UNIVERSITÀ DEGLI STUDI DI PADOVA
DIPARTIMENTO DI INGEGNERIA INDUSTRIALE
CORSO DI LAUREA MAGISTRALE IN INGEGNERIA CHIMICA E DEI PROCESSI INDUSTRIALI

GRADUATION PAPER IN
"INGEGNERIA CHIMICA E DEI PROCESSI INDUSTRIALI"

Energy recovery optimization in a brewery

A brewhouse case study

University supervisor: Spilimbergo Sara
Corporate supervisor: Marzaioli Alberto Maria

Student: **Gianluca Pagano**

Academic year 2022-2023

Abstract

The thesis presented is about a study I conducted during my stage period at Birra Peroni s.r.l., a beer producing industry situated in Padua.

Firstly, as an introduction, a brief history of beer is presented and Birra Peroni industry is introduced.

After that, the focus goes to the energy recovery optimization in the brewery.

The study is focused on two topics:

- Heat exchange optimization (PID, regulation, control…)
- Optimization of energy recovery by vapors produced during wort boiling.

Table of contents

Introduction

Beer is one of the world's oldest prepared alcoholic drinks. The earliest archaeological evidence of fermentation consists of 13,000-year-old residues of a beer with the consistency of gruel, used by the semi-nomadic Natufians for ritual feasting, in a cave in the Carmel Mountains in Israel.

There is evidence that beer was produced at Göbekli Tepe during the Pre-Pottery Neolithic (around 8500 BC to 5500 BC). The earliest clear chemical evidence of beer produced from barley dates to about 3500–3100 BC, from the site of Godin Tepe in the Zagros Mountains of Iran. Beer is also recorded in the written history of ancient Egypt, and archaeologists speculate that beer was instrumental in the formation of civilizations. During the building of the Great Pyramids in Giza, Egypt, each worker got a daily ration of four to five liters of beer, which served as both nutrition and refreshment that was crucial to the pyramids' construction. Furthermore, approximately 5000 years ago, workers in the city of Uruk (modern day Iraq) were paid by their employers with volumes of beer.

These were just some examples to show how old beer actually is.

Nowadays beer is the most widely consumed alcoholic beverage in the world.

The process of making beer is known as brewing. A dedicated building for the making of beer is called a brewery, though beer can be made at home and has been for much of its history, in which case the brewing location was usually called a brewhouse. Nowadays, a company that makes beer is called either a brewery, a brewhouse or a brewing company.

Chapter 1

Birra Peroni and beer production process

1.1 Birra Peroni

Started in Vigevano (Italy) in 1846 by Giovanni Peroni as a small brewery with an adjoining pub, Birra Peroni is grown over the years, becoming nowadays one of the most successful beer producer in our country.

Starting from 2017 "Peroni" is part of Asahi Europe & International. With its 750 employees, 3 factories—in Rome, Bari and Padua—as well as a malt house in Pomezia, over 50 brands marketed, and a supply chain of 1500 Italian farms, there are over 43200 people in Italy employed directly or indirectly by Birra Peroni. Birra Peroni produces 6 million hectoliters annually, of which over 2.5 million are destined for export.

1.2 The plant in Padua

Birra Peroni Padua plant has been built in 1973 in Padua industrial area, nearby the bottling plant, dating back 1960. It occupies an area of 73,300 square meters and has an average annual production capacity of 1.9 million hectoliters, most of which is exported and dedicated to the foreign market.

A lot of different brands are produced in the production lines of Padua, such as: Peroni, Peroni Cruda, Peroni Gran Riserva, Peroni Nastro Azzurro, Peroncino, Asahi Super Dry, Kozel dark, Kozel Premium Lager, and many others.

In the next page two photos of the plant of Padua are shown.

Figure 1.1: *Birra Peroni plant of Padua (1)*

Figure 1.2*: Birra Peroni plant of Padua (2)*

1.2 Beer production process

Beer is basically an alcoholic beverage, produced by the fermentation of sugars derived from malted cereals, and flavored with hops.

It is produced starting from common raw materials: water, malt (usually malted barley), hops and yeasts. Sometimes also some adjuncts are added, such as maize, rice, barley, sorghum, wheat, sugar or glucose syrup.

As an introduction, it is shown a simple scheme of the process in *figure 1.3* of next page, then each section is investigated in detail.

Brewing process, can be divided in 4 main steps:

1) Wort production: Starch, contained in cereals, is converted in fermentable sugars;
2) Fermentation and storage: yeast, in anaerobic conditions, converts sugars in alcohol and carbon dioxide and all aromatic substances (esters aldehydes) are produced during this step)
3) Filtration : yeast and proteins complexes are removed
4) Packaging: Bottles, cans , kegs

The wort is produced in the brewhouse.

The first step of production of wort is the milling.

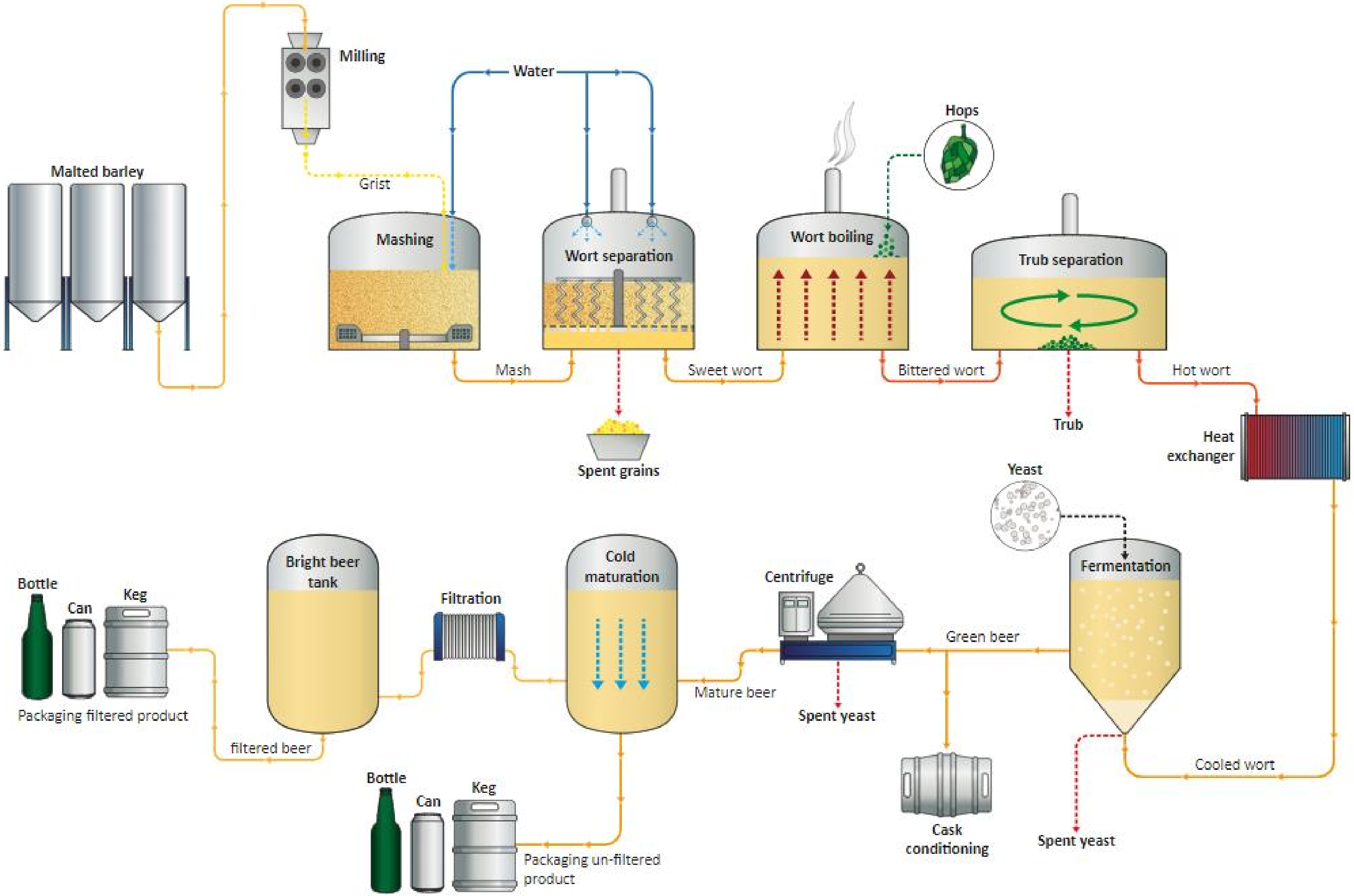

Figure 1.3: Beer production process scheme.

1.3.1 Malt milling

At the beginning of the process of wort production, the malt must be broken into small fragments, in order to give the malt enzymes access to the starch present in the malt.

Milling is a mechanical process and during it the whole grain of malted barley is crushed and fragmented in a *grist* mill; during this process the husks must be treated carefully because they are used as a filter material in the lautering stage.

Depending on the kind of mill used, a distinction is made between dry milling, wet milling and hammer milling.

1.3.2 Mashing

Mashing is a fundamental step in wort production. During mashing the grist and water are mixed together (mashed) in the mash tun kettle and the grain's starch and proteins are broken down into sugars and nutrients with the help of enzymes. The solution that forms is referred to as extract.

The degradation processes of importance for the brewer are basically:

- Starch degradation
- β-glucan degradation
- Protein degradation

1.3.2.1 Starch degradation

It is important to degrade the starch as much as possible to maltose.

Starch degradation occurs in three subsequential stages:

- Gelatinization
- Liquefaction
- Saccharification

Gelatinization is the process of swelling and bursting of starch granules in hot aqueous solution. In this way the starch molecules are more easily attacked by amylases enzyme. Each type of cereal has its own gelatinization temperature.

Liquefaction is the process of reduction of viscosity of the gelatinized starch by α-amylases.

When the complete degradation of starch to maltose and destrins by amylases is reached, saccharification is completed.

There are a few parameters that must be considered during mashing:

- Temperature has an impact on enzymes activity,
- Oxygen may have a harmful effect on the beer quality,
- pH has a relevant role on conversions,
- Time has an impact on mash conversion.

1.3.3 Wort separation

In wort separation, the wort is collected, separating it from the insoluble parts of the grain (spent grains). The wort draining off from spent grains is called first wort. After the first separation, the spent grains still contain extract and for economic reasons it is opportune to recover as much extract as possible. Thus, the grains are rinsed with hot water to help extract as much of the sugar and nutrients as possible. This is called sparging. The thinner wort draining off is called second wort and its extract content decreases rapidly at first and then more and more slowly since all the extract is washed out.

The spent grains can be used in different ways, e.g. as animal feed, in composting, or in energy generation.

This separation process is called lautering and it is commonly performed in a so-called lauter tun, which is a vessel with a false bottom constructed as a bar screen bottom available in different designs.

Otherwise, the separation can be performed by a mash filter, that basically comprises a plate and frame filter unit delimited by a fixed and movable end plate which are pressed together during filtration.

1.3.4 Wort boiling

In wort boiling, the wort is boiled vigorously for 50 (to 70) minutes in a vessel called wort kettle. In this stage hops are added to the wort.

During wort boiling different relevant processes occur:

- extraction and transformation of hop components to add bitterness, aroma and flavor to the beer,
- formation and precipitation of protein-polyphenol-compounds that is desirable to eliminate from the wort,
- evaporation of water,
- wort sterilization,
- destruction of all enzymes,
- lowering the pH of the wort,
- evaporation of undesirable substances.

There are different types of wort kettle, and they can be divided into:

- kettles with direct heating by coal, gas, or heating oil
- kettles with steam heating
- kettles with hot water heating

1.3.5 Wort clarification

After the wort is boiled it is clarified by removing the spent hops and other solid material produced in the boil (trub separation); the coarse trub must be removed since it is of no value in further beer production and also actually detrimental to quality.

One common way for coarse trub removal is using the method of the whirlpool.

A whirlpool is a vertical cylindrical vessel, with no internal fittings, into which wort is pumped tangentially. The rotational flow obtained causes the trub to settle in the middle of the vessel in the form of a cone.

The sedimentation is then removed, and it has the same fate of the spent grains.

1.3.6 Wort cooling and oxygenation

Next, the wort is chilled down passing through a heat exchanger (most commonly a plate heat exchanger) to a feasible temperature for the yeast to start the fermentation (usually from 5 to 10 °C).

Some type of yeasts need oxygen before they ferment, so oxygen may be added at this stage.

1.3.7 Fermentation

During fermentation, the yeast transforms wort into beer by converting sugars into alcohol and carbon dioxide and making the compounds that give beer its characteristic flavor. At the end of fermentation, the beer is cooled down, to help the yeast to settle out of the beer.

When transforming wort into beer, many thousands of other compounds are produced by yeasts, and many of them have an impact on beer taste. Flavor can be measured using the flavor-threshold value. Flavors produced during fermentation have concentration around the threshold value, so a slight change in concentration may have a great impact in taste. This is the reason why different yeasts produce the same type of compounds, but in different concentrations, changing the beer flavor. Other factors that have an impact on the taste of beer in this phase are the wort composition and the fermentation conditions.

Fermentation is not investigated in detail in this project, since it is not the focus, but it has been given an idea of the importance of the process.

1.3.8 Racking

With some cask beer, casks are filled with the beer at the end of fermentation; the beer racked into the cask contains live yeast cells and matures in the cask.

1.3.9 Maturation

In cold maturation, the beer is cooled down again and held at this temperature for a specified length of time. The beer is matured to improve its flavor and make it easier to filter. Unfiltered beers are packaged after maturation step.

1.3.10 Filtration

In filtration, any remained yeast is removed, along with any hazes that have formed during maturation. The beer leaving the filter is referred as bright beer.

1.3.11 Packaging

The beer from the bright beer tank is filled by very clever equipment into either kegs, bottles, or cans. Beer that has not been sterile filtered is sometimes heated to kill most of the microbes in the beer. This process is called pasteurization.

Chapter 2

Wort heating optimization

The first part of the project is focused on the pre-heating stage of the wort, before entering the wort kettle.

After wort separation, performed in the lauter tun, the wort is collected in a buffer tank called pre run vessel, to avoid the direct discharge of wort from the lauter tun into the wort kettle. From there, the wort flows into the wort kettle, passing through a heat exchanger which pre-heats the wort.

The wort is heated up by hot water coming from an *Energy Storage Tank* (also called energy recovery tank), a stratified tank that collects water at different temperatures. The pre-heating is made possible thanks to vapor heat recovery.

The goal of the study is to optimize the pre-heating process of the wort.

Before analyzing the wort pre-heater, it is important to explain what heat recovery means and how it is performed in the plant.

2.1 Vapor heat recovery

In vapor heat recovery, the hot vapor produced during wort boiling is passed through a heat exchanger (actually a condenser) that has cold water at the temperature of about 15 °C flowing through it. The vapor at approximately 100 °C is cooled and turned back to liquid. The water is then heated. This hot water can be used for heating wort before boiling, for brewing, or for cleaning.

In *figure 2.1* it is shown a scheme of the vapor heat recovery cycle; the temperatures indicated might not be exactly the temperatures in the plant of the study, but it helps to better understand what it is being said.

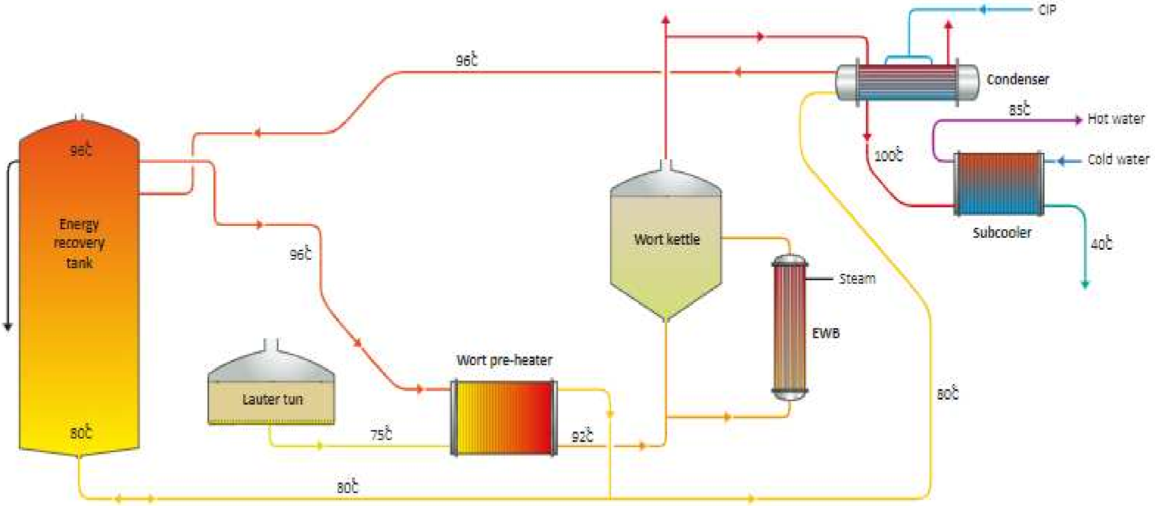

Figure 2.1: Vapor heat recovery cycle

2.2 Energy storage tank

The hot water (at about 96,5 °C) exiting from the former condenser is then collected in a tank, the so-called *energy storage tank*, which has the peculiarity to be thermically stratified, which means it has different temperatures at different levels inside. In this way, the recovery of heat is optimized, because the hot water is only within the upper part.

The water of the energy storage tank is in a sort of cycle because the cold water entering the condenser to be heated up is the water collected in the lower part of the tank, and the hot water exiting the condenser is collected in the upper part of the tank. The vapor condensed in the condenser does not take part in this cycle.

In the plant of the case study the storage has the following characteristics:

Table 2.1: *Energy storage tank operative conditions.*

Energy storage tank parameters	
Temperature at the top	97 °C
Temperature in the middle	96 °C
Temperature at the bottom	85 °C
Level of the tank	1750 hL

2.3 Condenser (shell-and-tube heat exchanger)

Condensers are special heat transfer devices used to liquefy vapors by removing their latent heats. The latent heat is removed by absorbing it in a cooler liquid called the coolant. Since the temperature of the coolant obviously is increased in a condenser, the unit also acts as a heater. In the case study a so-called shell- and-tube condenser is used, in which the condensing vapor and the coolant are separated by a tubular heat transfer surface.

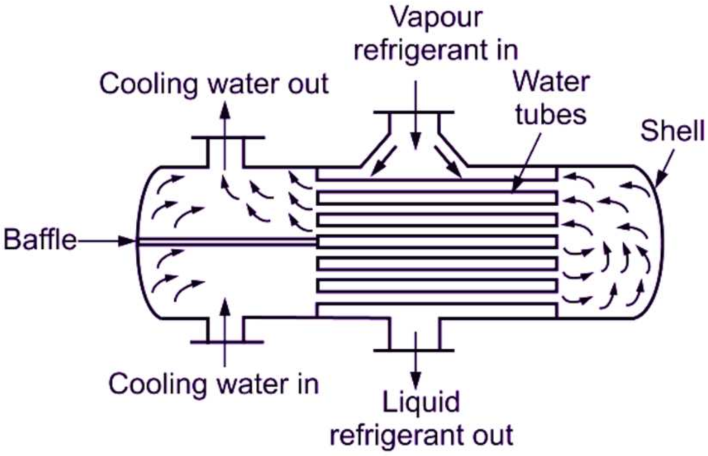

***Figure* 2.2:** *Common condenser scheme.*

***Figure* 2.3**: *Common view of a shell and tube condenser.*

2.4 Wort pre-heater (plate heat exchanger)

Before entering the wort kettle, filtered wort at the temperature of approximately 72 °C is heated up in a heat exchanger. In the case study plant a plate heat exchanger is used. In plate heat exchangers, metal plates, usually with corrugated faces, are supported in a frame; hot fluid passes between alternate pairs of plates, exchanging heat with the cold fluid in the adjacent spaces. The plates are typically 5 mm apart. They can be readily separated for cleaning; additional area may be provided simply by adding more plates. They are very efficient for heat transfer between fluids at low and moderate pressures, below about 20 atm; the maximum operating temperature is about 150 °C; maximum heat transfer areas are about 500 m^2.
In the following chapters the heat exchange will be investigated accurately.

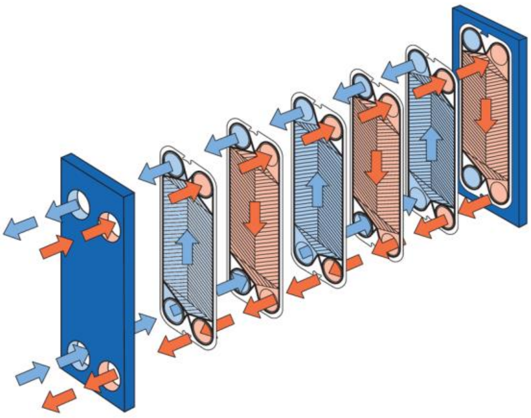

Figure 2.4: *Common plate heat exchanger scheme.*

Figure 2.5: *Common view of a plate heat exchanger.*

2.5 Objective of the investigation

The objective of the first part of the study is analyze the functioning of the wort pre-heater in order to find, if possible, a way to optimize its use, for instance increasing the temperature of the wort exiting the heat exchanger. This would be economically advantageous because a higher temperature of the wort entering the wort kettle means that less vapor is used to bring the wort to boil.

2.6 Efficiency of a heat exchanger

Firstly, it is convenient to evaluate the efficiency of the heat exchanger.
To do so, the *ε-NTU method* for a plate heat exchanger is used.
It starts by considering the fluid heat transfer capacity rates defined as:
Cold fluid capacity rate $C_c = \dot{m}_c \, c_{p,c}$ [W/K] (2.1)
Hot fluid capacity rate $C_h = \dot{m}_h \, c_{p,h}$ [W/K] (2.2)
Then the maximum amount of heat that can be transferred between the two fluids is the minimum fluid capacity rate times the difference in temperature of the hot fluid entering the exchanger and the cold fluid entering the exchanger:

$$C_{min} = min\ (C_c\ ,\ C_h) \tag{2.3}$$

$$q_{max} = C_{min}\ (T_{h,in} - T_{c,in}) \tag{2.4}$$

2.6.1 ε-NTU method for a plate heat exchanger

In *ε-NTU method*, the total heat-transfer rate from the hot fluid to the cold fluid in the exchanger is expressed as:

$$q = \varepsilon\, C_{min}\left(T_{h,in} - T_{c,in}\right) \tag{2.5}$$

Where ε is the heat exchanger effectiveness. It is nondimensional and for a direct transfer type heat exchanger, in general, it is dependent on NTU, C^*, and the flow arrangement:

$$\varepsilon = \Phi \text{ (NTU, } C^*\text{, flow arrangement)} \tag{2.6}$$

These three nondimensional parameters ε, NTU and C^* are defined next.

2.6.2 Heat capacity ratio C*

This is simply the ratio of the smaller to larger heat capacity ratio for the two fluid streams so that $C^* \leq 1$.

$$C^* = \frac{C_{min}}{C_{max}} = \frac{\left(m\, c_p\right)_{min}}{\left(m\, c_p\right)_{max}} \tag{2.7}$$

Here, C refers to the product of mass and specific heat of the fluid, and the subscript min and max refer to C_{min} and C_{max} sides, respectively. In a two-fluid heat exchanger, one of the streams will usually undergo a greater temperature change than the other. The first stream is said to be the ''weak'' stream, having a lower thermal capacity rate (C_{min}), and the other with higher thermal capacity rate (C_{max}) is the ''strong'' stream.

2.6.3 Number of transfer units NTU

NTU designates the nondimensional ''heat-transfer size'' or ''thermal size'' of the exchanger. It is defined as a ratio of the overall conductance to the smaller heat capacity rate.

$$NTU = \frac{U\,A}{C_{min}} \tag{2.8}$$

Where U is the overall heat-transfer coefficient [W/m^2 K] and A is the area of exchange [m^2]. Here, the overall heat-transfer coefficient U is assumed constant along the heat exchanger.

2.6.4 Heat exchanger effectiveness *ε*

Heat exchanger effectiveness ε is defined as the ratio of the actual heat-transfer rate, *q*, to the thermodynamically possible maximum heat-transfer rate (q_{max}) by the second law of thermodynamics.

$$\varepsilon = q_{act}/q_{max} \tag{2.9}$$

The value of ε ranges between 0 and 1. Using the value of actual heat-transfer rate q_{act} and q_{max} , the effectiveness of *equation 2.9* is given by:

$$\varepsilon = \frac{C_h\left(T_{h,i} - T_{h,o}\right)}{C_{min}\left(T_{h,i} - T_{c,i}\right)} = \frac{C_c\left(T_{c,o} - T_{c,i}\right)}{C_{min}\left(T_{h,i} - T_{c,i}\right)} \tag{2.10}$$

Alternatively, the efficiency for a counter flow configuration can be evaluated with the following formula:

$$\varepsilon = \frac{1 - e^{-NTU\left(1 - C_r\right)}}{1 - C_r e^{-NTU\left(1 - C_r\right)}} \tag{2.11}$$

This formula is particularly useful if we want to calculate the efficiency of an exchanger in the case when the exit temperatures are unknown.

2.6.5 ε-NTU method for a condenser

In the case of a condenser, the method is quite similar to the one already showed, with the difference that for the condensing liquid (we have steam condensing into water), the value of specific heat is considered infinity since it is much higher than the specific heat of water. Therefore $C_{max} = \infty$

and consequently R = $C_{min}/C_{max} = 0$

For R = 0, the effectiveness is given by: $\varepsilon = 1 - e^{(-NTU)}$ (2.12)

2.6.6 Dependence of ε on NTU

At low NTU, the exchanger effectiveness is generally low. With increasing values of NTU, the exchanger effectiveness generally increases, and in the limit, it approaches the maximum asymptotic value. However, there are exceptions such that after reaching a maximum value, the effectiveness decreases with decreasing NTU.

2.6.7 Efficiency of the wort pre-heater

For what concerns the wort pre-heater, it is known that:

- the temperature of the wort entering the HE is: ~ 72 °C
- the temperature of the wort exiting the HE is: ~ 93,5 °C
- the temperature of the water entering the HE is: ~ 96,5 °C

Moreover, since the minimum capacity rate is equal to the cold stream (wort) capacity rate, the second equation for efficiency can be rewritten as:

$$\varepsilon = \left(\frac{T_{c,out} - T_{c,in}}{T_{h,in} - T_{c,in}} \right) \tag{2.13}$$

The efficiency calculated is 0,88.

This result is more than acceptable considering thermal dispersions and fouling phenomena that can occur in a heat exchanger.

Knowing the efficiency, it is also possible to estimate the wort flowrate, rewriting the first equation for efficiency (*equation 2.10*):

$$m_c = \frac{m_h c_{p,h}}{\varepsilon c_{p,c}} \left(\frac{T_{h,in} - T_{h,out}}{T_{h,in} - T_{c,in}} \right) \tag{2.14}$$

The estimated wort volumetric flowrate is 850 hL/h.

Once the flowrate is estimated, it is also possible to evaluate the efficiency with the ε-NTU method. Firstly, the overall heat transfer coefficient must be calculated. Afterwards, knowing that:

- The exchange area of the HE is: 220,15 m^2
- The overall heat transfer coefficient is: ~ 1568 W/K m^2
- The number of transfer units (NTU) is: ~ 4,1
- The heat capacity ratio is: ~ 0,59

The efficiency calculated is 0,91.

This result is quite similar to the one obtained with the other method, meaning that the results are reliable.

Relationships for the calculation of heat transfer coefficients can be found on the appendix.

2.6.8 Efficiency of the condenser

For what concerns the condenser, the efficiency is evaluated from *equation 2.12*, knowing that:

- The exchange area is: ~ 270,20 m2
- The overall heat transfer coefficient is: ~ 1338 W/K m^2
- The number of transfer units (NTU) is: ~ 1,9
- The minimum heat capacity (the one of colder water) is: 189 kW/K

The efficiency calculate is 0,85. Also in this case the result is more than acceptable.

This and the previous results have certified that the heat exchangers are well designed, and they fit good for the operations in which they are involved.

Relationships for the calculation of heat transfer coefficients can be found on the appendix.

2.7 Temperature control

The outlet temperature of the wort exiting from the heat exchanger is regulated by a controller which regulates the wort temperature varying the power of the pump that pumps the wort into the heat exchanger.

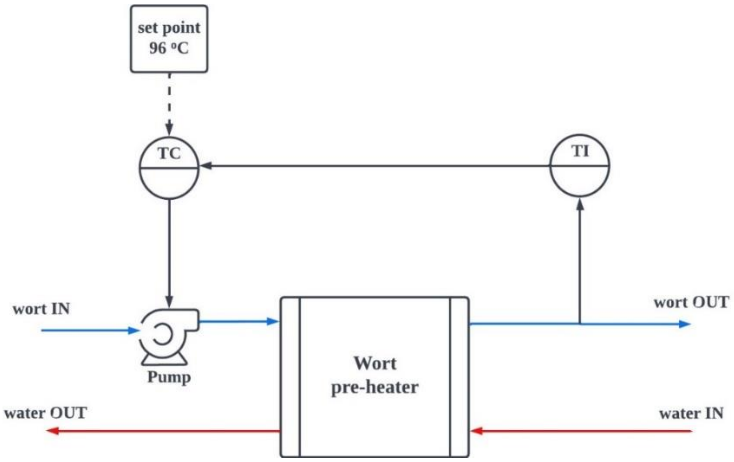

Figure 2.6: *Wort heating control system.*

The controller (TC) set point is set such that if the sensor of temperature (TI) of the wort exiting the heat exchanger detect a temperature greater than the set point, the controller intervenes, increasing the power of the pump in order to increase the wort flowrate and decrease the outlet temperature of the wort. At the beginning of the study the setpoint is set at 96°C, such that if the wort temperature exceeds 96°C, the controller raises a little bit the pump power, increasing the wort flowrate and bringing the temperature back to 96°C.

In this way, the controller isn't used in a convenient way, since, considering the design of the heat exchanger and the flowrates entering the heat exchanger, the temperature of the set point is never reached, and the controller never actually intervenes.

We are interested in finding a way to control the wort flowrate in an opportune way and, if possible, to guarantee the thermal exchange desired.

Doing that, a few considerations must be taken into account.

Firstly, it must be considered the fact that the wort kettle is filled from the bottom to avoid entrance of oxygen in the kettle, so during the filling process, there is a progressively increasing counter pressure against the wort flowrate. Practically, the effect of this counter pressure is that the wort flowrate is progressively decreasing during the filling.

It has been ascertained that at the beginning of the filling process, the minimum pump power necessary to transfer the wort is 25% (percentage of the maximum pump power), while at the end of the process the minimum pump power necessary to deliver the wort is 42%.

Moreover, the hot water reservoir is limited, in fact as it has been said before, the quantity of water stored in the energy storage tank is about 1750 hL, and only a part of it is at the temperature of approximately 96,5 °C (for the heat transfer it is only used water at this temperature). Thus, even if ideally it could be possible to heat the wort to 96 °C, in reality it is not possible because it would take a quantity of hot water greater than that available. In other words, once fixed the flowrate of hot water, to bring the wort to an ideal temperature of 96 °C the wort flowrate should be very low, but it has been already said that the wort flowrate has a minimum imposed by pressure drops.

It will be notable to see if it is possible to use the temperature controller in a way that the pump power is progressively raised from 25% to 42%, keeping the wort flowrate always at its minimum and the outlet temperature constant all along the transfer to the wort kettle.

It could be a significative advantage since, with the configuration used by operators in the plant, the set point of 96 °C is never reached and the pump is regulated to operate sometimes at 42% or sometimes at 45% of power for all the transfer.

It is clear that working with the pump always set for example at 42%, the outlet temperature of the wort is not constant during the transfer, since its flowrate is varying due to pressure drops while the flowrate of hot water is kept constant (there is no controller to relate the wort flowrate to the pump of the hot water).

In this way, it has been evaluated an average outlet temperature of the wort of approximately 93 °C. What has been said is notable in *figure 2.7*.

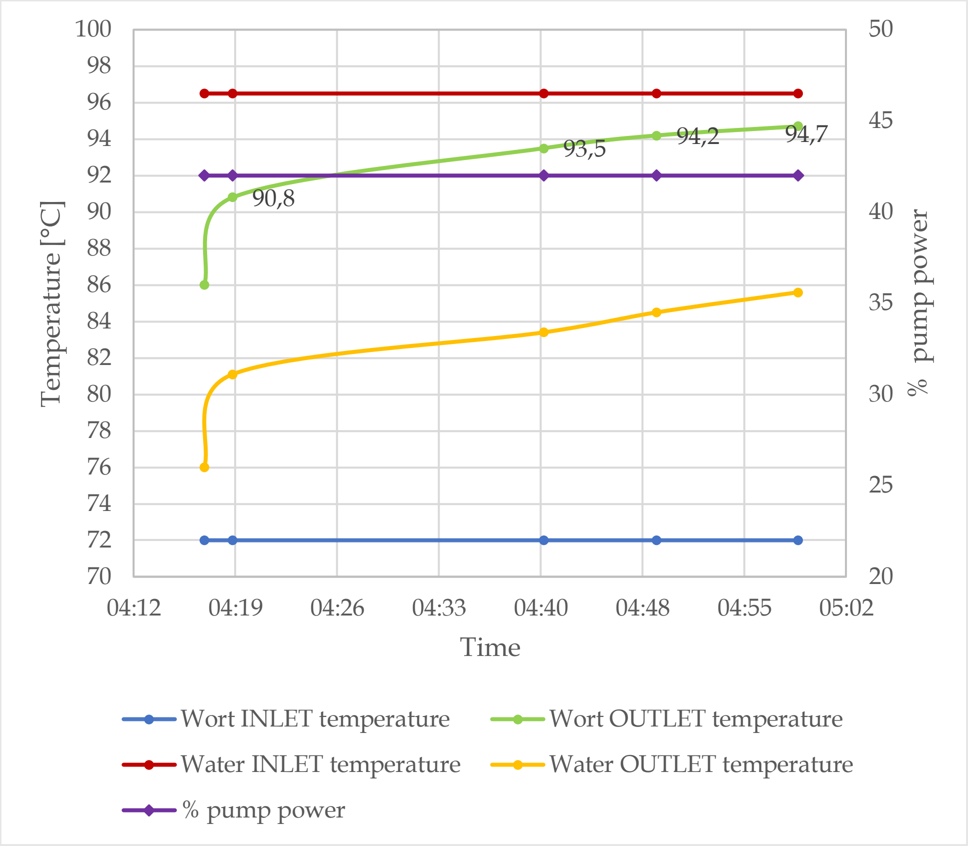

Figure 2.7: *Wort heating trends (1).*

In *figure 2.8* it is possible to see that the temperature of the wort entering the wort kettle is 92 °C. This value is always smaller than the temperature of the wort exiting the pre-heater, due to thermal dispersions. Our interest is to increase this temperature as much as possible, to reduce the amount of steam needed to boil the wort in the kettle.

Once established that the average temperature of the wort exiting the pre-heater is 93 °C, the aim of the study is to increase this average temperature as much as possible, also trying to keep the temperature constant, making easier to monitor and evaluate the efficiency of the process.

As a first try, it is chosen 94 °C as wort outlet temperature objective.

For what concerns the flowrate of hot water, it is chosen a value that guarantees the thermal exchange desired, e.g. the flowrate that brings the temperature of the wort up to 94 °C when the wort flowrate is at its minimum value (pump power at 25%).

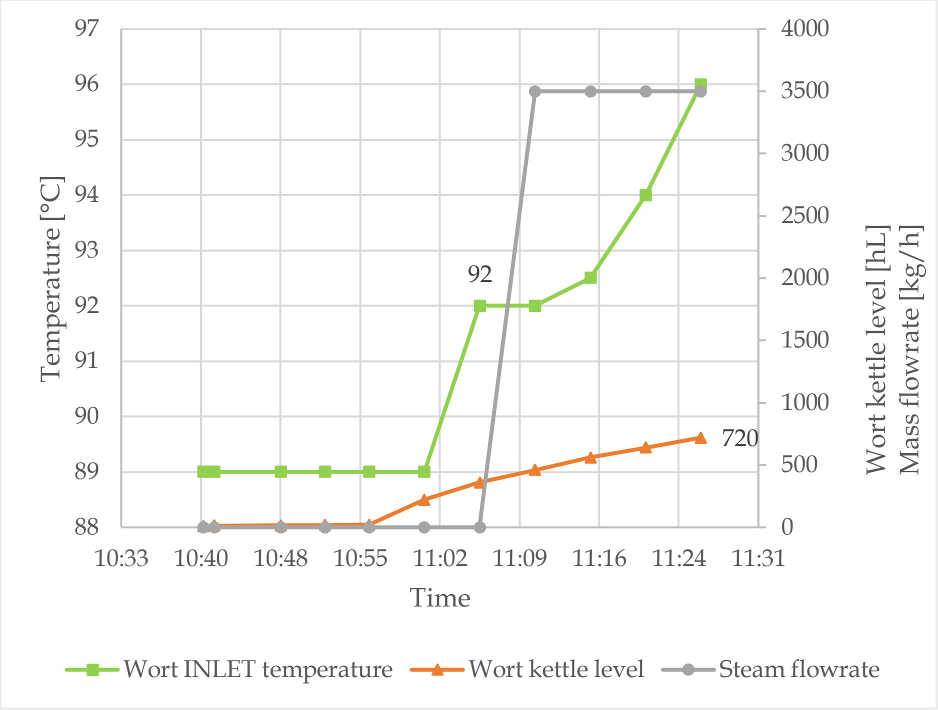

Figure 2.8: *Wort kettle trends (1).*

2.7.1 Operation: changing progressively the flowrate

As a first try, it is decided to change manually the power of the pump during the transfer operation. In other words, the flowrate of the wort is manually increased every time the outlet temperature of the wort exceeds the temperature of 94 °C.

In *figure 2.9* the results are shown.

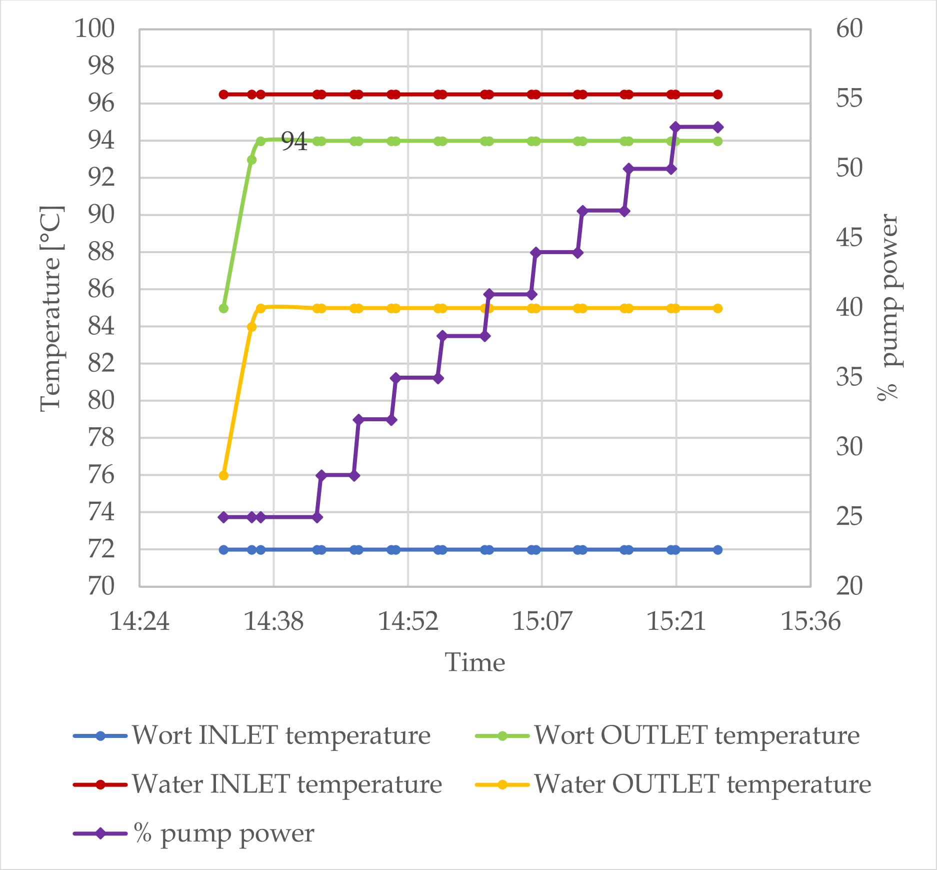

***Figure 2.9**: Wort heating trends (2).*

In *figure 2.9* it can be seen that the power of the pump is increased manually during the transfer, in order to keep the wort outlet temperature constant at 94 °C.

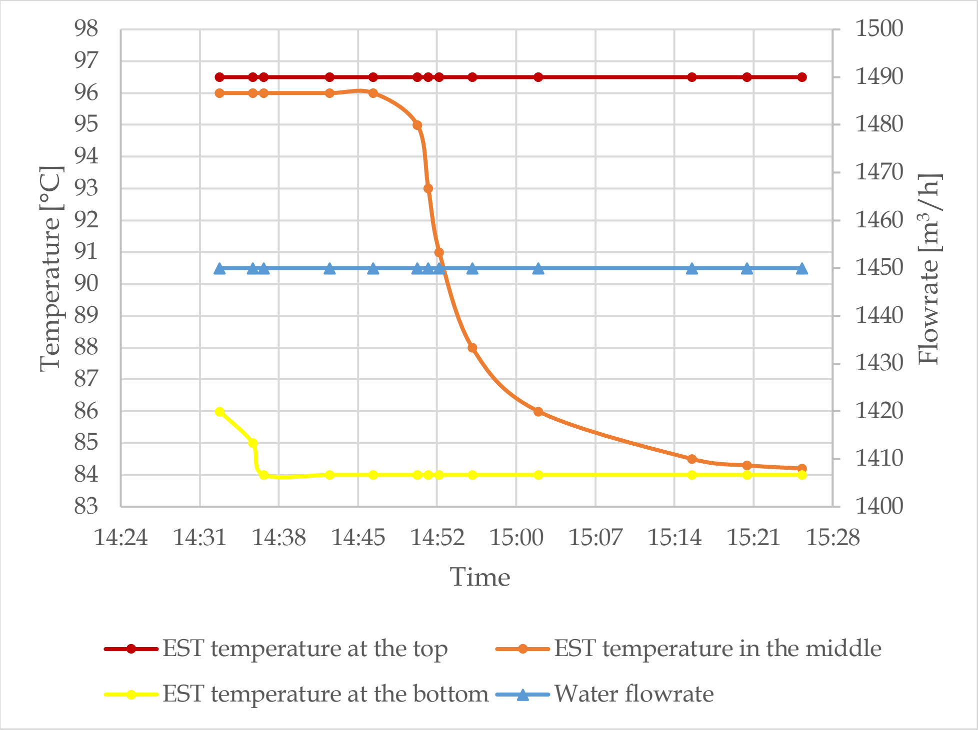

Figure 2.10: *Energy storage tank trends.*

In *figure 2.10* it can be observed that the hot water flowrate (light blue line) is constant at around 1450 hL/h.

It can also be noticed that the stratification is preserved within the energy storage tank, in fact the temperatures at the top and at the bottom remain almost unchanged.

In *figure 2.11* it can be observed that the temperature inside the wort kettle before the injection of hot steam in the kettle is almost 93 °C.

It must be said that a reliable value of temperature is given by the sensor of temperature only once the kettle has a level of approximately 280 hL, and that is the reason why we consider the temperature from that moment on.

Almost 1 °C is lost due to thermal dispersion in pipes, however this is a quite satisfactory result since previously the average temperature of the wort entering the wort kettle was 92 °C (while the average temperature of the wort exiting the heat exchanger was 93 °C).

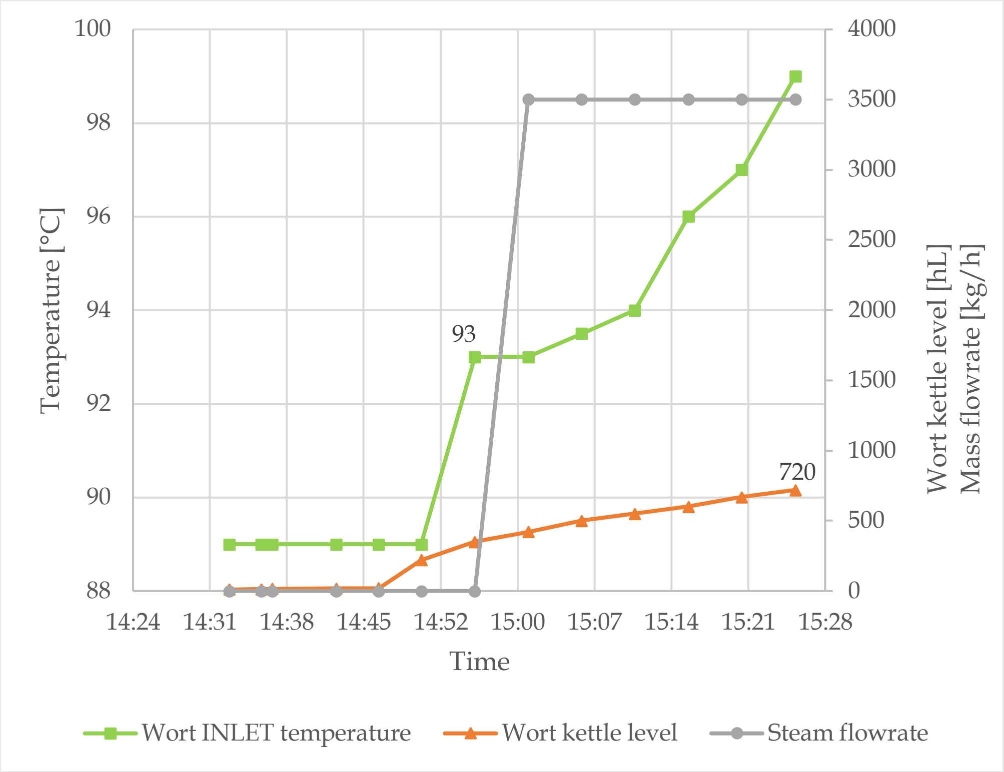

Figure 2.11: *Wort kettle trends (2).*

In *figure 2.11* it can be observed that the temperature inside the wort kettle before the injection of hot steam in the kettle is almost 93 °C.

It must be said that a reliable value of temperature is given by the sensor of temperature only once the kettle has a level of approximately 280 hL, and that is the reason why we consider the temperature from that moment on.

Almost 1 °C is lost due to thermal dispersion in pipes, however this is a quite satisfactory result since previously the average temperature of the wort entering the wort kettle was 92 °C (while the average temperature of the wort exiting the heat exchanger was 93 °C).

2.7.2 Operation: changing the set point

Since with the controller set point fixed at 96 °C, the set point is never reached, in the second try it is decided to change the controller set point to progressively increase the wort pump power; the set point is set at 95 °C, which is the new objective temperature for the wort outlet.

It has been observed that, at a certain point the inlet temperature of the hot water drops rapidly to a lower temperature, and therefore also the outlet temperature of the wort decreases. This is observable in *figure 2.12*.

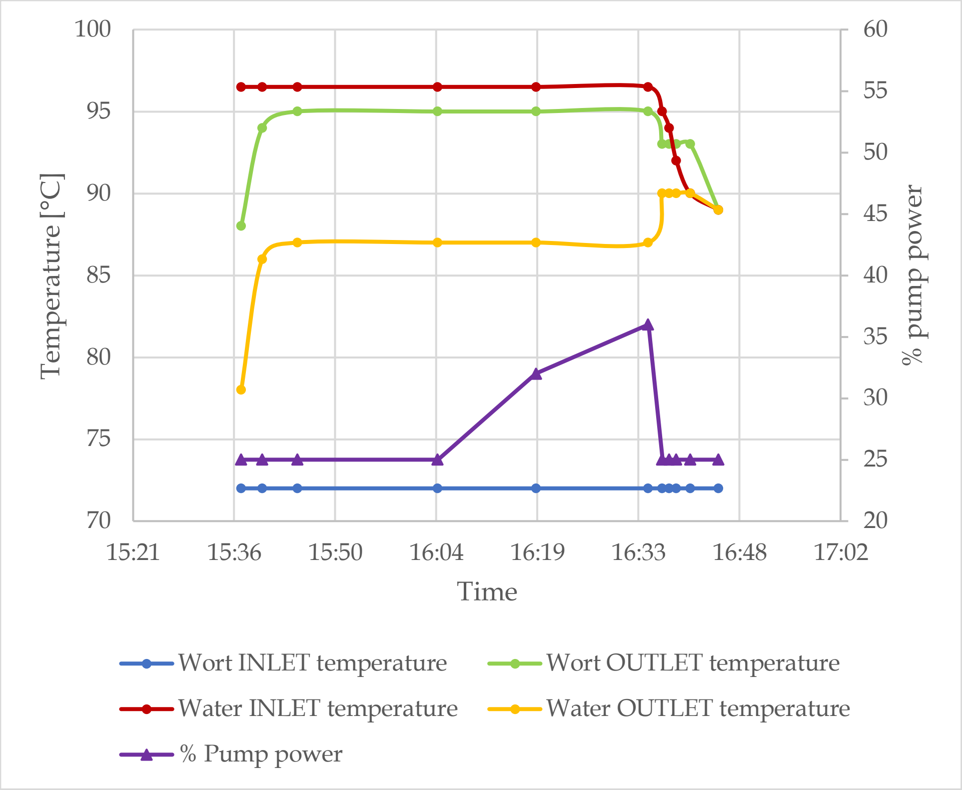

Figure 2.12: *Wort heating trends (3).*

This phenomenon is explained with the fact that there is not enough hot water at 96,5 °C within the energy storage tank to allow the thermal exchange from the beginning to the end, pumping the wort at its minimum flowrate value to guarantee an outlet temperature of 95 °C. Furthermore, this situation must be avoided because if the temperature at the top of the energy storage tank approaches the temperature at the bottom, it means that the stratification is lost, and more time and effort are required to reestablish the stratification.

It can otherwise be said that the transfer requires more time; the time for which the hot water has been available at the optimal temperature (about 96,5 °C) allow us to evaluate the actual quantity of hot water that can be used for the heat transfer.

In particular, since the time passed before the drop in temperature is about 50 minutes, and the water flowrate was set at 1450 hL/h, the quantity of water available for the heat transfer is:

$$V_{hot\ water} = 1450 \cdot \left(\frac{50}{60}\right) \approx 1208\ hL$$

Once we know the actual hot water available and we know the time limit for the transfer, we aim at finding the maximum temperature obtainable all along the heat exchange.

In order to find the maximum temperature, the formula of efficiency can be used.

The maximum outlet temperature can be evaluated with the following formula:

$$T_{c,out} = \left[\frac{C_{min}\,\varepsilon\left(T_{h,in} - T_{c,in}\right) + C_c\,T_{c,in}}{C_c}\right] \tag{2.15}$$

Since C_{min} in this case is equal to C_c, the equation can be rewritten in a simpler way:

$$T_{c,out} = \varepsilon\left(T_{h,in} - T_{c,in}\right) + T_{c,in} \tag{2.16}$$

Considering that:

- The efficiency ε is: 0,91
- The inlet hot water temperature is 96,5 °C
- The inlet wort temperature is 72 °C

The maximum wort outlet temperature at those operative conditions is 94,3 °C.

However, it is chosen 94 °C as set point for the controller, in order to not use all the hot water and lose the stratification within the energy storage tank (a sort of buffer zone is left with an intermediate temperature).

In *figure 2.13* it is shown the scheme of the wort heating process with the new set point.

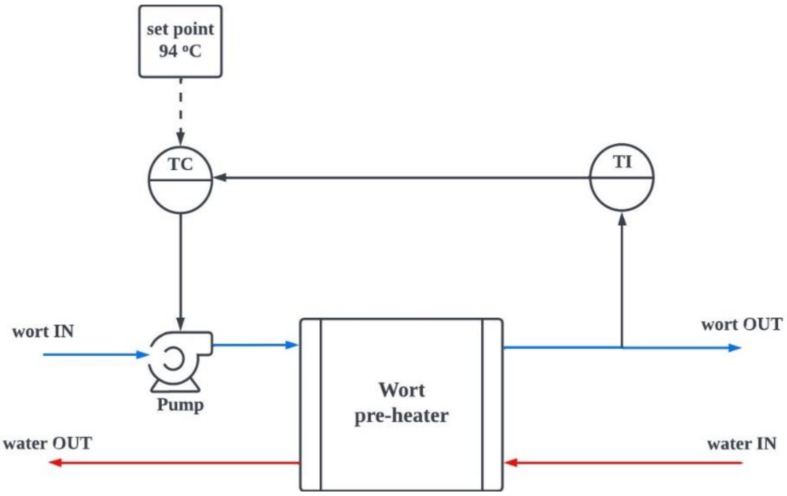

Figure 2.13: *Wort heating scheme (2).*

In *figure 2.14* the results are shown.

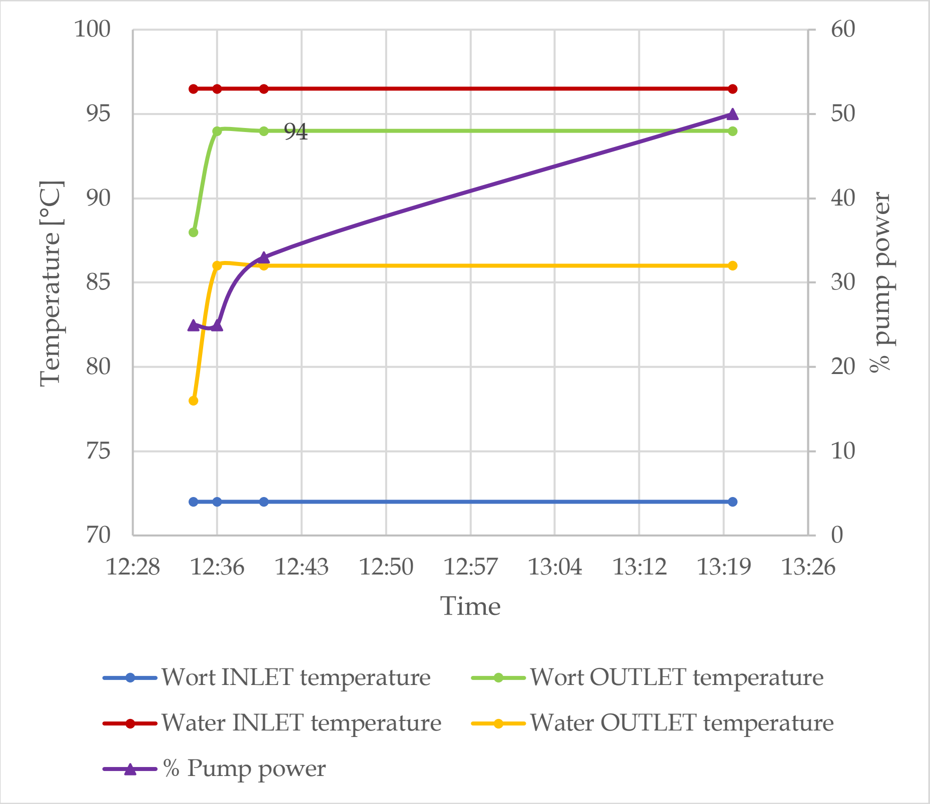

Figure 2.14: *Wort heating trends (4).*

In *figure 2.14* it can be seen that, fixing the set point in a convenient way, it is possible to maintain the temperature constant all along the transfer at the temperature of 94 °C (0.9-1 °C increment). In this way it is also easier to control the well-functioning of the operations over time, since it is not needed to calculate an average temperature to assess the performances of the heat exchanger over time. It should be easier, for instance, to see if fouling factors are becoming prominent in the operations and the efficiency of the exchanger is declining, in fact in this case, the hot water available for the heat transfer may not be enough, and the set point must be reduced to guarantee the thermal exchange all along the transfer.

It is not shown the figure with the trend of the energy storage tank since it is like the one already shown, since the hot water flowrate is kept constant.

For what concerns the trends of the wort kettle, they are very similar to the ones shown for the previous case, and the same considerations can be made.

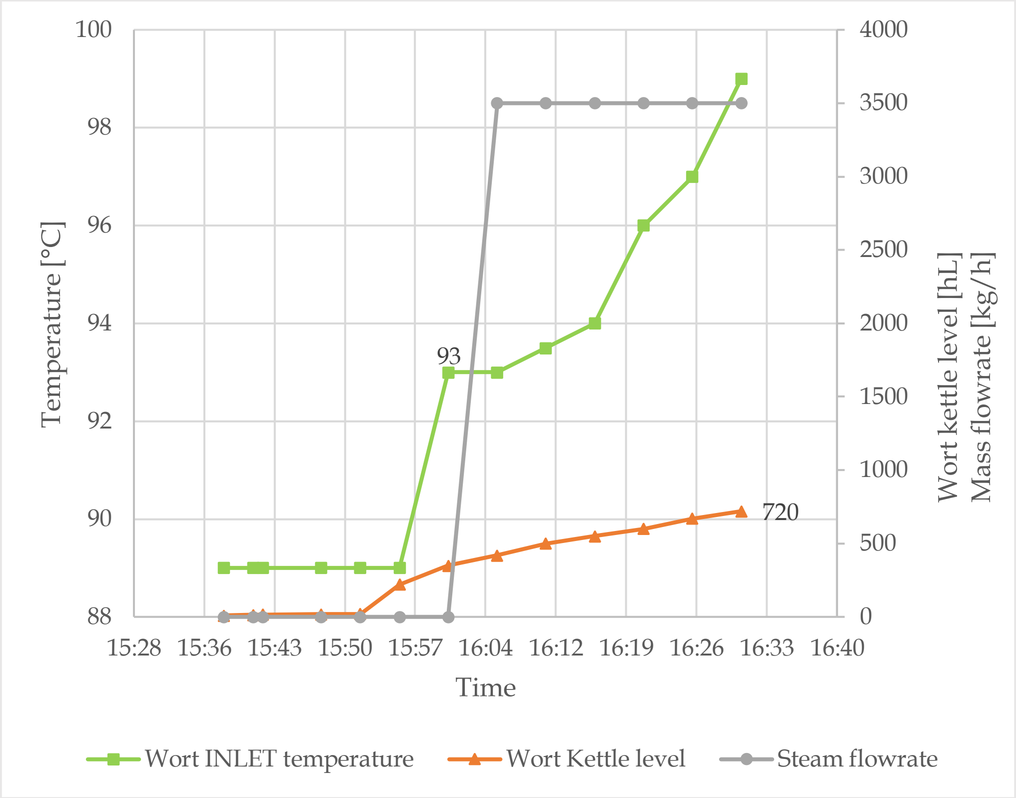

Figure 2.15: *Wort kettle trends.*

In conclusion, it can be said that changing the set point in a more convenient way, i.e. fixing it at 94 °C instead of 96 °C, has permitted to increase the average temperature of the wort transferred from the pre heater to the wort kettle by approximately 1 °C.

It may seem an insignificant result but when we are dealing with a quantity of at least 2500 hL of wort per day, it makes a great difference economically speaking.

Chapter 3

Optimization of warm water production

The second part of this thesis concerns the optimization of warm water production. With warm water we refer to water at about 82 °C; this water is stored in a tank, the so-called *Warm Water Tank* and it is used widely around the plant.

Warm water is produced in the plant in different ways: with boilers and throughout heat exchangers. We will concentrate in warm water produced trough heat exchangers, because we would like to optimize the energy recovery.

As we have already said, the vapors produced during wort boiling are recovered in a condenser that heats the water coming from the bottom of the energy storage tank from about 86 °C to 96,5 °C.

Anyway, once the energy storage tank is ''recharged'', i.e. the temperatures above, in the middle and below are restored such that the stratification is maintained, the remaining vapors are not wasted, but they are recovered in what is called ''the 2nd phase'' of the condenser.

3.1 "2nd phase'' of the condenser

Once the energy storage tank is recharged, the vapors coming from the wort kettle are recovered in the same condenser but this time it is used to heat up cold water (at about 15 °C) to the temperature of 85 °C; this water is then delivered to the warm water tank.

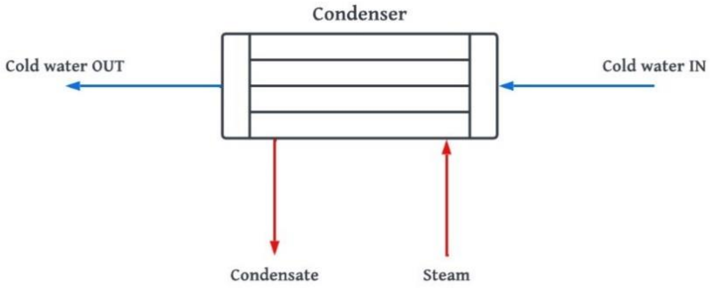

Figure 3.1: Condenser scheme.

Based on their evaporation rate each beer brand produces different quantity of warm water during wort boiling.

The second part of this work is focused on the optimization of brands alternation in the weekly program to optimize warm water recovery.

3.2 Wort cooler heat exchanger

The most relevant way to produce warm water through energy recovery is with the so-called *wort cooler,* which is a plate heat exchanger used to cool down the wort after boiling. By doing that, ice water at the temperature of 4 °C is brought up to approximately 85 °C.

Even in this case, different brands produce different quantities of warm water, because some brands are cooled down to 7 °C, others are cooled down to 11 °C, depending on the required stock conditions of the wort for the fermentation (it is clear that to obtain a different temperature of the wort outlet, the flowrate of ice water must be changed, and if the temperature of the outlet wort varies, also the temperature of the outlet water slightly varies).

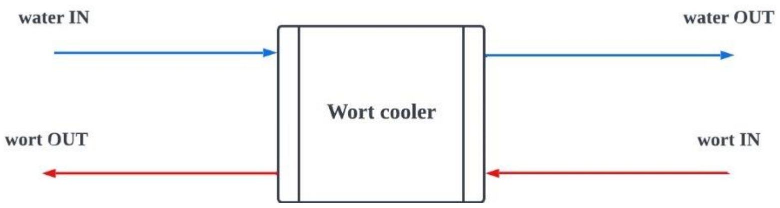

Figure 3.2: *Wort cooler scheme.*

3.3 Warm water production

7 different brands are investigated (each brand is labelled with fictitious name for privacy reasons).

For each of them it has been calculated the warm water quantity produced considering:

- For the water produced during the second phase of the condenser, it has been considered the flowrate of cold water entering the condenser;
- For the water produced during wort cooling, it has been considered the flowrate of ice water entering the heat exchanger during wort cooling.

3.3.1 Warm water from 2nd phase of the condenser

For the calculations, it has been taken into account the fact that the quantity of warm water produced for the same brand differs depending on the vapor needed to recharge the energy storage tank.

It means that, if in the previous brew, a large quantity of hot water has been used to pre-heat the wort, and the stratification inside the tank has been almost (or completely) lost for some reasons, a greater amount of vapor is needed to reestablish the equilibrium, i.e. the favorable stratification, inside the tank. As a consequence, there is less amount of vapor intended to the second phase.

Since, for each brand, a range of values has been found, it has been thought opportune to build an interval plot of the values for each brand and to take the mean as our interested value.

To do that, the program *Minitab* has been used.

Before showing that, a table with the retrieved data is presented.

Table 3.1: *Water produced during 2nd phase of condenser [hL].*

GREEN		LIGHT BLUE		PURPLE		MUDDY Y.	YELLOW	RED	ORANGE
58	65	33	42	171	146	133	46	150	58
70	88	21	46	196	171	146	58	117	74
58	88	71	33	138	100	138	70	138	63
88	80	54	77	154	129	125	67	108	61
29	65	71	53	150	117	129	54	130	69
79	75	46	60	158	140	132	92	121	87
75	91	46	13	176	113	154	80	132	69
88	42	46	46	189	221	129	46	104	
108	75	50	77	104	210	146	54		
67	58	50	53	163	192	104	67		
116	104	58	60	117	152	154			
79	33	13	79	120	142				
83		46	88	135	113				
87		54	42	167	117				
50		46	50	113	145				
79		58	25	133	208				
83		83	42	146	150				
138		44	63	142	150				
57		54	54	167	179				
121		67	46	182	163				
129		79	38	92	108				
54		25		158	79				
50		50		150	92				
54		42		129	96				
54		71		113	79				
100		21		158					

It is clearly notable that different amounts of data are available for each brand, due to different frequencies of production of each brand in the examined period; the three main brands are: Green, Light Blue and Purple.

In *figure 3.3* it is shown an interval plot, in which it is possible to see the mean values and the confidence ranges of the brands, while in *figure 3.4* it is shown a boxplot, in which the interquartile range can be seen.

Moreover, a few considerations concerning calculation of means and confidence intervals are reported in the appendix.

3.3.2 Interval plot for warm water quantities produced in 2nd phase

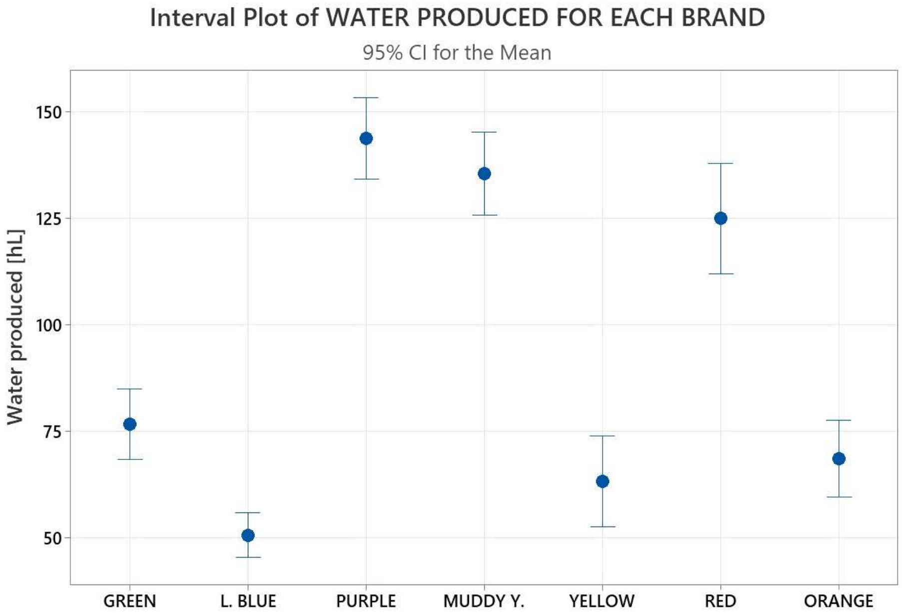

Figure 3.3: *Interval plot of warm water from condenser.*

The interval plot gives information about the mean value for each brand and its confidence interval, which tell us that for each brew there is a probability of 95% to find the value within the confidence interval. The intervals are quite tight, thus the study could take us to reliable results.

Table 3.2: *Water produced per brand from the condenser.*

Brand	Mean water produced [hL]
PURPLE	144
LIGHT BLUE	51
GREEN	77
YELLOW	63
MUDDY YELLOW	135
ORANGE	69
RED	125

3.3.3 Boxplot for warm water quantities produced during 2nd phase

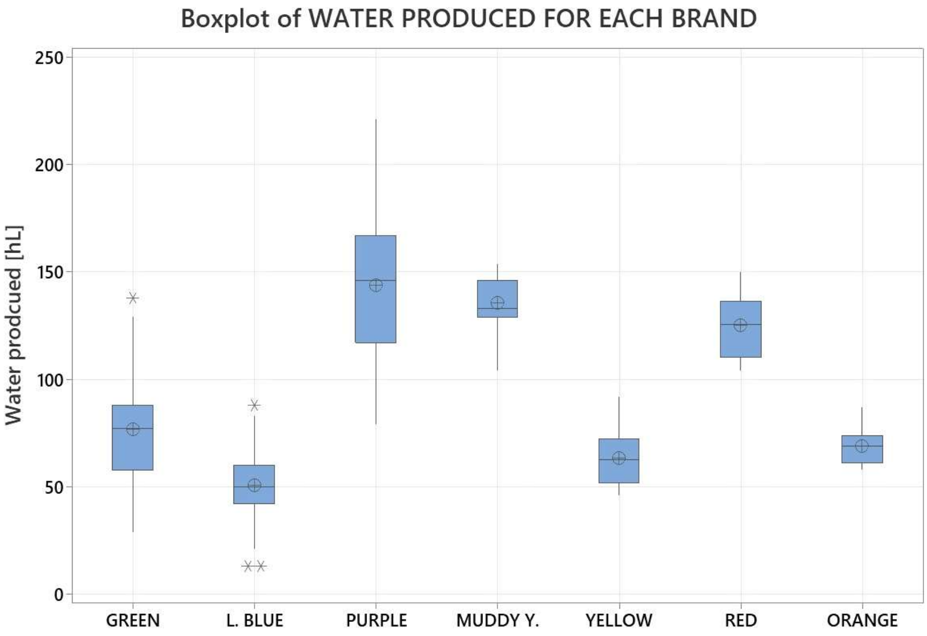

Figure 3.4: *Boxplot of warm water from the condenser*

The box plot gives us the following information:

- Minimum: it is the minimum value in the dataset excluding the outliers;
- First Quartile (Q1): 25% of the data lies below the First (lower) Quartile;
- Median (Q2): It is the mid-point of the dataset. Half of the values lie below it and half above;
- Third Quartile (Q3): 75% of the data lies below the Third (Upper) Quartile;
- Maximum: it is the maximum value in the dataset excluding the outliers;

In the boxplot it can be noticed that the 50% of the data retrieved for the brands is in a quite tight interval for all brands except for *Purple* (however, it has a tight confidence interval), confirming that the study may lead to reliable results.

3.3.4 Warm water from wort cooling

For this evaluation, amounts of water produced are considered constant for each brew, since the ice water flowrate and the cooling time are constant for a specific brand.

In particular, brands *Purple, Light Blue, Green, Muddy Yellow* and *Red* produce 670 hL of warm water, while brands *Yellow* and *Orange* produces 740 hL of warm water.

3.3.5 Total amount of warm water

In the end, it is possible to evaluate the total quantity of warm water produced for each brew. The values are shown in *table 3.3* of the next page.

***Table** 3.3: Warm water produced per brew.*

Brand	Water produced [hL]
PURPLE	814
LIGHT BLUE	721
GREEN	747
YELLOW	803
MUDDY YELLOW	875
ORANGE	739
RED	795

It is clear that the brand that produces the greatest quantity of warm water is the *Muddy Yellow*, whilst the brand that produces the smallest quantity is the *Light Blue*.

3.4 Objective of the study

Over a common week of production, around 40 brews are made, and how many brews per brand are decided accordingly to market requests; thus, the number of brews per brand is decided before starting the week.

Remembering that for each different brand a different amount of warm water is produced, we want to avoid that the warm water tank becomes full because, if this happens, we no more recover vapor to produce hot water but we waste it, since we don't have enough space in the warm water tank.

Thus, we are interested in finding a way to understand which is the best succession of brews in order to keep the level of the warm water tank as much constant as possible.

3.5 Mathematical model

To evaluate the impact of the warm water produced by a brew respect to the level of the warm water tank, a so-called *water ratio* is defined as:

$$WR = \frac{H2O_{2^{nd}phase} + H2O_{wort\ cooling}}{1500} \tag{3.1}$$

Where 1500 is the average quantity of water present in the tank in hL taken as a reference. It is taken this average value for a few reasons:

- The maximum quantity of water that can be stored in the tank is 2000 hL;
- When the level of the tank goes under 1000 hL, boilers start to produce water at 85 °C to refill the tank;
- In this way the ratios obtained are someway "normalized" (they are numbers between 0 and 1) and they are easier to compare.

When, for example, a succession of brews is considered, the *WR* becomes:

$$WR = \frac{\sum_{i}^{N}\left(H2O_{2^{nd}phase,\,i} + H2O_{wort\ cooling,\,i}\right)}{N \cdot 1500} \tag{3.2}$$

Where *i* is a certain brew, and *N* is the number of brews of the sequence.
Now that it has been defined the water ratio, it is possible to calculate the average water ratio for a given sequence of a certain number of brews, e.g. 40.
It has been decided to evaluate the water ratio of each group of 4 brews of the sequence, and to keep the level of the tank as much constant as possible, we want to find the sequence in which each group of 4 brews has a water ratio similar to the average water ratio of the whole sequence.
In other words, the condition imposed for the acceptability of the water ratios is for each group: $WR_{group} > WR_{average}$.

One way to obtain the optimal sequence is to randomly change the sequence of brews until every water ratio of each group of 4 brews satisfies the acceptability conditions, i.e. every water ratio is quite similar to the average one.

How much similar to the average one will be seen in the following.

To complete the task, the programs *Excel* and *Matlab* have been used.

3.5.1 *Excel* worksheet

In *Excel* it has been made a worksheet in which it is possible to insert the list of brand names to be brewed along the week, in whatever order.

The worksheet automatically associates each brand name with a color, a number and the relative quantity of water produced by the brand.

In *table 3.4* it is shown an example of what previously said.

Table 3.4: *Initial brews succession.*

Initial succession	Brand nr.	Water produced [hL]
PURPLE	1	814
PURPLE	1	814
PURPLE	1	814
PURPLE	1	814
PURPLE	1	814
PURPLE	1	814
PURPLE	1	814
PURPLE	1	814
ORANGE	6	739
ORANGE	6	739
GREEN	3	747
GREEN	3	747
GREEN	3	747
GREEN	3	747
GREEN	3	747
GREEN	3	747
GREEN	3	747
GREEN	3	747
GREEN	3	747
GREEN	3	747
GREEN	3	747
LIGHT BLUE	2	721
LIGHT BLUE	2	721
LIGHT BLUE	2	721

LIGHT BLUE	2	721
LIGHT BLUE	2	721
LIGHT BLUE	2	721
LIGHT BLUE	2	721
LIGHT BLUE	2	721
LIGHT BLUE	2	721
LIGHT BLUE	2	721
LIGHT BLUE	2	721
MUDDY YELLOW	5	875
MUDDY YELLOW	5	875
RED	7	795
RED	7	795
YELLOW	4	803
YELLOW	4	803

After that, the succession is inserted in a code in *Matlab.*

3.5.2 *Matlab* code

In *Matlab*, a code has been implemented that, starting from the initial list of brands, assesses the optimal list.

Firstly, it is shown a logical scheme of the code (*figure 3.5*) and it is explained.

In the appendix it is shown the exact code used, and as a demonstration, a succession of 38 brews is considered.

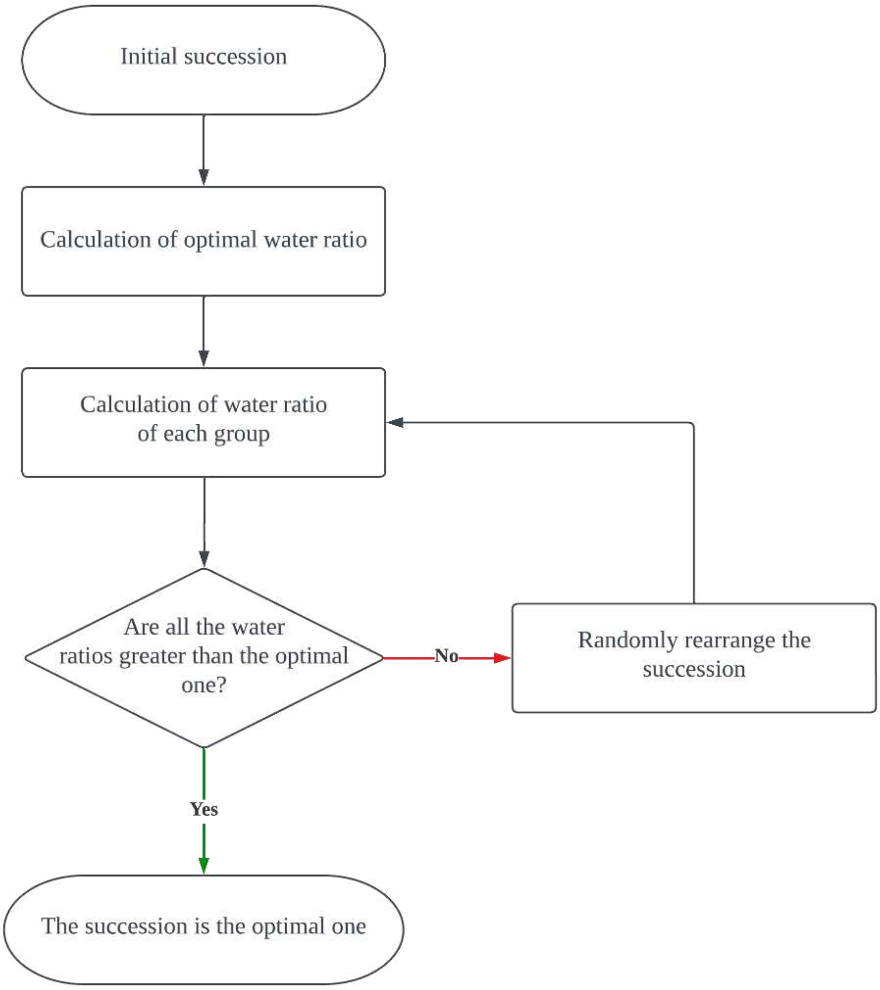

Figure 3.5: *Logical scheme of the model.*

3.5.3 Explanation of the code

Firstly, the succession of brews is copied to a *Matlab* table.

In this file the list is copied in terms of water produced per each brand; in other words, since the code evaluates the water ratios, for simplicity we insert directly into the code the quantity of water produced per each brand instead of the brand name.

From this file the code takes the first succession.

After that, the succession is divided in groups of 4 and for each group the initial water ratio is evaluated, accordingly to *equation 3.2*. In this case, since the brews are 38, the last group is made of 2 brews.

The average water ratio is also evaluated, and as a first try an optimal ratio equal to 99% of the average one is assumed.

In order to randomly rearrange the succession, the function *randperm* is used; it automatically changes the order in a random way and gives back the new configuration.

To find the optimal configuration a *while* cicle is used.

It is imposed that, while at least one of the water ratios of each group is less than the optimal one, the cycle continues to use the *randperm* function to rearrange the one.

The cycle continues until the imposed condition is satisfied (if possible).

Since the configuration is still expressed in terms of the water produced by each brand, each quantity is then substituted with the associated number of brands.

3.5.4 Results

As a result, after 274516 iterations the code gives the final configuration and the water ratios:

***Table** 3.5: Average and optimal water ratios (1).*

Average water ratio	Optimal water ratio
0.5102	0.5051

The optimal water ratio is calculated as 99% of the average water ratio, as previously said. It is not considered the average water ratio as the optimal one because it is not possible since the whole succession is divided in groups. The average water ratio is not reachable for all groups.

Table 3.6: *Initial and final water ratios (1).*

Initial water ratios	Final water ratios
0.5427	0.5078
0.5427	0.5078
0.4953	0.5107
0.4980	0.5098
0.4937	0.5107
0.4807	0.5098
0.4807	0.5128
0.5320	0.5060
0.5327	0.5160
0.4980	0.5117

It can be noticed that some of the initial water ratios were lower than the optimal water ratio while other were much higher. It is not a convenient configuration; indeed, great ratios might lead to the unwanted situation in which the warm water tank is fully filled and the production of water stops.

On the other hand, when the water ratios are much lower than the average one, the level of the warm water tank may become low enough to start the production of more warm water from boilers.

These situations arise in particular when two successive groups have both great or small water ratios.

For what concerns the final configuration, it is notable that all the water ratios are larger than the optimal one, and in this way the production of warm water is optimized.

In the end, the optimal configuration is brought back in *Excel,* where the worksheet converts the list of numbers in a list of brand names.

The final configuration is shown in *table 3.7,* where it is also shown a comparison with the initial succession.

***Table* 3.7:** *Comparison between initial and final succession.*

Initial succession	Final succession
PURPLE	ORANGE
PURPLE	GREEN
PURPLE	PURPLE
PURPLE	GREEN
PURPLE	GREEN
PURPLE	GREEN
PURPLE	ORANGE
PURPLE	PURPLE
ORANGE	LIGHT BLUE
ORANGE	GREEN
GREEN	LIGHT BLUE
GREEN	MUDDY YELLOW
GREEN	LIGHT BLUE
GREEN	YELLOW
GREEN	PURPLE
GREEN	LIGHT BLUE
GREEN	MUDDY YELLOW
GREEN	LIGHT BLUE
GREEN	LIGHT BLUE
GREEN	GREEN
GREEN	LIGHT BLUE
LIGHT BLUE	YELLOW
LIGHT BLUE	PURPLE
LIGHT BLUE	LIGHT BLUE
LIGHT BLUE	RED
LIGHT BLUE	LIGHT BLUE
LIGHT BLUE	GREEN
LIGHT BLUE	PURPLE
LIGHT BLUE	RED
LIGHT BLUE	GREEN
LIGHT BLUE	GREEN
LIGHT BLUE	GREEN
MUDDY YELLOW	PURPLE
MUDDY YELLOW	PURPLE
RED	LIGHT BLUE
RED	GREEN
YELLOW	LIGHT BLUE
YELLOW	PURPLE

That is the final configuration that will be used by the operator in charge of the brewing management. It could be of great help since, previously the choice of the succession was made by the operator thanks to his work experience.

3.6 Application to a real situation

In the following, it is shown another example of management of 40 brews of a week using the proposed model.

It is considered an actual list of brands that has been produced over a week in February.

***Table 3.8**: Initial brews succession (2).*

Initial brands succession	Brand nr.	Water produced [hL]
PURPLE	1	814
PURPLE	1	814
PURPLE	1	814
PURPLE	1	814
PURPLE	1	814
PURPLE	1	814
PURPLE	1	814
PURPLE	1	814
PURPLE	1	814
PURPLE	1	814
GREEN	3	747
GREEN	3	747
GREEN	3	747
GREEN	3	747
GREEN	3	747
GREEN	3	747
GREEN	3	747
GREEN	3	747
YELLOW	4	803
YELLOW	4	803
YELLOW	4	803
YELLOW	4	803
LIGHT BLUE	2	721
LIGHT BLUE	2	721
LIGHT BLUE	2	721
LIGHT BLUE	2	721
LIGHT BLUE	2	721

LIGHT BLUE	2	721
LIGHT BLUE	2	721
LIGHT BLUE	2	721
LIGHT BLUE	2	721
LIGHT BLUE	2	721
MUDDY YELLOW	5	875
MUDDY YELLOW	5	875
MUDDY YELLOW	5	875
MUDDY YELLOW	5	875
RED	7	795
RED	7	795
ORANGE	6	739
ORANGE	6	739

From the presented succession, after 3838 iterations, the following results are obtained in *Matlab*, and the same considerations of before can be done.

Table 3.9: *Average and optimal water ratios (2).*

Average water ratio	**Optimal water ratio**
0.5184	0.5132

Table 3.10*: Initial and final water ratios (2).*

Initial water ratios	**Final water ratios**
0.5427	0.5230
0.5427	0.5160
0.5203	0.5203
0.4980	0.5190
0.5167	0.5248
0.5080	0.5160
0.4807	0.5142
0.4807	0.5142
0.5833	0.5218
0.5113	0.5150

Table 4.11: *Comparison between initial and final succession (2).*

Initial succession	Final succession
PURPLE	RED
PURPLE	MUDDY YELLOW
PURPLE	LIGHT BLUE
PURPLE	GREEN
PURPLE	GREEN
PURPLE	PURPLE
PURPLE	PURPLE
PURPLE	LIGHT BLUE
PURPLE	LIGHT BLUE
PURPLE	YELLOW
GREEN	RED
GREEN	YELLOW
GREEN	PURPLE
GREEN	GREEN
GREEN	ORANGE
GREEN	PURPLE
GREEN	PURPLE
GREEN	LIGHT BLUE
YELLOW	ORANGE
YELLOW	MUDDY YELLOW
YELLOW	PURPLE
YELLOW	PURPLE
LIGHT BLUE	GREEN
LIGHT BLUE	LIGHT BLUE
LIGHT BLUE	GREEN
LIGHT BLUE	PURPLE
LIGHT BLUE	LIGHT BLUE
LIGHT BLUE	YELLOW
LIGHT BLUE	PURPLE
LIGHT BLUE	YELLOW
LIGHT BLUE	LIGHT BLUE
LIGHT BLUE	GREEN
MUDDY YELLOW	LIGHT BLUE
MUDDY YELLOW	PURPLE
MUDDY YELLOW	LIGHT BLUE
MUDDY YELLOW	MUDDY YELLOW
RED	MUDDY YELLOW
RED	GREEN
ORANGE	LIGHT BLUE
ORANGE	GREEN

Conclusions

The first part of the study was focused on finding a way to optimize the use of a heat exchanger and optimize the recovery of vapors during production.

It has been assessed that, changing the set point of the controller of the pump of wort flowrate, it has been possible to enhance the temperature of wort entering the wort kettle by approximately 1 °C. It is a great advantage since during a common day of production almost 2500 hL of wort are boiled, and 1 °C, which apparently seems a small difference, in reality has a great impact, economically speaking, in terms of steam consumed to heat the wort to boil.

The second part of the study was about finding a way to optimize the brews succession during a common week of production, trying to search for the best possible succession of brews in order to maintain as much constant as possible the production of water at around 85 °C from vapors recovery processes.

A mathematical model has been proposed, that rearranges the succession of brews until the desired configuration is obtained.

Finally, it can be said that both the main tasks have been fulfilled, and some little step through optimization of the process have been made.

Appendix A

Overall heat transfer coefficient in a heat exchanger

To find the overall heat transfer coefficient in a heat exchanger, the following equation has been used:

$$\frac{1}{U} = \frac{1}{h_{hot}} + \frac{1}{F_{f,hot}} + \frac{s_{plate}}{k_{plate}} + \frac{1}{h_{cold}} + \frac{1}{F_{f,cold}} \qquad \text{(A.1)}$$

Where U is the overall heat transfer coefficient, h_{hot} and h_{cold} are the local heat transfer coefficients for the hot and cold sides, s_{plate} is the plate thickness, $\mathrm{k_{plate}}$ is the conduction resistance of the plate, and $F_{f,hot}$ and $F_{f,cold}$ are the relevant fouling factors of each side (for simplicity, they could be ignored).

Appendix B

Heat transfer coefficient in a plate heat exchanger

It is important to know that the principal dimensionless groups governing heat transfer in a plate heat exchanger are the Prandtl, Reynolds and Nusselt numbers. The Prandtl and Reynolds numbers are defined as:

$$Pr = \frac{c_p \mu}{k} \;\; ; \;\; Nu = \frac{h D_h}{k} \;\; ; \;\; Re = \frac{G D_h}{\mu} \qquad \text{(B.1)}$$

here G is the mass velocity, defined as:

$$G = \frac{m}{A_{min}} \quad [\mathrm{kg/m^2\ s}] \qquad \text{(B.2)}$$

where m = total mass flow rate of fluid [kg/s], A_{min} = minimum free-flow cross-sectional area [$\mathrm{m^2}$] regardless of where this minimum occurs, and D_h is the hydraulic diameter [m] defined as:

$$D_h = \frac{4\,W\,b}{2(\,W + b)} \tag{B.3}$$

where W is the width of the plates and b is the spacing between plates.

One of the most widely used relationship for the Nusselt number in plate heat exchangers is the following one:

$$Nu = 0.374\,Re^{0.668}\,Pr^{0.33}\left(\frac{\mu_h}{\mu_w}\right)^{0.15} \tag{B.4}$$

where μ_h is the viscosity of the fluid at the bulk temperature, while μ_w is the viscosity of the fluid at the wall temperature.
For simplicity, during calculation, the viscosity ratio is considered equal to 1.
In the following, some calculations are shown.

Appendix C

Calculation of overall heat transfer coefficient

For the calculation of the water and wort heat transfer coefficients, the formulas of the previous paragraph have been used, where the needed parameters have been found in literature.

Table C.1: *Water heat transfer data.*

μ_{water}	[Kg / m s]	0,0003
k_{water}	[W / m °C]	0,675
Cp_{water}	[J / kg °C]	4200
G_{water}	[kg/m^2 s]	47304,76
$\dot{m}_{water}$	[kg / s]	40,20
cross area	[m^2]	0,00085
plate width	[m]	0,57

mean plate gap	[m]	0,0015
D_h	[m]	0,0030
Re_{water}		471798
Pr_{water}		1,87
Nu_{water}		1752
h_{water}	[W/m^2 °C]	395236

Table C.2: *Wort heat transfer data.*

μ_{water}	[Kg / m s]	0,0003
k_{water}	[W / m °C]	0,675
Cp_{water}	[J / kg °C]	4010
G_{water}	[kg/m^2 s]	26164,56
$\dot{m}_{water}$	[kg / s]	22,23
cross area	[m^2]	0,00085
plate width	[m]	0,57
mean plate gap	[m]	0,0015
D_h	[m]	0,0030
Re_{water}		260955
Pr_{water}		1,78
Nu_{water}		1170
h_{water}	[W/m^2 °C]	264023

In the following table, parameters used for the calculation of conduction and fouling factors are presented.

***Table C.3**: Conduction and fouling parameters.*

***s* plate**	[m]	0,0005
***k* plate (SS AISI316)**	[W / m °C]	16
***Ff* water**	[m^2 °C/ W]	0,0003
***Ff* wort**	[m^2 °C/ W]	0,0003

From *equation 19,* U = 1568 [W / m^2 K] is then calculated.

Appendix D

Heat transfer coefficient in a shell and tube condenser

Condensation occurs when a saturated vapor comes in contact with a surface whose temperature is below the saturation temperature. Normally a film of condensate if formed and this is called film-type condensation.

Firstly, it is calculated the heat transfer coefficient of shell side.

Film-type condensation is the most common therefore the development of equations for condensation are presented for film-type only.

The Reynolds number of the condensate film is: $Re = 4\Gamma/\mu$ (D.1)

where Γ is the loading rate of condensate per unit perimeter [kg/m s]. The thickness of the condensate film for Reynolds number less than 2100 is: $\delta = (3\mu\Gamma/\rho^2 g)^{1/3}$. (D.2)

For horizontal tubes, Reynolds number can be calculated by using:

$\Gamma = W_F/2L$ (D.3)

where W_F is the total rate of vapor condensation on one tube [kg/s] and L is the length of heat-transfer surface [m].

Nusselt number can be calculated with the following relationship:

$$Nu = \frac{h\,D}{k} = 0.76\left(\frac{D^3\rho^2 g}{\mu\,\Gamma}\right)^{1\backslash 3} \tag{D.4}$$

Alternatively, it can be expressed in a dimensional form:

$$h = b\left(\frac{k^3\rho^2 L}{\mu\,W_F}\right)^{1\backslash 3} \quad , \quad \text{where } b = 205.4 \text{ (SI)} \tag{D.5}$$

For steam at atmospheric pressure: $h = b\left(\frac{L}{W_F}\right)^{1\backslash 3}$, where $b = 2080$ (SI) (D.6)

Using *equation 24,* the heat transfer coefficient for the shell side is calculated:

Table D.1: *Heat transfer parameters for shell side.*

$\dot{m}_{vapor}$	[kg / s]	0,0007
L tube	[m]	3,7
h_{shell}	[W / m² °C]	36232

It is then calculated the heat transfer coefficient of tubes side (for turbulent regime). For a turbulent regime, the following correlation has been used:

$$Nu = 0.027 \cdot Re^{0.8} \cdot Pr^{1\backslash 3} \cdot \left(\frac{\mu_h}{\mu_w}\right) \tag{D.7}$$

Reynolds number is calculated as: $Re = \frac{G \cdot d_i}{\mu}$ (D.8)

Where G is calculated as: $G = \frac{\dot{m}}{\frac{N_t}{n_t} \cdot \pi \cdot \frac{d_i^2}{4}}$, With: (D.9)

N_t = number of tubes

n_t = number of passes

d_i = internal diameter of the tubes

Also in this case the viscosity ratio is considered, for simplicity, equal to 1.

From Nusselt correlation, the heat transfer coefficient h_{tubes} is calculated.

Table D.2: *Heat transfer parameters for tubes side.*

G	[kg/ s m^2]	1400
$\dot{m}_{water}$	[kg/s]	45
d_i	[m]	0,015
d_o	[m]	0,018
N tubes		364
N passes		2
Re		69994
Nu		249,90
Pr		1,87
h_{water}		11246

Finally, it is possible to evaluate the overall heat transfer coefficient for the condenser.

For the calculation of the overall heat transfer coefficient of the condenser a slightly different equation has been used:

$$\frac{1}{U} = \frac{1}{h_{tube}} + \frac{1}{F_{f,tube}} + \frac{d_i}{2 \cdot k_{tubes}} \cdot \ln\left(\frac{d_o}{d_i}\right) + \frac{d_i}{d_o} \cdot \frac{1}{F_{f,shell}} + \frac{d_i}{d_o} \cdot \frac{1}{h_{shell}} \qquad \text{(D.10)}$$

Finally, the overall heat transfer coefficient U = 1338 [W/m^2 °C] is calculated.

Appendix E

Mean, variance and confidence intervals

First of all, it is opportune to recall the definitions of confidence interval, normal distribution and standard deviation.

confidence interval (CI) is a range of estimates for an unknown parameter. A confidence interval is computed at a designated confidence level; the 95% confidence level is the most common.

In statistic, a normal distribution or Gaussian distribution is a type of continuous probability distribution for a real valued random variable. The general form of its probability density function is:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}, \tag{E.1}$$

Where μ is the mean of the distribution, while σ is the standard deviation. The standard deviation is a measure of the amount of variation or dispersion of a set of values. σ^2 is called the variance of the distribution.

The standard normal distribution has a typical curve, the so called “bell curve” for its shape.

It is shown in the following figure.

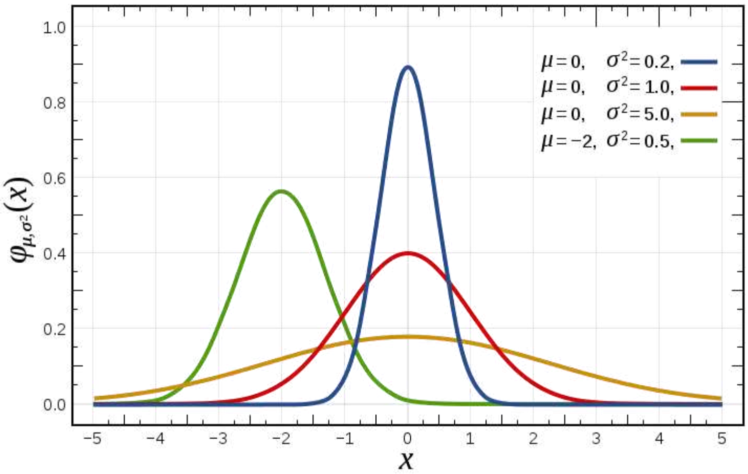

Figure E.1: *Normal distribution curves.*

Also an example of calculating a confidence interval for a normally distributed population is presented.

Suppose {X1,…,Xn} is an independent sample from a normally distributed population with unknown parameters mean and variance.

The sample mean $\bar{X}$ and the sample variance S^2 are defined as:

$$S^2 = \frac{1}{n-1}\sum_{i=1}^{n}\left(X_i - \bar{X}\right)^2 \tag{E.2}$$

$$\bar{X} = \frac{\left(X_1 + \ldots + X_n\right)}{n} \tag{E.3}$$

Then: $T = \frac{\bar{X} - \mu}{\frac{S}{\sqrt{n}}}$ has a Student's t-distribution with n-1 degrees of freedom. In probability and statistics, Student's t-distribution (or simply the t-distribution) is any member of a family of continuous probability distributions that arise when estimating the mean of a normally distributed population in situations where the sample size is small and the population's standard deviation is unknown.

Suppose we wanted to calculate a 95% confidence interval for μ. Thus, denoting c as the 97,5th percentile of this distribution: $Pr(-c \leq T \leq c) = 0,95$

Note that "97,5th" and "95" are correct in the previous expressions since there is 2,5% chance that T will be less than "-c" and a 2,5% chance it will be larger than "+c". Thus, the probability that T will be between -c and +c is 95%.

Consequently: $$Pr\left(\bar{X} - \frac{cS}{\sqrt{n}} \leq \mu \leq \bar{X} + \frac{cS}{\sqrt{n}}\right) = 0,95 \tag{E.4}$$

In this way, a theoretical 95% confidence interval for μ is obtained:

$$\left[\bar{x} - \frac{cs}{\sqrt{n}}\ ,\ \bar{x} + \frac{cs}{\sqrt{n}}\right]. \tag{E.5}$$

Appendix F

Matlab code for optimal succession

It is shown the actual code used in *Matlab.*

```
%% OPTIMAL BREWS SUCCESSION

Clearvars

% Initial configuration (water produced in hL) of 38 brews

load('brew_list.mat')

r_average = sum(brews)./(1500*length(brews)); % average water ratio

r_opt = 0.99*r_average; % optimal water ratio (assumption)

r1 = sum(brews (1:4,1))./(1500*4);
r2 = sum(brews (5:8,1))./(1500*4);
r3 = sum(brews (9:12,1))./(1500*4);
r4 = sum(brews (13:16,1))./(1500*4);
r5 = sum(brews (17:20,1))./(1500*4);
r6 = sum(brews (21:24,1))./(1500*4);
r7 = sum(brews (25:28,1))./(1500*4);
r8 = sum(brews (29:32,1))./(1500*4);
r9 = sum(brews (33:36,1))./(1500*4);
r10 = sum(brews (37:38,1))./(1500*2);

r = [r1 r2 r3 r4 r5 r6 r7 r8 r9 r10]; % initial water ratios


%% Permutation cycle of the succession

iterCount = 0;

while   (r(1,1) < r_opt) || (r(1,2) < r_opt) || (r(1,3) < r_opt)
     || (r(1,4) < r_opt) || (r(1,5) < r_opt) || (r(1,6) < r_opt)
     || (r(1,7) < r_opt) || (r(1,8) < r_opt) || (r(1,9) < r_opt)
     || (r(1,10) < r_opt)

      iterCount = iterCount + 1;


% Function to randomly rearrange the succession
```

```
    brews_rand = brews(randperm(length(brews)));

rr1 = sum(brews_rand(1:4,1))./(1500*4);
rr2 = sum(brews_rand(5:8,1))./(1500*4);
rr3 = sum(brews_rand(9:12,1))./(1500*4);
rr4 = sum(brews_rand(13:16,1))./(1500*4);
rr5 = sum(brews_rand(17:20,1))./(1500*4);
rr6 = sum(brews_rand(21:24,1))./(1500*4);
rr7 = sum(brews_rand(25:28,1))./(1500*4);
rr8 = sum(brews_rand(29:32,1))./(1500*4);
rr9 = sum(brews_rand(33:36,1))./(1500*4);
rr10 = sum(brews_rand(37:38,1))./(1500*2);

rr = [rr1 rr2 rr3 rr4 rr5 rr6 rr7 rr8 rr9 rr10]; % new water ratios


    if  (rr1 > r_opt) && (rr2 > r_opt) && (rr3 > r_opt)
        && (rr4 > r_opt) && (rr5 > r_opt) && (rr6 > r_opt)
        && (rr7 > r_opt) && (rr8 > r_opt) && (rr9 > r_opt)
        && (rr10 > r_opt)

        break
    end

end


% numbers = [ '1'    '2'    '3'    '4'    '5'    '6'    '7' ]
% names = [‘PURPLE’ ‘L. BLUE’ ‘GREEN’ ‘YELLOW’ ‘MUDDY Y.’ ‘ORANGE’
‘RED’]

cotte_rand(cotte_rand == 813) = 1;
cotte_rand(cotte_rand == 729) = 2;
cotte_rand(cotte_rand == 754) = 3;
cotte_rand(cotte_rand == 783) = 4;
cotte_rand(cotte_rand == 861) = 5;
cotte_rand(cotte_rand == 735) = 6;
cotte_rand(cotte_rand == 803) = 7;


disp('Optimal configuration'),   disp(cotte_rand)
disp('Iterations count'),         disp(iterCount)
disp('Average water ratio'),      disp(r_average)
disp('Optimal water ratio'),      disp(r_opt)
disp('Initial water ratios'),     disp(r)
disp('Final water ratios'),       disp(rr)
```

Bibliography

W. Kunze, *Technology Brewing and Malting,* VLB Berlin, 2004

D. W. Green – R. H. Perry, *Perry's chemical engineers' handbook - 8th edition*, McGraw-Hill Book Company Inc., 2008

R. B. Bird – W. E. Stewart – E. N. Lightfoot, *Transport phenomena - 2nd edition*, John Wiley & Sons Inc. , 2002

R. K. Sinnott, *Chemical Engineering Design - 4th edition*, Coulson & Richardson Chemical Engineering series - volume 6, Elsevier, 2005

T. Kuppan, *Heat Exchanger Design Handbook*, Marcel Dekker Inc., 2000

D. Q. Kern, *Process Heat Transfer*, McGraw-Hill Book Company Inc., 1965

W. L. McCabe – J. C. Smith – P. Harriott, *Unit Operations of Chemical Engineering - 5th edition*, McGraw-Hill Book Company Inc., 1993

"Beer", *Wikipedia*, Wikipedia.org, 30 January 2023, Beer - Wikipedia, Accessed 1st February 2023

"Birra Peroni – Chi siamo", Chi siamo | Birra Peroni, Accessed 2nd February 2023

J.M. Bland – D.G. Altman, *Statistics notes: measurement error*, BMJ, 1996

H. M. Walker, *Studies in the History of the Statistical Method. Baltimore,* Williams & Wilkins Co., 1931

A. Lyon, *Why are Normal Distributions Normal?*, The British Journal for the Philosophy of Science, 2014

Rees. D.G. Rees, *Essential Statistics - 4th Edition*, Chapman and Hall, 2001

H. J. Zar, *Biostatistical Analysis – 4th edition,* Upper Saddle River - Prentice Hall, 1999

F. M. Dekking – C. Kraaikamp – H.P. Lopuhaä – L.E. Meester, *A Modern Introduction to Probability and Statistics",* Springer, 2005