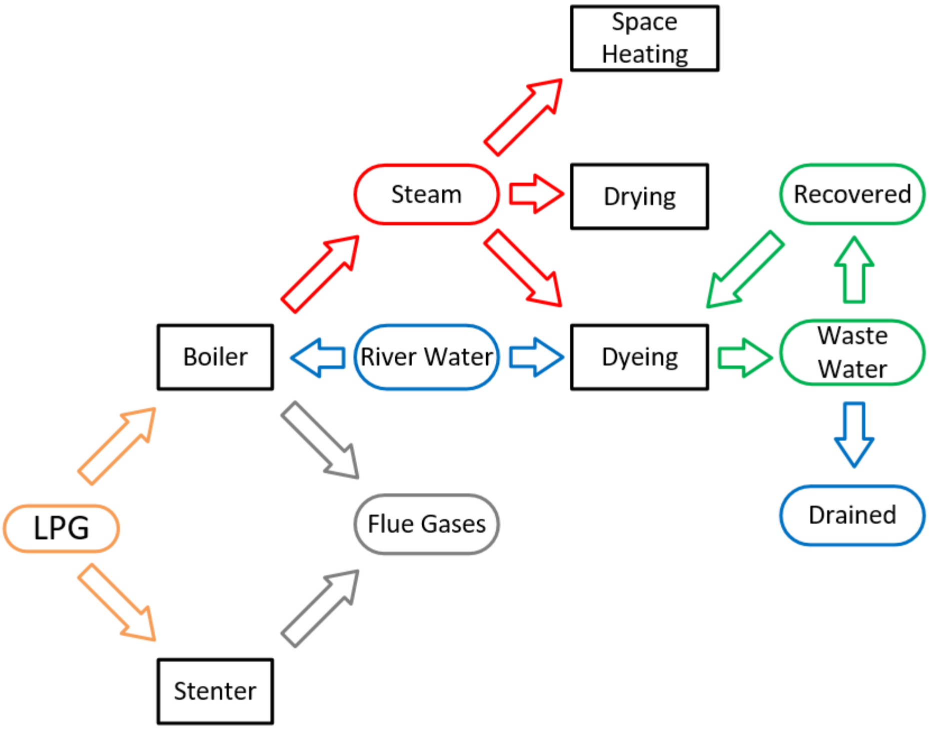

**Figure 3.1:** Flow chart over the streams involved in the analysed processes

The production needs large amounts of water where the majority is used in dyeing processes. The water used for production is river water from the nearby Viskan. The river water is cleaned in various steps at AB LS and is then used in the production.

## 3.1 The steam system

The primary heat source at AB LS is steam, which is used in the dyeing processes, drying processes and for space heating of some parts of the factory, illustrated in Figure 3.2. The steam is locally produced in steam boilers powered by LPG. Historically, two boilers have been running continuously, as one has been used only for back up. The largest and oldest steam boiler has a capacity of producing 8000 kg/h and was installed in 1961. The slightly smaller boiler was installed in 1966 and has a capacity of 6000 kg/h. Under the advice of energy consultants at ÅF only the smaller (6000 kg/h) is currently used, as an energy saving measure a few years back.

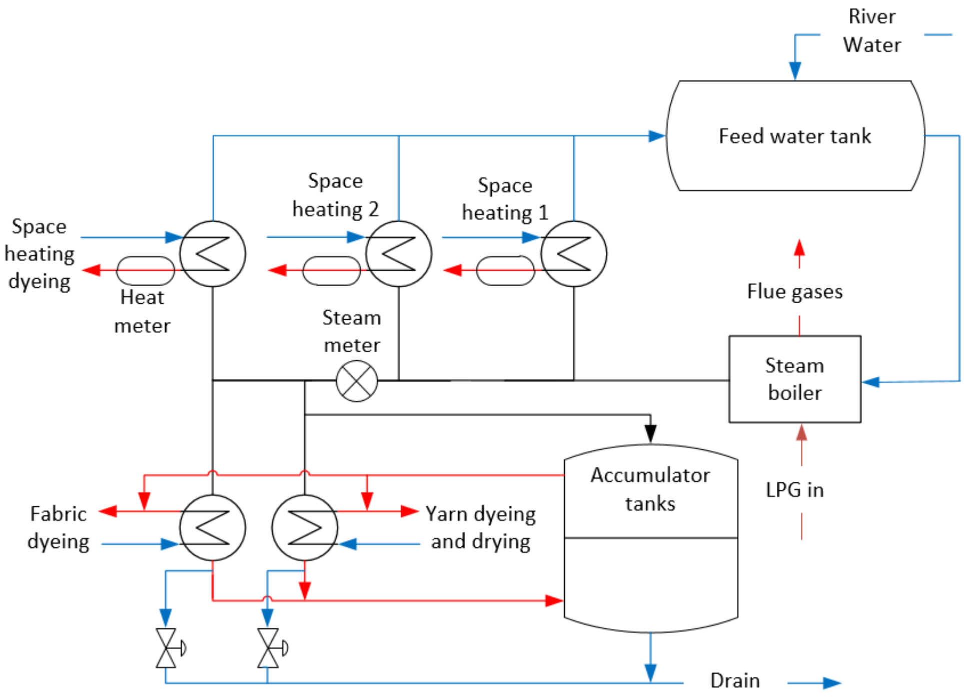

**Figure 3.2:** Basic overview of the steam system

Historically the steam used for production has been distributed at two levels within the factory, 5 and 7 bars. However, the 7 bars system have today been phased out which means that all steam used is at a pressure level of 5 bars. The majority of the produced steam is used for space heating in different areas of the factory. To assure the quality of the products, some parts of the production facilities also demand specific heat and moist conditions. These conditions are to a large extent covered by steam as well. All the hubs for space heating are equipped with heat meters that measure the flow and temperature and thus enables the estimation of the amount of energy allocated. The condensate from the space heating systems is directed back to the steam boiler through the feed water tank. Additional water for the boiler is supplied by river water that first is processed through the local water cleaning facility, and then injected to the feed water tank.

Within the production, steam is mostly used for heating water in the various dyeing machines. This is since the dyeing processes demand a certain water temperature to assure its quality. The temperature varies between different products and within the dyeing programs. Heating of water, by steam, in the different applications is done through tube-and-shell heat exchangers at each machine. Steam is then condensed and led to the *dirty hot* accumulator tank for heat recovery. The reason for not leading the condensate back to the *clean hot* tank is to minimise the risk of mixing dye with the clean water, according to AB LS. The water flows leaving the dyeing areas have a temperature criteria, if the temperature is above 40°C it is directed to the accumulator tank for heat recovery while it is led to the drain if the criteria is not fulfilled.

As mentioned in Section 2.1 it is important to recover the condensate that is formed in the steam system. The steam system at AB LS is equipped with steam traps to collect the produced condensate. This condensate is then led back to the feed water tank, which then later on brings the condensate back into the steam boiler to be shifted back into steam.

## 3.2 Production variations

The production method used at AB LS is so called *batch production*. This means that the production varies a lot with regards to both production steps and batch sizes. Furthermore, these batches and steps depend on what customers have already ordered, which is significant for the *just in time* system. This makes the batches customer specific and consequently smaller, which further cause unnecessary long redirection times of the production for some machines. The redirection times slows down the production as well as it is decreasing energy efficiency.

As the involved production steps can vary significantly between different batches the energy consumption is strictly linked to the production. The production is not planned with regards to energy consumption, which means that excess heat from one part of the production might not be used in another part, because of lack of synchronisation.

## 3.3 Studied production steps

Typically, the raw material to the process is yarn that is dyed and then weaved locally at AB LS. However, depending on the desired final product the yarn are of different qualities. The first step of the production process is, regardless of the raw material, to enter the dyeing step. This step is followed by a specific drying process. Drying of yarn is performed in the yarn drying machines, located next to the yarn dyeing machines, while the drying of fabric is done in the stenters.

To be able to allocate the energy consumption within the studied area at AB LS, a more detailed analysis is desired. As these components are identified as energy intensive and show potential for heat recovery they have been further studied within the project. The waste water from both the fabric dyeing machines and yarn dyeing machines is used for heat recovery, but not in an optimal way. Each of the studied production steps are presented in this section.

### 3.3.1 Dyeing of yarn

There are currently six yarn dyeing machines that are used for different types and batch sizes of the products. The volume of the machines are varying from 550 litres up to 4500 litres. What machine that is used for a specific process is mainly depending on the amount of yarn that is to be dyed in the same program. Since the machines needs to be totally filled with water to reach the desired pressure conditions, regardless of the amount of yarn inside, a significant amount of water is wasted if the larger machines would be used for a smaller amount of yarn.

In Table 3.1 an overview of the yarn dyeing machines are presented. All of the yarn dyeing machines are loaded from the top. The capacity of each machine equal the total volume, i.e. the total volume of yarn and process water.

**Table 3.1:** Overview of the yarn dyeing machines

| **Machines** | **Capacity [litres]** |
|---|---|
| GA1 | 1100 |
| GA2 | 2700 |
| GA3 | 1100 |
| GA4 | 550 |
| GAN5 | 4500 |
| GAG5 | 4500 |

The principle layout of the yarn dyeing process is visualised in Figure 3.3. The typical way of operation is filling equal parts of cold and hot water. The reason for mixing the hot and cold water is mostly a matter of habit according the operators at AB LS. The coupling of the filling equipment enables the operator to easily chose source of water. Another reason for filling up with a mix of hot and cold water is that the flow can be higher and thus the filling time decreased.

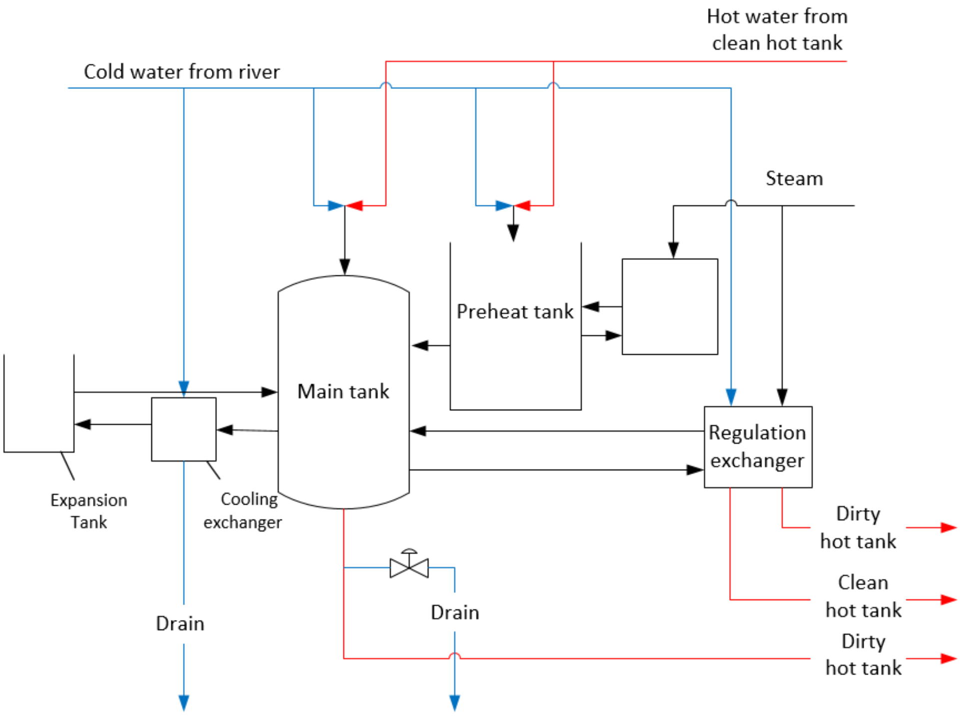

**Figure 3.3:** Overview of yarn dyeing process

During a dyeing process the machines are drained and refilled with water several times, which means that large amounts of water is used. This is even more significant in machines with the larger capacities. All water leaving the dyeing process is directed to an accumulator tank for heat recovery if it has a temperature of at least 40°C.

In the yarn dyeing process one additional tank is used to preheat the water before refilling the main tank. The purpose of this preheat tank is to save time by preparing the refill water by raising it to desired temperature while the previous steps of the dyeing process are running. However, since these preheat tanks are open, water is evaporating, which is not an optimal solution from an energy perspective. Furthermore, by heating the water in an additional tank more energy is consumed regards to the double amount of tank material that consequently is heated.

The water is heated by steam to the required temperature for the specific program. As a typical dyeing program involves several complete drains of the machine, this process repeats several times within a program and the required temperature might vary between different program steps. A program can also involve cooling steps, where the hot process water is cooled by cold river water. Both the cooling and heating of the main tank is achieved by heat exchange in the regulation exchanger. During a cooling step, cold water used for cooling is heated. As this water is clean, it is directed to the clean accumulator tank. For the condensate, formed from the heating steps, a risk for contamination is considered which results in that this stream is instead directed to the dirty accumulator tank. This is further explained Section 3.3.3, where processes of fabric dyeing are described.

Each of the dyeing machines are also connected to an adjacent expansion tank. The process water is continuously circulated from the machine to the expansion tank and back to the machine during a dyeing cycle. This allows the operator to add dyeing chemicals and also examine the process water composition during a dyeing cycle, without the need of draining and opening the dyeing tank of the machine. As the circulation continues throughout the dyeing process this means that the process water needs to be cooled to avoid boiling when the temperature inside the dyeing tank is high. In order to avoid boiling of the circulated water the circulated water is cooled in a the cooling exchanger when the temperature of the process water is above 80°C.

### 3.3.2 Drying of yarn

Drying is the consecutive production step after dyeing of yarn. There are currently two machines used for drying, *GT1* with the capacity of 4.5 $m^3$ and *GT2* with 1.5 $m^3$. In general, the larger machine is used if the batch size exceeds 1100 litres. Typical run-time for a drying cycle in each of the machines is about 2 hours. The drying machines look similar as the main tank of the yarn dyeing machines. They are loaded from the top and the principle of the largest drying machine is illustrated in Figure 3.4. The main operation principle is the same for the slightly smaller yarn drying machine. However, it also has some re-circulation of the circulating air for heat recovery. The extent of the heat recovery is further discussed in Section 4.4.1.

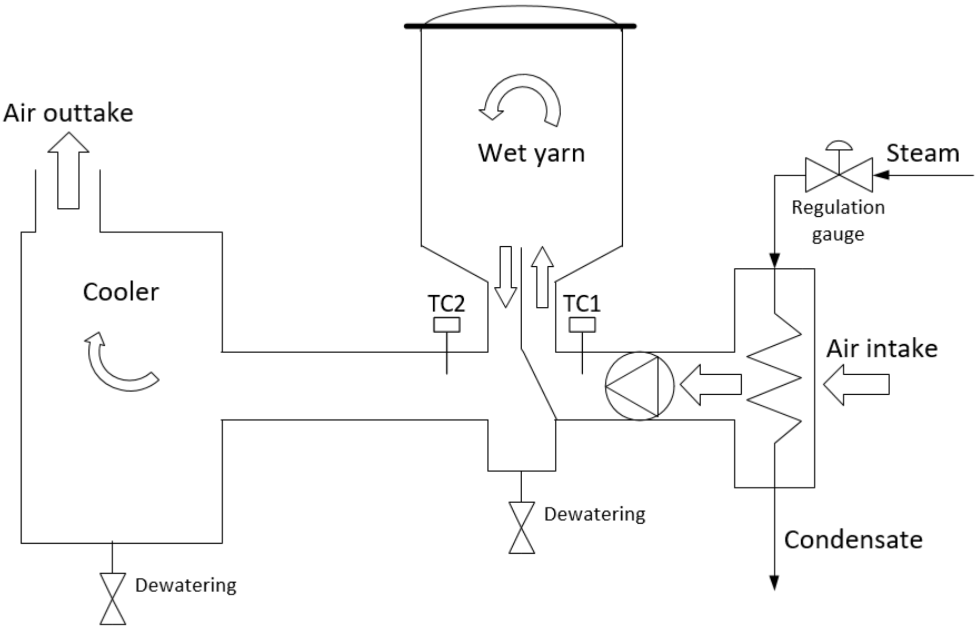

**Figure 3.4:** Overview of a yarn drying process

Air is taken from the surroundings and is heated to 90°C by a thermo battery that is regulated by steam. The supplying steam is regulated so that the intake air holds a temperature of 90°C (TC1) after the feeding fan. The air is then conducted to the inside of the main tank where the wet yarn is located. When the exhaust air has a constant temperature of 85°C (TC2), the yarn is considered to be dry. The exiting air is then directed through the outside wall and is then discharged without any heat recovery. The largest yarn drying machine has a fan with the installed capacity of 110 kW that pushes hot air through the wet yarn. The smaller machine is equipped with a fan with installed capacity of 70 kW.

### 3.3.3 Dyeing of fabric

The machines used for fabric dyeing is of varying dimensions and capacity, see Table 3.2. Similar as for yarn dyeing, the usage of a specific machine is depending on the batch size, but for fabric dyeing the width of the fabric is also a limiting factor. This is because the fabric is wrapped on a roll and can not be folded in the machine.

**Table 3.2:** Overview of the fabric dyeing machines

| Machines | Capacity [litres] |
|---|---|
| M3 | 4700 |
| 1600 | 4500 |
| 1200 | 2700 |
| HT5 | 1100 |
| Thies | 800 |

The water used for the process is typically a mixture of cold water from the outside and the *clean hot* tank. Similar as for the yarn dyeing process, steam is then used for heating the water to the desired temperature needed for the specific program.

A regular dyeing cycle takes about 6-8 hours altogether and involves up to ten complete drains of the machine. This means that about 45 $m^3$ process water can be used in one program in the 4.5 $m^3$ machine. However, the fabric dyeing machines are connected to a heat recovery system which means that waste water above 40°C is directed to an accumulator tank.

Similarly as for the yarn dyeing machines, the process water is circulating from the main tank of the dyeing machine to a smaller expansion tank where dyeing additives can be added and samples of the process water extracted, see Figure 3.5. Today this container is open at the top, which result in heat losses through evaporation. Likewise as for the yarn dyeing machines, the process water is cooled by cold water from the outside if the temperature of the circulated water is above 80°C.

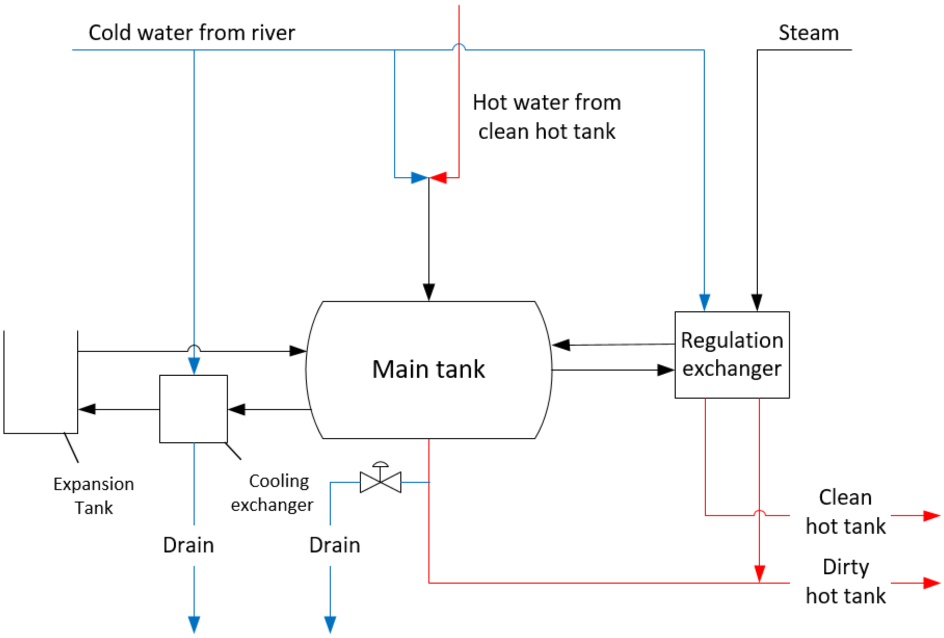

**Figure 3.5:** Overview of fabric dyeing process

The main differences between the dyeing of yarn and fabric are that the dyeing process of fabric does not involve a preheat tank. When the main tank is drained the water usually is transported to the accumulator tank, see Section 3.4.1, collecting dirty hot water. Water is also recovered from the cooling that has been used to regulate the temperature in the main tank, through the regulation heat exchanger. The cold water that is used to decrease the temperature in the main tank are thereby heated and used for recovery by being led straight to the accumulator tank collecting clean hot water. The condensate originating from the steam that has been used to raise the temperature in the main tank is recovered by being collected by the dirty hot accumulator tank. The reason that this stream is not led to the clean hot tank instead is because of the risk that the heat exchanger will leak and that dyeing chemicals consequently will end up in the condensate. This may be questioned, since the heat exchanger is a tube exchanger and should not leak. Also, if a leakage would occur, the consequence would be the same as the heat exchanger is used for cooling water with recovery as well. The heat exchanger should be trustworthy enough to lead this stream to the accumulator tank with clean water instead of to the accumulator tank with dirty water.

Furthermore, the stream of water coming out of the cooling exchanger in the circulation path is today led straight down to the drain. Since this water has cooled the water in the main tank from temperatures above 80°C down to around 80°C this stream may be hot enough to be led to the accumulator tank with clean hot water, just as the stream of water out of the regulation exchanger is. Therefore this is a potential of clean hot water that was investigated.

### 3.3.4 Drying and heat treatment of fabric

The two machines that are drying and heat treating fabric are called stenters. LPG is injected in several gas burners along the sides of the stenters, and to regulate the temperature an adjustable amount of ambient air is used. See Figure 3.6 for an overview of the gas system supplying LPG to the two stenters and the other LPG consuming unit, the steam boiler.

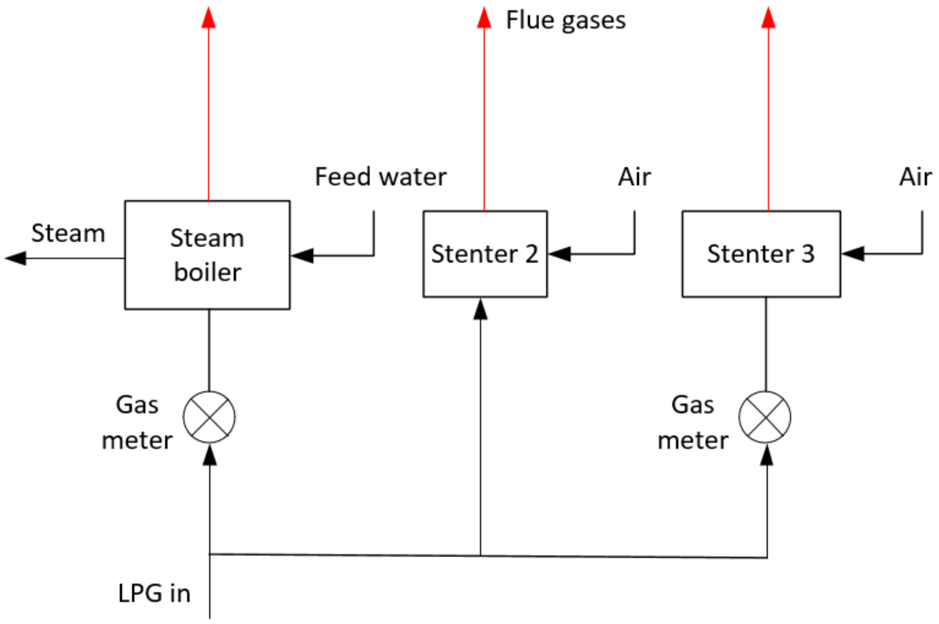

**Figure 3.6:** Overview of the equipment consuming LPG

Air from the industry indoor environment is injected into the stenters, where the combustion of LPG in the gas burners heat the air to desired temperature of the heat treatment program. An illustration of the stenter setups is shown in Figure 3.7. Fabric is fed into the stenter by rolls that are stretching out the fabric for an even heat treatment. Then it is led through the hot stenter at a pace of approximately 10 meters per minute. The stenter handling fabrics of three meter (Stenter 3) is normally operating 16 hours a day 5 days a week, according to AB LS. The slightly smaller stenter where fabrics of width up to two meter can be treated (Stenter 2) is operated more irregular depending on what orders that have been received.

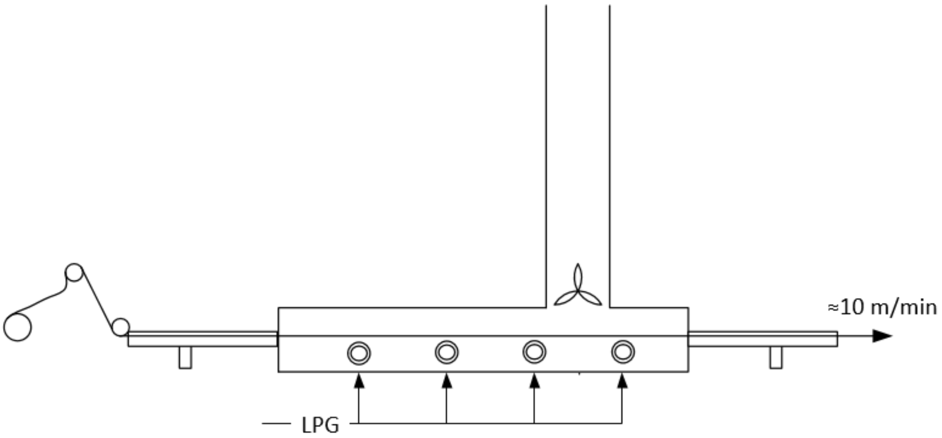

**Figure 3.7:** Principle layout of a stenter

How efficiently the stenters can be operated is depending on the batch size of the fabrics that are in need of heat treatment. This is because when a change of fabric is needed, the whole length of that fabric might need to come out of the stenter before the next fabric can enter the stenter in the other end. Since the fabric is fed all the way through the stenter, the whole length of the fabric needs to pass through before a new batch can enter if it demands different conditions in the stenter. Such a scenario results in a whole empty stenter length of wasted heat during the switching between two batches. As the feed of fabric is of relatively low speed this can mean longer time slots of idle running. Even though there is potential to optimise this by some production planning this is today not considered due to the prioritisation of delivering the orders to customers as fast as possible. The aim of minimising storage-keeping is another motivation for this.

The temperature in the stenter can vary between different types of production. Sometimes higher temperatures can be needed for a specific heat treatment while a lower temperature can be desired for drying of another product.

To assure that the fabric is not damaged by a too high temperature in the stenter, the temperature inside is regulated by air taken from the surroundings inside the building. The temperature variations are significant and depending on batch requirements. Some qualities are treated at ambient temperature while some qualities are treated with temperatures around 200°C. Also, as the stenters handle different qualities, the emissions from the process might shift between batches. According to AB LS the flue gases may contain different contamination from the production of the yarn, such as mineral oils, spin oils but also fabric softeners. The excess air from temperature regulation and flue gases from the production are then directed out of the roof through a chimney. Even though the typical operation time for the stenters are for the majority of the working week in combination with large volume flows of high temperature flue gases, none of them currently have any heat recovery units installed.

## 3.4 Heat recovery within the production

This section discusses the current installations of heat recovery within the studied area of production at AB LS. The most extensive system is the waste water recovery with the accumulator tanks that is connected to both the yarn dyeing and fabric dyeing machines. Further, in one of the yarn drying machines heat recovery is applied.

### 3.4.1 The accumulator tanks

The heat recovery system of waste water is consisting of two accumulator tanks of 25 $m^3$ each, situated on top of each other adjacent to the fabric dyeing machines. These were built during the oil crisis in the 1970s but have been in operation since with only smaller maintenance. The process water coming out of the dyeing machines together with the condensate from heating steps is categorised as dirty water and are consequently led to the bottom tank, denoted *dirty hot*. The heat recovery system is regulated so that if the drained water has a lower temperature than 40°C it is led straight to the drain instead. In the dirty hot accumulator tank the water level is kept constant due to the draining function. As can be seen in Figure 3.8 the pipe that is draining the dirty hot tank is U-shaped which makes this tank lose water only when the level is above the top level of the U-shaped draining pipe. The reason for this is to make sure that the dirty hot tank never goes empty which would damage the old pump system.

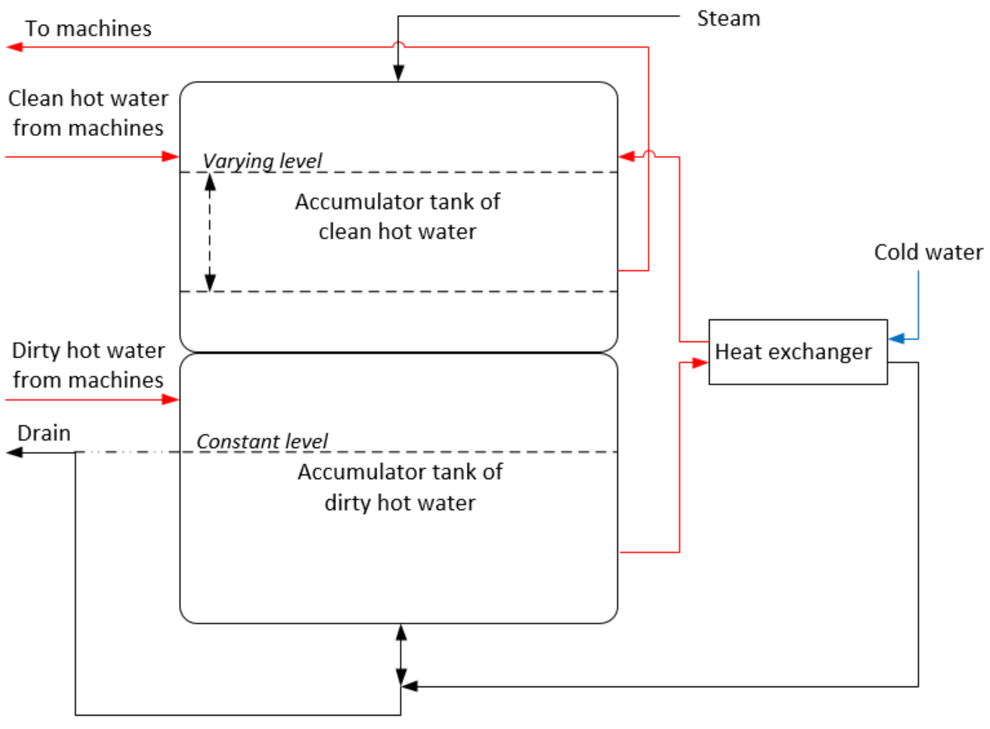

**Figure 3.8:** Overview of accumulator tanks

The water from the dirty hot tank is then heat exchanged with cold river water from the water cleaning facility, which ends up heated in the *clean hot* tank. The dirty water is then, after the heat exchange, led back to the draining pipe under the accumulator tank. This to fill up the dirty hot tank to the same constant level if it is not refilled by dirty hot water from the dyeing machines. The main idea is that the dirty hot accumulator tank is drained from the bottom to only lead the coldest water down the drain. However, this is not certain since the flow direction also depends on process dependent inflows to the accumulator tank.

Except the heat exchanged water the clean hot accumulator tank is also supplied with some water from the dyeing processes. During the cooling steps the heated water out of the regulation exchanger is directed to this tank. If this water stream would be of a volume enough to raise the level in the clean tank above the maximum level, the water is led down to the dirty tank. The temperature in the clean hot tank is set to be 50°C, which is regulated by steam from the top of the tank. This tank is then supplying clean hot water to the dyeing processes. When the level in the clean hot accumulator tank reaches a set lower level it is refilled to a specified upper level by the heat exchanged water from the dirty hot accumulator tank. Both these set levels are easily adjusted.

### 3.4.2 The yarn drying machines

As earlier mentioned, the smaller yarn drying machine, *GT2*, uses heat recovery by re-circulation of the heated air. However, the extent of the heat recovery is unknown to AB LS and the inaccessible location in combination with the compact machine setup makes it hard to estimate how well this works. The only accessible part that could be measure is the current used for the fan. However, as the remaining parts are inaccessible this leaves such an evaluation most uncertain in terms of steam consumption. The yarn drying machines are further discussed in Section 4.4.1.

# 4

# Methodology and modelling

This chapter presents the procedure of the project. It starts with a general approach and then continues with data collection and validation. Thereafter the mapping of relevant processes are described for the studied areas of the production, which is followed by a detailed description of the model setup. The chapter ends with a presentation of representative operations.

## 4.1 General approach

The energy audit performed by ÅF in 2017, for AB LS, was used as a benchmark for the evaluation of improvement work for the industry. The progress of the project was proceeded along with representatives from AB LS and ÅF. Suggested improvements from the audit were analysed in combination with possible additional improvements that were identified from site visits and data analyses.

Literature studies and data evaluation was complemented with site visits at AB LS. Except for only obtaining a general picture of the processes, it was as well possible to perform interviews with employees with appropriate knowledge on site. Another vital information that was utilised were the ÅF engineers that performed the energy audits and hence had valuable knowledge about the processes at AB LS.

The project started with an analysis of the heat demand of the industry, originating from the current steam demand. The possibilities were evaluated if the heat demand, that today to a major part is covered by steam locally produced in steam boilers, could be satisfied by another technical solution. A key point was to identify the heat demand that needs to be covered by steam and thus could not be replaced. Also, energy saving measures such as heat recovery from different parts of the process were evaluated. Since some new equipment could be needed in the system, either by replacement of old equipment or simply added to existing equipment, investment analyses were needed to evaluate if these proposals would be economically feasible.

The progress of the actions briefly explained above was continuously, during the thesis work, discussed with people of appropriate expertise both from AB LS and ÅF. This to ensure that the final design proposal, with as high energy saving potential as possible, was reached in an efficient way. This master thesis was as well supported by supervision from associate professor Stavros Papadokonstantakis from Department of Space, Earth and Environment at Chalmers University of Technology.

To be able to minimise the total steam consumption in the complete system, the system was divided into the different production steps consuming steam. In this way a clear understanding for the consumption was received, which further made it possible to map unemployed steam savings.

## 4.2 Data collection and validation

The data collection was based on available historical data from both ÅF and AB LS. Further data that was relevant for the analysis was measured and collected on site under the agreement of the involved parties. Collected data was summarised in Microsoft Excel and evaluated through calculations in MathWorks Matlab.

In cases when data collection was limited or even impossible, theoretical approaches were evaluated. To the largest extent possible, these theoretical assessments were to be verified or consolidated by temperature measurements or readings of adjacent equipment.

In order to be able to verify the steam consumption for the dyeing processes and accumulator system for waste heat recovery, these models were intended to be summarised for a setup that corresponds to the actual production planning. As can be seen in Figure 3.2 in Section 3.1 a steam meter is located after the split for the space heating in other areas of the facility, denoted Space heating 1 respectively Space heating 2. This steam meter is measuring the steam consumed in the drying and dyeing section of the industry, which includes the steam satisfying the space heating of this area, the dyeing process of fabric and yarn as well as the drying of yarn. The space heating system is equipped with a heat meter which makes it possible to estimate and deduct this steam from the steam meter. This is desirable since this part of the steam consumption is not analysed in this thesis due to the absence of distinct efficiency improvement possibilities and due to limitations of the project.

By summarising the model outputs of steam consumption for the models in the concerned area of the production, it would then be possible to compare this with the steam meter for a set amount of time. This could be done to evaluate the accuracy of the models but also for validation.

## 4.3 Mapping of dyeing processes

To be able to estimate the energy allocation within the dyeing processes data was needed to analyse what machine and what program that was running in each machine. It was also necessary to assure that the data would be representative for the dyeing processes. To receive a first indication of this, it was requested from LS AB to provide machines and programs typically operated during a period of about two weeks, where all major programs are represented. A more accurate representative daily operation will be presented later on the thesis, see Section 4.7.

As each colour or type is considered a separate program the first step was to confine the amount of programs. The idea with this was to divide all programs into program categories if the process steps in the dyeing cycles were identical except for the chemical additions. This was done for both the yarn and fabric dyeing areas and an example of the production schedule for two weeks is summarised in Table 4.1 and Table 4.2, respectively. As the acquired historical data only would tell the capacity of the machine in which it was run, the data was summarised for each capacity and according to the resulting program categories, from here on denoted programs.

**Table 4.1:** Summary of the yarn dyeing programs of each capacity

| Capacity [l]<br>Programs | 550 | 1100 | 2700 | 4500 |
|---|---|---|---|---|
| A | | | 2 | |
| B | 2 | 3 | 1 | |
| C | 1 | 1 | | 1 |
| D | | 7 | 2 | 5 |

Due to the nature of the historical data it was not possible to decide what program that had been run in what machine for the yarn dyeing processes since some yarn dyeing machines have the same capacity. However, since all the fabric dyeing machines are of unique sizes it was possible to link each program run to a specific machine.

**Table 4.2:** Summary of the fabric dyeing programs of each capacity

| Capacity [l]<br>Programs | 800 | 1100 | 2700 | 4500 | 4700 |
|---|---|---|---|---|---|
| E | 4 | | | | 1 |
| F | | | | | 1 |
| G | 1 | | | | |
| H | | | | | 2 |
| I | | | 2 | | |
| J | | | | | 1 |
| K | | | 1 | | |
| L | | 1 | | | |
| M | | 1 | 1 | 1 | |

The information of approximately how often each program is operated in each machine could later be used to estimate a common daily steam consumption. Yet, to be able to investigate the consumption of steam and hot water in the dyeing processes, information from the different dyeing programs was needed. For all dyeing programs, it was observed that involved process steps were similar, yet occurring at different times and between different temperatures. It was found that all dyeing processes could be translated into certain steps that were reoccurring during the processes. Seven different process steps were identified:

- Filling
- Draining
- Heating
- Cooling
- Keep temperature
- Circulation
- Overflow rinsing

Filling and draining represents the various fillings and drainages of process water during a program cycle. Due to the variation in capacities of the dyeing machines the duration of these process steps varies. By measuring the time for a filling respectively draining a mean filling and draining time for each capacity could be estimated.

Heating involves the energy used for heating the process water to a target temperature while cooling considers the contrary. Keep temperature means that process water is maintained at a given temperature while energy losses are covered by the steam supply. The circulation step involves circulation of the process water while losses to the surroundings are not compensated for. In the overflow rinsing step the main tank is constantly filled and drained simultaneously during a specific time.

The idea of translating the different processes in different, reoccurring steps was to enable a theoretical analysis of the energy consumption in terms of supplied energy from steam and water consumption. Calculations of effective energy, water consumption, heat losses and potential heat recovery from each step could thus be estimated with a model. The idea of such a model would then be to compare the theoretically achieved estimations with actual readings of the on-site steam meter. As was presented in Section 4.2, such a comparison would need the consideration of the heat used for space heating. In order to make the model as trustworthy as possible, regards to losses to the surroundings, heating and cooling demand of the process water together with heating and cooling of the tank material were evaluated. A more detailed description of the considerations of each step will be presented in Section 4.6.1.

After identification of the different dyeing process steps the dyeing machines were observed and measured to support the theoretical analysis. During the site visits the opportunities were also taken to ask questions to the employees operating the dyeing machines. This gave valuable information on how the different identified process steps were handled and how the dyeing operations usually were varying.

## 4.4 Mapping of drying processes

In the following section the studied drying processes are discussed. As the drying processes for yarn and fabric are two completely different processes in different parts of the factory, these are divided into two separate sections.

### 4.4.1 Drying of yarn

All yarn batches that are passing the yarn dyeing processes are usually thereafter directed to the yarn drying machines. The batches are mainly divided according to the batch sizes when it is decided what drying machine operated. In general, if a batch size exceeds 1100 litres, it is directed to the larger machine, *GT1*. In Table 4.3 the number of batches running in what machine is shown according to the obtained data for the two weeks. The total number of batches in the yarn dyeing area were 25 during that period of time.

**Table 4.3:** Summary of the number of batches in each of the yarn drying machines

| | **Number of batches** |
|---|---|
| **GT1** | 11 |
| **GT2** | 14 |

The yarn drying machines are located next to the yarn dyeing machines in the yarn dyeing area. The surrounding equipment to the yarn drying machines are located under this area in a compact compartment that is difficult to access. During the investigation of the yarn drying machines it could be concluded that the only energy saving measure that could be realisable for the yarn drying machines would be some sort of heat recovery of the circulating air. However, due to the lack of space and the difficulties of estimating the heat recovery potential, this area of the production was left unchanged. This decision was further motivated by the fact that the yarn drying equipment was lacking accessible metering options.

During a previous study of the largest yarn drying machine, performed by ÅF in 2015, the temperatures of the involved air flows were investigated during a period of time to evaluate its energy consumption. The outcome of that study estimated the total effective output of the heated air to 182 MWh in GT1 over a year. It can however be discussed how much the fan, due to its significant size and associated heat losses, influence this. For simplifying reasons this was however excluded in the future analysis and the heat demand was assumed to be covered by the supplied steam. For GT2, a corresponding analysis has not been performed. However, for modelling purposes, this was estimated by scaling the respective volume:

$$\frac{Q_{GT2,year}}{Q_{GT1,year}} = \frac{V_{GT2}}{V_{GT1}} \quad \rightarrow \quad Q_{GT2,year} = Q_{GT1,year} * \frac{V_{GT2}}{V_{GT1}} = 61 \quad [\mathbf{MWh/year}]$$

### 4.4.2 Stenters

A first step to map the behaviour of the stenters was to receive an indication of the LPG-consumption. Both stenters have a gas meter where the consumption of LPG can be read in cubic meters. However, these gas meters were recently installed and therefore not yet automatically logged. Thus a protocol was created, where the operator of the stenters before start-up every morning, could read the gas meter and write it down in the protocol. From these readings of the gas meters the LPG consumption could be estimated.

## 4.5 Mapping of heat recovery potential

This section discusses the areas of the production with obvious potential for energy improvements. The flue gases from the stenter are further investigated. Also the large amounts of waste water from the production will be explored in more detail.

### 4.5.1 Flue gases

The gas burners in the stenters are generating flue gases that today are directed straight out the chimney. Due to the fact that the fabric treated in the stenters can not withstand very high temperatures these flue gases have a maximum temperature slightly below 200°C. Even though this is a relatively low temperature for a flue gas stream, it is a significant potential for heat recovery in this system. This heat could be used to either warm up air for space heating or warm up water for the dyeing processes.

The steam boiler is also generating flue gases that theoretically could be utilised in some way. However, since the goal is to minimise the steam consumption this investigation will not handle any solutions regarding the steam boiler that requires investments.

To be able to assess the potential of heat recovery of the flue gases some measurements were needed, preferably temperatures and volume flows. The aim was that this would give enough information to be able to produce a realisable proposal, with the economic aspect taken into account as well.

Equipment to measure the temperature and the volume flow of the flue gases was borrowed from Chalmers and ÅF. To make sure that the potential of the flue gases could be utilised, with for example a heat exchanger, an investigation of the content of the flue gases would be useful. However, to measure the chemical content of the flue gases accurate enough appeared to be too expensive and complex for the time scope of this master thesis. The content of the flue gases was thus not considered to be a problem for a possible heat recovery equipment.

### 4.5.2 Accumulation of waste water

As stated in the description of the accumulation tanks in Chapter 3, the heat recovery system of waste water is not working optimally since a lot of hot waste water is lost out the drain due to the current operation of the accumulator system. The volume of some dyeing machines is almost 5 $m^3$, which represents 20% of the total volume of the accumulator tank for dirty hot water. The fact that multiple machines are operated simultaneously and that the machines in some programs are drained up to 11 times gives some indications of the amount of hot dirty water that is processed. Additionally, the condensate from the steam that is used to raise the temperature in the main tanks is also led to the accumulator tank with dirty hot water.

In order to map the amount of water lost down the drain, all streams that enter the dirty hot accumulator tank was theoretically calculated based on the information from the dyeing programs. This will be further explained in the following Section 4.6. The calculation of the amount of water that is being wasted in this way will further be evaluated by a suitable proposal to minimise this loss.

## 4.6 Setup of models

For each of the studied areas, the setup of models was performed to receive a clearer understanding of the involved energy flows. The models could be helpful for both estimating energy flows that are hard to measure, but also for evaluation of possible heat recovery potentials. The idea with establishing models of the processes was to enable evaluation of the control strategy. For the dyeing processes and the accumulation system this means that the dynamics of the steam consumption could be analysed in more detail.

The modelling included several assumptions of constants that were used in thermodynamic equations. The general constants and equations are summarised in Appendix B and referred to when applied, while the process specific ones are integrated in the text.

### 4.6.1 Sectioning of the dyeing process model

As visualised in Figure 3.2 in Section 3.1, the only steam meter is installed before the splitting of steam used for space heating. Consequently it is not possible to read the exact steam consumption for the production. Even though estimations can be done backwards through calculations of the steam used for space heating it is still impossible to see the energy consumption of a specific machine as it is dependent of the actual program that is running. In addition, steam can also be consumed in dyeing processes in adjacent machines, that take place at the same time. In order to make it possible to estimate the actual steam demand for a given process the model thus had to include all the processes that are running simultaneously.

The model was constructed to be generic for different kinds of dyeing programs and dyeing machines so it would be valid for any given scenario of operation. Due to the similarities between the yarn and fabric dyeing processes, the model was constructed to handle both types of machines and programs.

As mentioned in Section 4.3, all of the typical programs were collected from each of the yarn and fabric dyeing areas. They were then translated into seven reoccurring steps.

- **Filling**

  The filling step represents the filling of process water of a machine or a pre-heat tank. The amount of water is depending on the fabric-to-water ratio, $ratio_{ftw}$, defined as batch size relatively the capacity of the machine. For a smaller amount of fabric, more water is needed since the machine needs to be completely filled during operation. The optimal fabric-to-water ratio is 1:10 according to AB LS. The selection of machine and batch should consequently be such that this ratio is aim for, although this is not always secured by the planning. For modelling simplifications, this was however assumed to be fulfilled.

  In addition, the source of the water had to be included. The typical way of operation is a 50/50 mixture of cold river water from the cleaning facility and hot water from the clean hot accumulator tank. However, as the possibilities of only using hot or cold water was to be evaluated this was also to be taken into account in the model. This is because the theoretical steam consumption used for heating the process water is strictly dependent on the filling temperature. The model was configured so that steam would cover the heating to the target temperature of the filling step regardless of the source of the water.

  Further, the heating of the tank material is considered, which is depending on the surface area and wall thickness of each machine. For the yarn dyeing processes, filling steps during a program cycle is prepared in a pre-heat tank. For these scenarios also evaporation and radiation losses are estimated due to the fact that the pre-heat tanks are open tanks that are prepared in advance. The average preparation time for the pre-heat tank is estimated to 10 minutes regardless of what yarn dyeing machine that is used. Steam is assumed to cover all these losses to assure the conditions of the specific program. Also to approximate the duration for a filling step, a filling was timed for two different machines. The flow of the filling was estimated to 500 $l/min$.

- **Draining**

  The time for draining of a machine is limited by the dimensions of the pipes to the drain and accumulator system. The dimensions is however similar to each of the dyeing machines which means that the flow of the output can be estimated to be the same for each of the machines. By timing two draining steps, this was estimated to 500 $l/min$. Except the flow rate, the temperature of the water being drained is a key parameter. If this water is warmer than 40°C it is led to the dirty accumulator tank for heat recovery.

- **Heating**

  Similar as for the filling step, the model was designed to be covered by steam if the target temperature was higher than the start temperature of that specific step. Also the temperature of the tank material was considered since some heat would be absorbed by the tank walls. Since most of the heating steps were lasting for a longer period of time it was assumed that the surface temperature of the tank would reach the target temperature of the process water.

The heating step also involves the circulation of the process water to the expansion tank. Since the process water needs to be cooled if the process water reaches a temperature of 80°C or above, the forced cooling losses associated with the circulation have to be taken into account for those scenarios. This is to minimise the risk for boiling when the water is circulated to the open tank. Also, since the expansion tank is an open tank that is maintained at 80°C or at a lower process temperature, regards to evaporation losses are included. Due to the fact the different heating steps continue for some time, radiation losses for both the main tank and the expansion tank were considered as well.

- **Cooling**
  The cooling step is modelled so that it works like the heating step but with the opposite temperature difference, that is with a target temperature that is lower than the start temperature. The cooling effect is instead covered by cold water from the water cleaning facility that is heat exchanged with the process water. The cold water temperature before the heat exchange is known, as it is assumed to be the same as the river water. The exiting temperature is however dependent on the temperature of the heat exchanged streams. From temperature logs of different cooling scenarios it could be concluded that the temperature lift of the cooling water in the cooling step was similar to the decrease of the process water temperature. In Figure A.3 in Appendix A the trend of the temperature of the cooling water after the cooling step can be seen. It needs to be highlighted that these temperatures were measured during a cold winter day, which makes them likely to be expected as close to minimum temperatures. As can be seen in Figure 4.1 neither of the outflows after cooling and heating in the regulation exchanger is temperature regulated, which means that they are always fully directed to the accumulation tanks.

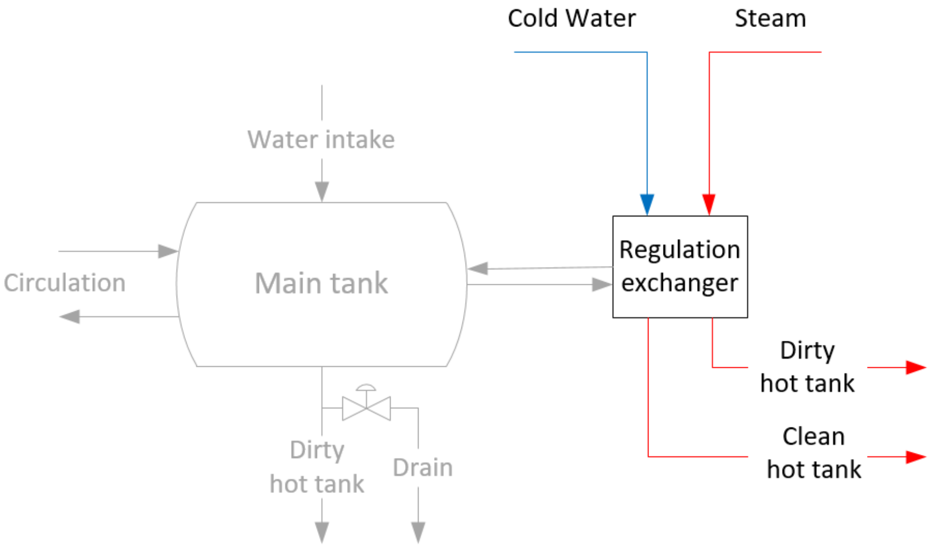

**Figure 4.1:** Principle of heating and cooling by the regulation exchanger

As for the heating step, the tank material is considered in the model as the hot tank walls will counteract the cooling of the process water. Besides, similarly as for the heating steps the cooling steps usually last for some time and it is thus assumed that the tank walls will reach the target temperature during the cooling step.

- **Keep temperature**
  Keeping the temperature is only a circulation step that is compensating for the losses to the surroundings. As the losses would cause the process water to decrease in temperature, steam is compensating, through the regulation exchanger, to assure the desired process conditions.

  For process steps when the process temperature is above 80°C, the forced losses for circulation need to be considered. In addition, evaporation losses in the expansion tank and radiation losses from all the tanks are taken into account throughout the whole process step.

- **Circulation**
  Circulation only involves circulation of the process water, see Figure 4.2. It is similar to the keep temperature step but with the difference that the forced cooling losses are not compensated for. Consequently, the temperature in the tank should slightly decrease, but since these process steps usually last for a shorter period of time it is assumed that the temperature remains constant. The considered losses are the same as for the keep temperature step.

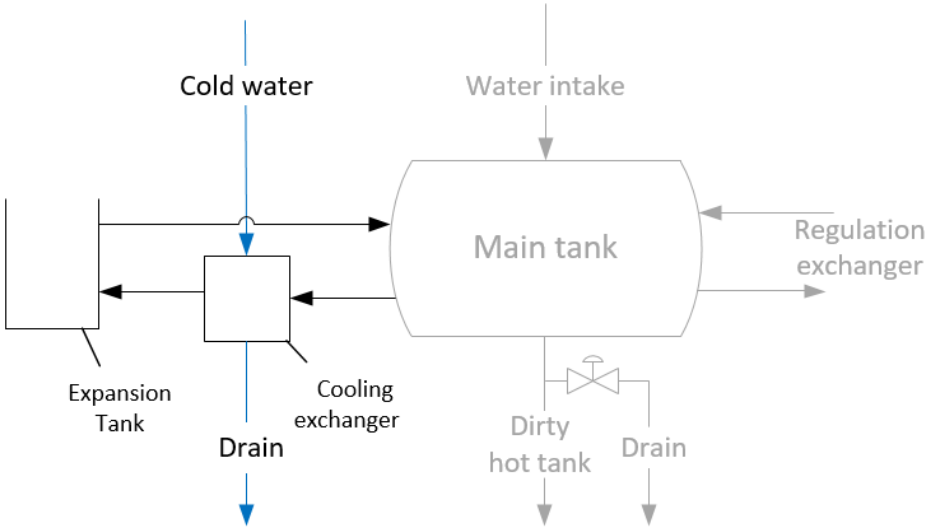

**Figure 4.2:** Close-up view of the circulation of water to and from the expansion tank

- **Overflow rinsing**
  This step is only included in the yarn programs and not in the fabric programs. Since it is just constant filling and draining, no temperature changes of the process water in the main tank is needed. As mentioned above the filling flow into the tanks and the draining flow out of the tanks were estimated to be 500 l/min. To include the water consumption and the possibility for heat recovery these flows were multiplied with the specified time for the overflow rinsing step.

### 4.6.2 Dyeing model calculations

The amount of water needed for filling is dependent of what machine that is used and of the fabric-to-water ratio. Given a constant density the total mass needed was found accordingly for a specific machine and fabric-to-water ratio:

$$m_{total} = machine\ capacity * ratio_{ftw} * \rho_{water} \quad \textbf{[kg]}$$

The total mass was then to be provided from either of the three ways of filling the machines; by only cold water, by only hot water or by mixing. For the filling scenario when mixing two streams of different temperatures the final temperature was found through Equation B.1.

Mixing is only considered for the current operation of filling a mixture of hot and cold components. For each of the other scenarios the temperature after the filling step is considered to be the same as for the stream input.

For the heating and cooling steps in a program, the energy demand was calculated from the start temperature to a target temperature for a specific program step. The required efficient energy, $Q_{eff}$ for heating or cooling the process water was given by Equation B.2.

For each of the heating and cooling steps the tank material had to be considered. This due to the fact that the tank walls will absorb some energy during a heating step as it strives to reach the temperature of the fluid. For a cooling step this will instead be a counteracting effect as hot tank walls will heat the process water for the same reason. In order to estimate these energy flows the mass of the tank material was needed. For each of the machines the tank surface area and material thickness were measured while the density of the tank material was assumed to be constant.

$$m_{tank} = machine\ surface\ area * t_{tank} * \rho_{steel} \quad \textbf{[kg]}$$

With a known mass of the tank material and operation under the assumption of a constant specific heat capacity the energy demand for heating or cooling the tank material, between the specific temperatures of the program step, was given by Equation B.3. Due to relatively thin tank walls and that these program steps tend to last for a longer period of time it is assumed that the tank material reaches the target temperature in each of these steps.

Radiation losses from the machines are calculated for the main tanks and also for the expansion tanks for those steps that include circulation. In the yarn dyeing processes it is also included for the pre-heat tanks when they are operating. The losses associated with radiation, $P_{rad}$, are estimated by Equation B.4. The surface temperature, $T_{surf}$ is estimated as a mean temperature between the start temperature and the target temperature of the process step. The ambient temperature is assumed, $T_{\infty} = 20°\text{C}$.

Associated energy losses were estimated for each program step accordingly:

$$Q_{rad} = P_{rad} * step\ duration \quad [\mathbf{kJ}]$$

For the circulation step associated losses were considered when cooling of the circulated process water was needed. The target temperature of the expansion tank is regulated to maintain $T_{expansion} = 80°\text{C}$ when the process water in the main tank is of a higher temperature. In order to estimate the forced cooling losses, $Q_{circ}$, for the circulation, the mass flow rate of the circulated water was needed. Through timing and consulting with the operators this was estimated to $\dot{m}_{circ} = 0.1\frac{kg}{s}$. With Equation B.2 the energy losses could thus be estimated. The temperature of the process water is estimated as the mean between the start and target temperature if the circulation occurs during a heating or cooling step.

$$Q_{circ} = \dot{m}_{circ} * c_{p,water} * (T_{process} - T_{expansion}) * step\ duration \quad [\mathbf{kJ}]$$

During circulation, the expansion tanks also have losses due to evaporation. Since the pre-heat tanks in the yarn dyeing area also are open tanks, they are also associated with evaporation losses. The losses linked with evaporation are strongly dependent on the temperature difference between the liquid surface and the surrounding air. Also the humidity of the surrounding air affects the evaporation rate, but is of less importance. Estimations of heat losses from the water surface are complex and to enable sufficient estimations, for different temperatures, a given relation presented in Table 4.4 was used. The table is a translation from a graphic relation provided by Spirax-Sarco Limited [23]. The graph considers heat losses to surrounding air of 15°C and 55% air humidity, which is assumed to be sufficiently accurate for the indoor conditions of the industry under investigation.

**Table 4.4:** Water heat losses relative to the water surface temperature [23]

| **X** $[°C]$ | 30 | 35 | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Y** $[\frac{W}{m^2}]$ | 500 | 700 | 1180 | 1500 | 2100 | 2600 | 3340 | 4200 | 5060 | 6100 | 7740 |

For a given program step, with a known temperature of the water in the expansion tank and a machine-specific open surface area, the losses, $Q_{evap}$, could then be calculated. The evaporation constant, $Y$, was estimated through spline interpolation for each temperature, $X$, for temperatures that deviated from the table values.

$$Q_{evap} = A_{exp}\,[m^2] * Y\left[\frac{W}{m^2}\right] * \frac{step\ duration}{1000}\,[s] \quad [\mathbf{kJ}]$$

With all losses included, the net energy demand could then be estimated. By summarising all involved energy transfer, the net energy that was to be covered by steam could be estimated. The steam consumption is depending on the net energy demand and assumes that the saturated steam from the 5 bar system is fully condensed to 1 bar saturated water according to Equation B.5.

With an established model with regards to reasonable losses, it was possible to evaluate the dynamics of the dyeing processes such as how much condensate that was formed by a heating step or the amount of cooling water that was needed to achieve a cooling step. Also an estimation of the water consumption for a given setup of program and machine could be calculated. Depending of the chosen scenario of water source, the model output estimate the consumption of hot and cold water respectively.

In order to take into account the possibilities of several simultaneous operations the model also includes the possibilities for operation of three different cooccuring dyeing setups with optional starting points. Based on theoretical duration of each program step the model can estimate steam demand and water consumption each minute.

However, the duration of all program steps are not clearly defined, which made it necessary to make some assumptions. For example, the pace of the heating and cooling steps (°C/min) may vary depending on the program and the machine. In these cases an average pace is applied, which is 2°C/min. Furthermore, some programs include taking test samples deciding if additional dyeing steps are needed or not.

### 4.6.3 Accumulation system recovery model

As the accumulation system for waste water is connected to both the yarn and fabric dyeing processes it is strictly dependent on programs that run in these areas of the production.

To enable identification of possible bottle necks of the accumulation system an observation of the different energy flows, to and from the tanks, had to be analysed. In order to make these approximations as accurate as possible the estimations of the involved flows had to be as accurate as possible. With respect to reasonable trade-offs between external factors of operation and model complexity, a reading per minute was assumed to induce sufficient estimations.

The model is configured to recover waste water from the draining step if the temperature of the water is 40°C or higher. However, for the streams out of the regulation exchanger no such criteria is used. As mentioned in Section 3.4.1, the actual setup of the heat recovery system direct the waste water from a tank drainage and the condensate to the dirty hot tank if the temperature criteria is fulfilled. The cooling water from the regulation exchanger is however directed to the clean hot tank as this stream is considered to always be free from contamination from the dyeing processes. If the temperature criteria is not fulfilled, that is the waste water is of a lower temperature than $T_{recovery} = 40°C$, it is disposed down the drain.

In order to make the model time dependent, the model for the dyeing processes was adapted so that the streams, to and from each machine, could be evaluated each minute. The duration for the majority of the program steps were given for each program while in some cases assumptions were required. For filling and draining of a specific machine, the timescale could be found by the estimated time for drainage from Section 4.6.1, with the assumption of equal time requirements for filling and draining.

$$duration = \frac{machine\ capacity\,[l] * ratio_{ftw}}{500\left[\frac{l}{min}\right]} \quad \textbf{[min]}$$

With an estimation of the duration for a filling or draining step, the streams to and from a dyeing machine could be modelled for each minute. This was done by dividing the theoretical amount of process water that was calculated for the program step by the estimated duration. The choice of water source scenario was also included in the model configuration, which includes the allocation of water output from the hot accumulator tank or the cold water facility for the filling step. For the remaining process steps the duration was either given by the program or calculated by the heating or cooling paces, stated in $[°C/min]$ for a program step.

From the model for the dyeing process a known net energy demand, to be covered by steam or cooling water, was found for each relevant program step. The mass and the volume of the condensate formed from steam used for heating was estimated with Equation B.6 and Equation B.7. The temperatures are estimated from the saturation temperature of the 5 bar steam to the temperature out of the regulation exchanger. The outlet temperature for the heat exchanger was estimated through logging of the condensate temperature for various setups. As the steam is maintained at constant conditions, the condensate was found to be relatively constant at $T_{water,out} = 85°\mathrm{C}$, see Figure A.2 in Appendix A.

Similarly as for the heating step, the cooling water leaving the regulation exchanger is recovered. However, the cooling water is assumed to always be free from contamination from the dyeing process and is hence directed to the clean hot accumulator tank. The amount of cooling water that potentially can be used for recovery is estimated from the net energy demand from each cooling step. The temperature of the exiting stream from the regulation exchanger was by on-site measurements estimated as described in Section 4.6.1.

In order to analyse the potential of recovering the cooling water leaving the cooling exchanger in the circulation, a temperature measurement of this stream was planned. As is visible in Figure 4.3, the current coupling dispose this flow regardless of its temperature. The conditions for this heat exchanger was modelled in the same way as the cooling in the regulation exchanger.

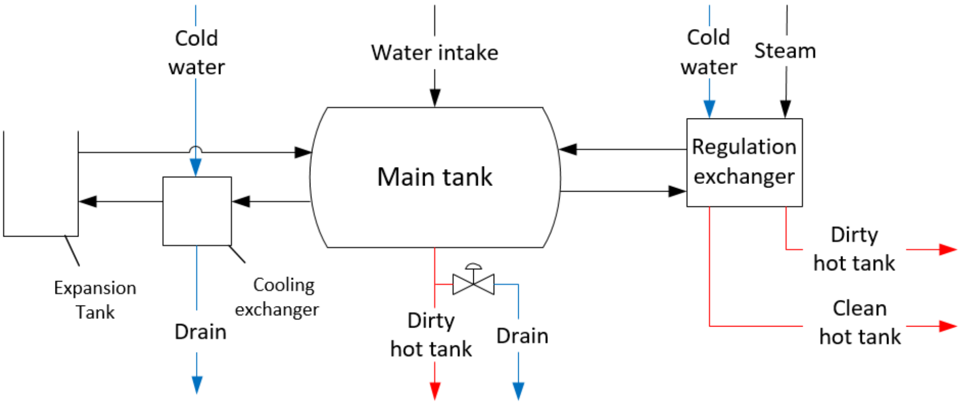

**Figure 4.3:** Overview of the outflows of the dyeing processes

For most of the machine and program setups, the majority of waste water for recovery was found from the drainage of the main tanks. As a drainage of the machine can be done for lower temperatures than the heat recovery limit, a temperature criteria of $T_{recovery} = 40°C$ for heat recovery was configured for this step as well.

Since it is quite common that multiple dyeing machines are operated simultaneously the accumulation system recovery model was constructed to handle this. This means that the water flows out of the dyeing process considered dirty had to be calculated the mix of, considering temperature and volume, and the same calculations were made for the mixing of water flows out of the dyeing process considered clean. The volumes of the different flows were simply added to each other, while the total temperature of the flow were calculated in the same way as previously shown in Equation B.1, with the only difference that it could be the mixing of more than just two streams this time.

Then the total volume and temperature of the flows entering the two accumulator tanks together with the previous temperatures and volumes in the tanks were used to calculate updated temperatures and volumes for the accumulator tanks. However, as explained in Section 3.4.1, the volume in the dirty tank is constant, as well as the temperature in the clean tank. But since the temperature is kept constant in the clean tank by adding steam, it was important to calculate the temperature of this tank without adding steam first, to be able to determine the steam demand.

The next step was to handle the integration between the accumulator tanks, i.e. the heat exchanger that uses the dirty hot water when heat exchanging a filling of the clean tank, see Figure 4.4. In order to evaluate the performance of the single-pass counter flow heat exchanger, a more detailed analysis was carried out. Except for the temperatures involved in the heat exchanger also the mass flow rate of the two heat exchanging medias was of importance.

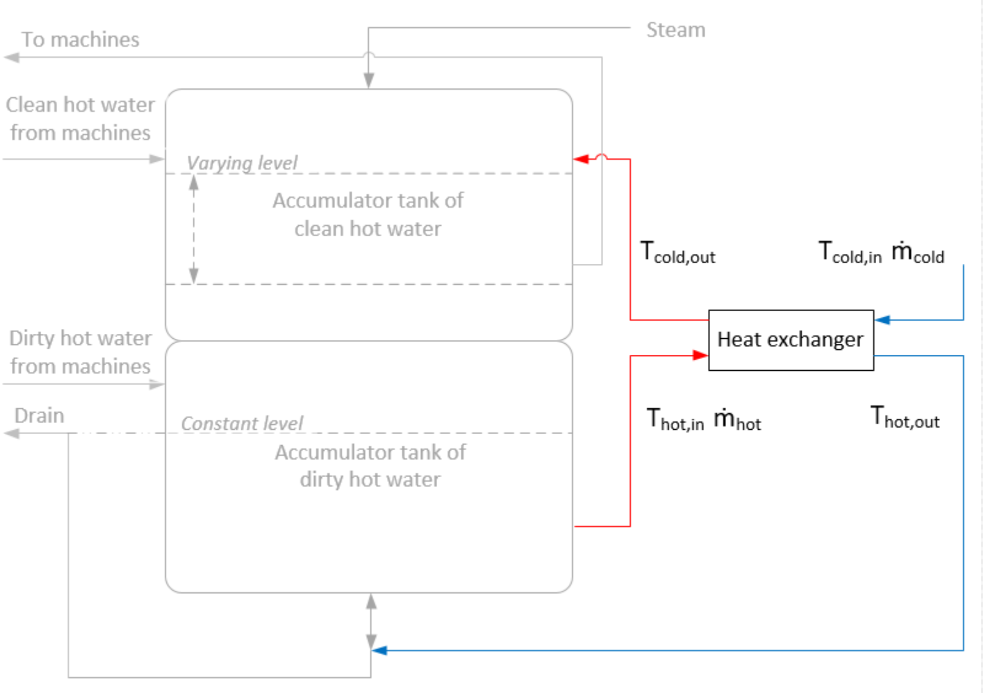

**Figure 4.4:** The in- and outflows of the heat exchanger supplying the heat exchange from the dirty accumulator tank to the clean accumulator tank

By timing and using installed metering equipment it could be concluded that the cold stream could be estimated as $\dot{m}_{cold} = 400$ kg/min during filling steps. In order to estimate the mass flow rate of the hot stream, instantaneous readings of the temperatures were made, the outcome of four readings is summarised in Table 4.5. The readings were taken from temperature logs that ÅF performed during August, thereof the in-going temperature of the river water, $T_{cold,in}$, are higher than expected for the period when the project was carried out. Temperatures of the in- and outflows of the heat exchanger from a day of operation can be found in Figure A.4 to A.7 in Appendix A. The extracted reading points were taken from different heat exchanges during the logging period.

**Table 4.5:** Temperature measurements for heat exchanger analysis

| Reading | $T_{hot,in}$ | $T_{hot,out}$ | $T_{cold,in}$ | $T_{cold,out}$ |
|---|---|---|---|---|
| 1 | 43.6 | 30.0 | 19.6 | 33.1 |
| 2 | 59.8 | 36.1 | 19.7 | 42.8 |
| 3 | 50.6 | 33.2 | 19.1 | 38.0 |
| 4 | 45.3 | 31.0 | 19.0 | 35.0 |

With a known mass flow rate of the cold stream, $\dot{m}_{cold}$, the total heat transfer could be estimated by Equation B.8. As the heat transfer was known, this could be used to estimate to mass flow rate of the hot stream through energy balance, $Q_{cold} = Q_{hot}$:

$$\dot{m}_{hot} = \frac{Q_{cold}}{c_{p,water} * (T_{hot,in} - T_{hot,out})} \quad \textbf{[kg/s]}$$

From the four studied readings, the average mass flow rate of the hot stream could be estimated as $\dot{m}_{hot} = 420$ kg/min. The relative relationship between the two mass flow rate was then estimated as:

$$ratio_{DHtoCH} = \frac{\dot{m}_{hot}}{\dot{m}_{cold}} = 1.05$$

The heat transfer area of the heat exchanger was given by the number of plates and the projected area of one plate for the single-pass heat exchanger.

$$A = n * w * l = 72.6 \quad [m^2]$$

where:
$n$=Number of plates
$w$=Width of plate [m]
$l$=Length of plate [m]

For the same four readings, the overall heat transfer coefficient, $U$, could be estimated for both $Q_{cold}$ and $Q_{hot}$ by rewriting the design equation, Equation 2.3:

$$U = \frac{Q}{A * \Delta T_{lm}} \quad \textbf{[W/m}^2\textbf{K]}$$

The mean overall heat transfer coefficient could thus be estimated as $U$=530 W/m$^2$K, during the studied period of time. The behaviour of the heat transfer coefficient could of course vary throughout the year as, mainly, the outdoor temperature of the water would vary. However, the heat exchanger was modelled according to the conditions stated.

With known specifications and estimated performance of the heat exchanger, it could be implemented to the model for the accumulation system. In order to make the model to operate generally, with only known temperatures of the dirty hot tank $T_{DH,tank}$ and the entering cold water from the outside, $T_{CW}$, accordingly adjustments had to be done. In accordance with theory described in Section 2.5, the outgoing temperatures could be found for every minute during a heat exchange. Implementing that, all involved streams and their temperatures were estimated for the heat exchanger in the integration to the model for the accumulator system.

### 4.6.4 Drain water recovery model

Since the heat exchange between the accumulator tanks only occurs when the clean tank reaches a lower set level and that the level is kept constant in the dirty tank, drainage of hot dirty water is common. This means that when there is no heat exchange, the same amount of water entering the dirty tank from the dyeing process, is leaving down the drain, with the temperature of the dirty accumulator tank. Even though the water leaves down the drain from the bottom of the dirty tank and that the water might be slightly colder there, this is a significant loss of hot water. Therefore, a model for recovering this drain water was constructed.

The main idea is to collect the hot drain water in an additional accumulator tank. This tank would primarily work as a buffer for a heat pump integration, since a heat pump is in need of a constant flow of a close to constant temperature. In addition to keep a constant temperature in the heat pump accumulator tank this additional accumulator tank will have enough heat capacity to also preheat the river water through a heat exchange, see Figure 4.5. Since it only is flow of river water here when there is a heat exchange between the large accumulator tanks this heat exchange is not constant.

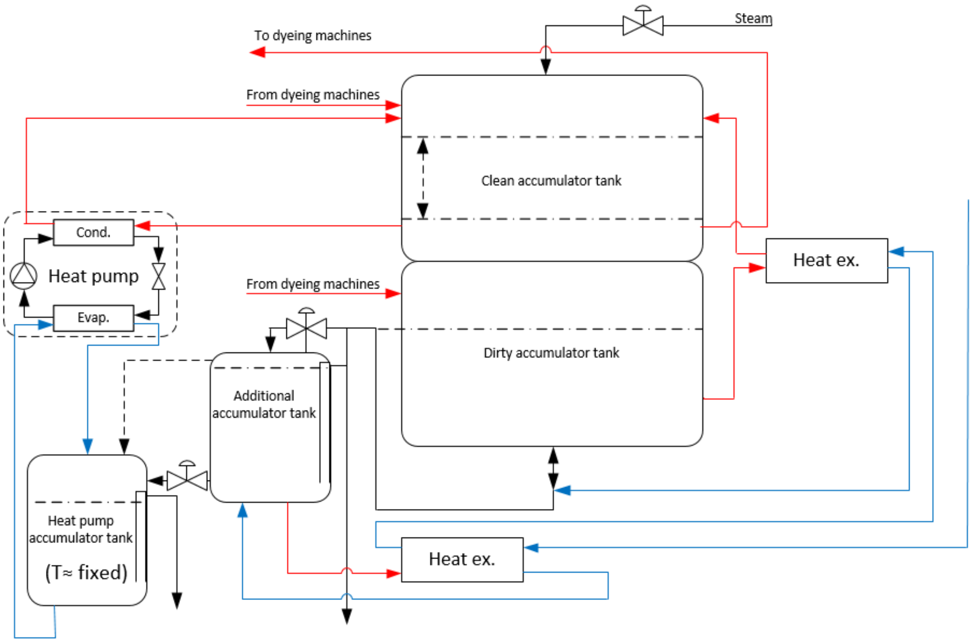

**Figure 4.5:** Overview of the concept of using a heat pump to decrease losses down the drain

The water volume in this additional accumulator tank would be constant by having a column from the bottom of the tank that leads the water out to the drain pipe, i.e. similar to the volume regulation in the big dirty accumulator tank. Then if the drain water would be led to this additional accumulator tank or straight down the drain would be regulated by a control valve that only let water through that has a higher temperature than the additional accumulator tank. By this regulation no water is entering that would cool the water that already is in this tank.

The heat exchange with the cold river water will only take place when there is a heat exchange between the two big accumulator tanks, since that is the only time when it is a flow of cold river water here. Due to this irregular operation this heat exchanger should not be too large since a large heat exchanger needs more time to be warmed up which would influence the efficiency of the heat exchanger.

Since the operation of a heat pump benefits from a close to constant temperature of the inflow in the evaporator another accumulator tank was added, since the temperature in the additional accumulator tank will be varying. Then the temperature in the heat pump accumulator tank can be kept close to fixed by adding hot water from the additional accumulator tank when the temperature decreases below a set temperature. This set temperature in the heat pump accumulator tank depends on the operation limits of the selected heat pump, but it will be aimed to be as high as the selected heat pump allows to maximise the heat lift in the heat pump. It will also be investigated if the heat pump can operate if the over rins flow from the additional accumulator tank will be led to the heat pump accumulator tank, as the black dotted arrow between these two tanks indicates.

After setting up the model this far appropriate heat pumps was searched for, with special regards to effects and temperature operation limits. Since the clean accumulator tank has a set temperature of 50°C the in- and outflow temperatures of the condenser is aimed to be slightly below and above this temperature, respectively.

### 4.6.5 Flue gas recovery model

In order to estimate the potential of heat recovery of the flue gases, primarily the content of the flue gases were to be investigated. However, due to the complexity of analysing the flue gas content in combination with the further need for evaluation of its impacts on the heat recovery equipment this was chosen to be excluded. This is due to the fact that a reliable result requires extensive studies over time that take into account the variations in production, as these variations are likely to cause the flue gas content to vary.

Given the assumption that heat recovery would be possible with a known flue gas content, the capacity of the flue gases was further investigated. To be able to estimate the energy content, that possibly could be used in a heat recovery unit, the volume flow and temperature of the flue gases were investigated. The volume flow can be regulated depending on the batch, since some qualities produce more particles depending on previous production steps. This means that the fan that evacuates the flue gases from the stenter can increase the outflow if the fabric content tend to form contamination that are detected inside the production premises. The fan is operated at a minimum level but is manually regulated to achieve adequate ventilation without excessive air supply. Studying the flue gas temperatures, the temperature difference between the target temperature in the stenters and the flue gas temperature exiting through the roof was investigated. Since the production is characterised with large variations and smaller batches, the flue gas temperature at the exit is varying a lot since the burners in the stenters usually are switched of during the conversion between different batches. This means that the potential for heat recovery is not only dependent on the temperature in the stenters but also on the batch sizes.

As the most accessible properties of the flue gases to be analysed were the temperature and the flow velocity, these stand as the starting-points of the model setup. With known dimensions of the flue gas channel a measurement of the flow velocity would entail an estimation of the volumetric flow. This was done with a *Pitot tube* that measures the stagnation pressure, $p_t$, of the fluid which is the sum of the static pressure, $p_s$, and the dynamic pressure. Given the stagnation pressure, the velocity of the flue gases was then estimated with Equation B.9 where the dynamic pressure is solved. The stagnation pressure was estimated as a mean of the cross section of the flue gas channel.

Solving the dynamic pressure, the fluid velocity could consequently be found accordingly:

$$v_{fg} = \sqrt{\frac{2(p_t - p_s)}{\rho}} \quad [\mathbf{m/s}]$$

The temperature of the flue gases were estimated through "termopipes" measured through control hatches in the flue gas channel at the roof. The temperature was assumed to be constant in the whole cross section of the flue gas channel.

The model was configured assuming that the volume flow and the temperature of the flue gases at the roof, were known. The model also assumes that the temperature of the supplied water is known.

LUWA AG is a company that provides and installs relevant heat recovery equipment. They have specialised in textile industries and can provide installations that are suitable for the conditions of the flue gases from the stenter. The main principle of such a flue gas heat recovery unit is illustrated in Figure 4.6.

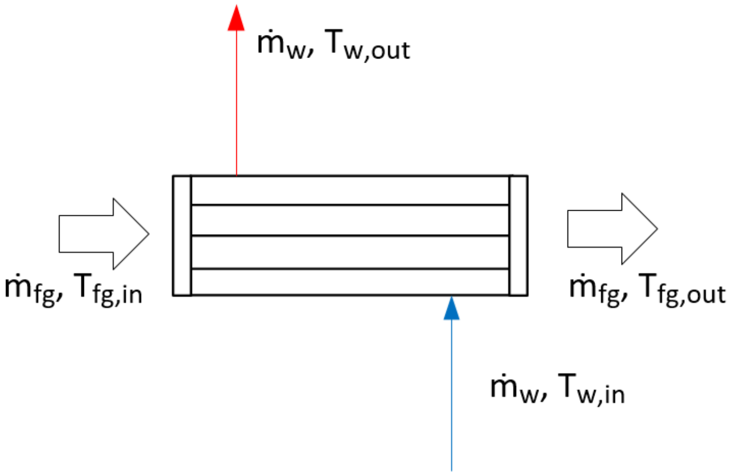

**Figure 4.6:** Illustration of the working principle of a flue gas heat recovery unit

According to specifications from LUWA AG, the temperature difference between the target temperature of the water and the stack temperature is around $\Delta T = 30°\text{C}$ [24]. Also the efficiency of the heat recovery unit is about $\eta_{fg} = 0.88$ for a heat exchanger of relevant size and type [24]. Given those assumptions, the first step was to estimate the stack temperature of the flue gases given a target temperature of the water.

$$T_{fg,out} = T_{w,out} + \Delta T \quad [^{\circ}\mathbf{C}]$$

As the physical properties of the flue gases were estimated as those of air, the density was estimated depending of the flue gas temperature according to Table 4.6. The flue gas density, $\rho_{fg}$, was then found through spline interpolation from the flue gas temperature profile.

**Table 4.6:** Flue gas density estimations [25]

| Flue gas temperature $[°C]$ | 100 | 125 | 150 | 175 | 200 |
|---|---|---|---|---|---|
| Flue gas density,$\rho_{fg}$ $[\frac{kg}{m^3}]$ | 0.9467 | 0.8868 | 0.8338 | 0.7868 | 0.7451 |

With a known estimation of the flue gas density, the mass flow could then be estimated with Equation B.10. The volume flow of the flue gases, $\dot{V}_{fg}$, was found from the measured flue gas flow velocity and the channel dimensions.

The energy content of the flue gases along with the power supplied could then be calculated in Equation B.11 and Equation B.12, given constant temperatures of the flue gases. This further made it possible to calculate the mass flow and volume flow of the water at targeted temperature, see Equation B.13 and B.14.

*Economic analysis.* In order to be able to estimate the potential savings of the heat recovery equipment, the energy content of the heated water was summarised and investigated. As the model was configured based on an minute average, the calculations had to be translated correspondingly. The energy content of the heated water was found accordingly:

$$Q_w = P_w * \text{minutes per day} * \frac{60s}{min} \quad [\mathbf{kJ}]$$

With a known estimation of the water output the potential gas savings could be evaluated. In order to quantify the savings an analysis of the traditional way of heating a corresponding amount of water was required. First of all the boiler efficiency was to be taken into account which, according to AB LS, could be estimated to $\eta_{boiler} = 0.9$. Also, transmission losses from the steam boiler to the dyeing area should be included in order to be able to make a fair comparison. From the energy audit performed by ÅF in 2017, the transmission losses were estimated to about 30% on average for the steam system. Under the assumption of $\eta_{transmission} = 0.7$ the gas savings could be estimated with a known energy density of the LPG, $h_{LPG} = 46.1\frac{MJ}{kg}$:

$$m_{LPG} = \frac{Q_w}{\eta_{boiler} * \eta_{transmission} * h_{LPG}} \quad [\mathbf{kg}]$$

As the cost for LPG, $C_{LPG}$ was known in $[SEK/kWh]$ by AB LS, the corresponding energy conversion was required to be able to find the actual economic savings:

$$\text{savings} = m_{LPG}[kg] * h_{LPG}\left[\frac{MJ}{kg}\right] * \frac{1}{3.6}\left[\frac{kWh}{MJ}\right] * C_{LPG}\left[\frac{SEK}{kWh}\right] \quad [\mathbf{SEK}]$$

The corresponding $CO_2$ equivalent savings associated with the decreased LPG consumption, $m_{LPG,sav.}$, could then be calculated with an estimation of the factor for $CO_2$ emission; $e_{CO_2}$=0.259 tonnes $CO_2$/MWh [26]:

$$CO_2\text{-eq.} = m_{LPG,sav.}[kg] * h_{LPG}\left[\frac{MJ}{kg}\right] * \frac{1}{3600}\left[\frac{MWh}{MJ}\right] * e_{CO_2}\left[\frac{\text{tonnes } CO_2}{MWh}\right] \quad \textbf{[ton]}$$

Final economic analysis, to analyse the possible investment, was carried out in accordance with the investment cost analysis presented in Section 2.7. The internal rate of return, $R$, was assumed as 5% on a yearly basis. The technical lifetime of the heat recovery unit is estimated as 30 years, the depreciation time is consequently estimated as equally long.

When integrating the flue gas recovery model in the dyeing process there are a few factors that is exceptionally important to consider. Since the operation of the stenters are quite irregular, and consequently the generation of flue gases as well, the heat demand covered by the flue gas recovery should not be strictly dependant on the flue gases. It needs to be another heat source to cover up when flue gases of high temperatures are not generated. The fact that the temperature in the flue gas channel is strongly varying also needs to be considered in the choice of heat exchanger. A larger heat exchanger needs more time with high temperatures than a smaller heat exchanger to exchange heat at its nominal efficiency [15].

It is also important to not just cover a heat demand by the flue gases without thinking about how this affect the efficiency of the dyeing process as a whole. The volume flow of the recovered water also needs to be considered regarding the losses of the dyeing process. Because if an additional stream is added to the system the same amount must be leaving the system somewhere else. At what conditions this additional flow leaves the system is deciding if the total efficiency is changed or maintained.

## 4.7 Representative operations

The operation in the industry is highly dynamic and varying from day to day depending on what batches have been ordered from the customers. To have a chance to analyse different changes of the operation or the equipment a representative operation was needed to be identified.

### 4.7.1 Daily dyeing operation

The identification of a representative daily operation was based on the production data from February 2018, see Appendix C. This monthly schedule showed that it is an average of six dyeing programs operated every day, out of which the majority are yarn dyeing programs. Since the most common yarn programs have an operation time of around eight hours the yarn dyeing area has to run two shifts a day to keep up with the schedule. This is under the assumption that no more than three setups are operated simultaneously.

Thus, in this representative dyeing operation a daily operation of six programs will be modelled, see Table 4.7. The three upper programs in the table will be started in the morning, with small delays for preparing the start of the programs. Then the bottom three programs will be started when the first three are done, which then would be in the beginning of a second shift. Therefore all these last three programs are yarn programs.

**Table 4.7:** Machines and programs applied in the representative daily operation

| | **Machine** | **Capacity [litres]** | **Delay [minutes]** |
|---|---|---|---|
| Yarn Program D | GAG5 | 4500 | 0 |
| Yarn Program D | GA1 | 1100 | 5 |
| Fabric Program E | F4700 | 4700 | 20 |
| Yarn Program C | GA3 | 1100 | 0 |
| Yarn Program D | GA4 | 550 | 5 |
| Yarn Program D | GA2 | 2700 | 20 |

When modelling a daily operation that will represent a series of days it is important that the following day will start with the same conditions. For the dyeing operation this means that the dynamic level in the clean accumulator tank needs to be considered. Because no matter what start level that is assumed for the clean accumulator tank in the representative daily operation it is not likely that the end level will be the exact same, see the example in Figure 4.7. This would mean that the following day would have different start conditions. Even though that might be the case in reality it will give an unfair theoretically result for the representative day. Because if the end level is higher than the start level steam has been consumed that have not been utilised. It could also be the other way around, that the end level is lower than the start level, which means that warm water has been utilised that has not been accounted for. Thus, the heat up of the volume difference between the start and end level, from now on called the *compensation volume*, needs to be compensated for. The steam consumption corresponding to this will be deducted from the steam consumption in the clean accumulator tank if the end level is higher than the start level, and added to the steam consumption if the end level is lower than the start level.

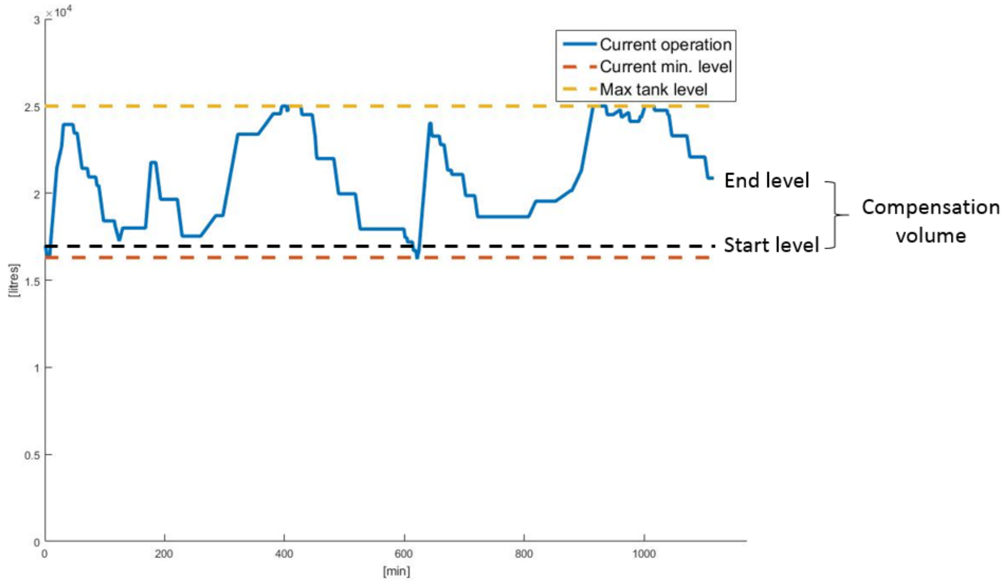

**Figure 4.7:** Example of the difference in start and end level in the clean accumulator tank during the representative daily operation

### 4.7.2 Daily stenter operation

In order to estimate the typical occupancy level of the stenters, the production schedule for one month was requested. The total production data for February 2018 is presented in Appendix C. From the data it could be concluded that Stenter 2 was operated far too sporadic to motivate a heat recovery investment. However, the summary of the production data for February 2018 are presented in Table 4.8 for Stenter 3. Both week 5 and week 9 are half weeks. The total number of work days during February 2018 were 20.

**Table 4.8:** Summary of the number of batches in Stenter 3, each week in February 2018

| | **Number of batches** |
|---|---|
| **Week 5** | 27 |
| **Week 6** | 72 |
| **Week 7** | 47 |
| **Week 8** | 57 |
| **Week 9** | 34 |
| **Sum** | 237 |
| **Avg. per day** | 11.85 |

According to AB LS the average temperature of the flue gases could be estimated to $T_{avg,fg} = 140°\text{C}$. From the production data for the stenters, in Appendix C, it was concluded that the average batch size was $L_{avg,batch} = 264.3$ m. As the average fabric feeding pace was known as $v_{avg,feed} = 10$ m/min an estimation of the average timescale could be found as $t_{avg,feed} = 26$ min. Since the width of the batches are varying and also the operation temperatures are ranging over a large temperature span, it is common that a previous batch needs to pass through the entire machine before the next run can begin. With a total stenter length of 30 m, the additional operation time, per batch, is about 3 min. This sums to a total batch operation time to about 29 min. In addition, different surrounding handling with both finishing a previous batch and preparation of a new is, according to operators at AB LS, an extra 30 min delay between stenter operations. The flue gas temperature during the batch changes are expected to descend to about $T_{avg,change} = 50°C$ since the gas burners are switched off during most of the batch changes. Given these assumptions, a theoretical temperature profile could be constructed for an average day, with 12 batch runs at average timescale and temperature, see Figure 4.8. The start up temperature, $T_{startup}$, is assumed to be the same as the ambient indoor temperature $T_{ambient} = T_{startup} = 20°C$.

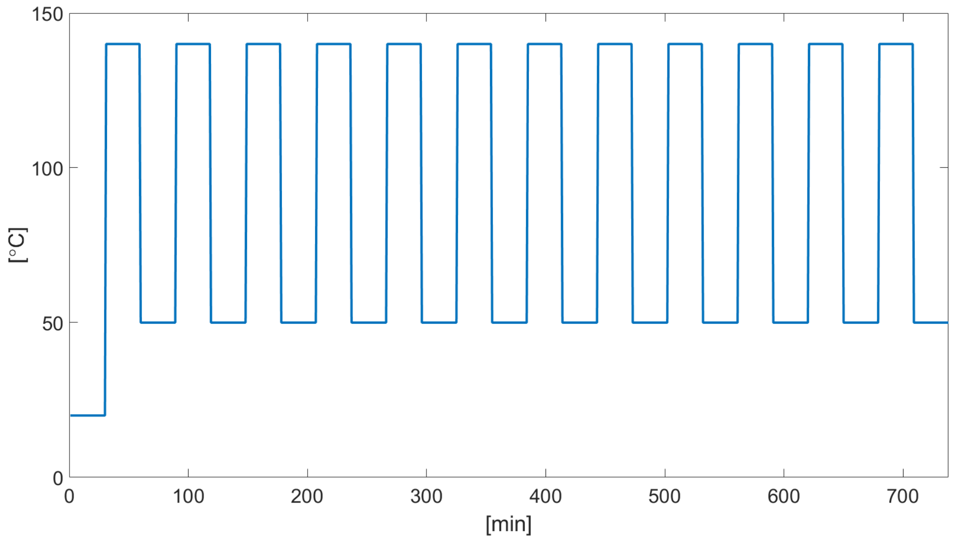

**Figure 4.8:** Constructed estimation of the temperature profile from average number of batches and temperatures during a workday

To estimate the potential of the flue gases a model was constructed to analyse different designs of heat recovery equipment. That is, different setups of water that is heated to different temperatures. If the target temperature of the heated water is lower, this means that more water can be heated. Consequently, with a higher target temperature a smaller amount of water can be heated to that temperature.

# 5

# Results and Discussion

This chapter presents the results from the various investigations and evaluations in the project. Different areas of the production that have been studied are divided accordingly in separate sections.

## 5.1 Dyeing processes and accumulation system

In this section the results from the dyeing processes, including the accumulator tanks, will be presented and discussed. Except for model characteristics relevant parameters, influencing the energy consumption, will be further investigated with sensitivity analyses. The main focus of the results from the dyeing processes will be the consumption of steam, since it is a source desirable to minimise, to consequently decrease the LPG consumption. In the dyeing processes, steam is consumed in the heat exchanger satisfying the temperature in the main tank and in the clean accumulator tank to keep the desired temperature of the hot filling water. The behaviour of these two steam demands will in the next subsections be thoroughly analysed for a representative day of operation by comparing the dyeing operations as they are today with different possible regulation measures.

### 5.1.1 Validation of model

In the dyeing model, the steam demand in the dyeing processes in the textile industry is calculated. However, to make these results trustworthy some kind of verification of the model was desired. As mentioned in Section 4.2 the goal, as the models were constructed, was to compare the steam consumption according to the models with the steam meter that was monitoring the steam consumption of the dyeing processes and the accumulator system. The steam meter was however defect and could not be fixed during the time frame of this thesis, so an actual verification of calculated consumed steam was not possible. Consequently, the results from the steam consumption calculations should be considered as an indication of the energy allocation rather than facts.

However, as all the heat meters for space heating were working, a theoretical estimation could be done from the LPG consumption in the steam boiler. This estimation would then include the boiler losses and additional losses such as transmission losses for the whole steam system. Since the LPG readings were done on a monthly basis, the summation of process steam had to be done for the same time span.

In order to be able to make an estimation of the process steam, an efficiency of the steam boiler had to be considered. According to AB LS, and after consultation with ÅF, this efficiency could be estimated as $\eta = 0.9$. The investigated time span was chosen as February 2018 with the data readings according to Table 5.1. The locations of the heat meters are shown in Figure 3.2 in Section 3.1. The meter that is logging the LPG consumption is located next to the steam boiler.

**Table 5.1:** Energy consumption in the steam system, February 2018

| **Location** | **Metered consumption [MWh]** |
|---|---|
| Steam boiler input (LPG) | $Q_{boiler,in} = 588.0$ |
| Steam boiler output | $Q_{boiler,out} = 529.2$ |
| Space heating 1 | $Q_{sp.heat,1} = 37.1$ |
| Space heating 2 | $Q_{sp.heat,2} = 109.1$ |
| Space heating dyeing | $Q_{sp.heat,dyeing} = 125.3$ |

The theoretical steam consumption for the studied area of the production could thus be found from simple subtraction:

$$Q_{steam,theoretical} = Q_{boiler,out} - Q_{sp.heat,1} - Q_{sp.heat,2} - Q_{sp.heat,dyeing} = 257.7 \quad \textbf{[MWh]}$$

With the given production data for the studied period of time, this was inserted in the dyeing model to get an estimation of the required amount of steam used for production. The summation of all yarn and fabric dyeing programs that were run in respective machine estimated the total steam consumption for the dyeing processes to $Q_{dyeing,tot} = 66.7$ MWh.

Given an estimation of the steam consumption for the dyeing processes, the remaining part of the production was investigated. As the model of the accumulator tank was configured so that it could only estimate the behaviour of the tanks for one day, the total steam consumption for a typical scenario had to be accounted for that in terms of steam demand for start-ups. During the weekends a larger temperature drop of $\Delta T_{weekend} = 15°C$ was estimated and a smaller temperature drop of $\Delta T_{night} = 5°C$ was assumed for the remaining workdays. The daily steam consumption with a start-up after a weekend, in the clean accumulator tank for a typical setup, was estimated as $Q_{acc.,Mon} = 0.9$ MWh with the model. For the remaining workdays the corresponding consumption was estimated as $Q_{acc.,avg} = 0.7$ MWh. Assuming an average volume of 15 $m^3$ in the clean accumulator tank, the corresponding steam demand could be estimated and accounted for, during the four Mondays in February 2018 and for the remaining 16 workdays during that month. Consequently, the total steam consumption for the accumulation system could be estimated as $Q_{acc.,tot} = 4 * Q_{acc.,Mon} + 16 * Q_{acc.,avg} = 14.8$ MWh for the whole month.

The remaining piece of equipment with a significant steam consumption, within the studied area of production, are the yarn drying machines. However, the compact location of the yarn drying machines and their closed system setup, which made them hard to evaluate from an energy perspective, entailed that the drying machines remained unchanged throughout the project. Yet, in order to be able to estimate the allocation of the steam used for production, the estimation from an earlier investigation of the yarn drying machines of $Q_{yarn,drying,year} = 243$ MWh/year was used. Consequently the average monthly consumption could be estimated as $Q_{yarn,drying,year}/11\ months = Q_{yarn,drying} = 22.1$ MWh, assuming 11 months with production each year.

With estimations of all major energy consuming areas of the production, the remaining part, to add up to the total theoretical steam consumption of the whole production area, could be estimated as:

$$Q_{rest} = Q_{steam,theoretical} - Q_{dyeing,tot} - Q_{acc.,tot} - Q_{yarn,drying} = 154.1 \quad [\mathbf{MWh}]$$

As earlier mentioned the remaining steam, $Q_{rest}$, includes all losses within the steam system. In Figure 5.1, the allocation of the production steam and their relative proportions are presented.

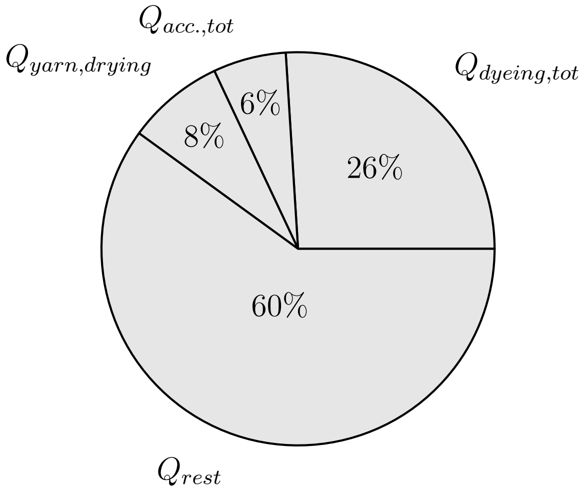

**Figure 5.1:** Pie chart over the different shares of steam used for production

An indication, that the verification results are accurate and reliable enough, is that the Energy Audit performed by ÅF in 2017 estimated the transmission losses in the steam system to about 1230 MWh during a year. Just for an indication, the average monthly losses would be about 110 MWh, assuming that the losses are somewhat equal throughout the 11 months of operation and no major differences have been performed since the time of the audit, within this area of the production. However, as steam is used for space heating, the usage and corresponding losses are likely to increase during the colder winter months, but is still neglected for model simplifications. Subtracting that amount from the unlisted share of the production steam, the remaining part of unlisted steam would be about $154.1 - 110 = 44.1$ MWh corresponding to roughly 17% of the steam used for production. This is considered to be accurate enough for verification of the model given the scenario with a defect steam meter which would have enabled a more accurate reading of the steam consumption.

### 5.1.2 Model characteristics

Since the source of cold water is the adjacent river, the temperature of this stream is varying throughout the calendar year. Except the temperature of the filling water this also affects the temperature in the clean accumulator tank. This is due to the fact that both water streams into the clean accumulator tank is heat exchanged river water, which means that these two streams in general are lower during winter time. The steam consumption in the clean accumulator tank is therefore higher during winter time, since it is used to keep the water temperature at a certain level. The model of the dyeing process allows the user to choose if the results should correspond to winter- or summer mode, or yearly average. The results in this thesis will be based on the yearly average river temperature.

As mentioned in Section 4.6.3 the recovery potential of the water flow out of the cooling exchanger in the dyeing machines were about the be measured. The purpose of this was to investigate whether this water stream could be hot enough to be recovered. The result from this measurement can be seen in Figure A.1 in Appendix A. The measurement was performed during a dyeing program that can be seen as representative for most of the dyeing programs in terms of temperatures. The temperature of this water peaked at around 30°C, which could be argued to be worth recovering. However, most of the time this water was below 20°C which makes it questionable to recover any heat from this stream. On the other hand, instead of leading this stream down the drain it could be used instead of water coming straight from the river in another part of the process, since the additional heat this stream gains is a bonus compared to regular river water, no matter how small this additional heat may be. This stream could for example be used to support the river water entering the heat exchanger between the two accumulator tanks. However, in the model this stream is not accounted for in the heat recovery system.

Today the condensate from the steam heating the water in the dyeing machines are led to the dirty accumulator tank, to cover up for eventual leakage in the heat exchanger. This is because dyeing chemicals could end up in the clean accumulator tank, which would be hard to notice right away. However, the heat exchanger is of the type shell-and-tube, which should be trustworthy enough to not leak for the condensate to be led to the clean tank instead. This would save steam in the clean accumulator tank since the condensate is a very hot stream that today is not efficiently used, since it is mixed in the dirty tank and then heat exchanged. In the base mode the model aims to simulate the dyeing process as similar to how it works today, which is why the condensate will be calculated to be led to the dirty accumulator tank.

### 5.1.3 Sensitivity analyses

For the representative daily operation presented in Section 4.7.2, the regular operation conditions will be compared with alternated operation modes for the dyeing machines and the accumulator tanks. This to estimate possible energy savings, which in this case is by saving steam. The two steam streams in the dyeing section of the industry is the steam that is heating up the process water in dyeing machines and the steam that is heating up the water in the clean accumulator tank. This sensitivity analysis will aim to minimise the total of these steam consumptions.

Since the dyeing programs are set to certain conditions to assure a good dyeing result there will not be an effort made to try to change any of these conditions in the main tank where the dyeing is taking place. However, there are parameters affecting the energy use in the surrounding equipment that may be of subject to change.

*Set temperature in the clean accumulator tank.* The temperature in the clean accumulator tank is today set to 50°C. This may be questioned when it is combined with the filling operation of mixed water. Water is then first heated in the accumulator tank, cooled when mixed with river water and then heated again in the main tank. Therefore a sensitivity analysis of the set temperature in the clean hot accumulator tank was performed, see Figure 5.2.

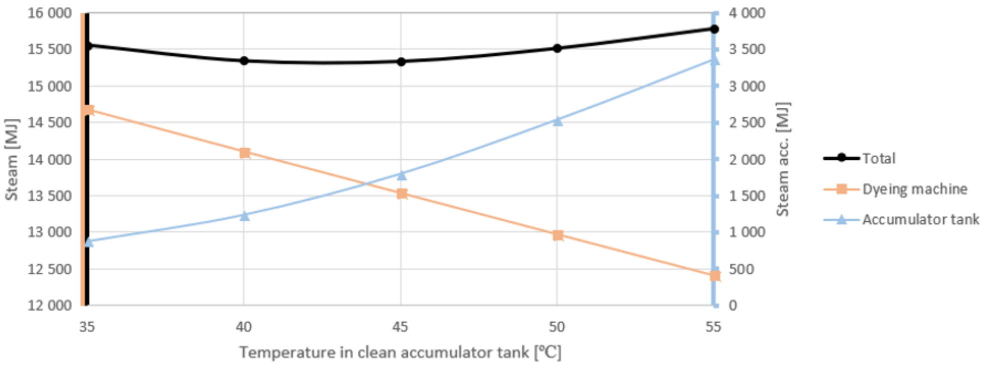

**Figure 5.2:** Steam consumption variation with a varied set temperature in the clean accumulator tank

It is quite trivial to understand that a lower temperature in the clean accumulator tank decreases the steam consumption here since it is steam that is controlling the temperature in the clean accumulator tank. The reason the steam consumption in the dyeing machine is increasing with a lower temperature in the clean accumulator tank is that the filling stream into the dyeing machines then is colder, which consequently increases the steam demand to raise the water to a certain temperature. Even though the trends of these two steam streams are strictly of the opposite character, the total steam consumption that is received when adding them together is not as clear. It can hardly be seen in the graph, but it is a marginal minimum for the tank temperature of 45°C for the representative operation. The total steam consumption of 40° and 45° is 15 350 MJ and 15 342 MJ, respectively, so the difference is however minor.

The reason a minimum steam consumption is in the middle of the range of temperatures is that the steam consumption in the accumulator tank is not increasing linearly with the increased tank temperature. A significant part of the steam consumption in the accumulator tank is the start up steam consumption, i.e. the steam it takes to in the morning, heat up the tank to the set temperature from the temperature the tank has after the steam has been switched off over the night. This means that this part of the steam consumption can not be significantly affected by changing the set temperature in the tank, other than that a smaller temperature difference between the tank and the ambient temperature slightly decrease the temperature fall. When the set temperature in the tank is lowered and the steam consumption is decreased, the greater part of the steam consumption is the start up steam consumption. When the temperature is lowered to 40°C the start up steam consumption part reaches a size where the benefit of a low temperature in the clean tank is smaller than the resulting extra steam consumption in the dyeing machine.

*Filling temperature of dyeing machines.* As mentioned in Section 4.6.1 the dyeing machines are in general filled with a mixture of cold river water and steam heated water from the accumulator tank. However, to investigate if this is the most effective operation from an energy perspective, this filling operation will be compared with filling by only cold water or only hot water. As can be seen in Figure 5.3 this significantly affects the steam consumption.

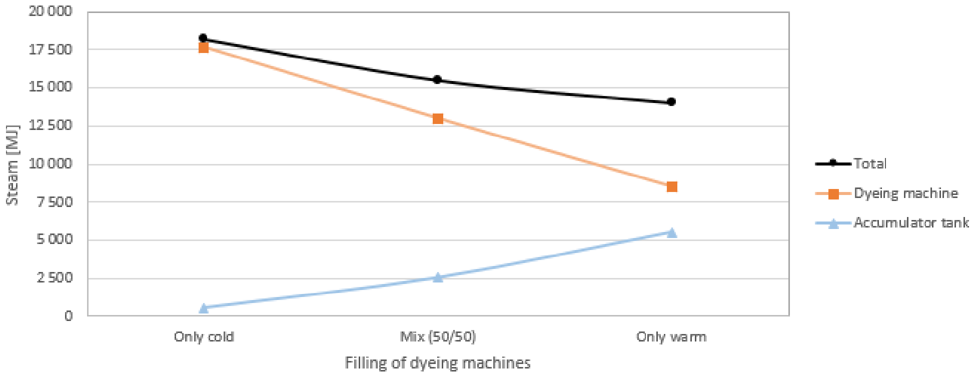

**Figure 5.3:** Steam consumption variation with a varied filling temperature of the dyeing machines

Similarly to the previous sensitivity analysis the trend of the steam consumption in the dyeing machines and the clean accumulator tank is of opposite character. In this case the decrease of the steam consumption in the dyeing machines is stronger than the increase of the steam consumption in the clean accumulator tank. This results in a clear decrease of the total steam consumption when filling by only warm water.

A reason for filling the machines with a mix of hot and cold water have been that the flow can be higher and thus the filling time decreased. However, since the total time of most programs is over 6 hours a few minutes longer filling would be fine. Since the yarn dyeing machines are using preheat tanks that can be filled simultaneously during operation, the total program time is not affected for most of the dyeing programs. Furthermore, if the machines would be filled by only hot water the duration of the following heating step would decrease.

*Minimum level in clean accumulator tank.* The minimum level in the clean accumulator tank is defining when the heat exchange with the dirty accumulator tank starts. Today this minimum level is set to about 16 300 litres. In this sensitivity analysis it is investigated how the steam consumption in the clean tank, and consequently the total steam consumption, will be affected if this minimum level is decreased, see Figure 5.4. The steam consumption in the dyeing machines is not included in this graph since it is not affected by these changes and thus stays constant.

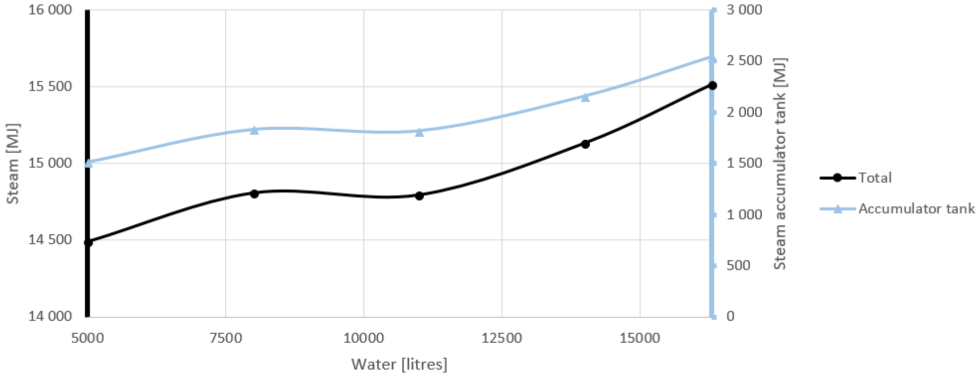

**Figure 5.4:** Steam consumption for various minimum levels in the clean accumulator tank

The irregular S-shape of the curve is due to the random timing of heat exchange and the temperature and volume of the water entering the dirty accumulator tank. For the minimum level of 8 000 litres the first heat exchange is occurring right after large amounts of colder ( 50°C) waste water has entered the dirty accumulator tank. Consequently the heat exchanged water flow into the clean accumulator tank is colder as well, which increases the demand for steam. Thus, it needs to be highlighted that the shape of the steam consumption would most certainly change if the representative operation would change.

However, the trend that the steam consumption is in general decreased when the minimum level in the clean accumulator tank is decreased is trustworthy. Because a lower minimum level will result in a lower level in general in the clean tank, which will require less steam to be kept at the set tank temperature. But since the flow out of the clean accumulator tank, i.e. for the refill of dyeing machines, can be larger than the flow in from the heat exchange the minimum level should not be set too low. With a minimum level of 5000 litres there will be a safe marginal to avoid that the clean tank will go empty.

*Refill target level in clean accumulator tank.* Another level parameter in the clean accumulator tank is to what level the tank is filled up to when a heat exchange is initialised. Since it might be another flow into or out of the tank simultaneously as it is filled up by the heat exchange this parameter is set to a certain fill target level above the minimum level in the tank. In Figure 5.5 it is visualised how this fill level above the minimum level is affecting the steam consumption in the accumulator tank.

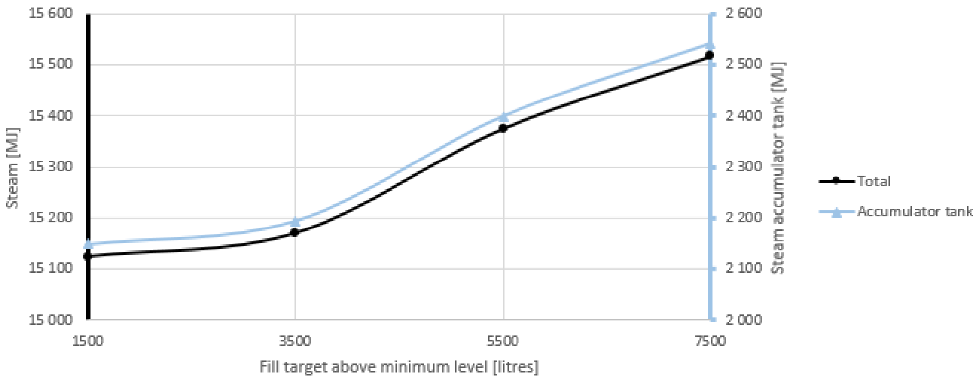

**Figure 5.5:** Steam consumption variation when fill level above the minimum level of clean accumulator tank is varied

The steam consumption slightly decreases with a smaller fill target level. Again the random timing of heat exchanges and the temperature in the dirty tank is making the trend a bit nonlinear. Since the change in steam consumption for the different fill levels are relatively small, the timing of the other flows in and out of the clean accumulator tank affects these small changes in steam consumption. The smaller the fill target is, the sooner the level will go down to the minimum level again and initialise a new heat exchange. This means that a smaller fill target level increases the number of heat exchanges, which further might tear on the pumps that is operated during a heat exchange. Therefore the fill target level should not be too small even though it seems like a smaller fill target than 1500 litres would decrease the steam consumption even more.

*Combination of sensitivity analyses with varying temperature and lowered start level in clean tank.* Finally the parameters showing the best result in the previous sensitivity analyses will be combined and analysed with a varying clean tank temperature. This is since the clean tank temperature showed a trend in the steam consumption minimisation that had a marginal peak in the middle of the tested range, and it needs to be verified that this would still be the most beneficial temperature with a change in the other parameters. Furthermore, with a considerably lower minimum level and fill up level it is not reasonable with the original start level in the clan tank of 16 300 litres. Since the level in the end of the representative daily operation for the lowered conditions is slightly above the minimum level, a new start level of the clean tank was estimated to be 7 000 litres. As can be seen in Figure 5.6 the tank temperature of 40°C now slightly was the most beneficial temperature from a steam saving perspective, when combined with the other changed parameters.

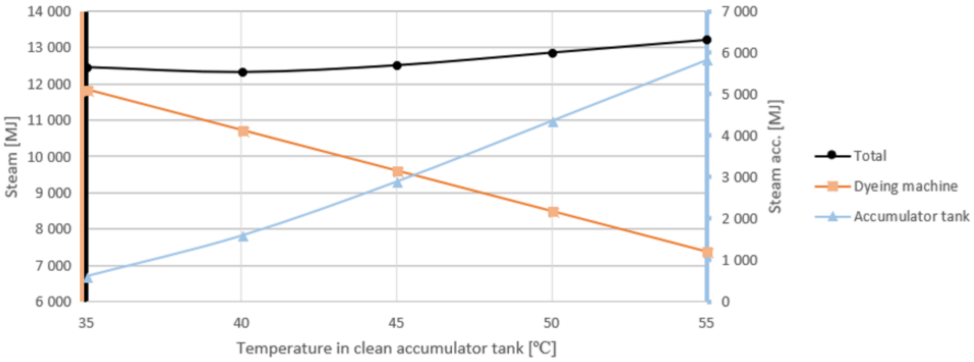

**Figure 5.6:** Steam consumption for different clean tank temperatures when the most beneficial parameters from sensitivity analyses is applied

Therefore this operation had the highest steam saving potential that was found in these sensitivity analyses. To lower the temperature in the clean accumulator tank to 40°C is not limiting the temperature of the two inflows of water into the clean accumulator tank. As can be seen in Figure A.3 and Figure A.7 in Appendix A it is rare that any of these flows exceeds 40°C, which means the temperature of the clean tank would not exceed 40°C, by these streams. However, a drawback with lowering the temperature to 40°C that needs to be considered is the spread of legionella. This is a bacteria that reproduces the most between 35°C and 40°C [27].

By changing the operation parameters to what the sensitivity analyses suggests the steam consumption in the dyeing process could be decreased by more than 20%. Related to the steam savings, the proposed operation also decreases the drain heat losses from the dirty accumulator tank by over 25%. This since the smaller but more frequent heat exchanges utilise the hot water in the dirty accumulator tank better than large and few heat exchanges. The saved steam corresponds to a saving of 26.2 tonnes LPG per year, which further saves over 100 000 SEK yearly and decreases emitted $CO_2$ by 76.5 tonnes every year. See Table 5.2 for a summary of the differences between the current and proposed operation, along with the corresponding savings the proposed operation would have for the representative dyeing operation.

**Table 5.2:** Comparison of parameters of current operation and proposed operation, along with the savings of proposed operation for the representative daily operation

| | **Current operation** | **Proposed operation** |
|---|---|---|
| Clean tank temperature [°C] | 50 | 40 |
| Filling of machines | Mix (50/50) | Only warm |
| Minimum level clean tank [litres] | 16 300 | 5 000 |
| Fill level clean tank [litres above min.] | 5 000 | 1500 |
| **Total steam savings [%]** | - | **20.5** |
| **Decreased drain losses [%]** | - | **25.8** |
| **Saved LPG [tonnes/year]** | - | **26.2** |
| **Decreased $CO_2$ emissions[tonnes/year]** | - | **76.5** |
| **Economic savings [SEK/year]** | - | **103 000** |

### 5.1.4 Model uncertainties

A prominent potential source of error for the heat recovery system are the actual losses of the system. For the dyeing processes, radiation and evaporation losses are estimated, but as they are approximated with average temperatures of the surroundings these might be inaccurate. A likely larger error of the calculations are the neglected transmission losses of the process water streams. For the yarn dyeing area, which is the most energy intensive dyeing area, the losses for transmission are likely to be noticeable due to a significantly longer distance to the accumulator tanks. In addition, for the accumulator tanks the only losses are those due to radiation, which also are approximated with average surrounding temperatures. Especially the transmission losses but also other losses could likely add up to an overestimation of the temperatures in the dirty hot tank. As most of the surrounding calculations are based on these temperatures, this could also lead to subsequent overestimations in terms of temperatures. With an overestimated temperature in the clean hot tank, the corresponding steam consumption for keeping the target temperature, would instead be underestimated.

Other potential errors could be the estimated overall heat transfer coefficient of the heat exchanger between the two accumulator tanks. As this might vary, mainly with the outdoor water temperature throughout the year, the estimated temperature lift could be inaccurate which could induce further errors.

Another notable circumstance is that the representative daily operation only is an estimation of the daily processes in the dyeing areas. These estimations, in combination with the estimated start temperatures in the different accumulator tanks, only show a possible scenario during a day. However, as these are assumptions and the actual values vary from day to day the actual behaviour of the water level, in the clean hot tank in particular, may behave considerably different from that of the representative daily operation.

Another factor to consider is that the dyeing programs are constructed with no room for unforeseen events. This means that a whole dyeing process may take longer time than it theoretically should.

The temperature of the river water is varying almost 20°C during a calender year. Even though an average temperature is used in the models produced in this thesis, these variations have a significant impact of the process.

## 5.2 Drain water recovery

In this section the result from the drain water recovery model will be presented and discussed. Just as in the previous section the result will be estimated by running this model for the representative daily dyeing operation. First the heat pump integration will be analysed for both the current dyeing process operation and the proposed dyeing process operation that was presented in the previous subsection. Then an additional drain water recovery concept will be presented for further investigation.

### 5.2.1 Integration of heat pump

Other than only a heat pump, the investment of an additional heat exchanger was a part of the heat pump integration concept presented in Section 4.6.4. It could be argued that this additional heat exchanger would decrease the efficiency of the already existing heat exchanger. However, the additional accumulator tank is a heat source that otherwise would not be fully utilised. Because it was shown through tests in the model that the water in the additional accumulator tank was too hot to be led to the heat pump accumulator tank when it would be full, as the dotted black arrow shows. Thus, the additional accumulator tank has a heat capacity that would not have been utilised otherwise. But if this additional accumulator tank would not have been for the purpose of integrating the heat pump, it could have been questioned if it would not have been a better idea to improve the performance of the already existing heat exchanger instead.

Since the main energy saving potential in this concept lied in the integration of a heat pump, the investment of the additional heat exchanger was not thoroughly investigated. Without deep contemplation this was assumed to be a plate heat exchanger of the same characteristics as the already existing plate heat exchanger. The only difference was that the new heat exchanger had a higher U-value and were half the size, which would be appropriate for the varying operation conditions for this heat exchanger. The calculations of the streams involved in this heat exchanger were preformed in the same manner as it was explained for the already existing heat exchanger in Section 4.6.3.

When searching for a heat pump to utilise the drain water out of the dyeing recovery system, focus was in finding a heat pump that could allow a water inflow temperature of approximately 20°C to the evaporator. This since the drain water out of the dirty accumulator tank through modelling showed to be able to keep a constant temperature in the heat pump accumulator tank of approximately this temperature. First a heat pump supplier that offered hybrid heat pumps were contacted due to the flexible operating conditions of a hybrid heat pump, but the steam saving possibilities appeared to not be sufficient to cover the high investment cost of a hybrid heat pump. After further research a company called Carrier was found, that had a series of mechanically driven heat pumps called 61WG that could handle liquid evaporator inflows of 18°C [28], which could be up to 25°C from consultancy with Carrier. Furthermore, there was one heat pump series with a leaving water temperature (LWT) satisfying the current operation and another series with a LWT suitable for the proposed operation. Both heat pump series that will be considered has the cooling media R-410A, a temperature fall of the water flow through the evaporator of 3°C and a temperature increase of the water flow through the condenser of 5°C for LWT below 55°C. Heat pump specific data will be presented further down.

When assessing the heat pumps the focus will be on the steam consumption in the accumulator tank, since that is the only steam consumption that will be affected by the different heat pumps, along with the corresponding payback period. The payback period is calculated from how much steam the heat pump is saving in comparison with the same operation without the heat pump. Then this decrease in steam will be converted into saved LPG and furthermore to saved money by a decreased LPG consumption. The costs included when calculating the payback period was the investment cost for the heat pump, the two additional accumulator tanks and the heat exchanger. The investment cost of the heat pump was received from Carrier and the other investment costs were estimated from typical investment cost of the equipment. An estimated installation cost of 50% of the investment costs were also included. Other than that the economical analysis was performed as explained in Section 2.7.

*Heat pump for current operation.* When investigating in a heat pump integration for the current operation the LWT was desired to be 50°C since that is what the clean tank temperature is set to in the current operation. The heat pumps in this series was in the range of 33-130 kW. It was the five smallest of these heat pumps, regards to heat capacity, that turned out to show the best results for this case. Specific data for these heat pumps, with Carrier index names of 020-040, can be found in Table 5.3.

**Table 5.3:** Heat pumps with LWT of 50°C analysed for the current operation

| **Parameters** | **020** | **025** | **030** | **035** | **040** |
|---|---|---|---|---|---|
| Heat capacity [kW] | 32.8 | 38.8 | 43.6 | 50.2 | 57.0 |
| COP [kW/kW] | 4.52 | 4.48 | 4.35 | 4.40 | 4.39 |
| $m_{cond}$ [litre/s] | 1.6 | 1.9 | 2.1 | 2.4 | 2.7 |

It appeared that the steam consumption was decreased when the capacity of the heat pump was increased. However, the additional saved steam could not cover up for the additional investment and pump cost, which resulted in increased payback periods, see Figure 5.7.

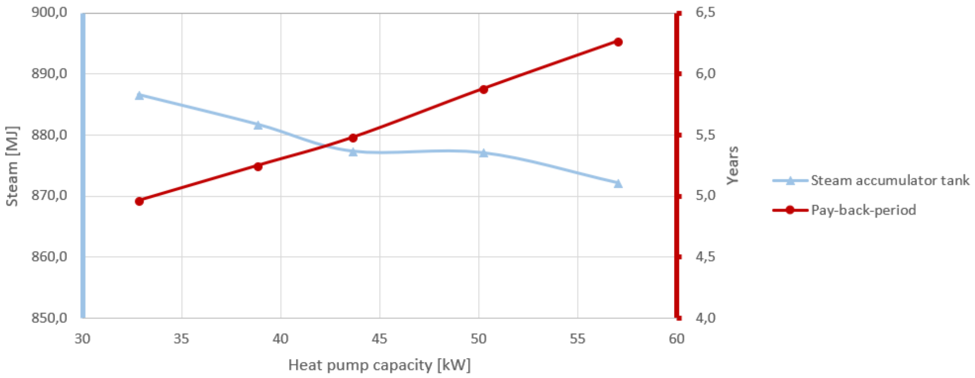

**Figure 5.7:** Steam consumption in the accumulator tanks with the corresponding payback period for heat pumps suitable for the current operation

When these heat pumps were applied it was only in the beginning of the representative day that steam was needed in the clean accumulator tank to keep the desired temperature. This was the case despite that the drain water recovery model starts with the desired temperature in the clean accumulator tank, i.e. steam is accounted to take care of the first heat up of the tank in the morning. This first heat up requires steam of 355 MJ, but the remaining approximately 500 MJ of steam is consumed during the first half an hour of operation. The reason the heat pumps still can not take care of the heat demand in the clean accumulator tank in the beginning of the day is that the heat source of the heat pump is the drain water. It takes almost 10 minutes before there is any drain water at all, and then it takes around 20 minutes more before there is enough hot drain water to make it possible for the heat pump to satisfy the heat demand. During this first half an hour in the representative day it is multiple fillings of machines, which makes this extra critical. It could therefore be of beneficial character to investigate if there is any possibility to preheat the heat pump accumulator tank for the critical start of the dyeing operation.

*Heat pump for proposed operation.* In the proposed operation the temperature in the clean accumulator tank is lowered to 40°C, which makes the LWT of the heat pump for this integration desirable to be 40°C as well. As mentioned before, the proposed operation use hot water when filling up the dyeing machines, in comparison with the current filling of a 50/50 blend of hot water and cold river water. This results in a doubled demand of hot water from the clean accumulator tank, but due to the significantly lowered level in the clean tank the steam demand in the accumulator tank is still decreased.

Therefore it was the five smallest heat pump in the Carrier series, regards to heat capacity, that resulted in the lowest payback periods for the proposed operation as well. However, with a lowered LWT the other parameters are a bit increased, see Table 5.4.

**Table 5.4:** Heat pumps with LWT of 40°C analysed for the proposed operation

| **Parameters** | **020** | **025** | **030** | **035** | **040** |
|---|---|---|---|---|---|
| Heat capacity [kW] | 34.9 | 41.5 | 46.0 | 52.7 | 59.7 |
| COP [kW/kW] | 5.65 | 5.46 | 5.38 | 5.45 | 5.45 |
| $m_{cond}$ [litre/s] | 1.7 | 2.0 | 2.2 | 2.5 | 2.9 |

As can be seen in Figure 5.8 the steam consumption in the accumulator tank is slightly lowered when the heat pump capacity is increased. That is because a higher heat capacity increases the volume flow of heated water out of the condenser, which further make the heat pump able to cover a larger heat demand.

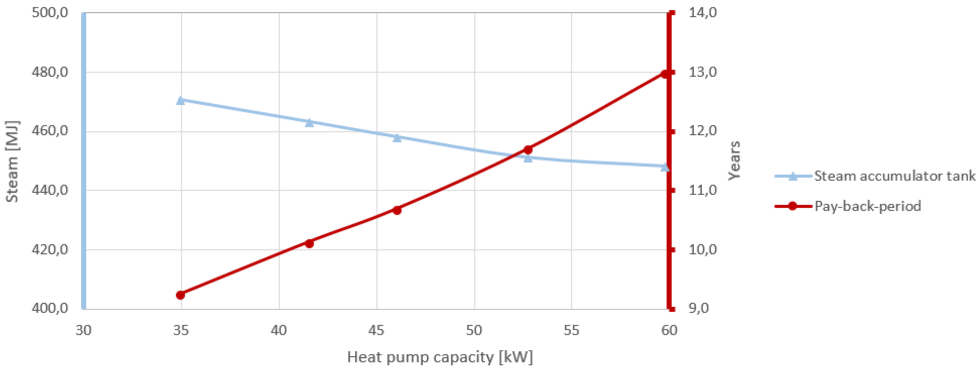

**Figure 5.8:** Steam consumption in the accumulator tanks with the corresponding payback period for heat pumps suitable for the proposed operation

However, the payback period for the proposed operation is significantly increased compared to the payback period for the current operation. This is due to the fact that for the proposed operation the steam consumption in the accumulator tank already is cut to an extent that the heat pump can not save enough steam to generate a low payback period.

Because in the proposed operation all consumed steam is the steam it takes to heat up the clean tank to the set temperature in the morning and the steam consumption in the beginning of the representative day. The start-up steam consumption in the accumulator tank can not be covered by the heat pump, since the heat pump is dependent of drain water that not exist until the dyeing process have started. Then similarly to the heat pump integration for the current operation the heat pump can not fully cover the heat demand in the beginning of the representative day. This is because multiple machines are starting up in a short time interval, which initiates heat exchange with the dirty accumulator tank, that further results in cold drain water and too cold condition for the heat pump to operate.

After the initial steam consumption no more steam is needed in the accumulator tank during the proposed operation of the representative day for these heat pumps. But for the proposed operation this does not save enough steam to achieve a low enough payback period for an investment recommendation. Even though it was the same heat pump that resulted in the lowest payback period for the proposed operation as for the current operation, the *020 Carrier* heat pump, an investment is not recommended for the proposed operation.

In Table 5.5 the outcome of this heat pump integration investigation is summarised for both the current and the proposed operation of the representative daily dyeing operation. The economic analysis assumes that the cost for gas is constant.

**Table 5.5:** Summary of heat pump integration investigation for current and proposed operation

| Parameters | Current operation | Proposed operation |
|---|---|---|
| Leaving water temperature (LWT) [°C] | 50 | 40 |
| Heat capacity [kW] | 32.8 | 34.9 |
| Steam consumption acc. tank [MJ] | 886.7 | 470.6 |
| Total steam savings [MJ/year] | 396 790 | 269 220 |
| Payback period [years] | 4.96 | 9.24 |
| Savings after payback period [SEK/year] | 45 940 | 29 870 |

### 5.2.2 Model uncertainties

Even though the representative daily operation consists of the most common programs it is not common that a day in the dyeing part of the industry looks exactly like that. There are fluctuations between what programs are operated during a day, which further affects all flows in the dyeing process. It is around 6 programs operated each day in average, but some days it can be more and some days less.

Due to the dynamic characteristics of the dyeing operation and the following uncertainties a more perspicuous analysis of a heat pump integration was estimated to be suitable for this thesis. For a more detailed and accurate analysis it could have been investigated in for example different cooling medias or different kind of heat pumps, e.g. the hybrid heat pump.

The highly varying level in the clean accumulator tank makes it hard for a heat pump to keep the temperature exactly constant, if the heat pump should be efficiently operated as continuously as possible. In the model including the heat pump there was therefore set a temperature tolerance of 5°C of the set temperature, which means that for the current operation the temperature is allowed to vary between 45°C and 55°C. The average temperature in the clean tank during the representative daily operation still is the set temperature of 50°C, so this inaccuracy does not affect the total steam consumption.

### 5.2.3 Additional concept for further investigation

Except the drain water recovery model that has been presented an additional promising concept for drain water recovery were found. However, this was in the end of the thesis and there was no time to construct a model out of this concept. For the purpose of further investigation it will still be presented here.

Instead of utilising the water going down the drain from the accumulation system this concept aims to minimise the flow of hot water down the drain instead. This is achieved by adding an accumulator tank for clean water after the heat exchanger, see Figure 5.9.

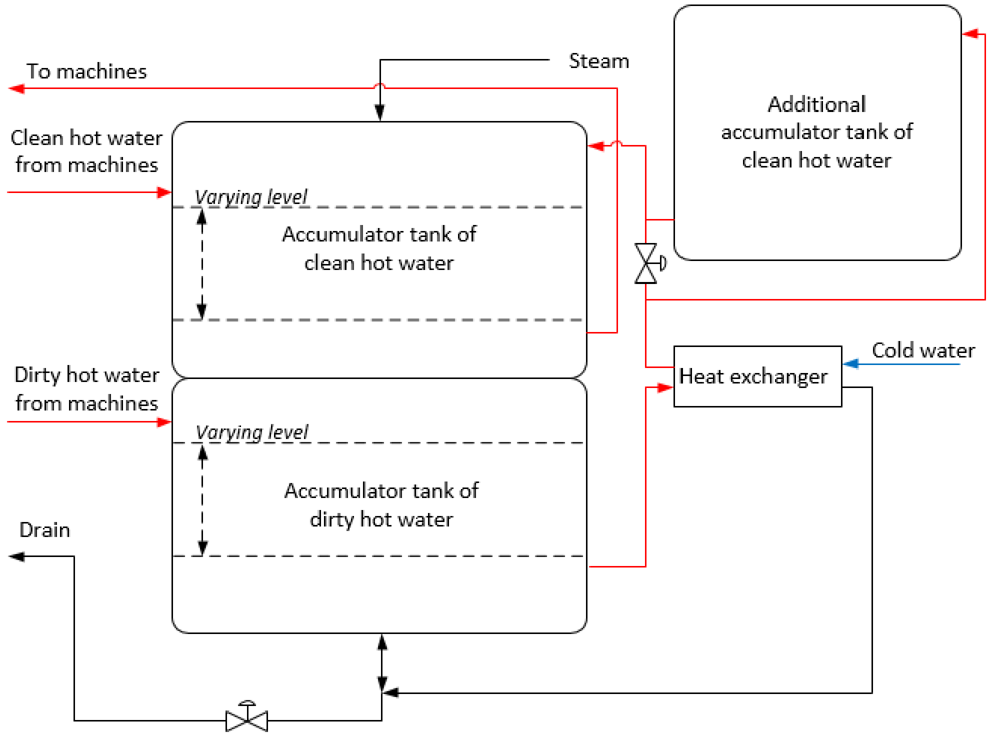

**Figure 5.9:** Layout of the accumulation system if another accumulator tank for clean water would be included

The purpose of this additional accumulator tank is to decrease the losses down the drain by heat exchanging whenever there are large amounts of water entering the dirty tank, even when there is not a demand for heat exchange in the clean tank. This heat exchange water could instead be stored in the additional accumulator tank of clean water until there is a demand in the regular large clean hot tank. When there is a demand for hot water in the clean tank the additional clean tank could also be bypassed.

The level in the dirty tank would then have to vary, to make it possible to start a heat exchange whenever large amounts of hot water enter. A pressure valve under the dirty tank would take care of this level regulation by only letting water pass if the level in the dirty tank reaches an upper set level. Then the U-shaped draining pipe could be adjusted to a lower level than it is today to guarantee a lower lowest level of the dirty tank. The pressure valve could be set off to during night time so it only is this new lowest level that need to be heated up the following morning.

## 5.3 Flue gas heat recovery

This section includes the outcome of the investigation of the flue gas heat recovery evaluation. The model validation is followed by the analysis of installing a heat recovery unit. Further a potential integration with current system is presented.

### 5.3.1 Validation of model

Studying the obtained production data for the stenters for February 2018, it could be concluded that only Stenter 3 would be relevant for a possible investment of heat recovery equipment. In order to analyse the accuracy of the estimations of the flue gas recovery potential, the actual LPG consumption was to be verified with the estimated energy output. Stenter 3 was recently equipped with a gas meter that displays the LPG consumption in $[m^3]$. To receive an indication that the amount of flue gases is a reasonable estimation of reality, the operators of the stenter, were asked to document the LPG consumption every day during a few weeks. Unfortunately, the gas meter was installed after the period that the obtained production data covers, but in agreement with AB LS the weeks with manual gas readings could be considered as representative. The gas consumption for a few weeks are summarised in Table 5.6. The table also includes the estimation of the theoretical gas consumption for February 2018 that was to be used for model verification.

**Table 5.6:** Summary of the gas consumption in Stenter 3 for a few weeks in March 2018

| | **Gas consumption** $[m^3]$ |
|---|---|
| **Week 11 (5 workdays)** | 267.2 |
| **Week 12 (5 workdays)** | 408.3 |
| **Week 13 (4 workdays)** | 426.0 |
| **Week 14 (4 workdays)** | 236.6 |
| **Week 15 (5 workdays)** | 274.2 |
| **Week 16 (5 workdays)** | 361.1 |
| Sum workdays: 28 | |
| **Avg. per day** | 70.5 |
| **Est. Feb. 2018 (20 workdays)** | 1410 |

With a given estimation of the LPG consumption, this could be compared with the energy output of the flue gas model. The power of the flue gases was estimated with Equation 5.1. The mean power each minute was calculated according to the temperature profile in Section 4.6.5, illustrated in Figure 4.8.

$$P_{fg}(min) = \dot{m}_{fg} * c_{p,fg} * (T_{fg,in}(min) - T_{amb}) \quad \textbf{[kW]} \tag{5.1}$$

From the flue gas effect, the total energy of the flue gases consequently could be estimated. For each operating minute of the day the energy content of the flue gases was estimated. Summing for each operating minute, the total energy supplied could be estimated for the average day.

$$Q_{fg,day} = \sum_{min=1}^{n} P_{fg}(min) * \frac{60s}{min} = 9664 \quad \textbf{[MJ]}$$

where $n$ is the number of minutes the machines are operated during the average day. Given the number of workdays in February, the total estimation of the energy content for that period could be estimated:

$$Q_{fg,Feb} = Q_{fg,day} * 20 \text{ workdays} = 1.93 * 10^5 \quad \textbf{[MJ]}$$

The actual energy consumption, calculated from the gas readings, was estimated from the energy content of the LPG, $h_{LPG} = 46.1\frac{MJ}{kg}$ and the density of the LPG, $\rho_{LPG} = 2\frac{kg}{m^3}$. In Table 5.6, the estimated gas consumption was found as $V_{act,Feb} = 1410\ m^3$, which enabled the comparison of the energy consumption.

$$Q_{act,Feb} = V_{theo,Feb}[m^3] * \rho_{LPG}\left[\frac{kg}{m^3}\right] * h_{LPG}\left[\frac{MJ}{kg}\right] = 1.3 * 10^5 \quad \textbf{[MJ]}$$

This makes the deviation between the calculated energy content and the theoretically estimated energy $Q_{diff,LPG}$=$Q_{fg,Feb} - Q_{act,Feb} = 6.3 * 10^4$ MJ. This corresponds to:

$$\text{number of days difference} = \frac{Q_{diff,LPG}}{Q_{fg,day}} = 6.5 \quad \textbf{[days]}$$

As the deviation shows that the calculated energy content is larger, it can be concluded that this is somewhat overestimated. The difference indicates that some of the estimations in the assumed representative average temperature profile, are overestimated from the actual scenario. The deviation from the monthly average are to be taken into account in an investment analysis but the behaviour is considered to be reasonable enough for model verification.

### 5.3.2 Data analysis

The key factor for the outcome of a flue gas heat recovery equipment is the generation and accumulation of flue gases in the chimney regards to temperature and volume flow. These parameters were measured to a maximum of 135°C and 11 m/s when the targeted temperature was 150°C in the stenter. However, due to occasional technical issues with the burners in the stenters, during the studied time slot, the targeted temperatures were often lagging. This also resulted in that the actual temperature in the stenters were varying a lot. Given the conditions of the stenter during the studied time period, a possible temperature drop from the stenter through the duct to the roof, could not be determined. Yet, from consultation with AB LS an average temperature in the stenters could be assumed as 140°C.

From the studied production planning in combination with interviews with the operators of the stenters the following could be concluded:

- Average batch run time: 29 min
- Batch change time: 30 min
- Average temperature in stenter $T_{avg} = 140°\text{C}$ during operation

As a first step to analyse the potential of installing a heat recovery unit, the scenario of constant flow with the average temperature was investigated. As described in Section 4.6.5, the model was constructed to evaluate different designs for the water output. These outputs, with the maximum potential, are visualised in Table 5.7.

**Table 5.7:** Maximum heat recovery potential of flue gases

| **Water temperature [°C]** | **Water volume [m$^3$/h]** | **Thermal water power [kW]** | **Payback period [year]** |
|---|---|---|---|
| 30 | 8.79 | 204.1 | 3.3 |
| 40 | 5.12 | 178.6 | 3.9 |
| 50 | 3.30 | 153.1 | 4.8 |

However, as earlier mentioned there are significant amount of interruptions of the production which means that this maximum potential is not consistent. This is mainly because of the small batches and the time it takes to change between batches. In order to imitate the typical way of operation a temperature profile was estimated from the production data. This enabled an estimation of the actual potential of installing a flue gas heat recovery equipment. Translating the model output into hourly average, this ended up in an approximated heat recovery as stated in Table 5.8.

**Table 5.8:** Heat recovery potential of flue gases at current operation conditions

| **Water temperature [°C]** | **Average water volume [m$^3$/h]** | **Average thermal water power [kW]** | **Payback period [year]** |
|---|---|---|---|
| 30 | 4.14 | 96.2 | 9.3 |
| 40 | 2.41 | 84.2 | 11.7 |
| 50 | 1.55 | 72.2 | 15.6 |

It can be concluded that the benefit of installing the heat recovery equipment is varying a lot between the ideal scenario and the estimation of the actual scenario.

With the approximation of the daily temperature profile the water outputs could be estimated for the actual scenario, see Figure 5.10. Given the temperature requirements for supplying the water output, the behaviour of the water output can easily be related to the temperature profile.

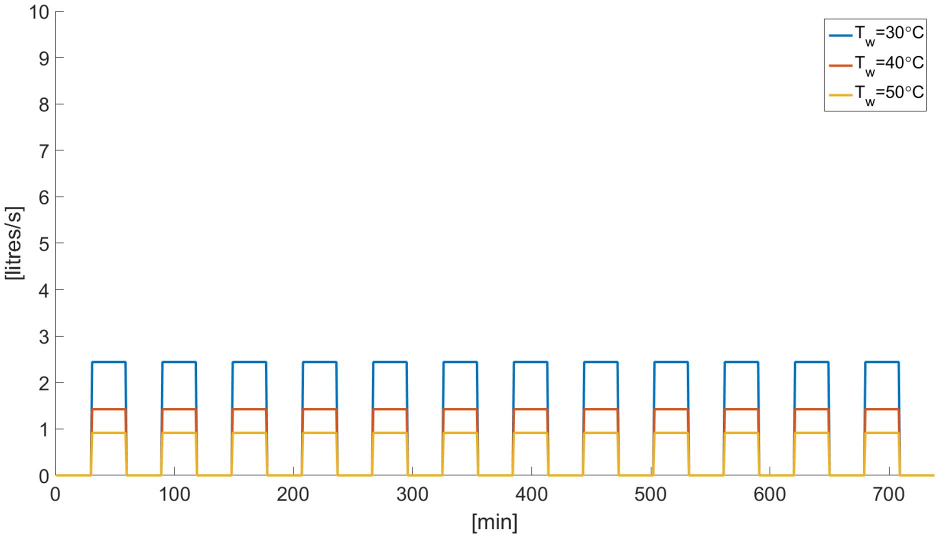

**Figure 5.10:** Approximated behaviour of the water output from the estimated temperature profile

From the result of the flue gas recovery of current operation it is hard to defend an investment of a heat exchanger. The amount of time required for change of batch is considerable from a heat recovery perspective. This is since the LPG burners generating the flue gases usually are switched off between the batches, which causes the temperature of the flue gases to decreased to around 50°C during that period. This is of course better in terms of energy efficiency but the temperature fluctuations will likely affect the efficiency of the flue gas heat recovery equipment.

The stenter is operating at an average speed of 10 meters per minute and the average length of a batch is roughly 260 meters, which means an average batch is produced during 26 minutes. In addition, an extra 3 minutes is added to the batch change time if the stenter needs to be emptied between batches. Still, the time it takes to detach the fabric, attach a new batch of fabric and change the operation conditions, such as temperature or width, takes roughly 30 minutes. This means that during the two daily shifts (roughly 16 hours) the stenters are operated, flue gases are on average generated half of the time. Furthermore, some batches do not require as high temperatures as the batches that are generating the maximum temperature of the flue gases. In average the temperature of the flue gases is 140°C but there are also batches that are treated at the ambient air temperature, just for ventilating the fabric.

### 5.3.3 Integration with dyeing process

One way to integrate the flue gas recovery is to apply a heat exchange with water that is led to the clean accumulator tank, see Figure 5.11. In this way the heat recovery from flue gases would decrease the steam consumption when the stenters are running, while the accumulator system operates as usual when the stenters are not generating hot flue gases.

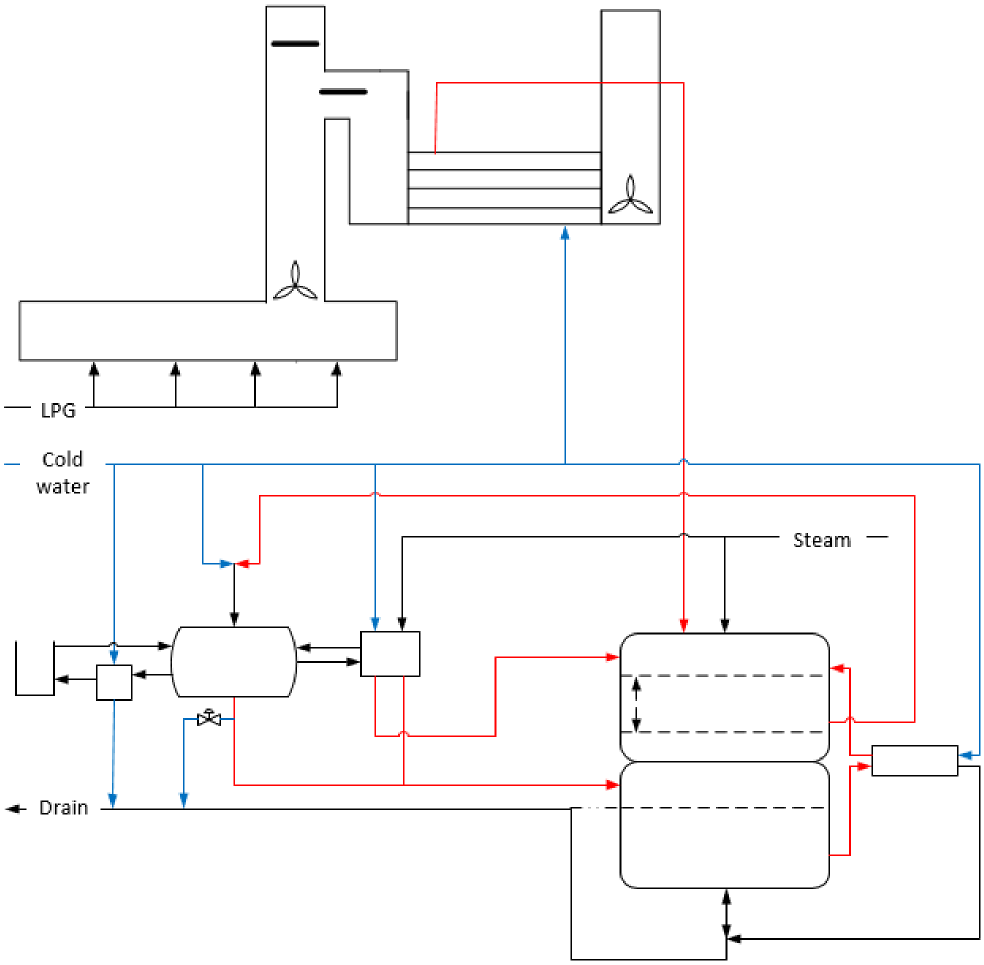

**Figure 5.11:** Preliminary overview of integration of flue gas heat recovery

However, this might be insufficient if the volume flow of water from the heat recovery would be of a size that can not be handled by the limited size of the clean accumulator tank. Even though the hot water in the clean accumulator tank is led to the dirty accumulator tank when it is full, the steam saving potential of the flue gas heat recovery decreases. It needs to be highlighted that the payback periods for the flue gas heat exchangers were calculated for the case that all heated water would replace steam that consequently would replace LPG. But if the heated water would be led to the clean accumulator tank and it would be full, not as much steam would be saved and the payback period would be increased. Since the payback period for investing in a heat exchanger for flue gas recovery with the current operation already were high it would not be invested time in estimate an even higher payback period of an integration with the accumulation system.

But if the operation of the stenters would change to a more continuous operation with less interruptions it could be economically viable with an integration with the accumulation system. Then, with larger volumes of hot water from the flue gas heat exchange, an investment in an additional accumulator tank for this hot stream may be considered. In that case an economic analysis of the payback period for this investment would be needed. Alternatively it could be enough to lower the levels in the clean accumulator tanks as in the proposed operation. Then it would be more space for hot water from the flue gas heat exchange in the already existing clean accumulator tank. Anyhow, it should also be considered that leading larger volumes of water into the system may also be risky with regards to the total efficiency of the process, since an increase of inflow to the system means an increase of the outflow as well.

Another integration possibility could instead be an installation of the flue gas heat recovery unit so water destined for, or already in the clean accumulator tank is heated. This would not need the consideration of extra streams into the system but would instead need further investigation in control strategy of the accumulator system, the clean tank in certain. This concept was however not evaluated further due to the current operation of the stenters.

### 5.3.4 Model uncertainties

The model only estimates the energy potential for heat recovery of the flue gases. However, as mentioned in Section 3.3.4, the flue gases from the stenters may contain contamination from previous production steps of the yarn or fabric. How this contamination will influence the heat recovery, for instance the risk for fouling of the heat recovery equipment, is not considered within the thesis. Another potential source of error since the actual content of the flue gases is not known, is the heat capacity of the flue gases. It is modelled as air but if it contains oil or other media with a different specific heat capacity the actual potential could diverge. This is recommended to be evaluated further before a possible implementation of a heat recovery equipment is done.

# 6

# Conclusion and Recommendations

## 6.1 Final recommendation

Here the final recommendations from this energy efficiency investigation will be concluded. First the recommendations that can be applied right away will be presented, which will be followed by the recommendations that requires investment in new equipment.

### 6.1.1 Current equipment

In the current operation of the dyeing process the prioritisation lies in an operation that runs smoothly without any interruptions. From a guarantee of delivery point-of-view this is a good approach, but such operation is on the expense of the efficiency of the processes.

With the models constructed in this thesis the flows and levels have been mapped accurate enough to see the result of changing the way to operate. By performing this theoretically it was affordable to try a wide range of changes, some that just made the operation worse from an energy perspective. But in the end an operation of significant energy savings was found, without changing any of the current equipment or any investment costs.

This new way of operation, that has been denoted as *the proposed operation*, includes:

- Filling of dyeing machines by only warm water from accumulator tanks
- Lowering the temperature in the clean accumulator tank
- Lowering the water level in the clean accumulator tank
- Make the heat exchanges between the accumulator tanks smaller and instead more frequent.

The result of these regulations have theoretically been measured to decrease the total steam consumption with over 20%, which would save approximately 103 000 SEK/year in decreased consumption of the base fuel LPG. Furthermore, the heat losses in drained water would be decreased by 25%.

### 6.1.2 Investing in additional equipment

Despite the significant energy savings that were possible without any need of investment, more savings were possible if there would be interest in investing in new equipment. This part of the investigation were focused on possible heat recovery of the flue gases from the stenters and utilising the drain water from the accumulator tanks by investing in a heat pump.

With the current irregular operation with small batches in the stenters the generation of flue gases was not consistent enough to justify in an investment of a heat exchanger of a suitable size. However, a model was created that showed that an investment of a heat exchanger would be profitable if the operation planning of stenters would change to a more consistent operation with less interruptions.

When investigating in the integration of a heat pumps in the drain water recovery system, both the current operation and the proposed operation were evaluated. The result was that it was the very same heat pump that gave the shortest payback period for both operation modes. For the current operation mode that heat pump saved enough steam to have the investment payed back in five years, while it for the proposed operation would take over 9 years for the heat pump investment to be profitable. Thus, an investment of a heat pump for the current operation is a relatively good option, while it is not profitable for the proposed operation.

If the proposed operation is applied, a further investigation of the pump used for heat exchanging between the accumulator tanks is recommended. This is because the proposed operation increases the pump usage since more heat exchanged water is needed. The pump is old, and if it operates inefficiently, there could be savings associated with replacing the current pump.

In conclusion, the final recommendation is to apply the proposed operation, which saves enough steam and LPG that it for the current production schedule is not profitable with investment of the additional equipment that has been investigated in this thesis.

## 6.2 Future research

In this thesis the steam consumption in the dyeing and drying processes of the textile industry have been analysed and decreased. However, steam is also used for space heating, which have not been part of this steam saving investigation. Even though this is a subject in the ongoing energy cooperation between AB LS and ÅF, it could be looked further into in a future research.

When constructing the models in this thesis effort has been made to make them as flexible as possible. This was successfully accomplished, but all investigations of changing parameters or conditions have to be made manually. To instead construct models that can be optimised automatically would be beneficial in a future research.

A deeper investigation in the production planning for the benefit of minimising the energy consumption could be a a subject for future research. It could then also be looked into how the production planning could be changed for an increased energy efficiency, without changing the priority of satisfying the orders from the customers as fast as possible.

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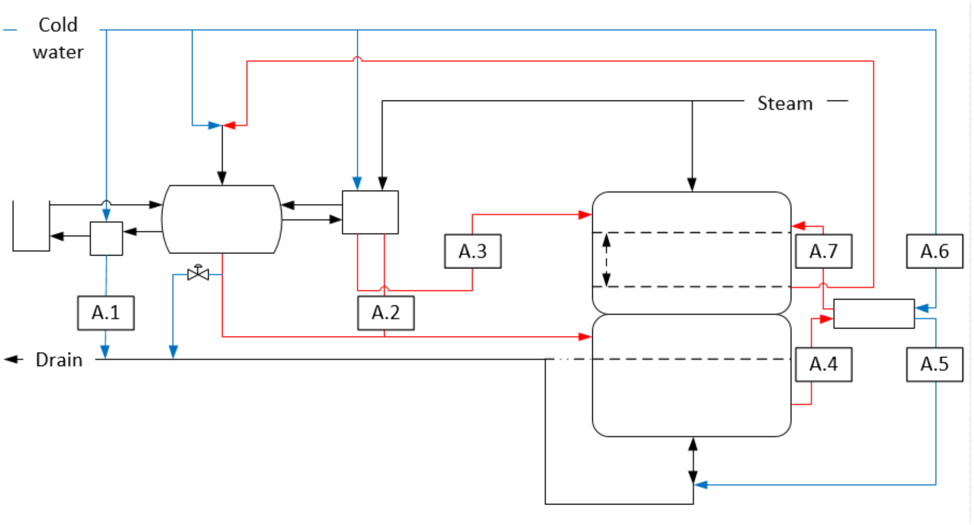
# A

# Appendix A - Temperature logs

Appendix A includes a selection of the temperature measurements that was performed during the project. The figure below shows the location of the each temperature log.



For the dyeing processes, the temperature logs were used for verification or investigation of some of the involved streams. In the accumulator system the temperature logs were helpful for investigation of the behaviour of the system. Also the temperature logs could give indications of how well the heat recovery system work. All temperature logs have been measuring irregular flows, which means that it is only the peaks in the graphs that is the actual temperature of the flows, the constant temperatures is the ambient temperature.

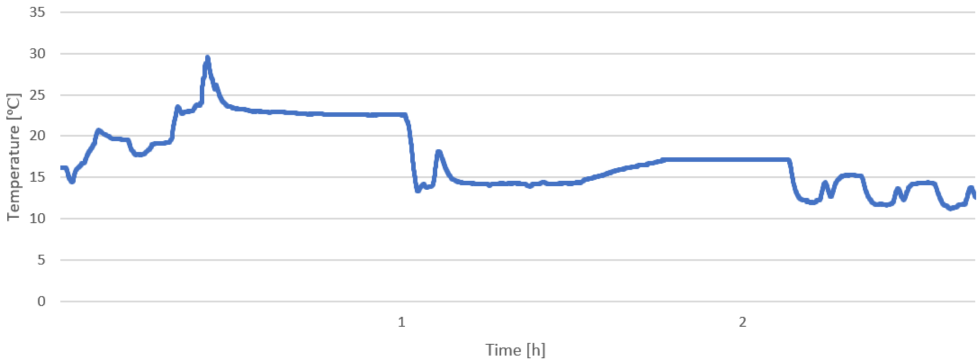


**Figure A.1:** Temperature of river water after cooling hot process water in the circulation between dyeing machine and additive tank

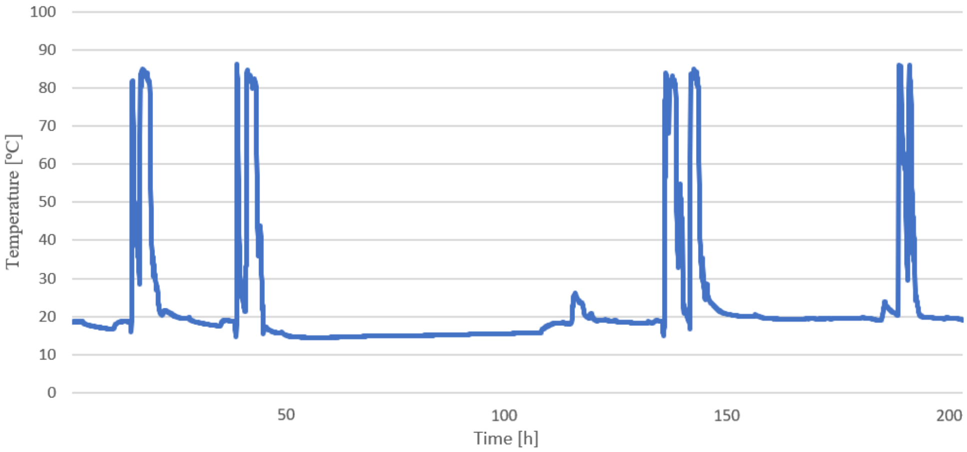


**Figure A.2:** Temperature of condensate out of dyeing process during heating step

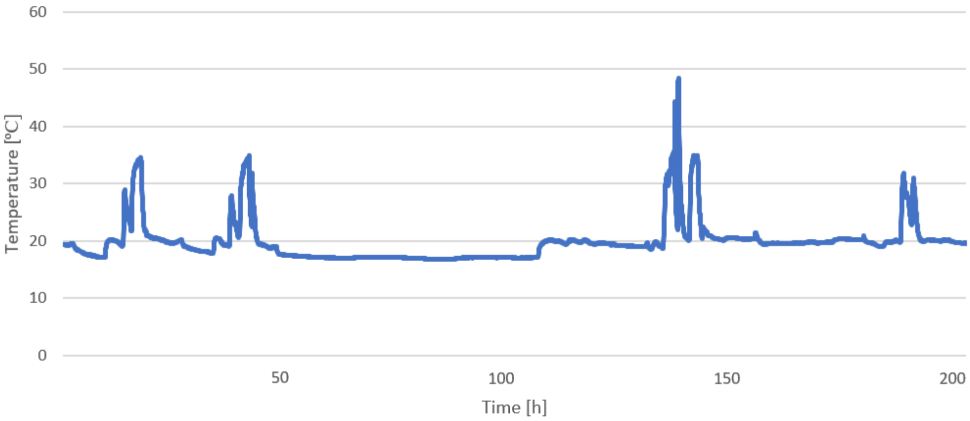


**Figure A.3:** Temperature of cooling water out of dyeing process during cooling step, that is led to the clean accumulator tank

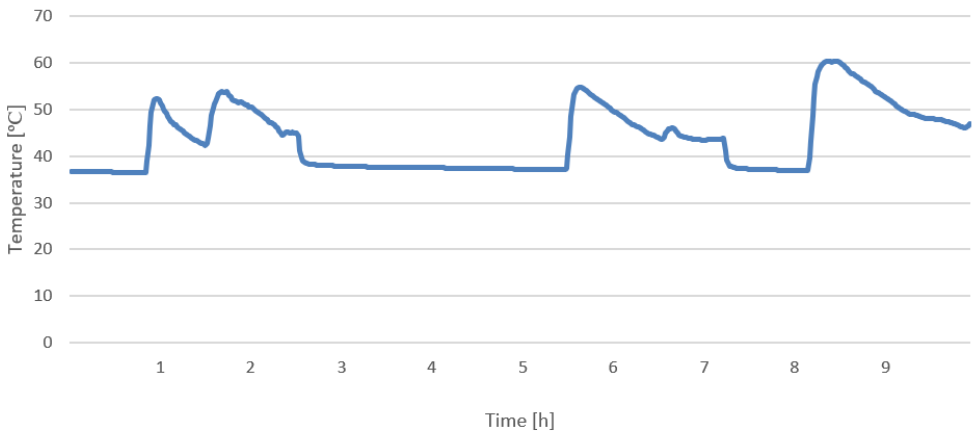


**Figure A.4:** Temperature of water from the dirty accumulator tank entering the heat exchanger

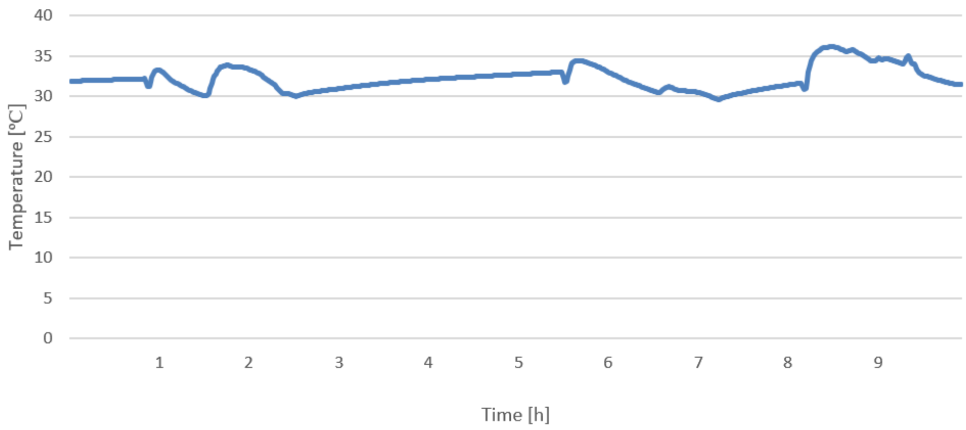


**Figure A.5:** Temperature of dirty water after the heat exchanger

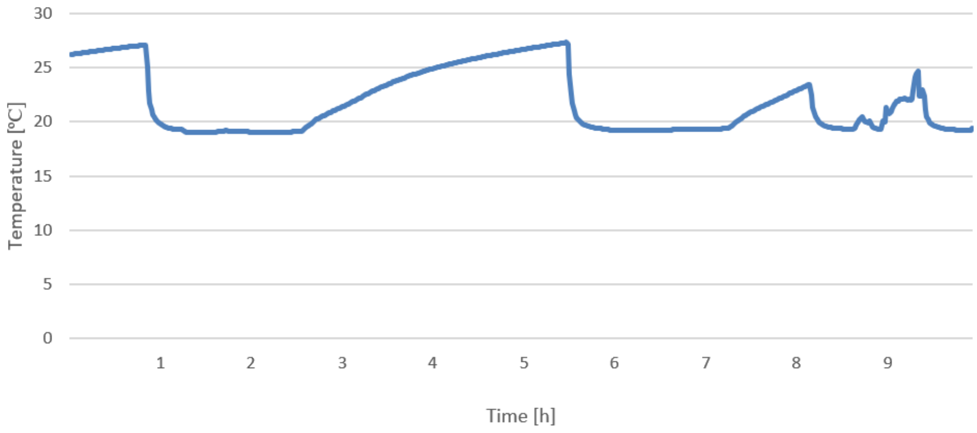


**Figure A.6:** Temperature of cold river water entering the heat exchanger

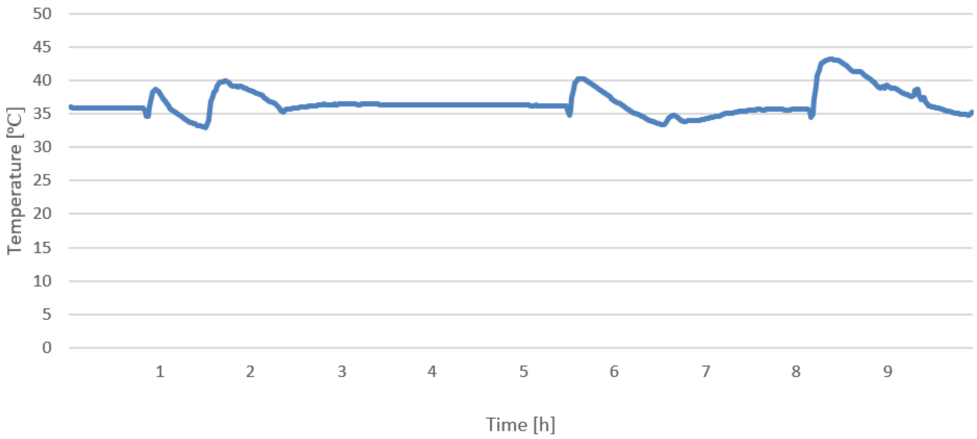


**Figure A.7:** Temperature of heated exchanged river water after heat exchange entering the clean accumulator tank

# B

# Appendix B - General constants and equations for modelling

In Appendix B general constants and equations used for the model configuration are summarised. Also model assumptions are stated.

**Dyeing modelling**
The model included the following assumptions, constants are collected from [25]:

- Constant water density, $\rho_{water} = 1000\frac{kg}{m^3}$
- Constant specific heat capacity of the process water, $c_{p,water} = 4.18\frac{kJ}{kg*K}$
- Constant density of the tank material, steel, $\rho_{steel} = 7820\frac{kg}{m^3}$
- Constant specific heat capacity of steel, $c_{p,steel} = 0.46\frac{kJ}{kg*K}$
- Full condensation of saturated steam to saturated water.

The temperature of the hot stream is considered to be the same as in the hot accumulator tank, $T_1 = T_{hot}$. While the temperature of the cold stream is considered to be the same as the river temperature, $T_2 = T_{cold}$. Given that the mixing fluids have the same heat capacity the resulting mixing temperature was then obtained accordingly to Equation B.1

$$T_3 = \frac{m_1 * c_{p,1} * T_1 + m_2 * c_{p,2} * T_2}{m_1 * c_{p,1} + m_2 * c_{p,2}} = \frac{m_1 * T_1 + m_2 * T_2}{m_1 + m_2} \quad [^{\circ}\mathbf{C}] \tag{B.1}$$

Given a 50/50 mixing this could be further simplified, however to enable the model to evaluate other ratios of the mixing fluids this was also included in the model. The share of water that is taken from the hot accumulator tank is represented by $x$, and the sum of the masses of the mixing fluids equals the total mass of the process water, $m_1 + m_2 = m_{total}$.

$$x * m_1 + (1 - x) * m_2 = m_{total}$$

$$Q_{eff} = m_{total} * c_{p,water} * \Delta T \quad [\mathbf{kJ}] \tag{B.2}$$

$$Q_{tank} = m_{tank} * c_{p,steel} * \Delta T \quad [\mathbf{kJ}] \tag{B.3}$$

$$P_{rad} = A_{surface} * \epsilon * \sigma * (T_{surf}^4 - T_{\infty}^4) \quad [\mathbf{kW}] \tag{B.4}$$

Where:

- The temperatures are expressed in kelvin [K]
- Emissivity $\epsilon$=0.88 was estimated for the steel tank [25]
- The Stefan–Boltzmann constant, $\sigma = 5.67 * 10^{-8} \frac{W}{m^2 * K^4}$ [25]

$$m_{steam} = \frac{net\ energy\ demand}{h_{steam,5bar} - h_{water,1bar}} \quad [\mathbf{kg}] \tag{B.5}$$

Where [25]:

- $h_{steam,5bar}$=2749 $\frac{kJ}{kg}$
- $h_{water,1bar}$=418 $\frac{kJ}{kg}$

### Accumulation system recovery model

With the saturation temperature of $T_{steam,5bar}$ = 151.85°C [25] the mass of the condensate was found.

$$m_{cond} = \frac{net\ energy\ demand}{c_{p,water} * (T_{steam,5bar} - T_{water,out})} \quad [\mathbf{kg}] \tag{B.6}$$

Given a known mass of the condensate and the assumption of a constant water density of $\rho_{water} = 1000 \frac{kg}{m^3}$, the volume of the waste water was estimated accordingly:

$$V_{cond} = \frac{m_{cond}}{\rho_{water}} \quad [\mathbf{m}^3] \tag{B.7}$$

$$Q_{cold} = \frac{\dot{m}_{cold}}{60} * c_{p,water} * (T_{cold,out} - T_{cold,in}) \quad [\mathbf{kW}] \tag{B.8}$$

### Flue gas recovery model

The flue gas model includes the following assumptions, constants collected from [25]:

- Physical properties of flue gases were estimated as those of air
- Constant water density, $\rho_{water} = 1000 \frac{kg}{m^3}$
- Constant specific heat capacity of the process water, $c_{p,water} = 4.18 \frac{kJ}{kg * K}$

- Constant specific heat capacity of the flue gases, $c_{p,fg} = 1.02\frac{kJ}{kg*K}$
- Energy content LPG, $h_{LPG} = 46.1\frac{MJ}{kg}$

$$p_t = p_s + \left(\frac{\rho v_{fg}^2}{2}\right) \quad [\mathbf{Pa}] \tag{B.9}$$

$$\dot{m}_{fg} = \dot{V}_{fg} * \rho_{fg} \quad [\mathbf{kg/s}] \tag{B.10}$$

$$P_{fg} = \dot{m}_{fg} * c_{p,fg} * (T_{fg,in} - T_{fg,out}) \quad [\mathbf{kW}] \tag{B.11}$$

Consequently, as the efficiency of a suitable heat exchanger was estimated to $\eta_{fg} = 0.88$, the power supplied on the water-side could be estimated:

$$P_w = P_{fg} * \eta_{fg} \quad [\mathbf{kW}] \tag{B.12}$$

This enabled the calculations of the mass flow of the water, $\dot{m}_w$, at the targeted temperature. With the mass flow also the volume flow could be estimated.

$$\dot{m}_w = \frac{P_w}{c_{p,w} * (T_{w,out} - T_{w,in})} \quad [\mathbf{kg/s}] \tag{B.13}$$

$$\dot{V}_w = \frac{\dot{m}_w}{\rho_w * 3600} \quad [\mathbf{m^3/h}] \tag{B.14}$$

# C

# Appendix C - Production data February 2018

Appendix B contains the production data for the two dyeing areas and the stenters for February 2018. The data was used as indication of typical operation but also for model verification of the steam system.

**Table C.1:** Production data for the yarn dyeing machines for February 2018

| Program | Machine | Year-Month | Week |
|---|---|---|---|
| D | GA3 | 2018-02 | 5 |
| D | GA1 | 2018-02 | 5 |
| B | GA1 | 2018-02 | 5 |
| D | GAN5 | 2018-02 | 5 |
| C | GAG5 | 2018-02 | 6 |
| D | GAN5 | 2018-02 | 6 |
| B | GA1 | 2018-02 | 6 |
| D | GA2 | 2018-02 | 6 |
| D | GA2 | 2018-02 | 6 |
| D | GA2 | 2018-02 | 6 |
| D | GA2 | 2018-02 | 6 |
| B | GA3 | 2018-02 | 6 |
| B | GA3 | 2018-02 | 6 |
| D | GA1 | 2018-02 | 6 |
| D | GA4 | 2018-02 | 6 |
| B | GAN5 | 2018-02 | 6 |
| D | GAN5 | 2018-02 | 6 |
| C | GA3 | 2018-02 | 6 |
| C | GAN5 | 2018-02 | 6 |
| C | GA2 | 2018-02 | 6 |
| C | GA3 | 2018-02 | 6 |
| C | GAN5 | 2018-02 | 6 |
| B | GA1 | 2018-02 | 6 |
| D | GA1 | 2018-02 | 6 |
| D | GA3 | 2018-02 | 6 |
| D | GA3 | 2018-02 | 6 |
| D | GA1 | 2018-02 | 6 |

| | | | |
|---|---|---|---|
| D | GAG5 | 2018-02 | 7 |
| D | GA1 | 2018-02 | 7 |
| D | GA4 | 2018-02 | 7 |
| C | GA2 | 2018-02 | 7 |
| D | GA1 | 2018-02 | 7 |
| D | GA2 | 2018-02 | 7 |
| D | GA3 | 2018-02 | 7 |
| C | GA2 | 2018-02 | 7 |
| C | GA4 | 2018-02 | 7 |
| B | GA3 | 2018-02 | 7 |
| D | GAN5 | 2018-02 | 7 |
| D | GA1 | 2018-02 | 7 |
| D | GA2 | 2018-02 | 7 |
| D | GA4 | 2018-02 | 7 |
| C | GAG5 | 2018-02 | 7 |
| C | GA3 | 2018-02 | 7 |
| B | GAN5 | 2018-02 | 7 |
| D | GAN5 | 2018-02 | 7 |
| C | GA4 | 2018-02 | 7 |
| B | GA2 | 2018-02 | 7 |
| D | GAN5 | 2018-02 | 7 |
| D | GA1 | 2018-02 | 7 |
| D | GA4 | 2018-02 | 7 |
| D | GA1 | 2018-02 | 7 |
| D | GA3 | 2018-02 | 7 |
| D | GA3 | 2018-02 | 7 |
| D | GA3 | 2018-02 | 7 |
| C | GA4 | 2018-02 | 7 |
| D | GA4 | 2018-02 | 7 |
| D | GA1 | 2018-02 | 8 |
| D | GA2 | 2018-02 | 8 |
| C | GA2 | 2018-02 | 8 |
| D | GAN5 | 2018-02 | 8 |
| D | GA3 | 2018-02 | 8 |
| D | GAN5 | 2018-02 | 8 |
| D | GA3 | 2018-02 | 8 |
| C | GAG5 | 2018-02 | 8 |
| D | GAN5 | 2018-02 | 8 |
| D | GA3 | 2018-02 | 8 |
| C | GA2 | 2018-02 | 8 |
| D | GA1 | 2018-02 | 8 |
| D | GA3 | 2018-02 | 8 |
| D | GA2 | 2018-02 | 8 |
| D | GA1 | 2018-02 | 8 |
| D | GAN5 | 2018-02 | 8 |
| D | GA1 | 2018-02 | 8 |

| | | | |
|---|---|---|---|
| D | GA4 | 2018-02 | 8 |
| D | GA2 | 2018-02 | 8 |
| D | GA3 | 2018-02 | 8 |
| D | GA4 | 2018-02 | 8 |
| D | GA1 | 2018-02 | 8 |
| D | GAG5 | 2018-02 | 9 |
| D | GA1 | 2018-02 | 9 |
| D | GA3 | 2018-02 | 9 |
| B | GAN5 | 2018-02 | 9 |
| D | GA2 | 2018-02 | 9 |
| D | GA1 | 2018-02 | 9 |
| D | GA4 | 2018-02 | 9 |
| C | GA3 | 2018-02 | 9 |
| B | GA1 | 2018-02 | 9 |
| B | GA1 | 2018-02 | 9 |
| D | GA2 | 2018-02 | 9 |
| C | GA4 | 2018-02 | 9 |
| D | GAG5 | 2018-02 | 9 |
| D | GA3 | 2018-02 | 9 |
| C | GA2 | 2018-02 | 9 |
| D | GA3 | 2018-02 | 9 |
| B | GA3 | 2018-02 | 9 |

**Table C.2:** Production data for the fabric dyeing machines for February 2018

| Program | Machine | Year-Month | Week |
|---|---|---|---|
| E | F2700 | 2018-02 | 5 |
| E | F4700 | 2018-02 | 5 |
| I | F4500 | 2018-02 | 6 |
| E | F4500 | 2018-02 | 6 |
| M | F2700 | 2018-02 | 6 |
| L | F800 | 2018-02 | 6 |
| E | F4700 | 2018-02 | 6 |
| L | F2700 | 2018-02 | 6 |
| L | F800 | 2018-02 | 6 |
| E | F4500 | 2018-02 | 7 |
| E | F4700 | 2018-02 | 7 |
| E | F4700 | 2018-02 | 7 |
| L | F800 | 2018-02 | 7 |
| E | F4500 | 2018-02 | 8 |
| H | F4500 | 2018-02 | 8 |
| M | F800 | 2018-02 | 8 |
| M | F2700 | 2018-02 | 8 |
| E | F4700 | 2018-02 | 8 |
| L | F2700 | 2018-02 | 8 |
| L | F2700 | 2018-02 | 8 |

| | | | |
|---|---|---|---|
| L | F2700 | 2018-02 | 8 |
| E | F4700 | 2018-02 | 8 |
| L | F2700 | 2018-02 | 9 |
| I | F800 | 2018-02 | 9 |

**Table C.3:** Production data for the stenters for February 2018

| Product | Machine | Manufactured Quantity [m] | Year - Month | Week |
|---|---|---|---|---|
| Batch 1 | SP2 | 108 | 2018-02 | 5 |
| Batch 2 | SP3 | 272 | 2018-02 | 5 |
| Batch 3 | SP3 | 1068 | 2018-02 | 5 |
| Batch 4 | SP3 | 50 | 2018-02 | 5 |
| Batch 5 | SP3 | 537 | 2018-02 | 5 |
| Batch 6 | SP3 | 110 | 2018-02 | 5 |
| Batch 7 | SP3 | 90 | 2018-02 | 5 |
| Batch 8 | SP3 | 146 | 2018-02 | 5 |
| Batch 9 | SP3 | 87 | 2018-02 | 5 |
| Batch 10 | SP3 | 99 | 2018-02 | 5 |
| Batch 11 | SP3 | 3900 | 2018-02 | 5 |
| Batch 12 | SP3 | 93 | 2018-02 | 5 |
| Batch 13 | SP3 | 236 | 2018-02 | 5 |
| Batch 14 | SP3 | 118 | 2018-02 | 5 |
| Batch 15 | SP3 | 458 | 2018-02 | 5 |
| Batch 16 | SP3 | 97 | 2018-02 | 5 |
| Batch 17 | SP3 | 120 | 2018-02 | 5 |
| Batch 18 | SP3 | 60 | 2018-02 | 5 |
| Batch 19 | SP3 | 200 | 2018-02 | 5 |
| Batch 20 | SP3 | 41 | 2018-02 | 5 |
| Batch 21 | SP3 | 188 | 2018-02 | 5 |
| Batch 22 | SP3 | 100 | 2018-02 | 5 |
| Batch 23 | SP3 | 100 | 2018-02 | 5 |
| Batch 24 | SP3 | 302 | 2018-02 | 5 |
| Batch 25 | SP3 | 200 | 2018-02 | 5 |
| Batch 26 | SP3 | 100 | 2018-02 | 5 |
| Batch 27 | SP3 | 200 | 2018-02 | 5 |
| Batch 28 | SP3 | 200 | 2018-02 | 5 |
| Batch 29 | SP2 | 89 | 2018-02 | 6 |
| Batch 30 | SP3 | 831 | 2018-02 | 6 |
| Batch 31 | SP3 | 307 | 2018-02 | 6 |
| Batch 32 | SP3 | 83 | 2018-02 | 6 |
| Batch 33 | SP3 | 144 | 2018-02 | 6 |
| Batch 34 | SP3 | 200 | 2018-02 | 6 |
| Batch 35 | SP3 | 471 | 2018-02 | 6 |
| Batch 36 | SP3 | 2069 | 2018-02 | 6 |
| Batch 37 | SP3 | 120 | 2018-02 | 6 |
| Batch 38 | SP3 | 87 | 2018-02 | 6 |

| | | | | |
|---|---|---|---|---|
| Batch 39 | SP3 | 105 | 2018-02 | 6 |
| Batch 40 | SP3 | 90 | 2018-02 | 6 |
| Batch 41 | SP3 | 99 | 2018-02 | 6 |
| Batch 42 | SP3 | 150 | 2018-02 | 6 |
| Batch 43 | SP3 | 271 | 2018-02 | 6 |
| Batch 44 | SP3 | 100 | 2018-02 | 6 |
| Batch 45 | SP3 | 108 | 2018-02 | 6 |
| Batch 46 | SP3 | 29 | 2018-02 | 6 |
| Batch 47 | SP3 | 86 | 2018-02 | 6 |
| Batch 48 | SP3 | 100 | 2018-02 | 6 |
| Batch 49 | SP3 | 295 | 2018-02 | 6 |
| Batch 50 | SP3 | 113 | 2018-02 | 6 |
| Batch 51 | SP3 | 118 | 2018-02 | 6 |
| Batch 52 | SP3 | 303 | 2018-02 | 6 |
| Batch 53 | SP3 | 118 | 2018-02 | 6 |
| Batch 54 | SP3 | 1200 | 2018-02 | 6 |
| Batch 55 | SP3 | 97 | 2018-02 | 6 |
| Batch 56 | SP3 | 88 | 2018-02 | 6 |
| Batch 57 | SP3 | 118 | 2018-02 | 6 |
| Batch 58 | SP3 | 97 | 2018-02 | 6 |
| Batch 59 | SP3 | 28 | 2018-02 | 6 |
| Batch 60 | SP3 | 7 | 2018-02 | 6 |
| Batch 61 | SP3 | 130 | 2018-02 | 6 |
| Batch 62 | SP3 | 7 | 2018-02 | 6 |
| Batch 63 | SP3 | 92 | 2018-02 | 6 |
| Batch 64 | SP3 | 93 | 2018-02 | 6 |
| Batch 65 | SP3 | 100 | 2018-02 | 6 |
| Batch 66 | SP3 | 300 | 2018-02 | 6 |
| Batch 67 | SP3 | 300 | 2018-02 | 6 |
| Batch 68 | SP3 | 1051 | 2018-02 | 6 |
| Batch 69 | SP3 | 375 | 2018-02 | 6 |
| Batch 70 | SP3 | 206 | 2018-02 | 6 |
| Batch 71 | SP3 | 353 | 2018-02 | 6 |
| Batch 72 | SP3 | 88 | 2018-02 | 6 |
| Batch 73 | SP3 | 90 | 2018-02 | 6 |
| Batch 74 | SP3 | 120 | 2018-02 | 6 |
| Batch 75 | SP3 | 118 | 2018-02 | 6 |
| Batch 76 | SP3 | 89 | 2018-02 | 6 |
| Batch 77 | SP3 | 83 | 2018-02 | 6 |
| Batch 78 | SP3 | 1000 | 2018-02 | 6 |
| Batch 79 | SP3 | 96 | 2018-02 | 6 |
| Batch 80 | SP3 | 303 | 2018-02 | 6 |
| Batch 81 | SP3 | 305 | 2018-02 | 6 |
| Batch 82 | SP3 | 274 | 2018-02 | 6 |
| Batch 83 | SP3 | 200 | 2018-02 | 6 |
| Batch 84 | SP3 | 211 | 2018-02 | 6 |

| | | | | |
|---|---|---|---|---|
| Batch 85 | SP3 | 150 | 2018-02 | 6 |
| Batch 86 | SP3 | 305,15 | 2018-02 | 6 |
| Batch 87 | SP3 | 152 | 2018-02 | 6 |
| Batch 88 | SP3 | 305,15 | 2018-02 | 6 |
| Batch 89 | SP3 | 300 | 2018-02 | 6 |
| Batch 90 | SP3 | 100 | 2018-02 | 6 |
| Batch 91 | SP3 | 304 | 2018-02 | 6 |
| Batch 92 | SP3 | 45 | 2018-02 | 6 |
| Batch 93 | SP3 | 150 | 2018-02 | 6 |
| Batch 94 | SP3 | 300 | 2018-02 | 6 |
| Batch 95 | SP3 | 100 | 2018-02 | 6 |
| Batch 96 | SP3 | 349 | 2018-02 | 6 |
| Batch 97 | SP3 | 200 | 2018-02 | 6 |
| Batch 98 | SP3 | 231 | 2018-02 | 6 |
| Batch 99 | SP3 | 200 | 2018-02 | 6 |
| Batch 100 | SP3 | 300 | 2018-02 | 6 |
| Batch 101 | SP3 | 194 | 2018-02 | 6 |
| Batch 102 | SP2 | 250 | 2018-02 | 7 |
| Batch 103 | SP2 | 250 | 2018-02 | 7 |
| Batch 104 | SP2 | 108 | 2018-02 | 7 |
| Batch 105 | SP3 | 119 | 2018-02 | 7 |
| Batch 106 | SP3 | 35 | 2018-02 | 7 |
| Batch 107 | SP3 | 823 | 2018-02 | 7 |
| Batch 108 | SP3 | 107 | 2018-02 | 7 |
| Batch 109 | SP3 | 117 | 2018-02 | 7 |
| Batch 110 | SP3 | 115 | 2018-02 | 7 |
| Batch 111 | SP3 | 87 | 2018-02 | 7 |
| Batch 112 | SP3 | 150 | 2018-02 | 7 |
| Batch 113 | SP3 | 20 | 2018-02 | 7 |
| Batch 114 | SP3 | 20 | 2018-02 | 7 |
| Batch 115 | SP3 | 95 | 2018-02 | 7 |
| Batch 116 | SP3 | 298 | 2018-02 | 7 |
| Batch 117 | SP3 | 149 | 2018-02 | 7 |
| Batch 118 | SP3 | 88 | 2018-02 | 7 |
| Batch 119 | SP3 | 92 | 2018-02 | 7 |
| Batch 120 | SP3 | 15 | 2018-02 | 7 |
| Batch 121 | SP3 | 120 | 2018-02 | 7 |
| Batch 122 | SP3 | 90 | 2018-02 | 7 |
| Batch 123 | SP3 | 105 | 2018-02 | 7 |
| Batch 124 | SP3 | 62 | 2018-02 | 7 |
| Batch 125 | SP3 | 200 | 2018-02 | 7 |
| Batch 126 | SP3 | 1985 | 2018-02 | 7 |
| Batch 127 | SP3 | 1800 | 2018-02 | 7 |
| Batch 128 | SP3 | 300 | 2018-02 | 7 |
| Batch 129 | SP3 | 20 | 2018-02 | 7 |
| Batch 130 | SP3 | 15 | 2018-02 | 7 |

| | | | | |
|---|---|---|---|---|
| Batch 131 | SP3 | 91 | 2018-02 | 7 |
| Batch 132 | SP3 | 120 | 2018-02 | 7 |
| Batch 133 | SP3 | 194 | 2018-02 | 7 |
| Batch 134 | SP3 | 600 | 2018-02 | 7 |
| Batch 135 | SP3 | 100 | 2018-02 | 7 |
| Batch 136 | SP3 | 400 | 2018-02 | 7 |
| Batch 137 | SP3 | 200 | 2018-02 | 7 |
| Batch 138 | SP3 | 250 | 2018-02 | 7 |
| Batch 139 | SP3 | 119 | 2018-02 | 7 |
| Batch 140 | SP3 | 300 | 2018-02 | 7 |
| Batch 141 | SP3 | 300 | 2018-02 | 7 |
| Batch 142 | SP3 | 250 | 2018-02 | 7 |
| Batch 143 | SP3 | 300 | 2018-02 | 7 |
| Batch 144 | SP3 | 257 | 2018-02 | 7 |
| Batch 145 | SP3 | 257 | 2018-02 | 7 |
| Batch 146 | SP3 | 100 | 2018-02 | 7 |
| Batch 147 | SP3 | 200 | 2018-02 | 7 |
| Batch 148 | SP3 | 600 | 2018-02 | 7 |
| Batch 149 | SP3 | 200 | 2018-02 | 7 |
| Batch 150 | SP3 | 200 | 2018-02 | 7 |
| Batch 151 | SP3 | 200 | 2018-02 | 7 |
| Batch 152 | SP3 | 2000 | 2018-02 | 8 |
| Batch 153 | SP3 | 203 | 2018-02 | 8 |
| Batch 154 | SP3 | 89 | 2018-02 | 8 |
| Batch 155 | SP3 | 3470 | 2018-02 | 8 |
| Batch 156 | SP3 | 204 | 2018-02 | 8 |
| Batch 157 | SP3 | 185 | 2018-02 | 8 |
| Batch 158 | SP3 | 198 | 2018-02 | 8 |
| Batch 159 | SP3 | 200 | 2018-02 | 8 |
| Batch 160 | SP3 | 180 | 2018-02 | 8 |
| Batch 161 | SP3 | 121 | 2018-02 | 8 |
| Batch 162 | SP3 | 121 | 2018-02 | 8 |
| Batch 163 | SP3 | 90 | 2018-02 | 8 |
| Batch 164 | SP3 | 151 | 2018-02 | 8 |
| Batch 165 | SP3 | 204 | 2018-02 | 8 |
| Batch 166 | SP3 | 96 | 2018-02 | 8 |
| Batch 167 | SP3 | 123 | 2018-02 | 8 |
| Batch 168 | SP3 | 162 | 2018-02 | 8 |
| Batch 169 | SP3 | 923 | 2018-02 | 8 |
| Batch 170 | SP3 | 832 | 2018-02 | 8 |
| Batch 171 | SP3 | 87 | 2018-02 | 8 |
| Batch 172 | SP3 | 100 | 2018-02 | 8 |
| Batch 173 | SP3 | 182 | 2018-02 | 8 |
| Batch 174 | SP3 | 194 | 2018-02 | 8 |
| Batch 175 | SP3 | 208 | 2018-02 | 8 |
| Batch 176 | SP3 | 194 | 2018-02 | 8 |

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| Batch 177 | SP3 | 158 | 2018-02 | 8 |
| Batch 178 | SP3 | 190 | 2018-02 | 8 |
| Batch 179 | SP3 | 150 | 2018-02 | 8 |
| Batch 180 | SP3 | 853 | 2018-02 | 8 |
| Batch 181 | SP3 | 300 | 2018-02 | 8 |
| Batch 182 | SP3 | 120 | 2018-02 | 8 |
| Batch 183 | SP3 | 147 | 2018-02 | 8 |
| Batch 184 | SP3 | 120 | 2018-02 | 8 |
| Batch 185 | SP3 | 89 | 2018-02 | 8 |
| Batch 186 | SP3 | 105 | 2018-02 | 8 |
| Batch 187 | SP3 | 89 | 2018-02 | 8 |
| Batch 188 | SP3 | 182 | 2018-02 | 8 |
| Batch 189 | SP3 | 158 | 2018-02 | 8 |
| Batch 190 | SP3 | 120 | 2018-02 | 8 |
| Batch 191 | SP3 | 300 | 2018-02 | 8 |
| Batch 192 | SP3 | 252 | 2018-02 | 8 |
| Batch 193 | SP3 | 150 | 2018-02 | 8 |
| Batch 194 | SP3 | 159 | 2018-02 | 8 |
| Batch 195 | SP3 | 600 | 2018-02 | 8 |
| Batch 196 | SP3 | 318 | 2018-02 | 8 |
| Batch 197 | SP3 | 100 | 2018-02 | 8 |
| Batch 198 | SP3 | 100 | 2018-02 | 8 |
| Batch 199 | SP3 | 50 | 2018-02 | 8 |
| Batch 200 | SP3 | 50 | 2018-02 | 8 |
| Batch 201 | SP3 | 153 | 2018-02 | 8 |
| Batch 202 | SP3 | 250 | 2018-02 | 8 |
| Batch 203 | SP3 | 201 | 2018-02 | 8 |
| Batch 204 | SP3 | 30 | 2018-02 | 8 |
| Batch 205 | SP3 | 100 | 2018-02 | 8 |
| Batch 206 | SP3 | 100 | 2018-02 | 8 |
| Batch 207 | SP3 | 150 | 2018-02 | 8 |
| Batch 208 | SP3 | 250 | 2018-02 | 8 |
| Batch 209 | SP3 | 121 | 2018-02 | 9 |
| Batch 210 | SP3 | 119 | 2018-02 | 9 |
| Batch 211 | SP3 | 200 | 2018-02 | 9 |
| Batch 212 | SP3 | 200 | 2018-02 | 9 |
| Batch 213 | SP3 | 200 | 2018-02 | 9 |
| Batch 214 | SP3 | 120 | 2018-02 | 9 |
| Batch 215 | SP3 | 200 | 2018-02 | 9 |
| Batch 216 | SP3 | 216 | 2018-02 | 9 |
| Batch 217 | SP3 | 192 | 2018-02 | 9 |
| Batch 218 | SP3 | 108 | 2018-02 | 9 |
| Batch 219 | SP3 | 795 | 2018-02 | 9 |
| Batch 220 | SP3 | 361 | 2018-02 | 9 |
| Batch 221 | SP3 | 200 | 2018-02 | 9 |
| Batch 222 | SP3 | 119 | 2018-02 | 9 |

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| Batch 223 | SP3 | 161 | 2018-02 | 9 |
| Batch 224 | SP3 | 100 | 2018-02 | 9 |
| Batch 225 | SP3 | 23 | 2018-02 | 9 |
| Batch 226 | SP3 | 190 | 2018-02 | 9 |
| Batch 227 | SP3 | 239 | 2018-02 | 9 |
| Batch 228 | SP3 | 120 | 2018-02 | 9 |
| Batch 229 | SP3 | 158 | 2018-02 | 9 |
| Batch 230 | SP3 | 150 | 2018-02 | 9 |
| Batch 231 | SP3 | 413 | 2018-02 | 9 |
| Batch 232 | SP3 | 95 | 2018-02 | 9 |
| Batch 233 | SP3 | 93 | 2018-02 | 9 |
| Batch 234 | SP3 | 86 | 2018-02 | 9 |
| Batch 235 | SP3 | 318 | 2018-02 | 9 |
| Batch 236 | SP3 | 300 | 2018-02 | 9 |
| Batch 237 | SP3 | 400 | 2018-02 | 9 |
| Batch 238 | SP3 | 400 | 2018-02 | 9 |
| Batch 239 | SP3 | 151 | 2018-02 | 9 |
| Batch 240 | SP3 | 100 | 2018-02 | 9 |
| Batch 241 | SP3 | 158 | 2018-02 | 9 |
| Batch 242 | SP3 | 89 | 2018-02 | 9 |