

Feasibility Study of Virtual Energy Reporting based on Process Data in Historian

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Master's dissertation submitted in order to obtain the academic degree of
Master of Science in Electrical Engineering Technology - Automation

Academic year 2023-2024

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FOREWORD

I was given the opportunity to contribute to the academic community by writing a thesis on an interesting topic. I am pleased with the outcome of this master's thesis, which I can reflect on with satisfaction. I think it is interesting how energy consumption and consumer mapping work together with process knowledge. As the world becomes more eco-conscious, understanding process consumption will become increasingly important. The goal of this thesis is to develop an algorithm to gain a better understanding in process consumption in a cost-effective way.

I wrote my thesis in collaboration with Actemium. I am appreciative of the guidance and assistance I received. In the first instance, I would like to thank the data science team at Actemium's Beverage division, particularly Ir. Jeroen Pandelaere, my mentor at Actemium, who provided me with technical ideas, data expertise, and weekly follow-up. Secondly, I would like to thank ing. Justin Vande Casteele, who has extensive experience of the considered process and was able to answer many of my technical questions. Next, I would like to thank Dr. ir. Nele De Geeter, my mentor at UGent, for her invaluable support in the planning, design, revision and administrative aspects of this thesis. I would also like to thank Actemium for giving me the opportunity to undertake this research. Finally, I would like to thank Puratos, a customer of Actemium, for their assistance and responding to my technical queries.

I hope that the energy tool developed in this thesis will prove to be a valuable resource for those seeking to gain insight into energy consumption.

The files that are relevant to this thesis can be accessed by following the link in Appendix E to the shared folder.

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ABSTRACT

This master's thesis is titled "Feasibility Study of Virtual Energy Reporting Based on Process Data in Historian," and is conducted as part of the Master of Science in Electrical Engineering Technology - Automation for the academic year 2023-2024. The goal of this thesis is to develop a virtual, low-cost energy monitoring system using process data. This research was supervised by Dr. ir. Nele De Geeter and ir. Jeroen Pandelaere from Actemium Beverage Aalter. The thesis explores the feasibility of implementing a virtual energy reporting system based on existing process data stored in a historian database.

The aim of this work is to gain a better understanding of the energy consumption of an industrial process in a cost-effective way. It is applied to a UHT process at Puratos, one of Actemium's customers.

From an economic and environmental point of view, it is important to minimize the energy consumption of such a process, but the problem is that there is little insight into the energy consumption. In addition, process optimization is done by trial and error, resulting in an inefficient and costly method of improvement.

The developed system uses data from existing sensors used to control the relevant industrial processes. By analysing these data and components, the theoretical energy consumption is calculated, providing an approximation of the actual energy consumption.

The main advantage of this type of virtual energy monitoring system is that a virtual model can be used to evaluate different scenarios without the need for extensive real-world testing. This approach allows the optimal solution to be identified more quickly and cost-effectively. It also provides a better idea of the production cost of treating the product, resulting in a better revenue model.

Keywords: virtual energy, virtual energy monitoring system, UHT process, process dashboard, process data, historian

EXTENDED ABSTRACT

Feasibility Study of Virtual Energy Reporting based on Process Data in Historian

Lukas Favoreel

Supervisors: Jeroen Pandelaere, Nele De Geeter

Abstract: The study focuses on the energy consumption of an industrial UHT process at Puratos. The research addresses the lack of visibility into energy consumption and the inefficiencies of trial-and-error process optimization. Using existing sensor data stored in a historian database, the system calculates theoretical energy consumption that approximates actual consumption. This virtual model makes it easier to evaluate different scenarios without extensive real-world testing, resulting in faster, more cost-effective identification of optimal solutions. It also provides a better understanding of production costs, thereby improving revenue models.

Keywords: virtual energy, virtual energy monitoring system, UHT process, process dashboard, process data, historian

1. INTRODUCTION

The aim of this work is to gain a better understanding of the energy consumption of an industrial process in a cost-effective way. It is applied to an Ultra High Temperature (UHT) process at Puratos, one of Actemium's customers. This type of process is a good choice to focus this algorithm on because it consists of several different consumers, demonstrating the high flexibility of this algorithm.

From an economic and environmental point of view, it is important to minimize the energy consumption of such a process, but the problem is that there is little insight into the energy consumption. For example, it is often only possible to see the total energy consumption on the energy bill. It is not possible to see how much each component consumes. In addition, process optimization

is done by comparing the UHT line under consideration with a more performing line. The problem is that Puratos does not know if the change is energetically advantageous.

The main advantage of this type of virtual energy monitoring system is that a virtual model can be used to evaluate different scenarios without the need for extensive real-world testing. This approach allows the optimal solution to be identified more quickly and cost-effectively. It also provides a better idea of the production cost of treating the product, resulting in a better revenue model.

2. METHODS

The methods of creating an algorithm that can calculate energy consumption can be divided into three main parts. The first part is gaining process knowledge. The second part is performing the calculations based on the process knowledge, and the third part is summarizing the calculations into (visual) results.

To develop an algorithm that calculates the energy consumption of each component of a process, a lot of process knowledge is needed as a first step. So the first step is to get to know the process well. This is done by reading the plant manual and analyzing the piping and instrumentation diagram (P&ID). This work focusses on the UHT process implemented at Puratos. It first delves into the intricate workings of each component in the UHT line, providing detailed insights into their functions and roles. Once the components are known, the method of production is investigated. For example, other liquids pass through the UHT tubes during several pre- and post-operation processes. It is therefore important to distinguish the different steps in which the

process takes place, identified by a step number. Then it is necessary to distinguish the different products that can be treated, which can lead to different energy consumption because of different thermal properties. Possible configurations should also be distinguished.

Since the process is now well known, the energy calculations can be done in this second part. It examines what information is available about each component or sub-process and, based on that, suggests one or more methods for calculating consumption. Often the information is too short, so an approximation has to be introduced. The formulas are proposed using theoretical equations. The next step is to access the data that is used for the calculations and address the associated problems. These need to be exported and formatted. Once the data is stored in a database, it can be used for calculations. The final step in this section is to perform the effective calculations for the different types of consumers in the process. There will also be checked here that the calculated powers can be correct.

This last part focuses on clearly visualizing the results obtained and comparing certain production sessions. This visualization can be done in two ways. First, it can be done through dashboards, where a lot of relevant information can be found on one screen. This is a dynamic and user-friendly way, where the user can easily find the information he needs. A second type of visualization is the use of swarm plots. These are plots that show the distribution of production sessions by points on a selected variable. For example, the total energy consumption of these production sessions can be plotted by product so that they can be compared. Further distinctions can be made by working with different colors or IDs. Finally, the concept of an energy baseline (EnB) is introduced and applied to the UHT process. The purpose of this EnB is to compare certain setups in terms of their efficiency using graphs and energy performance indicators (EnPI's). This is done in a stepwise manner according to IEE (2016). The process is analyzed in order to know what has a relevant contribution to this EnB. In addition, all factors that may have an influence are listed and evaluated.

The files that are relevant to this thesis can be accessed by following the link in Appendix E to the shared folder.

3. RESULTS AND DISCUSSION

The results of the discussed calculations are presented and analyzed here. Moreover, with the created virtual energy monitoring algorithm, a new process setup can first be tested virtually so that these results can be compared energetically with the existing setup.

This insight can be obtained primarily through dashboards. These user-friendly tools make it possible to select a specific time period and view all the desired data about it. This is done using info boxes, graphs and tables as shown in Figure 1. In the example below, the total energy consumption is displayed in three different ways. First, in a colored stat box, where the energy is expressed in kWh over the selected period for each type of consumption. Secondly, it is presented in a graph, also with this distinction. Finally, the total energy consumed for each type of energy source per production batch is displayed in a table. With the help of this visualization, it is possible to compare energetically different products and facilities.

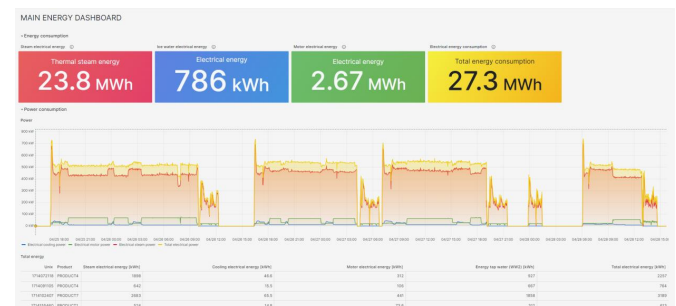


Figure 1: Energy dashboard

The dashboards are all linked to a main dashboard from which it is possible to navigate to the other dashboards for a more specific component. Using a visual process diagram, also called a Flowcharting panel, it is possible to click on the desired component and a dashboard with all relevant information about that component will appear. An example is shown in Figure 2.

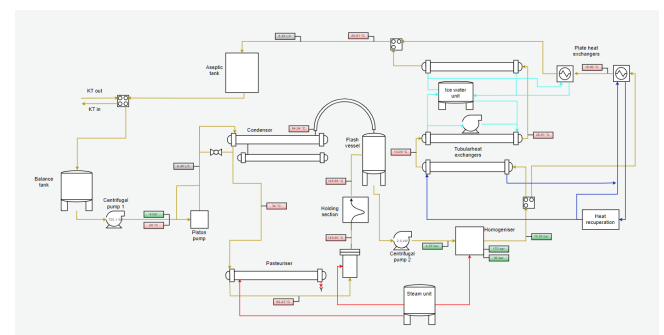


Figure 2: Flowcharting panel with process overview

A second way to gain more insight into the energy consumption of the process is to use the energy baseline, which plots the consumption of specific components or the entire process on the same graph during production as shown in Figure 3. This visually shows when and which process sessions are more energy efficient than others.



Figure 3: Total electrical power consumption of different production batches

A third way to get more insight is by using swarm plots. These plots show the distribution of production sessions and there are several ways to distinguish between those sessions. For example, the type of heat exchanger used can be indicated by color or the type of energy source. In addition, a distinction is also made by product since they have different thermal properties. An example is shown in Figure 4.

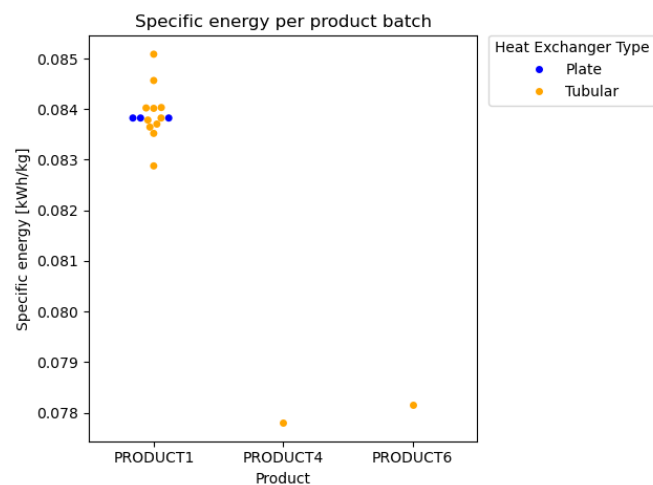


Figure 4: Swarm plot of the specific energy per product batch, split up for product type and heat exchanger type

Another example for a swarm plot is plotting KPIs. In this thesis the utilization ratio and recovery ratio are calculated as performance indicators. Figure 5 shows whether the motors used in the process still have expansion capacity. For example, the piston pump is already at maximum load while the others can be loaded higher. In addition, due to recipe dependency, the homogenizer capacity for product 1 is lower than for the others.

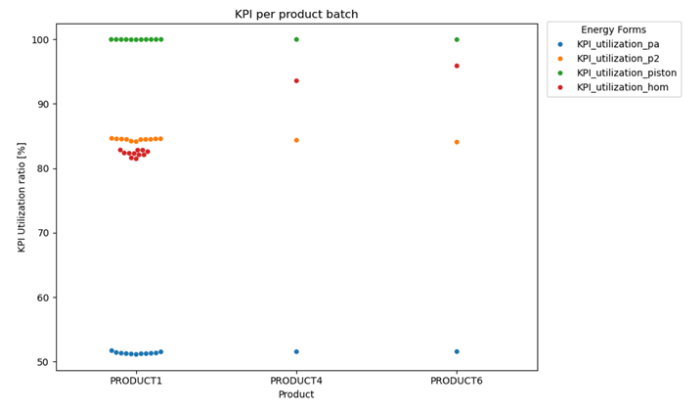


Figure 5: Swarm plot of utilization ratio KPI per production batch, split up for product type and energy source

4. CONCLUSION AND FUTURE WORK

This work presents a feasibility study on incorporating process data into a virtual energy monitoring system, with a particular focus on electrical and thermal usage. It outlines a methodical process starting with comprehensive data collection, followed by the derivation of relevant formulas and subsequent calculations to determine key indicators such as efficiency and KPIs. Visual representations of energy consumption patterns are then generated for enhanced understanding.

Beyond the technical implementation, the study aims to serve as an inspiration to others, particularly those operating within constrained budgets, by demonstrating the flexibility of such systems. Despite the challenges encountered, the document offers constructive suggestions for improvement.

Future work will aim to have real-time Grafana updates by connecting the database. Secondly, more detailed data and process information will be collected to make calculations more accurate and reduce uncertainty. By comparing the energy consumption of different production lines, such as UHT Line 1 by Tetra Pak, interesting results could be derived to make the processes more efficient. The focus will also be on developing optimization strategies to minimize energy consumption at key production stages. This includes estimating potential savings and assessing the value of investments through the use of mathematical models and predictive analysis.

5. REFERENCES

IEE. (2016, May 22). *The Importance of Setting an Accurate Energy Baseline* – IEE. <https://ieeegypt.org/the-importance-of-setting-an-accurate-energy-baseline/>

EXTENDED ABSTRACT (NEDERLANDS)

Haalbaarheidsstudie van virtuele energierapportage op basis van procesgegevens in Historian

Lukas Favoreel

Begeleiders: Jeroen Pandelaere, Nele De Geeter

Abstract: Het onderzoek focust zich op het energieverbruik van een industrieel UHT-proces bij Puratos. Hierbij richt dit werk zich op het gebrek aan inzicht in het energieverbruik en de inefficiëntie van trial-and-error procesoptimalisatie. Met behulp van bestaande sensorgegevens die zijn opgeslagen in een historische database, berekent het systeem een theoretisch energieverbruik dat het werkelijke verbruik benadert. Dit virtuele model maakt het eenvoudiger om verschillende scenario's te evalueren zonder uitgebreide tests in de echte wereld, wat resulteert in een snellere, meer kosteneffectieve identificatie van optimale oplossingen. Het biedt ook een beter inzicht in de productiekosten, waardoor de verdienmodellen worden verbeterd.

Trefwoorden: virtuele energie, virtueel energiemonitoringsysteem, UHT-proces, procesdashboard, procesgegevens, historicus

Vanuit economisch en ecologisch oogpunt is het belangrijk om het energieverbruik van zo'n proces te minimaliseren, maar het probleem is dat er weinig inzicht is in het energieverbruik. Het is bijvoorbeeld vaak alleen mogelijk om het totale energieverbruik op de energierekening te zien. Het is niet mogelijk om te zien hoeveel elk onderdeel verbruikt. Daarnaast wordt procesoptimalisatie gedaan door de betreffende UHT-lijn te vergelijken met een beter presterende lijn. Hierbij is het probleem dat Puratos niet weet of de verandering energetisch voordelig is.

Het belangrijkste voordeel van dit type virtueel energiemonitoringsysteem is dat een virtueel model kan worden gebruikt om verschillende scenario's te evalueren zonder dat er uitgebreide tests in de praktijk nodig zijn. Met deze aanpak kan de optimale oplossing sneller en kosteneffectiever worden geïdentificeerd. Het geeft ook een beter idee van de productiekosten voor de behandeling van het product, wat resulteert in een beter verdienmodel.

1. INTRODUCTIE

Het doel van dit werk is om op een kosteneffectieve manier een beter inzicht te krijgen in het energieverbruik van een industrieel proces. Het is toegepast op een Ultra High Temperature (UHT) proces bij Puratos, een van de klanten van Actemium. Dit type proces is een goede keuze om dit algoritme op toe te spitsen omdat het uit verschillende type verbruikers bestaat, wat de grote flexibiliteit van dit algoritme aantoont.

2. METHODES

De methodes voor het maken van een algoritme dat het energieverbruik kan berekenen, kunnen worden verdeeld in drie hoofdonderdelen. Het eerste deel is het verzamelen van proceskennis. Het tweede deel is het uitvoeren van de berekeningen op basis van de proceskennis en het derde deel is het

samenvatten van de berekeningen in (visuele) resultaten.

Om een algoritme te ontwikkelen dat het energieverbruik van elk onderdeel van een proces berekent, is als eerste stap veel proceskennis nodig. De eerste stap is dus om het proces goed te leren kennen. Dit wordt gedaan door de fabriekshandleiding te lezen en het leiding- en instrumentatiediagram (P&ID) te analyseren. Dit werk richt zich op het UHT-proces dat bij Puratos wordt geïmplementeerd. Eerst wordt de complexe werking van elke component in de UHT-lijn onderzocht, waarbij gedetailleerde inzichten worden gegeven in hun functies en rollen. Zodra de componenten bekend zijn, wordt de productiemethode onderzocht. Er passeren bijvoorbeeld andere vloeistoffen door de UHT-buizen tijdens verschillende pre- en postoperatieprocessen. Het is daarom belangrijk om de verschillende stappen te onderscheiden waarin het proces plaatsvindt, geïdentificeerd met een stapnummer. Vervolgens moet onderscheid worden gemaakt tussen de verschillende producten die behandeld kunnen worden, wat kan leiden tot een verschillend energieverbruik vanwege verschillende thermische eigenschappen. Mogelijke configuraties moeten ook worden onderscheiden.

Aangezien het proces nu goed bekend is, kunnen de energieberekeningen in dit tweede deel worden uitgevoerd. Er wordt gekeken welke informatie beschikbaar is over elk onderdeel of deelproces en op basis daarvan worden een of meer methoden voorgesteld om het verbruik te berekenen. Vaak is deze informatie te summier, waardoor een benadering moet worden ingevoerd. De formules worden voorgesteld met behulp van theoretische vergelijkingen. De volgende stap is toegang krijgen tot de gegevens die voor de berekeningen worden gebruikt en de bijbehorende problemen aanpakken. Deze moeten worden geëxporteerd en geformatteerd. Zodra de gegevens in een database zijn opgeslagen, kunnen ze worden gebruikt voor berekeningen. De laatste stap in dit onderdeel is het uitvoeren van de effectieve berekeningen voor de verschillende soorten

consumenten in het proces. Hier wordt ook gecontroleerd of de berekende vermogens correct kunnen zijn.

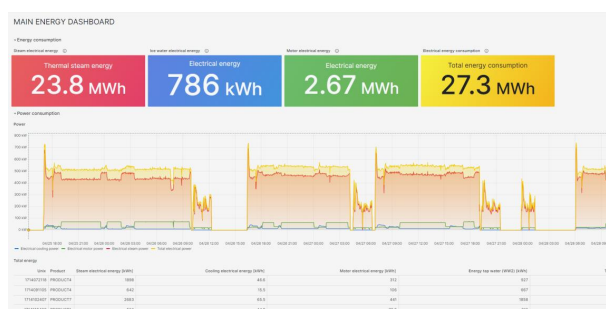
Dit laatste deel richt zich op het duidelijk visualiseren van de verkregen resultaten en het vergelijken van bepaalde productiesessies. Deze visualisatie kan op twee manieren worden gedaan. Ten eerste kan het via dashboards, waar veel relevante informatie op één scherm te vinden is. Dit is een dynamische en gebruiksvriendelijke manier, waarbij de gebruiker gemakkelijk de informatie kan vinden die hij nodig heeft. Een tweede vorm van visualisatie is het gebruik van swarm plots. Dit zijn plots die de verdeling van productiesessies door middel van punten op een geselecteerde variabele weergeven. Het totale energieverbruik van deze productiesessies kan bijvoorbeeld worden uitgezet per product, zodat ze kunnen worden vergeleken. Verder onderscheid kan worden gemaakt door te werken met verschillende kleuren of ID's. Tot slot wordt het concept van een energy baseline (EnB) geïntroduceerd en toegepast op het UHT-proces. Het doel van deze EnB is om bepaalde opstellingen te vergelijken wat betreft hun efficiëntie met behulp van grafieken en energieprestatie-indicatoren (EnPI's). Dit gebeurt stapsgewijs volgens IEE (2016). Het proces wordt geanalyseerd om te weten wat een relevante bijdrage heeft aan deze EnB. Daarnaast worden alle factoren die van invloed kunnen zijn geïnventariseerd en geëvalueerd.

De bestanden die relevant zijn voor deze scriptie zijn toegankelijk via de link in Bijlage E naar de gedeelde map.

3. RESULTATEN EN DISCUSSIE

De resultaten van de besproken berekeningen worden hier gepresenteerd en geanalyseerd. Bovendien kan met het gecreëerde virtuele energiemonitoringalgoritme een nieuwe procesopstelling eerst virtueel getest worden zodat deze resultaten energetisch vergeleken kunnen worden met de bestaande opstelling.

Dit inzicht kan voornamelijk worden verkregen via dashboards. Deze gebruiksvriendelijke tools maken het mogelijk om een specifieke tijdsperiode te selecteren en alle gewenste gegevens daarover te bekijken. Dit gebeurt met behulp van infoboxen, grafieken en tabellen zoals weergegeven in figuur 1. In het onderstaande voorbeeld wordt het totale energieverbruik op drie verschillende manieren weergegeven. Ten eerste in een gekleurd gegevensbox, waar de energie wordt uitgedrukt in kWh over de geselecteerde periode voor elk type verbruik. Ten tweede wordt het weergegeven in een grafiek, ook met dit onderscheid. Tot slot wordt de totale verbruikte energie voor elk type energiebron per productiebatch weergegeven in een tabel. Met behulp van deze visualisatie is het mogelijk om energetisch verschillende producten en installaties met elkaar te vergelijken.



Figuur 1: Energie dashboard

De dashboards zijn allemaal gekoppeld aan een hoofddashboard van waaruit het mogelijk is om naar de andere dashboards te navigeren voor een specifiekere component. Met behulp van een visueel procesdiagram, ook wel een Flowcharting-paneel genoemd, is het mogelijk om op de gewenste component te klikken en er verschijnt een dashboard met alle relevante informatie over die component. Een voorbeeld wordt getoond in Figuur 2.

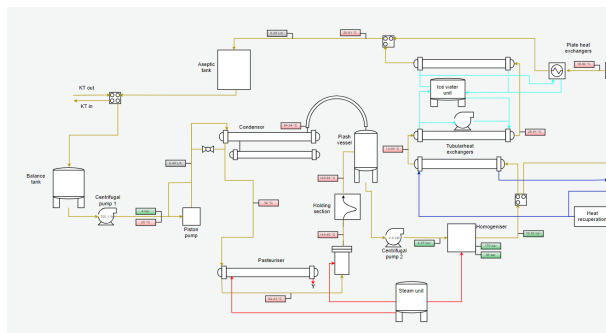
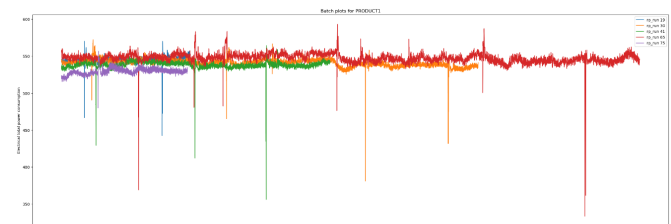


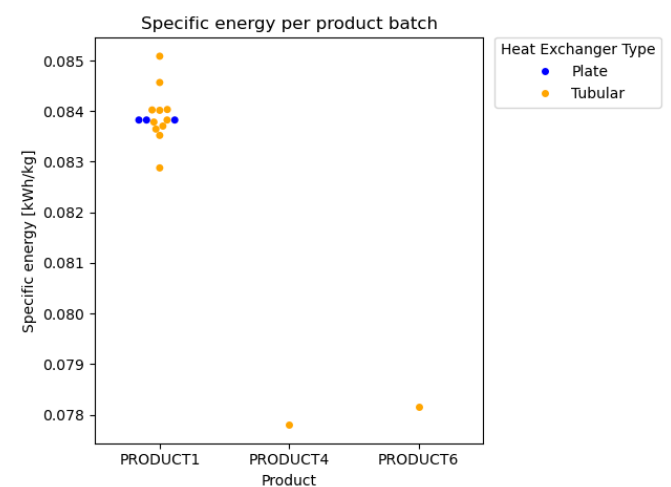
Figure 2: Flowcharting paneel met procesoverzicht

Een tweede manier om meer inzicht te krijgen in het energieverbruik van het proces is het gebruik van de energy baseline, die het verbruik van specifieke onderdelen of het hele proces tijdens de productie in dezelfde grafiek weergeeft, zoals weergegeven in figuur 3. Dit laat visueel zien wanneer en welke processessies energiezuiniger zijn dan andere.



Figuur 3: Totaal opgenomen elektrisch vermogen van verschillende productiesessies

Een derde manier om meer inzicht te krijgen is door gebruik te maken van swarm plots. Deze plots tonen de verdeling van productiesessies en er zijn verschillende manieren om onderscheid te maken tussen die sessies. Het gebruikte type warmtewisselaar kan bijvoorbeeld worden aangegeven door kleur of het type energiebron. Daarnaast wordt ook een onderscheid gemaakt per product, aangezien deze verschillende thermische eigenschappen hebben. Een voorbeeld wordt getoond in Figuur 4.



Figuur 4: Swarm plot van de specifieke energie per productiesessie, opgesplitst per producttype en type warmtewisselaar

Een ander voorbeeld voor een swarm plot is het plotten van KPI's. In dit proefschrift worden de bezettingsgraad en de terugwinningsgraad berekend als prestatie-indicatoren. Figuur 5 laat zien of de motoren die in het proces worden gebruikt nog uitbreidingscapaciteit hebben. De zuigerpomp is bijvoorbeeld al maximaal belast, terwijl de andere motoren hoger belast kunnen worden. Bovendien is de capaciteit van de homogenisator voor product 1 door de receptafhankelijkheid lager dan voor de anderen.



Figure 5: Swarm plot van gebruiksratio KPI per productiesessie, opgesplitst per producttype en energiebron

4. CONCLUSION AND FUTURE WORK

Dit werk presenteert een haalbaarheidsstudie naar het opnemen van procesgegevens in een virtueel energiemonitoringsysteem, met speciale aandacht voor elektrisch en thermisch gebruik. Het schetst een methodisch proces dat begint met uitgebreide gegevensverzameling, gevolgd door de afleiding van relevante formules en daaropvolgende berekeningen om sleutelindicatoren zoals efficiëntie en KPI's te

bepalen. Vervolgens worden visuele weergaven van energieverbruikpatronen gegenereerd voor een beter begrip.

Afgezien van de technische implementatie is het de bedoeling dat het onderzoek anderen inspireert, met name degenen die met beperkte budgetten werken, door de flexibiliteit van dergelijke systemen aan te tonen. Ondanks de uitdagingen biedt het document constructieve suggesties voor verbetering.

Toekomstig werk zal gericht zijn op real-time Grafana-updates door het koppelen van de database. Ten tweede zullen meer gedetailleerde gegevens en procesinformatie worden verzameld om de berekeningen nauwkeuriger te maken en de onzekerheid te verminderen. Door het energieverbruik van verschillende productielijnen te vergelijken, zoals UHT Lijn 1 van Tetra Pak, kunnen interessante resultaten worden verkregen om de processen efficiënter te maken. De nadruk zal ook liggen op het ontwikkelen van optimalisatiestrategieën om het energieverbruik in belangrijke productiefasen te minimaliseren. Dit omvat het inschatten van potentiële besparingen en het beoordelen van de waarde van investeringen met behulp van wiskundige modellen en voorspellende analyses.

5. REFERENCES

- IEE. (2016, 22 mei). *The Importance of Setting an Accurate Energy Baseline – IEE*. <https://ieeegypt.org/the-importance-of-setting-an-accurate-energy-baseline/>

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LIST OF USED ABBREVIATIONS

CIP	Cleaning in place
COP	Coefficient of performance
EnB	Energy baseline
EnPI	Energy performance indicator
ID	Identification
KPI	Key performance indicator
PHE	Plate heat exchanger
PID/ P&ID	Piping and instrumentation diagram
ROI	Return of investment
SCADA	Supervisory control and data acquisition
SDG	Sustainable development goal
SI	Step index
SIP	Sterilization in place
UHT	Ultra-high temperature
VM	Virtual machine

1 INTRODUCTION

The aim of this thesis is to gain a better understanding of the energy consumption of an industrial factory. This is done using theoretical calculations based on process data already available for process control. The process considered is an Ultra High Temperature (UHT) process, which is a good choice because there is a lot of heat transfer between different fluids. As this process operates at critical temperatures, many sensor measurements are required for the theoretical calculations. The process is well analysed, so the calculations would match the function of each component, allowing the most accurate estimation of the actual performance.

The results of these calculations are presented on a Grafana dashboard, an open-source tool that Actemium uses for several clients, providing a comprehensive overview of the entire process. There are several summary dashboards that provide a broader perspective on the process, while numerous component dashboards present detailed statistics for each component.

The use of swarm plots and energy baseline techniques enables the comparison of different production batches on various aspects, including the type of heat exchangers, energy consumption types and product types.

In chapter 2, the general UHT process is discussed in detail, with a particular focus on the specific UHT process of Puratos. This includes an overview of the process's history and a discussion of the process's P&IDs.

In chapter 3, each component is discussed individually, as their working principle is important for calculating power consumption.

The 4th chapter addresses further technical aspects of the process, including the step index, the active product and the active configuration. It is of the utmost importance to comprehend these elements and integrate them into the calculations. Furthermore, a simplified block diagram of the process is presented. This provides a comprehensive overview of the available sensors.

Given that not all the desired information about every component is known, chapter 5 presents the available data with assumptions based on this data for both components and substances. The more information about the component, the better the calculation.

Chapter 6 presents the data flow and data processing. As a significant amount of time was invested in this section, the two employed methodologies are presented herewith. The data in question pertains to a client of Actemium, and ensuring the security of data transmission is of paramount importance.

In chapter 7, the energy calculations are discussed based on the assumptions made in chapter 5. The formulas and results of these calculations are presented in the following chapters.

In chapter 8, several examples of dashboards are presented, with the functionality of each one demonstrated and in chapter 9, swarm plots that show the energy variability, are discussed.

The concept of the energy baseline is discussed in detail in Chapter 10, with the accompanying practical implementation also provided.

The files that are relevant to this thesis can be accessed by following the link in Appendix E to the shared folder.

2 PROCESS

This section describes how the process works on which the energy system is calculated. To make a virtual energy monitoring system, it's important to have process knowledge and the process should have several components that exert energy on the product such as pumps, heaters and heat exchangers. The sensors provide the data to calculate the energy consumptions.

The files such as datasheets that are relevant to this thesis can be accessed by following the link in Appendix E to the shared folder.

2.1 General

There are three notable methods of conserving food for longer and safer storage: pasteurization, sterilization, and UHT (ultra-high temperature) process, according to Hyfoma (2016). It is important to note that these methods are used to heat products and not to cook them. The differences between these methods lie in the temperature range and heating time. Pasteurization involves the lowest temperature range over a longer period, while UHT involves the highest temperature range over a shorter period.

The process discussed in this thesis is UHT. According to Hyfoma, UHT is a brief heat treatment process lasting only a few seconds, conducted at a temperature of approximately 140°C (ranging from 135°C to 150°C). This results in a sterilized product with minimal heat-induced damage to its properties, ensuring that the taste remains largely unchanged. UHT treatment is employed in a continuous flow system, where the product is sterilized before being conveyed to previously sterilized containers under a sterile atmosphere, requiring aseptic processing.

Eiser conducted in 2021 research on common technologies in the dairy industry and identified two types of UHT: 'direct' and 'indirect'. Direct UHT involves rapidly increasing the product's temperature by mixing it with steam to kill bacteria at a high heat rate. This can be achieved through steam injection, where steam is directly injected into the milk, or steam infusion, where milk enters an infusion chamber containing superheated steam. The method's advantage is that the product is heated and cooled quickly, leading to a reduced heat load. Indirect UHT, on the other hand, ensures that the product never comes into contact with the heating fluid. The heating fluid can also be steam or hot water under high pressure. To transfer heat, a heat exchanger is used. There are three different types of heat exchangers: tubular, plate, and scraped-surface exchangers (Boyd International, n.d.). Both methods have heat recovery capability.

These two methods can be compared on several aspects such as temperature profile in function of the time, which is demonstrated in Figure 2-1. According to Eiser, direct heating is less severe because of the shorter period of high temperature heating, indirect heating is more gradual and has a longer exposure to high temperatures. Secondly, direct heating involves less energy than the indirect heating which needs to heat the product over a longer period. To finish the comparison, indirect heating affects

more the product properties because of the longer exposure to heat. This leads to more pronounced chemical changes, such as protein denaturation and loss of certain nutrients.

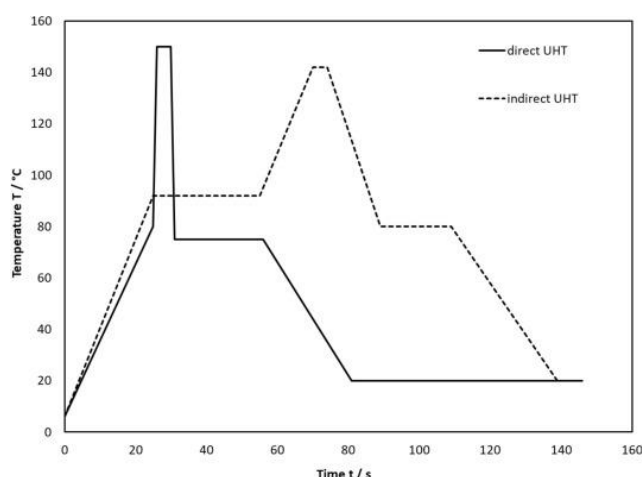


Figure 2-1: Difference between direct and indirect heating (Eiser, 2021)

A general UHT process is described here, but it should be noted that the order of the components may differ between different UHT processes. The first step in UHT treatment is preheating the raw product until a specific temperature below the sterilization temperature. The second step is homogenization where the fat globules become the same size. This is achieved by letting the product collide to a surface which will split the fat globules, reducing the tendency to form cream. The next step is to heat the product to sterilization temperature. After that, the product is cooled by heat exchangers which usually happens in multiple steps. Sometimes there is also a heat recuperation unit that collects the heat that is transferred to the first heat exchanger. This heats tap water, which can be used for other processes such as the CIP. The final step is to transfer the product to the aseptic tank.

To clean the product line, there is a mechanism called 'cleaning in place' (CIP). This is an automated set of instructions to properly clean an installation by sending cleaning fluids in the process pipes. There are a lot of different types of CIP including one or multiple tanks with different cleaning substances, but this depends on the type of the product and the size of the installation (CSE Designs, 2019). After a batch, fluids such as water, acids and bases are sent through in a specific sequence to completely clean the pipes.

After CIP, sterilization in place (SIP) is often performed to sterilize the equipment without disassembly. SIP results in aseptic connections, meaning there is no contamination in the tubing. The duration varies according to application and system type. It can be done with steam, dry heat, liquid or gas. (Mycoscience, n.d.)

2.2 UHT Puratos

The thesis is associated with Actemium, a company within the VINCI Energies Group that specializes in designing and implementing industrial processes. Actemium provides consultancy services to other companies, which are considered its clients. The logo of Actemium is shown in Figure 2-2.



Figure 2-2: Logo Actemium (<https://www.actemium.be/>)

One of Actemium's customers is Puratos, a Belgian family-owned company operating in the food industry, producing ingredients for bakers, pastry chefs, and chocolatiers. The UHT process focused on in this master's thesis is used by Puratos to produce dairy products, such as vegetable cream, through a direct UHT process. The logo of Puratos is shown in Figure 2-3.



Figure 2-3: Logo Puratos (<https://www.puratos.be/nl>)

2.2.1 History

Puratos has two production lines for this type of product. The older line is from Tetra Pak, while the newer line is from Reggiani, both specialized in UTH processes. However, the Reggiani line did not meet Puratos' expectations, so it has been gradually converting it to the Tetra Pak standard. Currently, there are a few changes that they wish to implement. For instance, the initial heat exchanger on line 2 consisted of a tubular design with three cooling stages. However, this was deemed insufficient, and a plate heat exchanger, which is common at Tetra Pak, was added in parallel with the existing tubular heat exchangers. The plate heat exchanger has only two cooling stages. Furthermore, modifications were required for the balance tank, as well as for the homogenizer and flash vessel bypass. While Figure 2-4 shows the Reggiani direct UHT line, Figure 2-5 shows the Tetra Pak direct UHT line.

This paper is written during the transition phase from the tubular heat exchangers to the plate heat exchangers. This results in data accessibility before and after the component change. This may lead to interesting conclusions in the energy baseline calculations.



Figure 2-4: Reggiani direct UHT process (manual)



Figure 2-5: Tetra Pak direct UHT process (Tetra Pak)

2.2.2 Process overview

Puratos' manual of the Reggiani type describes the process as follows:

"The machine is designed and built for specific use in the food industry, utilizing specifically chosen materials, components, and instruments related to the respective product. The DV 6500 installation is geared towards producing plant-based cream with a maximum hourly capacity of 6,500 liters. Its main feature is its "direct injection" setup, where sterilization of the food liquid occurs through direct steam injection. The "raw" product, still untreated, is collected in a tank, from which it is sent via a piston pump to the condenser, where it undergoes an initial heating phase. Subsequently, the product is directed to the pasteurizer, which raises and stabilizes the temperature to a level suitable for passage to the injector. The product, referred to as the "injector," undergoes a sterilization process, namely a new and abrupt heating, through direct steam injection. It then moves to the high-temperature "holding" section, where the sterilization process is concluded. Next, the product passes through the expansion cooler (de-aerator), where, due to the expansion phenomenon, it experiences a sudden temperature drop. During this process, water vapor is generated, which, thanks to a vacuum pump, is directed through specific pipes into the condenser casing. The cooled product exits the de-aerator and proceeds to the homogenizer, where it undergoes a micronization process under high pressure before ultimately entering the cooling chamber." (Instructions for Use and Maintenance Uht Block_6.500 s.n.1928_Puratos_Lummen_REV.01_2021.pdf, n.d.)

Please note that when reference is made to the "manual" later in this chapter, it refers to the previously mentioned pdf document.

Figure 2-6 shows a schematic diagram of the Reggiani direct UHT process. The components are numbered and connected using the production line. Table 2-1 provides a description of these components, and chapter 3 explains their functions in more detail.

The product is heated in three stages, including the condenser, pasteurizer, and direct steam injection. It is then held at a critical temperature before being expanded in the deaerator. Next, the product is sent through the homogenizer and cooled down by the heat exchangers. It is worth noting that the homogenizer is placed behind the steam injector, although it is often placed before the injector. Placing it after the injector can help achieve a more stable, consistent product quality.

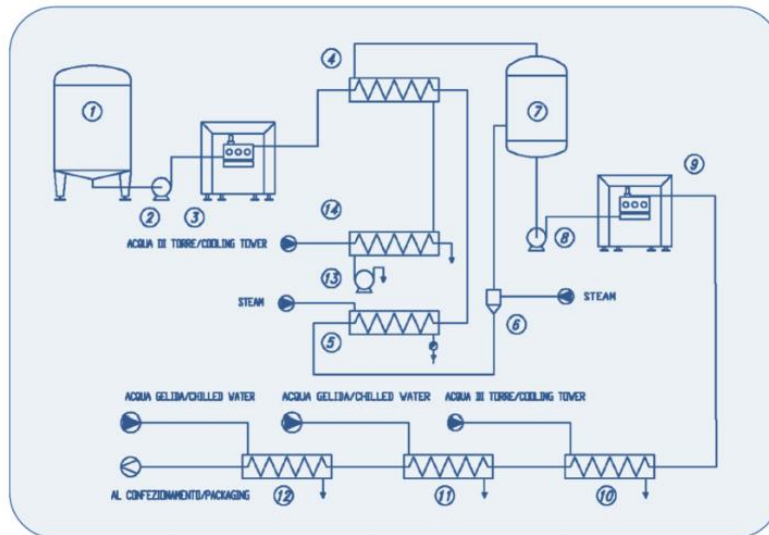


Figure 2-6: Schematic overview UHT line 2 Puratos

Table 2-1: Legend of the components in Figure 2-6

Number	Component
1	Raw product tank
2	Centrifugal pump PA
3	Piston pump P1
4	Condenser
5	Pasteurizer
6	Injector
7	Deaerator
8	Centrifugal pump P2
9	Homogenizer P3
10	First cooling section
11	Second cooling section
12	Third cooling section
13	Vacuum pump P5
14	Post condenser

2.2.3 Piping and instrumentation diagram

Figure 2-7 and Figure 2-8 show the piping and instrumentation diagram of line 2 of a factory in Lummen. This is also called a P&ID or PID and displays the piping and related components of a physical process flow. The colours used to indicate different substances, they are crucial for maintaining and indicating changes in the process (Lucidchart, n.d.). In Figure 2-7, the global process is illustrated, while in Figure 2-8 shows the heat recovery unit. This is indicated on the P&ID of the global process with a black box at the bottom right.

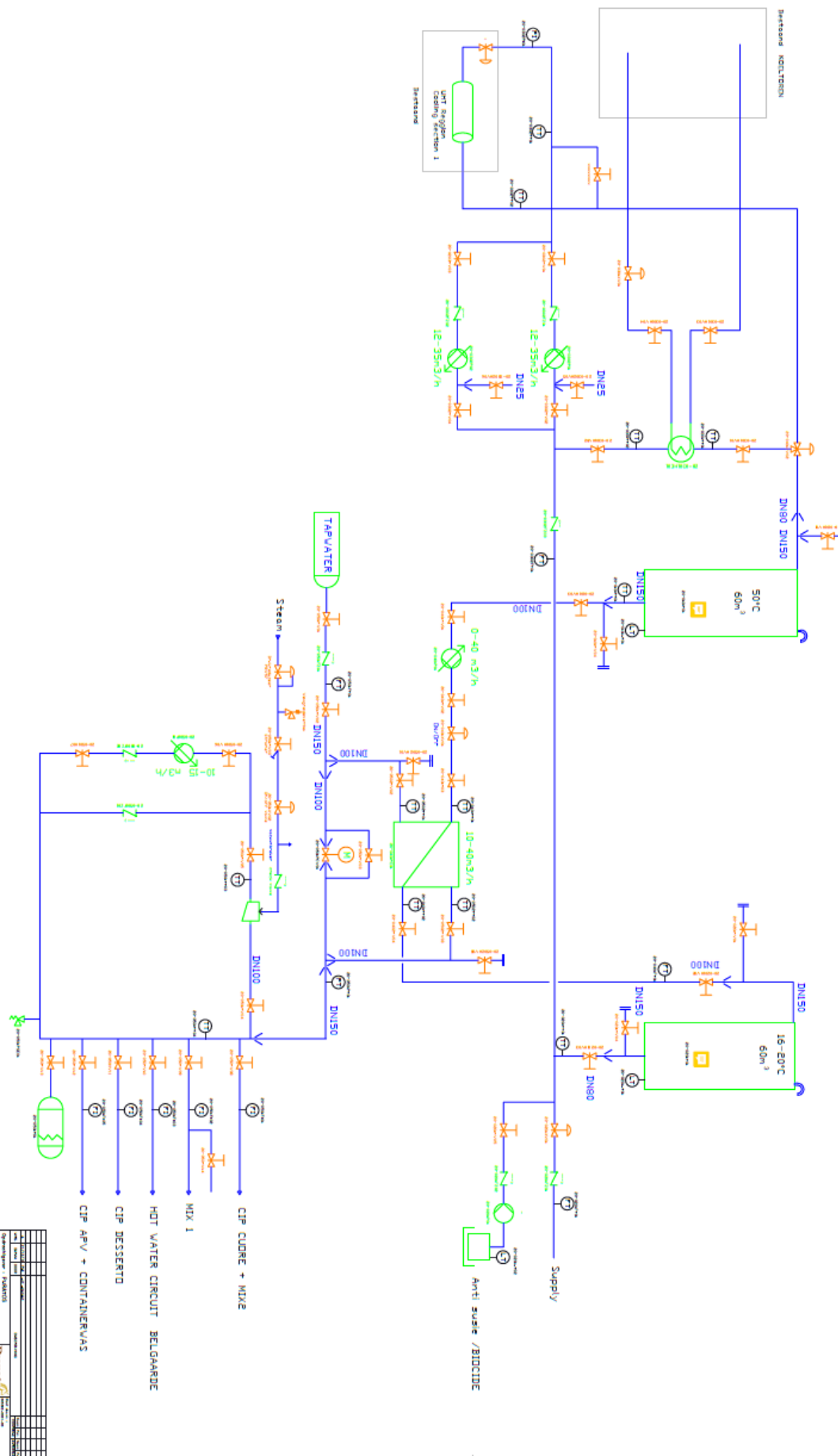


Figure 2-8: P&ID heat recuperation block UHT line 2 Puratos

2.2.4 Sensor measurements

The UHT process requires precise monitoring using multiple sensors to ensure that the correct pressure, temperature and flow are maintained. Failure results in product loss.

Many abbreviations are used in P&IDs to indicate the type of component, such as TT1, PT24 and so on. These codes are often company specific, but the following syntax is commonly used. The first letter corresponds to the type of measurement. This can be pressure, temperature, flow, level or quality. The following letters indicate the function of the component. This can be an indicator, controller, recorder or transmitter. Table 2-2 gives a summary of this code.

Table 2-2: Abbreviations measurements

First letter	Variable	Succeeding letter(s)	Function
P	Pressure	I	Indicator
L	Level	R	Recorder
F	Flow	C	Controller
T	Temperature	T	Transmitter
Q	Quality		
C	Conductivity		

TB is an exception and is used to indicate turbulence, which is a detection method for water and other fluids such as lye and acids. In addition, conductivity measurements are indicated with CT allowing products to be detected.

This master's thesis aims to develop a model that calculates energy consumption based on this sensor data. Expensive energy sensors are not present, but energy can be calculated using temperature, pressure, and flow measurements. It is challenging to estimate all types of energy losses, such as small turbulent flows in bends or heat losses in components. Therefore, some assumptions and simplifications will be made.

There are two kinds of logging systems, including OSIPi and a local logging system which is not connected to the database. The function of this last system is to comply with the legislation, but Puratos does not need these measurements to control their process.

3 COMPONENTS

In the previous chapter, the UHT process is explained, while in this section, the function of the components is described more in detail. The components are described in the order that it is based on the process sequence as shown in Figure 2-7.

3.1 Filters

There is not much known about these filters, but the main reason they are placed before the balance tank is to make sure that impurities and particles from the feedstock are removed before entering. Without removal, the quality of the product would be degraded, and the equipment could be damaged. Figure 3-1 shows the filters used.



Figure 3-1: Filters used in Reggiani (manual)

3.2 Balance tank

The balance tank is a kind of buffer tank which regulates the product flow. It's an important component in this process because the inlet product flow may vary. Using this buffer of 500 litres, the outlet product flow can be kept constant. Secondly the tank provides a steady pressure for the pump after this balance tank, preventing cavitation in this section. In Figure 3-2 the tank is shown with the filters in front.

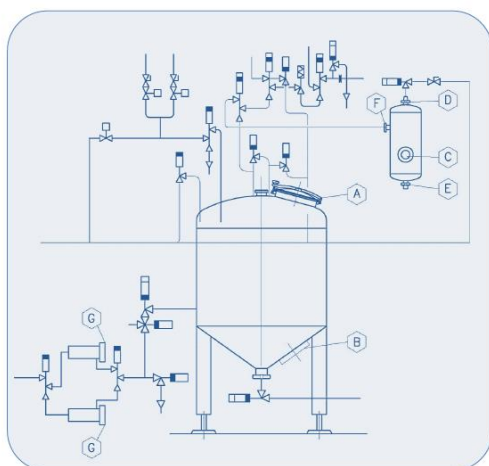


Figure 3-2: Filters used in Reggiani (manual)

3.3 Pumps

There are two pumps which have two slightly different functions including the centrifugal pump and the piston pump. Both are explained in this section.

3.3.1 Centrifugal pump

In this process, four centrifugal pumps are summarized in Table 3-1. The last two columns are references to the datasheets of the pumps. The centrifugal pumps all have the same function, which is to allow the product to flow. They are placed at different locations in the production line resulting in slightly different functions.

Table 3-1: Overview centrifugal pumps with product codes

Name	Pump ref A	Pump ref B
UHT - PA	CS 40-210-4-5.5/BM.P F82	C100900
UHT - P2	CS 40-260-4-5.5/BM.PQ7	C100899
UHT - P6	AS 50-4-5.5/BA.PT82	A040188
UHT - P8	CLC41-2-1.5/BM.PT8	C100902

The centrifugal pump PA for instance, is mainly used to extract the product from of the balance tank to perform the heating process on the product. Behind the flash vessel, there is another centrifugal pump P2 which maintains the flow to the homogenizer. Pump P6 is used to recover water and P8 enables the flow in the cooling circuit. Pump PA is given in Figure 3-3. Pumps P6 and P8 are not considered in the calculations due to insufficient information.



Figure 3-3: Pump PA used in Reggiani (manual)

3.3.2 Piston pump

The piston pump is placed after the centrifugal pump to accurately meter the product and maintain a constant flow rate. This pump operates by linear movement of pistons and, unlike centrifugal pumps, is effective at dosing due to its closed volume system. Figure 3-4 displays the piston pump, which shares a physical design with the homogenizer, differing only in power.



Figure 3-4: Piston pump used in Reggiani (manual)

3.4 Condenser

The condenser is used to preheat the product for the first time using the excess heat of the gasses that are secreted by the deaerator, which is explained in chapter 3.8. This way, the gasses are condensed, and the product is slightly heated. Figure 3-5 shows the condenser.



Figure 3-5: Condenser used in Reggiani (manual)

3.5 Pasteurizer

In the pasteurizer, the product is heated to a specific stabilized temperature for a predetermined time to kill already pathogenic bacteria, yeast and fungi, but there are some heat resistant bacteria that can't be eliminated by pasteurization. This pasteurizer is constituted by a tub-in-shell heat exchanger.

3.6 Sterilizer

The sterilizer is the key to the UHT process. In this case of the Reggiani, it is a direct UHT, which means that there should be a direct steam injection system. This heats the product at a very high speed for a limited time. Unlike the pasteurizer, it heats up to a higher temperature for a shorter period so that all micro bacteria can be eliminated. This results in an increase of the water content of the product, which is going to be extracted by the deaerator. The sterilizer is shown in Figure 3-6 and is called the injector.



Figure 3-6: Injector used in Reggiani (manual)

3.7 Holding section

The holding section is placed right behind the direct sterilization place and has as primary function to allow the product to maintain a high temperature for a limited time to get a specific level of microbiological sterilization. It consists of a tube with a length of 7,5 meter with a lot of loops to minimize the occupied space. The inner diameter is 48 mm and this section is shown in Figure 3-7.

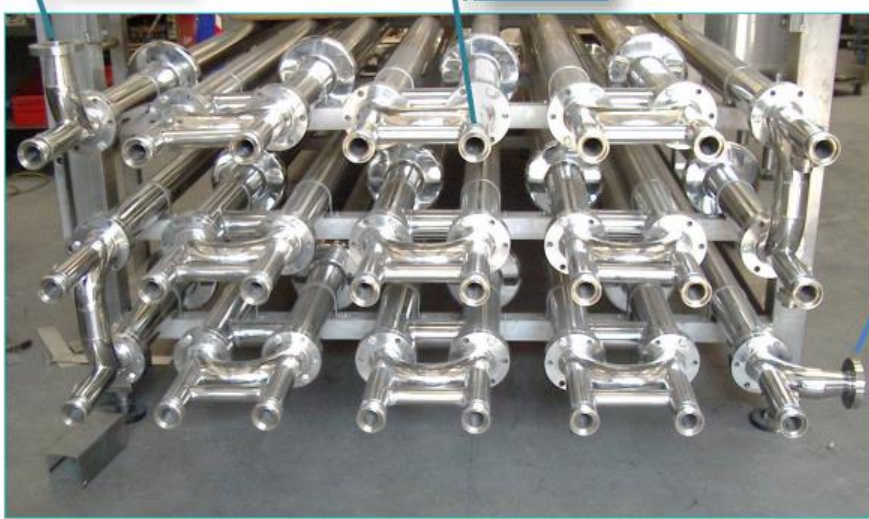


Figure 3-7: Holding section used in Reggiani (manual)

3.8 Flash vessel

A flash vessel, also known as a deaerator (degasser), is essential for removing dissolved gases from liquids, especially when they are heated to high temperatures. This component facilitates rapid cooling because the pressure is lower than the atmospheric pressure. The dissolved gases removed can include oxygen and carbon dioxide, as well as any steam that was added. These gases can have undesirable effects on the final product, such as promoting oxidation and reducing its shelf life. The hot gases are then routed to the condenser, where they heat the product in the first step. The deaerator is shown in Figure 3-8.



Figure 3-8: Deaerator used in Reggiani (manual)

3.9 Homogenizer

The homogenizer is a component that causes reduction of fat globules into much smaller ones. It also reduces the tendency to clump together. This is achieved by pushing the product at high speed through a small passage using a volumetric pump. Because of this narrow slit decreases the pressure below the static pressure which causes the product to boil locally (Tetra Pack, 2023). The working principle is shown in Figure 3-9 and the physical component in Figure 3-10.

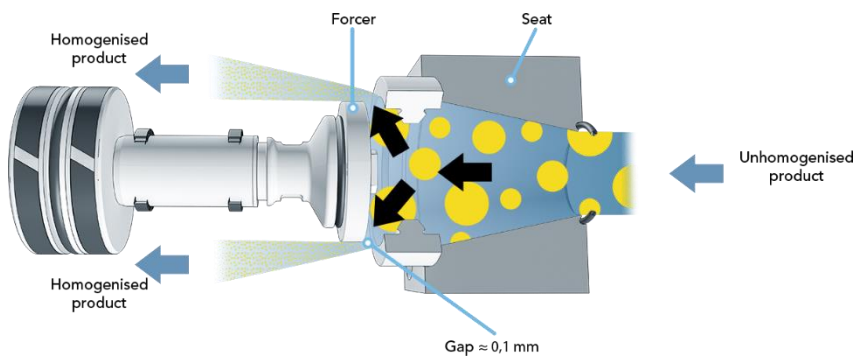


Figure 3-9: Working principle homogenizer (Tetra Pack)



Figure 3-10: Homogenizer used in Reggiani (manual)

3.10 Heat exchanger

The function of heat exchangers is to cool the product to packaging temperature and, in some cases, attempt to recover this heat from the cooling fluid. Consequently, they play a crucial role in determining the cost price of the product through heat recuperation. Puratos uses two types of heat exchangers in their UHT process on line 2: the plate heat exchanger and the tubular heat exchanger. The tubular heat exchanger corresponds to the Reggiani production line, while the plate heat exchanger is a new addition with promising heat transfer properties.

3.10.1 Tubular heat exchanger

This type is often called a concentric tube cooler and consists of one or more tubes. In the most common case, there is a tube containing hot fluid that is placed inside a larger tube containing cold fluid. Heat transfer occurs between these tubes.

The cooling section consists of three cooling stages: water at room temperature, ice water at 10°C, and ice water at 1°C, resulting in a product temperature of about 12°C. In the case of a special product,

there is a bypass system that should be selected before production, allowing the second tubular heat exchanger to be avoided. This bypass is also visible on the P&ID of the UHT process. This can be seen in Figure 3-11.

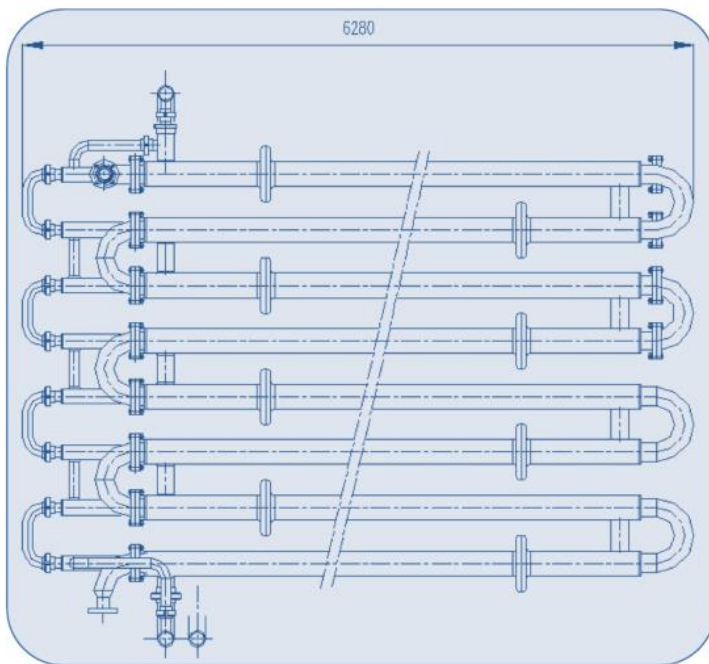


Figure 3-11: Tubular heat exchanger used in Reggiani (manual)

3.10.2 Plate heat exchanger

The plate heat exchanger is also called the PHE and consists of multiple steel plates which conduct heat. As indicated in Figure 3-12, there are two inlets and two outlets. These relate to each other by the plates. The physical form of the plates differs each time. In the first plate, the hot fluid stream is connected and in the next, the cold fluid stream. Then the plates are pressed together to optimize heat transfer. By alternating the cold and heat plates, the hot stream is cooled and the cold stream is heated (Savree, n.d.).

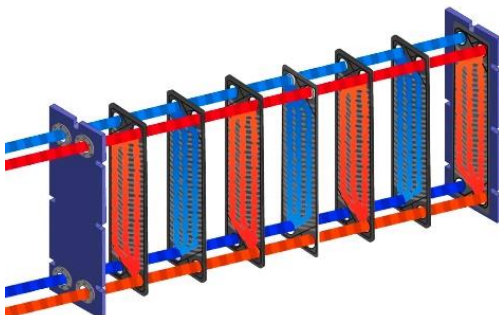


Figure 3-12: Plate heat exchanger (Savree, n.d.)

3.11 Aseptic tank

The function of the UHT line is to thermally sterilize liquid foods. Therefore, packaging and storage must also be strictly sterile. The product is stored in an aseptic tank before being filled aseptically. Prior to production, the tank must be sterilized with steam and then cooled. Sterile air should be maintained in

the tank until the sterilized product enters the aseptic tank. Finally, the food is transferred to the aseptic tank after passing through the UHT line. Once the food has been transferred, it can be packaged aseptically. This system offers advantages in terms of flexibility, safety, and cleaning efficiency (Neologic Engineers, n.d.). The aseptic tank is shown in Figure 3-13.



Figure 3-13: Aseptic tank used in Reggiani (manual)

4 PROCESS TECHNICS

The production process consists of several stages, with the primary stage being the actual production step. This is where the product is transferred to the aseptic tank after treatment and awaits aseptic filling. Pre- and post-treatment steps, such as pre-sterilization, water circulation, filling, emptying, and cooling, occur before and after this stage.

This chapter provides further technical details to fully understand the process steps and operation of the installation in chapter 4.1. The following two chapters demonstrate how the active product and arrangement are determined. Additionally, measurement details are given in chapter 4.4 and a block diagram of the installation is included to provide a clearer view of the components in chapter 4.5. There are a couple code fragments shown, written in python. Further explanation about this code can be found in chapter 0.

4.1 Sequential steps

There are many different stages before and after the actual production. If nothing happens, the step index (SI) is idle and therefore zero. This SI is saved as an integer in the dataset and is mapped to a physical phase in the process. The explanation of these numbers is summarized below.

Table 4-1: Step index explanation

Step	Explanation
Step 0	Idle (inactive state).
Step 110	Empty flash vessel to drain (A: Open valves).
Step 115	Empty flash vessel to drain (B: Start pumping).
Step 130	Heating process.
Step 140	Pre sterilisation process.
Step 150	Cooling (A1: Fill flash vessel to empty level).
Step 155	Cooling (A2: Wait before starting vacuum pump).
Step 160	Cooling (B1: Wait before cooling section 1 starts).
Step 165	Cooling (B2: Wait before cooling section 2 starts).
Step 170	Cooling (B3: Wait before cooling section 3 starts).
Step 175	Cooling (B4: Wait for low temperature at the end).
Step 200	Water circulation.
Step 250	Water circulation standby.
Step 300	Fill product to UHT (A: Fill to UHT).
Step 305	Fill product to UHT (B: Empty balance tank to flash vessel).
Step 310	Fill product (A: Water to drain).
Step 320	Fill product (Mix phase to waste tank).
Step 330	Production process (To aseptic tank).
Step 340	Empty aseptic tank.
Step 350	Empty product to waste tank.
Step 700	Emptying from system to drain.
Step 710	Cooling before closure.
Step 720	Shutting down system (A: Stop pumping).
Step 725	Shutting down system (B: Close valves).
Step END	End of process.

The focus of this work is on optimization rather than conducting the full operation of a UHT line. However, it is necessary to understand the steps involved to get an idea of the procedure. First, the flash vessel is drained and the first preheating stage is carried out. Once the cooling sections have been set up (steps 150 to 175), water circulation begins (step 200). This process is similar to production step 330, but is executed in a circular manner and the water is not put into the aseptic tank. The production process can start from this step, where product is put in the circuit which pushes water to drain. If the first product reaches the end of the production line, a valve switches from circulation to the aseptic tank to ensure safe storage. Subsequently, water pushes the product to the aseptic tank until all product is passed. At this point, the whole installation is filled with water again. During the transition stage, when water is added to or removed from the product, a low-quality mixture is collected in a tank. This mixture is then reused in the next production cycle for water recirculation or for dosing in the product. Additionally, an aseptic rinse is occasionally performed, followed by a drain and shutdown.

It can be concluded that the most crucial step to monitor and optimize is step 330, which involves working with critical temperatures and takes a significant amount of time. The use of SI can monitor production during busy periods. Additionally, the water circulation step consumes a lot of energy. An example of how this can be displayed in a discrete manner to indicate the production line's phase is shown in Figure 4-1. The mappings of the text are linked to the discrete values of the step index and assigned a colour.

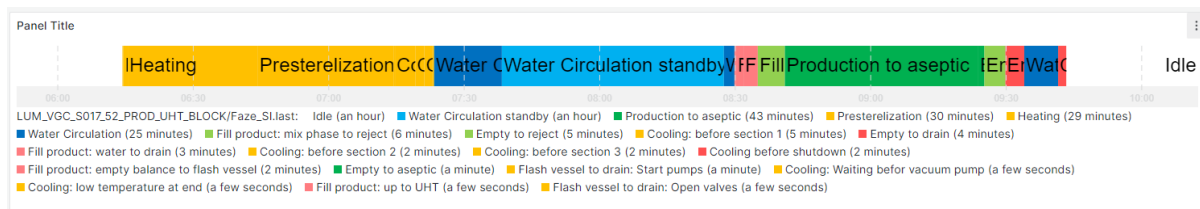


Figure 4-1: Discrete panel with production phases linked to the SI.

4.2 Active product

This UHT line produces several different products. There is no tag representing the active recipe, but it can be derived. The idea is that there can always be two tanks of untreated product connected to the balance tank that allows the product to be taken in. The names of the products in these tanks are stored in two material variables "LUM_VGC_S017_52-20T01/Unit_MAT_NAME" and "LUM_VGC_S017_52-20T02/Unit_MAT_NAME". There are two tanks so that one can supply product to the UHT line while the other is loaded. When one is empty, the active recipe is the one from the other. This can be done with the following code:

```
df2["rp_name"] = df2["LUM_VGC_S017_52-20T01/Unit_MAT_NAME"]
indexen = df2[df2["LUM_VGC_S017_52-20T01/Unit_MAT_NAME"] == 'Empty'].index
df2.loc[indexen, "rp_name"] = df2["LUM_VGC_S017_52-20T02/Unit_MAT_NAME"]
```

As described in the code above, the variable "rp_name" contains the recipe name which is linked to the two product tanks. This variable retains the recipe name even when the process is not producing to the aseptic tank. The fact that this variable retains the product while there could be for example water in the tubes, is undesirable since the calculations are based on the thermal properties of what is present in the UHT pipes.

Therefore, several steps are taken. Firstly, the products are mapped to the corresponding product number where each product category has unique thermal properties. An example of this mapping is shown in Figure 4-2. Secondly, a variable called 'main_product' is introduced that contains the product

code of what is present in the tubes. To do so, the values of “rp_name” are adopted when there is produced to the aseptic tank (SI 330). After this step, the product in the tubes is water. This is done with the following code:

```
df2["main_product"] = df2.apply(lambda row: row["rp_name"] if
row["LUM_VGC_S017_52_PROD_UHT_BLOCK/Faze_SI"] == 330 else 'Water',
axis=1).apply(get_product_category)
```

```
3002457 - Sunset Glaze CLND - C5 [PRODUCT1]
3002457 - Sunset Glaze CLND - C544 [PRODUCT1]
3002458 - Sunset Glaze CN20 [PRODUCT1]
3002460 - Sunset Glaze EC [PRODUCT1]
3002584 - Sunset Glaze RSP0 - C5 [PRODUCT1]
3002584 - Sunset Glaze RSP0 - C577 [PRODUCT1]
3003419 - Dulcerio Tres Leches [PRODUCT8]
3003556 - Sunset Glaze EC Xt1r - [PRODUCT1]
3004537 - Sunset Glaze CN40 [PRODUCT1]
3005249 - Sunset Glaze EC Kosher [PRODUCT1]
3005303 - Sunset Glaze Easy Plus [PRODUCT1]
3005303 - Sunset Glaze Easy Plus (BE) [PRODUCT1]
3005355 - Ambiente Kosher [PRODUCT6]
3005376 - Festipak [PRODUCT7]
3006273 - Festipak Sugar-free [PRODUCT7]
3006802 - Sunset Glaze Post-Bake [PRODUCT1]
3006802 - Sunset Glaze Post-Bake 01 [PRODUCT1]
3007409 - Sunset Glaze Easy Plus [PRODUCT1]
3007409 - Sunset Glaze Easy Plus 20 NK AT [PRODUCT1]
3007684 - Sunset Glaze Easy Plus [PRODUCT1]
3007684 - Sunset Glaze Easy Plus AT [PRODUCT1]
3007715 - UHT GLAZE NK 1000L [PRODUCT1]
3100310 - Chantypak - C321 [PRODUCT3]
3100315 - Whippak Blanco - C342 [PRODUCT4]
3100325 - Ambiente White - C409 [PRODUCT6]
3100333 - Montamix - C550 [PRODUCT7]
Name: Productid, dtype: object
```

Figure 4-2: Product mapping

This uses the `get_product_category` function. This function contains the mapping between the extended recipe name and the product code.

```
def get_product_category(recipe_name):
    # Define the mapping based on keywords
    mapping = {
        'Glaze': 'PRODUCT1',
        'Sunset': 'PRODUCT1',
        'Chantypak': 'PRODUCT3',
        'Whippak': 'PRODUCT4',
        'None': 'PRODUCT5',
        'Ambiente': 'PRODUCT6',
        'Festipak': 'PRODUCT7',
        'Montamix': 'PRODUCT7',
        'Dulcerio': 'PRODUCT8',
        'Fabuloso': 'PRODUCT9',
        'Starbucks': 'PRODUCT10',
        'Water': 'Water',
        'Empty': 'Water'
    }
    for keyword, category in mapping.items():
        if keyword in recipe_name:
            return category
    return ""
```

4.3 Active configuration

Since the new plate heat exchanger is placed in parallel with the older tubular heat exchanger, the active setup must be known to compare both cooling methods. It is not possible for the plate heat exchanger and the tubular heat exchanger to be used simultaneously, as the entire flow is dedicated to the active setup. A tag, designated as 'LUM_VGC_S017_52_PROD_UHT_BLOCK/OP_HEAT_CHOICE_Q0', is used to indicate the switching of the valve. If the tag indicates a false value, the tubular heat exchanger is activated, while a true value indicates that the plate heat exchanger should be activated. This can be achieved with the following script:

```
df2['Bool_tub'] = df2.apply(lambda row: 1 if  
row['LUM_VGC_S017_52_PROD_UHT_BLOCK/OP_HEAT_CHOICE_Q0'] == 'False' else 0, axis=1)  
df2['Bool_plt'] = 1-df2['Bool_tub']
```

These columns are used to calculate the heat exchange within the coils. The process flow of the tubular heat exchanger is multiplied by 'Bool_tub' to ensure that the flow is only active when the tubular heat exchanger is engaged. There is an analogous reasoning for the plate heat exchanger. This results in zero heat exchange in the plate heat exchanger instead of an incorrect value if the tubular heat exchanger is selected.

4.4 Measurement details

This section explains the units of measurement in more detail. Table 4-2 shows the units of measurement. Most of them have one standardized unit, but the flow has two different units. For the whole process the common unit is m³/h, but for some of the cooling circuits m³/s is used.

Table 4-2: Units of the measurements

Measurement	Naming	Unit
Pressure	PT	Bar
Level	LT	Percentage of full tank volume
Temperature	TT	°C
Flow	FT	m ³ /s or sometimes m ³ /h
Control valve position	Ending on 'PID_MV'	Percentage open

4.5 Block diagram

The P&IDs are translated into Excel schematics that include all relevant measurements and components to facilitate calculations. It can be consulted in the document 'Block_diagram_UHT.xlsx' which can be found via the link to the shared folder in appendix E. This summarizes all the available measurements for each component. The following chapter covers the actual calculations, while this chapter focuses on data collection and assumptions. The process is divided into several parts, with assumptions being made at each stage. Two examples of this scheme are shown below.

The diagram consists of all the components shown as a block with the available information. The corresponding unit is also shown and a colour chart is used to indicate the type of fluid being measured. This colour mapping is shown in Table 4-3.

Table 4-3: Color mapping fluid block diagram

Colour	Measurement fluid
	Product
	Steam
	Cooling water
	Technical water
	Tap water

4.5.1 Centrifugal pump PA

The first example is the centrifugal pump after the balance tank. The datasheets show a power of 4 kW is found. The pressures before and after this pump are given in bar and the flow Q is given in L/h. On the right, the measurements are noted in green because it is a measurement on product. Eventually, the temperature is indicated in orange because the measurement is not available. A print screen of this diagram is shown in Figure 4-3.

Centrifugal pump PA	P_instal	4 kW			
	p1	bar	PT21		
	p2	bar	PT22		
	Q	L/h	FT01		
	T	°C	TR01	Separate logging system	

Figure 4-3: Block diagram centrifugal pump PA

4.5.2 Cooling sections

In the second example, both cooling sections are considered. The tubular one has three cooling sections, while the plate heat exchanger has two cooling sections. Every stage requires two temperature, two pressure and one flow measurement per fluid. The product measurements are indicated in green and the cooling fluid in dark blue according to Table 4-3. A print screen of this part of the block diagram is shown in Figure 4-4 and Figure 4-5.

Tubular heat exchanger (ZS02)		Product		Coolant			
<u>Cooling with technical water</u> heat recup	T1	°C	T1	°C		TT09	20-0302TT01
	T2	°C	T2	°C		TT19	20-0302TT02
	p1	bar	p1	bar		PT03	PT09
	p2	bar	p2	bar		PT10	?
	Q	L/h	Q	L/h		FT02	20-0302FT01
<u>Cooling with ice water (10°C)</u>	T1	°C	T1	10 °C		TT19	17-1402TT01
	T2	°C	T2	°C		TT18	17-1402TT02
	p1	bar	p1	bar		PT10	PT08
	p2	bar	p2	bar		PT11	?
	Q	L/h	Q	L/h		FT02	17-1201FT01
<u>Cooling with ice water (1°C)</u>	T1	°C	T1	1 °C		TT18	17-1201TT04
	T2	°C	T2	°C		TT12	17-1401TT01
	p1	bar	p1	bar		PT11	PT07
	p2	bar	p2	bar		PT06	?
	Q	L/h	Q	L/h		FT02	17-1201FT01

Figure 4-4: Block diagram cooling section (tubular heat exchangers)

Plate heat exchanger (ZS03)		Product		Coolant			
<u>Cooling with technical water</u> heat recup	T1	°C	T1	°C		TT30	TT32
	T2	°C	T2	°C		TT38	TT31
	p1	bar	p1	bar		PT03	PT09
	p2	bar	p2	bar		PT24	?
	Q	L/h	Q	L/h		FT02	20-0302FT01
<u>Cooling with ice water (1°C)</u>	T1	°C	T1	1 °C		TT38	TT34
	T2	°C	T2	°C		TT35	TT33
	p1	bar	p1	bar		PT24	PT07
	p2	bar	p2	bar		PT06	?
	Q	L/h	Q	L/h		FT02	17-1201FT01

Figure 4-5: Block diagram cooling section (plate heat exchangers)

5 AVAILABLE DATA WITH ASSUMPTIONS

This chapter presents the available data for each component or principle. The goal is to make as less assumptions as needed, but considering the available data, it is sometimes necessary to make assumptions. The greater the quantity of data pertaining to a process, the more precise the estimation of energy expenditure will be.

In this section, the notation with the dot above the letter is used to indicate a flow. This can be mass, volume or energy per unit time.

5.1 General

5.1.1 Mass flow

The process uses only volumetric flow measurements. However, the volumetric flow in the process is not constant due to temperature and pressure changes. Therefore, the mass flow is used, which is calculated according to formula [1]. The mass flow remains constant according to the law of conservation of mass. In this equation, the density ρ in kg/m³ is multiplied by the volumetric flow $\dot{V}$ in m³/s resulting in a mass flow $\dot{m}$ in kg/s. Note that the density ρ is varying since it is based of the according temperature measurement which is explained in 5.1.3.

$$\dot{m} = \rho * \dot{V}$$

[1]

There are two volumetric flow measurements in the product line, one at the beginning of the UHT line (FT01) and one at the end (FT02) which are shown in Figure 5-1. There is seen a difference between these measurements. This is mainly due to pressure and temperature variations and the direct steam injection. The cases below are from a production batch where the preheating starts at 8h49 and the production starts at 11h38. The batch ends at 17h39.

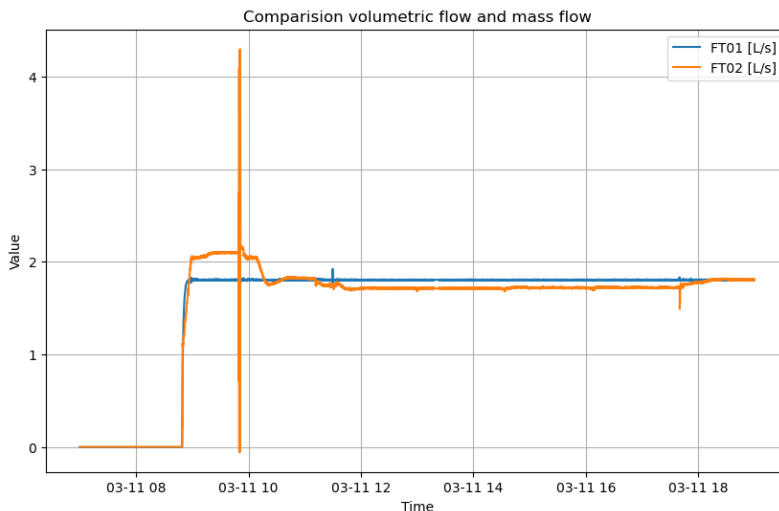


Figure 5-1: Flow sensors FT01 and FT02

In Figure 5-2, the mass flow is calculated according to FT02 with temperature sensor TT12 that makes it possible to calculate the density at the point. This mass flow is used in the formulas to calculate heat transfer.

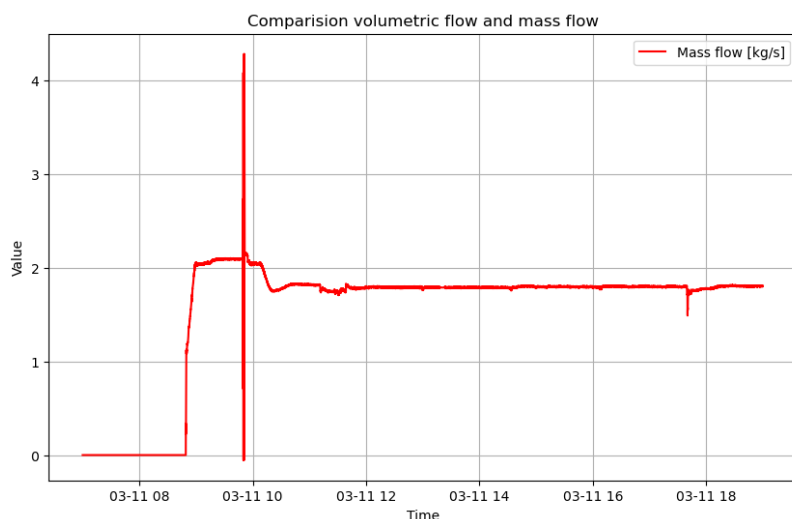


Figure 5-2: Mass flow calculated with FT02

There are several volumetric measurements throughout the process. In addition to the process flow discussed earlier, there are relevant flows shown in the table. These are based on a volumetric measurement combined with the corresponding temperature measurement linked to the temperature dependence of the fluid.

Note that the volumetric flows have different units, so they must be converted correctly.

Table 5-1: Summary of mass flows with explanation

Mass flow name	Volumetric flow	Temperature	Explanation
mass_flow_proces	52-4000FT02 [L/h]	52-4000TT12	Product flow in UHT unit
mass_flow_hr_to_hot	20-0302FT01 [m³/h]	20-0201TT01	Flow of cold technical water, heated by the product in the heat exchanger (WW1) and is stored in the hot water tank
mass_flow_hr_to_cold	20-0401FT01 [m³/h]	20-0401TT01	Flow of hot technical water, cooled in the heat exchanger (WW1) by the tap water and is stored in the cold water tank
mass_flow_ring	20-0501FT01 [m³/h]	20-0502TT01	Flow of cold tap water, heated by the technical water in the heat exchanger (WW2) and is stored in the hot water tank
mass_flow_tub2	/	/	Cooling water flow in the second tubular heat exchanger
mass_flow_tub3_plt2	/	/	Cooling water flow in the last tubular or plate heat exchanger depending on the selection

The mass flow of tub2 and of tub3/plt2 is estimated using virtual measurements as explained in 5.1.2.

5.1.2 Cooling unit

The cooling unit is a common feature of industrial plants and consists of several parallel consumers that require the supply of cooled water. The unit consists of several pumps that regulate the demand for cooling water. The electrical power consumption is beyond the scope of this paper. However, the electrical cooling energy is included in the calculations.

Figure 5-3 shows a detailed visualization of the WinCC program, as the P&ID does not include data on the common parts of the factory. The figure demonstrates the collective cooling tank, which serves to cool various components of the UHT line 1, including tubular heat exchangers 2 and 3 and the second plate heat exchanger. Additionally, the cooling tank is responsible for cooling other consumers, such as the air conditioning and smoobies. Smoobies are soft filling pearls used in cakes. The labels "UHT Reg. 3e section" and "UHT Reg. 2e section," refer to tubular heat exchangers 2 and 3, respectively. The first tubular and plate heat exchangers are connected to the heat recovery block and placed in parallel.

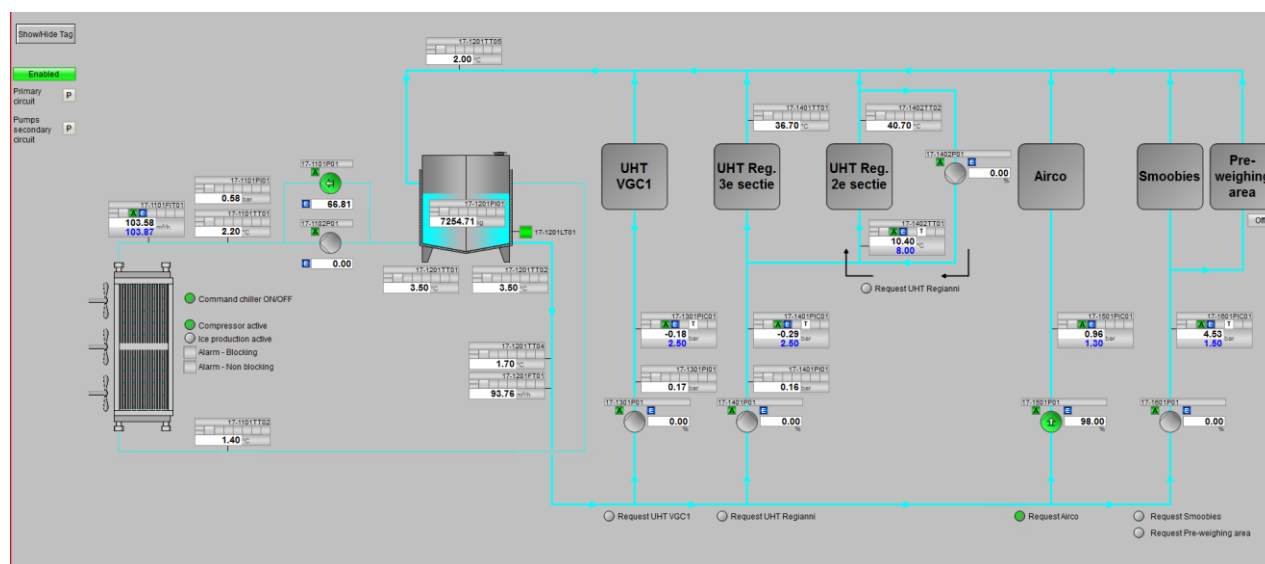


Figure 5-3: WinCC visualization of cooling unit

The cooling unit presents a few issues regarding the derivation and division of flow rates. These issues are addressed in the following sections, and solutions are provided for each case.

5.1.2.1 Problem 1: Common flow meter

The first difficulty here is that there is a common flow meter for all these consumers, but no individual flow meters which makes it difficult to know these flows.

To solve this problem, the data from other elements is used. Using the common features of these pumps located before the consumer blocks (see Figure 5-3), the flow rate ratios can be determined. Since the only common feature is the torque of the pumps, it is not possible to make an accurate prediction because there is no direct proportional relationship between torque and flow rate.

The torques are examined to see a relation between the flow and the torques, see Figure 5-4. The theory is that if only the air conditioning is running, the required flow for the air conditioning can be set as a constant if the torque remains constant. Since this torque (blue curve) varies between 1.5 and 1.75

Nm, this is an approximation. The same method can be applied to the other consumers, allowing the individual flows to be estimated. Sometimes, the relationship is more difficult to calculate but Actemium has a solution for that problem.

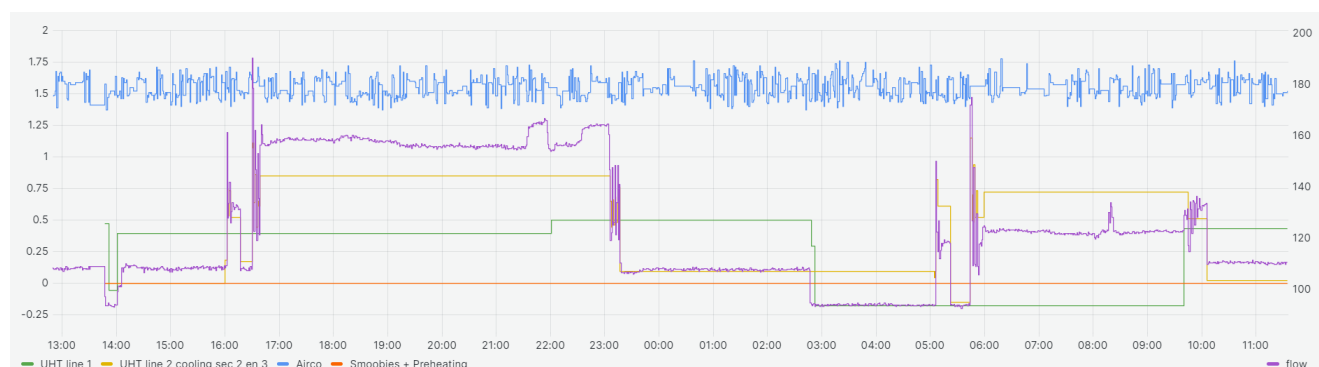


Figure 5-4: Flow of cooling unit (purple) with motor torques.

Actemium has a calculation tool that permits the determination of the individual flows in the respective branches, provided that a branch-specific feature is available that has a decent correlation with the main flow. This may be the state of a control valve or a motor feature. In this instance, where only the torques are known for all the pumps, this feature is employed. The tool then calculates the weights that must be multiplied with the feature. The air-conditioning is an exception where the flow is constant 93 m³/h. The results of this example are shown in Table 5-2.

Table 5-2: Weights by virtual measurement calculation

Flow	Motor	Weight	Flow [m ³ /h]
UHT 1	1301P01	31.407	Torque * Weight
UHT 2	1401P01	53.217	Torque * Weight
Air-conditioning	1501P01	/	93
Smoobies + Preheating	1601P01	1	Torque * Weight

The results of these virtual energy monitors are not very accurate due to process inertia. The relationship between the motor torque and the flow is not direct enough. The results of this method are shown in Figure 5-5.

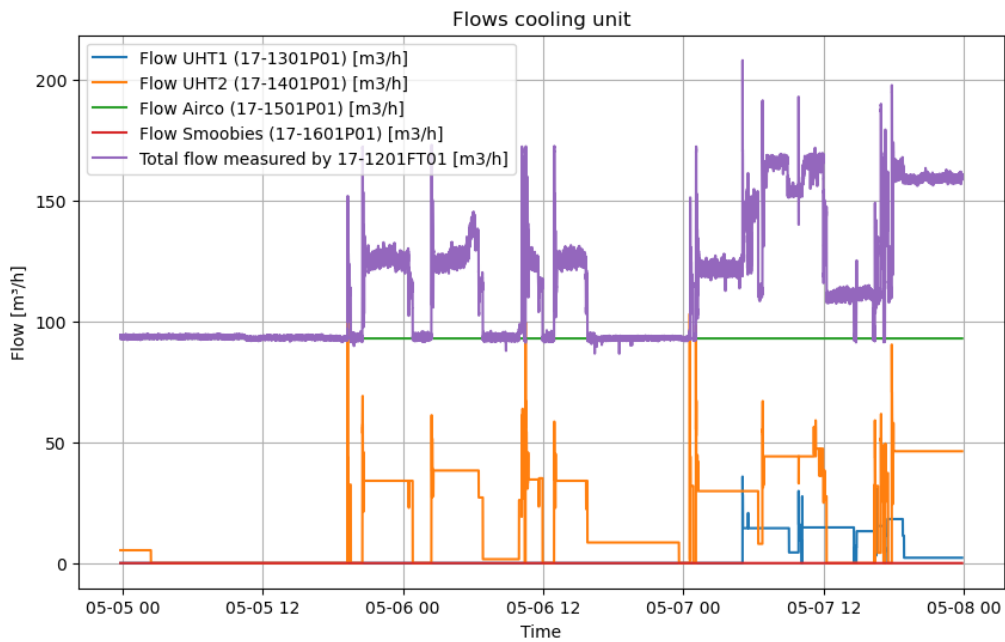


Figure 5-5: Flows cooling unit calculated using motor torque

5.1.2.2 Problem 2: Division and recirculation

The flow in the branch of 'UHT Reg. 3e section' and 'UHT Reg 2e section' is divided between the second and third tubular heat exchangers and there is a recirculation through the second one.

To solve this problem, the data of the two control valves TCV17_1 and TCV17_2 are consulted. The difficulty is that there is a recirculation pump. If this recirculation were not present, Actemium's virtual energy measurement solution could solve this problem, but this recirculation makes it hard to calculate. Due to the lack of information about this recirculation, a large approximation is introduced. It is approximated that the flow calculated for the branch of UHT 2 is divided equally between the cooling sections.

With that approximation, the flow of the recirculation pump can be derived. Figure 5-6 shows a more specific diagram of the cooling unit with the naming of the temperatures and flows that are worked with.

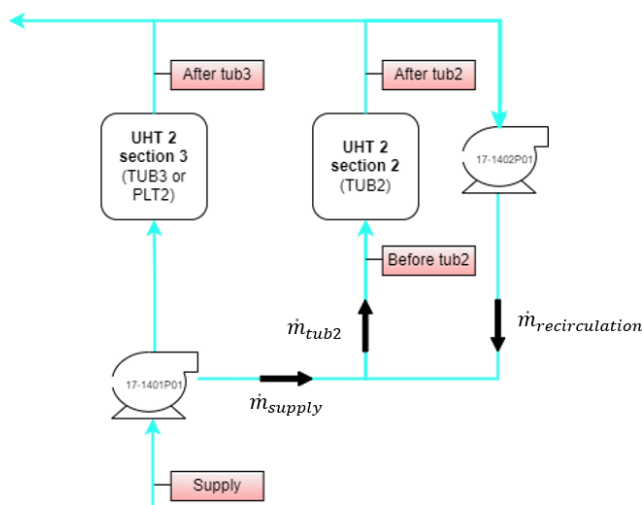


Figure 5-6: Diagram cooling unit (problem 2)

Following the law of conservation of energy, there can be derived [2]:

$$\dot{m}_{supply} c_{water} T_{supply} + \dot{m}_{recirculation} c_{water} T_{after\ tub2} = \dot{m}_{tub2} c_{water} T_{before\ tub2} \quad [2]$$

In this formula is $\dot{m}_{supply}$ half of the mass flow calculated in solution 1 that pump 1401P01 delivers with the temperature T_{supply} of the cooled water. $T_{after\ tub2}$ and $T_{before\ tub2}$ are respectively the temperatures of the cooling fluid before and after the second tubular heat exchanger. Further is $\dot{m}_{recirculation}$ the mass flow of the recirculation caused by pump 1402P01 and is $\dot{m}_{tub2}$ the mass flow of the cooling fluid in this heat exchanger.

This can be simplified in [3]:

$$\dot{m}_{supply} T_{supply} + \dot{m}_{recirculation} T_{after\ tub2} = \dot{m}_{tub2} T_{before\ tub2} \quad [3]$$

With the law of conservation of mass in [4]:

$$\dot{m}_{supply} + \dot{m}_{recirculation} = \dot{m}_{tub2} \quad [4]$$

When [4] in [3]:

$$\dot{m}_{supply} T_{supply} + \dot{m}_{recirculation} T_{after\ tub2} = (\dot{m}_{supply} + \dot{m}_{recirculation}) T_{before\ tub2} \quad [5]$$

This leads to two equations and two unknowns. From this, $\dot{m}_{recirculation}$ can be calculated as follows:

$$\dot{m}_{recirculation} = \frac{T_{before\ tub2} - T_{supply}}{T_{after\ tub2} - T_{before\ tub2}} \dot{m}_{supply} \quad [6]$$

The temperature values are assumed to be constant in the production step 330. Varying temperatures would make these equations difficult and since the energy consumption is only considered in the production step, this should provide a good approximation during the production step. The temperature values here are:

$$\begin{aligned} T_{before\ tub2} &= 8^{\circ}\text{C} \text{ (Setpoint during production)} \\ T_{after\ tub2} &= 26^{\circ}\text{C} \text{ (approximation)} \\ T_{supply} &= 1^{\circ}\text{C} \text{ (Tag)} \end{aligned}$$

In the final stage of the process, the mass flow of the recirculation is multiplied by a Boolean variable that is true when the recirculation pump is active. This is based on the torque of the pump, with a positive torque indicating that the pump is active. The results of this calculation are shown in Figure 5-7.

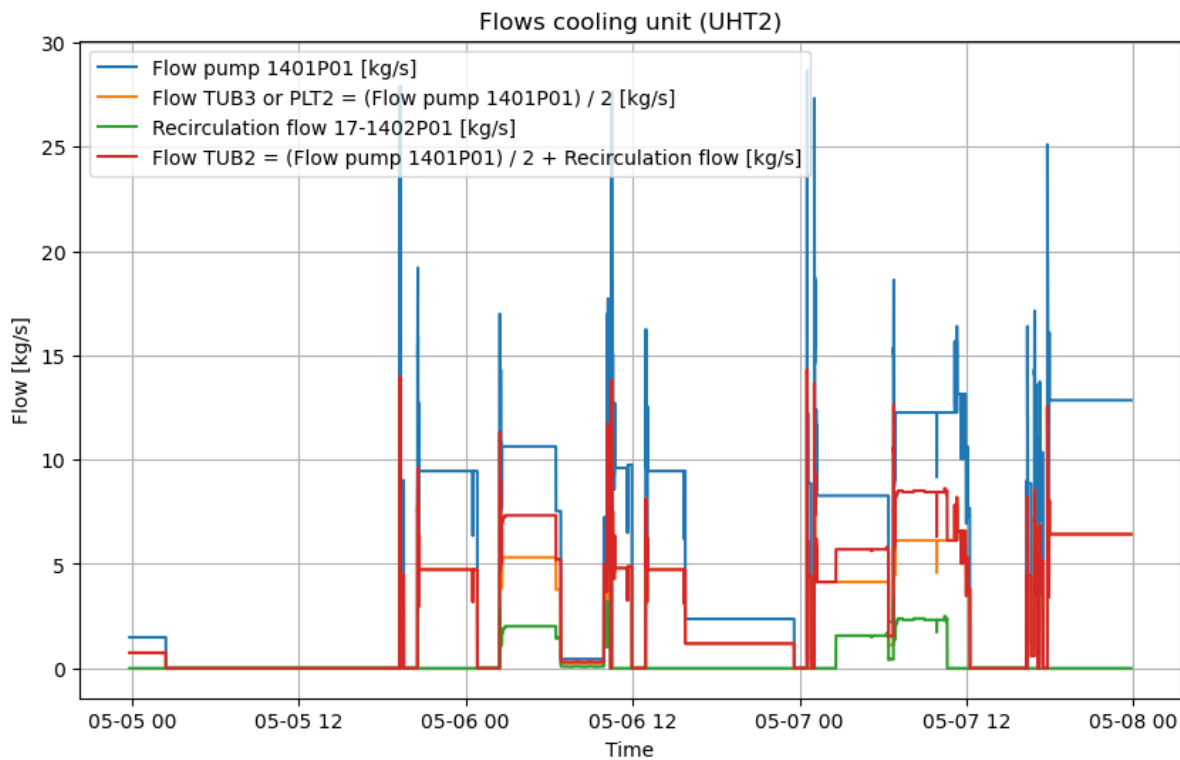


Figure 5-7: Results of virtual energy measurement algorithm for cooling flows

5.1.2.3 Problem 3: Parallel heat exchangers

This visualization is outdated, since the second plate heat exchanger is now placed in parallel with the third tubular heat exchanger (UHT Reg. 3e section).

The Boolean indicating which heat exchanger is active can be used to solve this problem. This is explained in 4.3 and this Boolean can be used by multiplying it with the correct heat exchanger. This establishes the flow for the specified heat exchanger to the calculated value, while setting the other heat exchanger to zero.

5.1.2.4 Results

The flows estimated from the virtual measurement calculation for the second and third tubular and the second plate heat exchanger are much larger than expected. The error is about a factor of 10 to get acceptable results. There can be several reasons for this error, such as a calculation error or a conversion error. In addition, it can also be caused by the fact that the P&ID of the cooling unit is not complete. For example, there may be other loads sitting there that reduce the flow in the other branches. Probably, the motor torques are not a good approach to base the virtual energy meters on.

Since these results are not acceptable, a value is used that yields possible results. Experimentally is seen that a flow of 0.5 kg/s cooling water gives acceptable results for both heat exchangers. The calculations continue with this value. An example is shown in Figure 5-8. Note that the product power should be negative, but the absolute value is used to compare both powers.

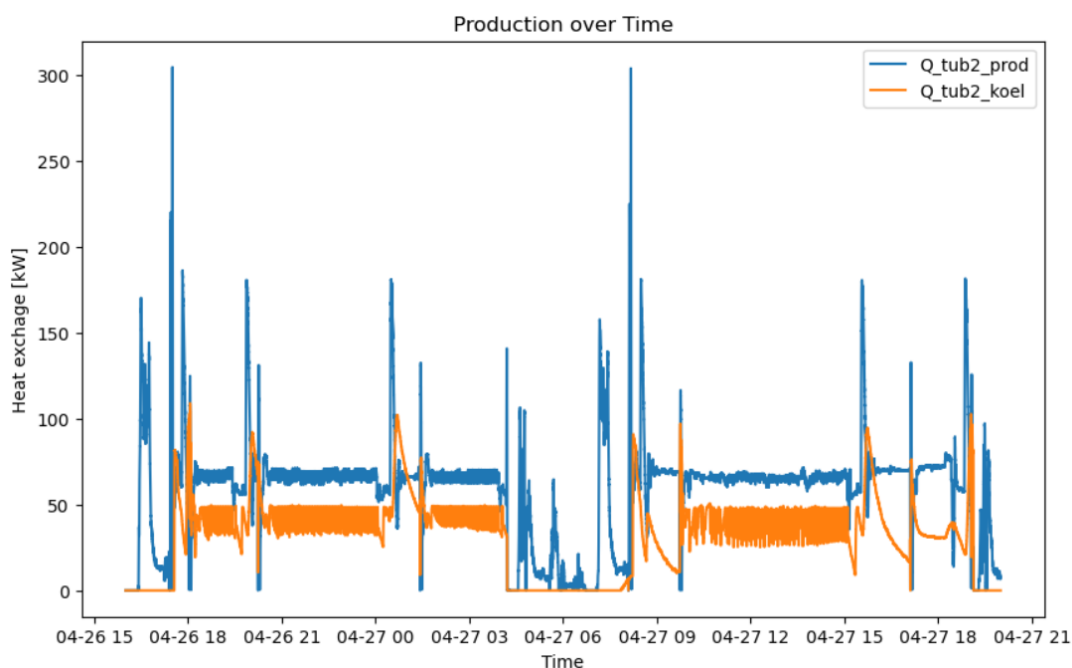


Figure 5-8: Example tub2 with adjusted cooling flow

5.1.3 Product

In the considered UHT line 2, various products are treated. There are ten products whose thermal product characteristics are known and are shown in Table 5-3. Note that the density and heat capacity depend on the temperature.

Table 5-3: Thermal product properties

	Density kg / m3			Heat capacity , J/(g.°C)							
				Heating			Cooling				
	10°C	40°C	80°C	10-40	40-80	80-110	110-85	85-65	65-40	40-12	
				Av	Av	Av	Av	Av	Av	Av	
PRODUCT 1	1,024	1,021	1,018	3,95	4,01	4,17	4,11	3,90	3,78	3,70	
PRODUCT 2	1,023	1,020	1,019	4,15	4,17	4,29	4,17	4,03	3,94	3,88	
PRODUCT 3	1,046	1,031	1,028	*	*	*	*	*	*	*	
PRODUCT 4	1,053	1,030	1,027	4,19	3,40	3,58	3,52	3,38	3,29	3,40	
PRODUCT 5	1,077	1,054	1,052	3,86	3,52	3,71	3,53	3,36	3,24	3,29	
PRODUCT 6	*	1,068	1,061	3,51	3,21	3,37	3,53	3,36	3,24	3,29	
PRODUCT 7	1,093	1,071	1,070	4,44	3,56	3,79	3,42	3,24	3,11	3,28	
PRODUCT 8	1,099	1,092	1,091	*	*	*	*	*	*	*	
PRODUCT 9	*	*	*	3,85	3,91	4,05	3,82	3,67	3,57	3,50	
PRODUCT 10	*	1,284	1,290	2,77	2,91	3,05	2,89	2,76	2,65	2,52	
PRODUCT 11											

Two principal methodologies may be employed to incorporate this table into the calculations. The initial approach is based on the intervals outlined in the data table. The temperature value is used to extract the corresponding heat capacity values from the table. The density is then linearly interpolated. The second method is more precise but necessitates a greater computational time. This entails plotting a polynomial using the provided data points, thereby enabling a more exact approach.

5.1.3.1 Method 1: Intervals

The used function is called 'calc_prop', which calculates the density and specific heat capacities. This function has three arguments including temperature, the dictionary and the product. It returns the values of the three table variables based on the given temperature by selecting the correct temperature interval for the specific heat capacity. The density is linearly interpolated because here is not worked with intervals.

5.1.3.2 Method 2: Polynomial

The second method fits a second-degree polynomial curve to the three or four heat capacity data points. For the intervals the average temperature is calculated. The second degree is chosen because the results are acceptable and a higher degree would increase the computation time and cause overfitting. The coefficients of the polynomial curves are stored in a dictionary for quick calculation of predicted values for variable temperatures. Examples are shown in Figure 5-9 for product two and Figure 5-10 for product 7. Note that only two points are known for the density, the curve plots a straight line, as shown in Figure 5-11 and Figure 5-12 for product two and ten.

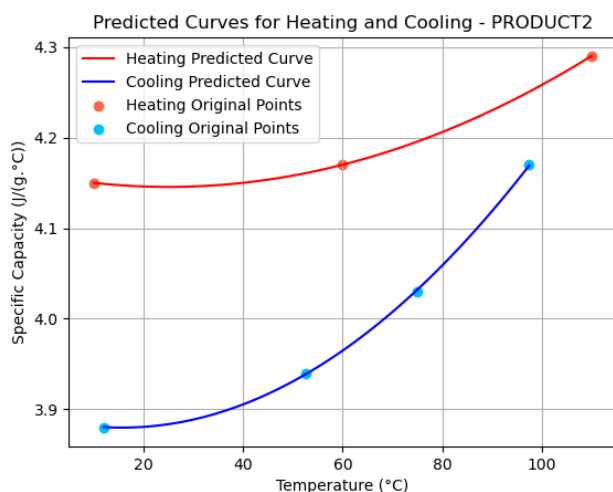


Figure 5-9: Specific heat capacity for product 2

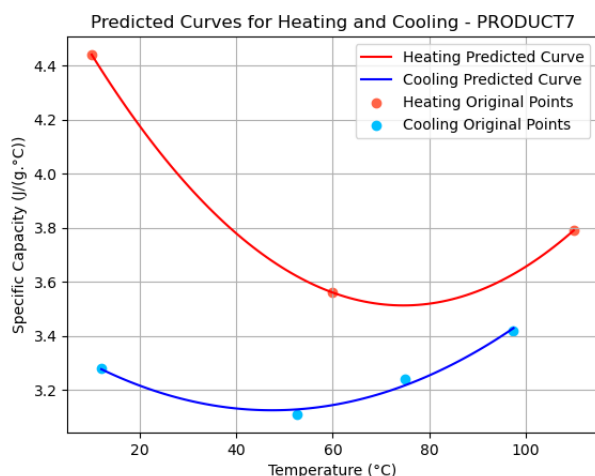


Figure 5-10: Specific heat capacity for product 7

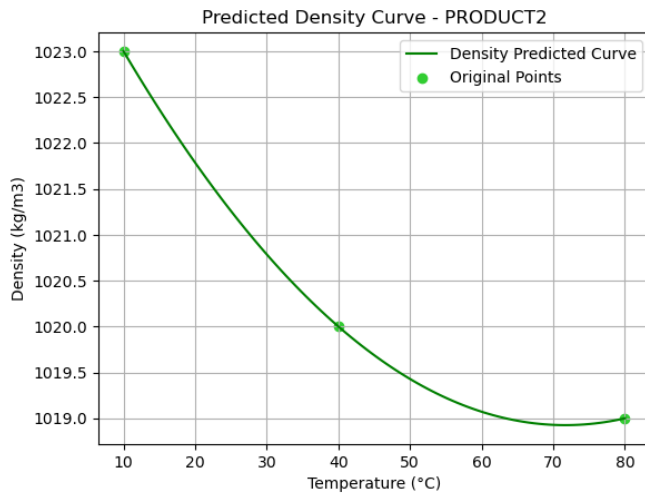


Figure 5-11: Density temperature dependence product 2

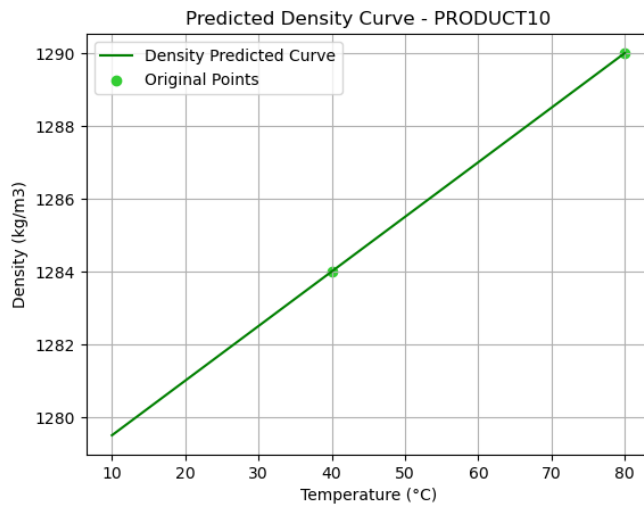


Figure 5-12: Density temperature dependence product 10

5.1.3.3 Comparison of both methods

Both methods calculate the temperature dependence of the density and the specific heat capacity. The first method divides the range into parts, resulting in a less accurate calculation. The disadvantage of the second method is the calculation time, but the accuracy is significantly better than the first method. In addition, this calculation can be performed only once, so the second method is chosen.

Both functions are still not functional in a DataFrame calculation involving row-by-row multiplication. This problem is solved by inserting one density and two heat capacities columns per temperature measurement in the same DataFrame. This is achieved by running through all the temperature values and applying the function to that measurement. Since they now have a unique column, the calculation is computable. It is notable that this calculation time is rather long.

Furthermore, it is necessary to distinguish between temperature measurements that are always on water and those that are on the product line and thus sometimes on water. This distinction can be made by examining the tag naming. All process tags that are applied to the product line always begin with 'LUM_VGC_S017_52-4000' followed by TT if this is a temperature measurement. These are applied to

the product thermal properties, which include water (see section 4.2). All the other temperature tags are applied on water.

5.1.3.4 Missing values

As illustrated in Table 5-3, the product properties are not available for all products. As Puratos lacks further information on these missing measurements, these values are approximated using values from other products, as shown in Table 5-4. The choice of matching is random and can be adjusted when the data is available.

Table 5-4: Approach missing values product properties.

Product	Measurement	Approximated by
Chantypak	Heating specific capacity	Whippak
	Cooling specific capacity	
Dulcerio	Heating specific capacity	Festipak & Montamix
	Cooling specific capacity	
Fabuloso	Density	SSG

5.1.4 Water

The specific heat capacity and density are relevant values to calculate the heat exchange, the formula is shown in equation [7]. Two different methods are considered to obtain these values, both implying an approximation.

$$\dot{Q} = \dot{m}(h_2 - h_1) = \dot{m}c_p(T_2 - T_1) \quad [7]$$

Where $\dot{Q}$ is the heat exchange in kJ/s, $\dot{m}$ the mass flow in kg/s, h the enthalpy in kJ/kg, c_p the specific heat capacity in kJ/(kg*°C) and T the temperature in °C.

5.1.4.1 Method 1: Specific enthalpy

The first method uses the specific enthalpy difference to calculate this heat transfer. The specific heat capacity c_p and density ρ depend on temperature and pressure, so a separate data frame is used to calculate the thermal properties of this water. This table contains the identifying variables pressure and temperature, but also other variables such as specific volume, density, specific internal energy, specific enthalpy and specific entropy. The disadvantage of this method is that the closest value for pressure and temperature should be taken and therefore there may be a deviation in the heat exchange. In addition, the pressure measurements are needed for before and after the heat exchanger, but in most cases only one of them is measured, by which the other value should be approximated. This table is shown in Table 5-5 and can be found on the internet (Hendren, 2022).

Table 5-5: CSV of compressed liquid (Hendren, 2022)

	Pressure (MPa)	Temperature (°C)	Specific Volume (m ³ /kg)	Density (kg/m ³)	Specific Internal Energy (kJ/kg)	Specific Enthalpy (kJ/kg)	Specific Entropy (kJ/(kg K))	Phase
0	0.01	0.0	0.001000	999.80	-0.040002	-0.03	-0.00015	"liquid"
1	0.01	5.0	0.001000	999.92	21.019999	21.03	0.07625	"liquid"
2	0.01	10.0	0.001000	999.66	42.019997	42.03	0.15109	"liquid"
3	0.01	15.0	0.001001	999.06	62.979991	62.99	0.22446	"liquid"
4	0.01	20.0	0.001002	998.17	83.909982	83.92	0.29648	"liquid"
...	...	...	...	...	...	...	...	...
9522	1000.00	1200.0	0.001343	744.75	3674.000000	5016.70	5.70360	"supercritical fluid"
9523	1000.00	1400.0	0.001452	688.50	4244.800000	5697.20	6.13680	"supercritical fluid"
9524	1000.00	1600.0	0.001563	639.92	4812.000000	6374.70	6.51930	"supercritical fluid"
9525	1000.00	1800.0	0.001672	598.26	5376.700000	7048.20	6.86090	"supercritical fluid"
9526	1000.00	2000.0	0.001778	562.52	5939.800000	7717.50	7.16910	"supercritical fluid"

9527 rows × 8 columns

Two functions are used for collection the density and specific enthalpy out of the Dataframe. The first one is `find_colosest_temp_pres` which approximates the given temperature and pressure with the nearest value in the Dataframe. The second function is `calc_prop_koel` that searches in the Dataframe the collect density and specific enthalpy and returns it. These calculations are written in functions because they can be applied on columns of a Dataframe.

5.1.4.2 Method 2: Specific heat capacity

The second method is to calculate the heat exchange with a constant value for the specific heat capacity c_p , since this value remains virtually constant for small temperature changes in the compressed liquid zone. Table 5-6 shows the temperature dependence for the substance water.

Table 5-6: Properties of common fluids (Claessens, 2022)

TABLE A-3							
Properties of common liquids, solids, and foods							
(a) Liquids							
Substance	Boiling data at 1 atm		Freezing data		Liquid properties		
	Normal boiling point, °C	Latent heat of vaporization h_{fg} , kJ/kg	Freezing point, °C	Latent heat of fusion h_{if} , kJ/kg	Temperature, °C	Density ρ , kg/m ³	Specific heat c_p , kJ/kg·K
Ammonia	-33.3	1357	-77.7	322.4	-33.3	682	4.43
					-20	665	4.52
					0	639	4.60
					25	602	4.80
Argon	-185.9	161.6	-189.3	28	-185.6	1394	1.14
Benzene	80.2	394	5.5	126	20	879	1.72
Brine (20% sodium chloride by mass)	103.9	—	-17.4	—	20	1150	3.11
n-Butane	-0.5	385.2	-138.5	80.3	-0.5	601	2.31
Carbon dioxide	-78.4*	230.5 (at 0°C)	-56.6	—	0	298	0.59
Ethanol	78.2	838.3	-114.2	109	25	783	2.46
Ethyl alcohol	78.6	855	-156	108	20	789	2.84
Ethylene glycol	198.1	800.1	-10.8	181.1	20	1109	2.84
Glycerine	179.9	974	18.9	200.6	20	1261	2.32
Helium	-268.9	22.8	—	—	-268.9	146.2	22.8
Hydrogen	-252.8	445.7	-259.2	59.5	-252.8	70.7	10.0
Isobutane	-11.7	367.1	-160	105.7	-11.7	593.8	2.28
Kerosene	204-293	251	-24.9	—	20	820	2.00
Mercury	356.7	294.7	-38.9	11.4	25	13,560	0.139
Methane	-161.5	510.4	-182.2	58.4	-161.5	423	3.49
					-100	301	5.79
Methanol	64.5	1100	-97.7	99.2	25	787	2.55
Nitrogen	-195.8	198.6	-210	25.3	-195.8	809	2.06
					-160	596	2.97
Octane	124.8	306.3	-57.5	180.7	20	703	2.10
Oil (light)					25	910	1.80
Oxygen	-183	212.7	-218.8	13.7	-183	1141	1.71
Petroleum		230-384			20	640	2.0
Propane	-42.1	427.8	-187.7	80.0	-42.1	581	2.25
					0	529	2.53
					50	449	3.13
Refrigerant-134a	-26.1	217.0	-96.6	—	-50	1443	1.23
					-26.1	1374	1.27
					0	1295	1.34
					25	1207	1.43
Water	100	2257	0.0	333.7	0	1000	4.22
					25	997	4.18
					50	988	4.18
					75	975	4.19
					100	958	4.22

5.1.4.3 Comparison of both methods

A test is set up to compare the two values. In this test, the heat absorbed by the water from the product in the first tubular heat exchanger is plotted as a function of time according to method 1 and method 2. There are significant differences, but they can be explained. The first method looks up the enthalpies in a table and therefore this heat transfer is more graded.

Since water is the only fluid that has access to such a table and all other calculations are done with the c_p value, method 2 is chosen to do these calculations. It is important to perform all calculations in a consistent manner to eliminate anomalies. In addition, pressure measurements are available in limited locations making this method often not possible.

An example is given to compare both methods. It is about the cooling process of the first tubular heat exchanger is shown. Before 1h44 is the preparation for production with the presterilization and afterwards is production to aseptic. The start temperature T_1 remains constant and the temperature after the heat exchanger depends on the production phase and the flow in the heat recuperation circuit. The pressure P_2 before is heat exchanger is plotted in Figure 5-14 and the flow as well. Figure 5-13 compares both methods of producing the heat exchange. Here there is seen that method two is more precise and less stepped. It is worth noting that in the constant parts, the heat transfer calculated with method 2 is higher than method 1. This can be explained by the pressure dependence. Method 1 is pressure dependent while method 2 is not. This results in a larger discrepancy at higher pressures.

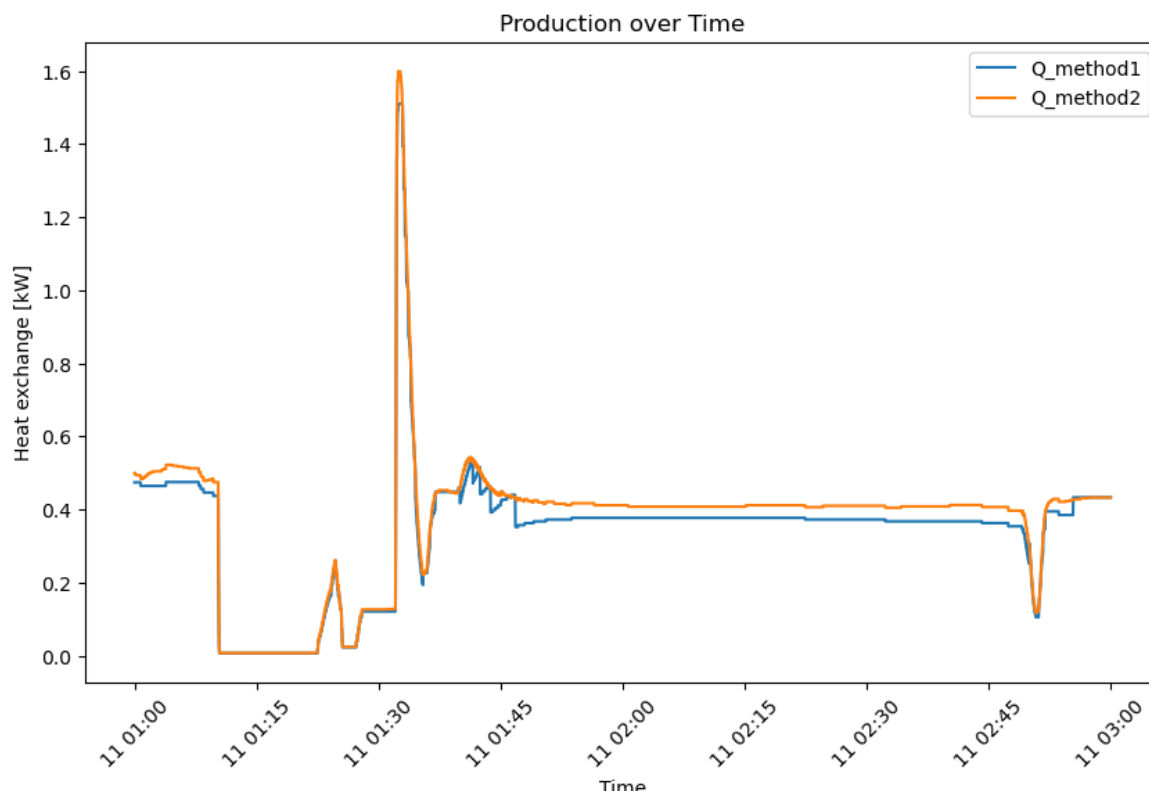


Figure 5-13: Heat exchange calculated of both methods.

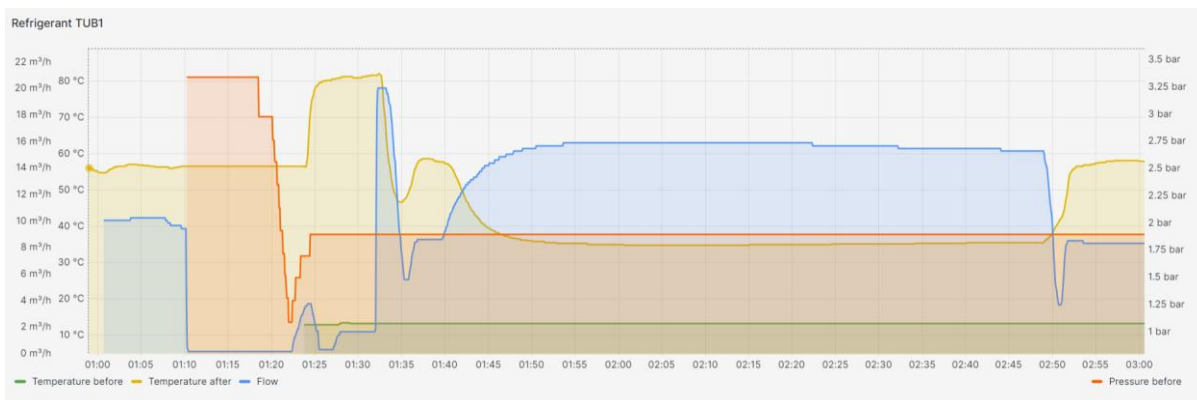


Figure 5-14: Temperatures, pressure and flow rate of this test

5.1.5 Steam

Prior to April 22, 2024, Puratos lacked awareness of the quantity of steam consumed during the UHT process on line 2. On that date, a vortex flow sensor was connected to the common steam tube of this process. As illustrated in the process and instrumentation diagram (P&ID) in Appendix A, the steam branch of 12 bar is divided into two lines at different pressures. A line at 10 bar is responsible for the direct steam injector, while a line at 4 bar is in charge of the pasteurization, homogenization, and connected to a condenser. A summary is shown in Table 5-7.

Table 5-7: Summary of valves and consumers of the steam

Valve	Pressure [bar]	Consumer
TCV16	10	Sterilizer
TCV07	4	Pasteurizer
TCV33	4	Heat exchanger
I	4	Homogenizer

The steam measurement is expressed in kg/h. There are two considerable methods of calculating the steam flow with the matching energy consumption. The first method is the more accurate and theoretical method, while the second method is just based on an assumption.

5.1.5.1 Method 1

The first method assumes that the pressure in the pipes is constant, set to the value on the P&ID, because there is no pressure tag available. The first step is to determine what phase the steam is in. This can be wet steam, where there is still a liquid fraction in the steam, or superheated steam, where there is no liquid fraction in the steam. This is measured by the steam fraction x , where 0 is completely liquid and 1 is dry steam.

For the 10-bar line, the saturation temperature is 179,88 °C. Since the temperature is always below 150 °C, the steam is in the wet steam range. The same conclusion is reached for the 4-bar line with a saturation temperature of 143.61 °C and a physical temperature that is lower than 85 °C. The information, available in the steam tables, is accessed via an online CSV file (Hendren, 2022).

The next step is to assume on the vapor fraction. The definition of the vapor fraction is shown in equation [8]:

$$x = \frac{m_{steam}}{m_{steam} + m_{liquid}} \quad [8]$$

For both lines, x is assumed to be 0.8, which is a guess. In the next step, the enthalpy, the specific volume and the density are calculated using the following formulas [9], [10] and [11].

$$v_{steam} = (1 - x) * v_{liquid} + x * v_{vapor} \quad [9]$$

$$h_{steam} = (1 - x) * h_{liquid} + x * h_{vapor} \quad [10]$$

$$\rho = \frac{1}{v} \quad [11]$$

Here v_{steam} is the specific volume of the used steam in m³/kg, v_{liquid} and v_{vapor} are the specific volumes of the pure liquid and the pure vapor, respectively, at the pressure. The same analogy for the enthalpy h, which is expressed in kJ/ kg. Finally, the density of the steam is calculated by taking the inverse of the specific volume. The idea is that by using the density and the valve openings, the mass flows of the steam can be estimated with the virtual energy measurement algorithm of Actemium.

The two minor steam consumers are neglected. These are the line to the homogenizer and the line to the small heat exchanger. The model could not handle the fact that this valve is open for long periods and this would not be possible to estimate the flow. The results of the other two are shown in Table 5-8.

Table 5-8: Weights for the steam flow rate split

Valve	Pressure [bar]	Density [kg/m ³]	Weights
TCV16	10	6.42	1.544873
TCV07	4	2.72	0.290786

The mass flow of each branch can be calculated by multiplying the valve opening by the density and the weight that is calculated by the algorithm. Since the individual flows are known, the heat flow can be calculated using the enthalpy and the mass flow.

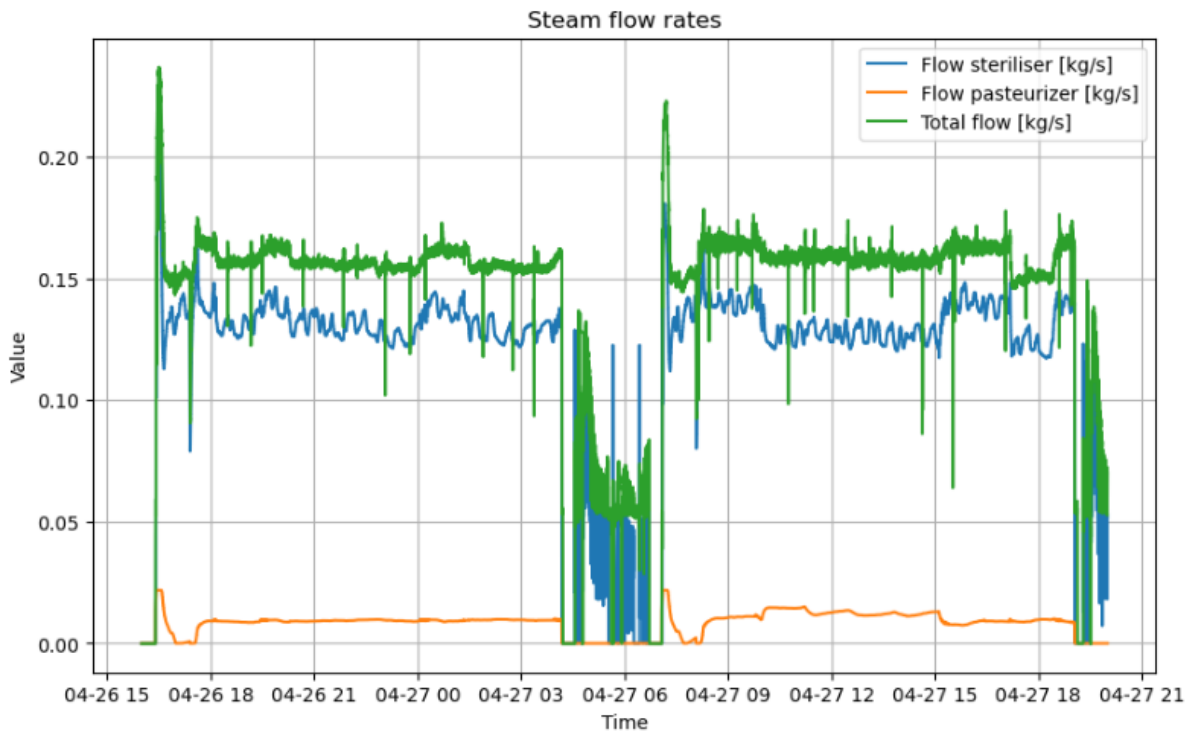


Figure 5-15: Steam flow rates

5.1.5.2 Method 2

The second method is based on a total amount of energy per ton steam. Since the steam flow is measured in kg/h, the heat transfer can be calculated. The distribution in the different pressure lines, is an assumption with the valve position and corresponding pressure of the line.

This method implies a large approximation, since an energy value should be assigned to each kg of steam and is therefore not further elaborated.

5.2 Specific for components

In this section, it is useful to consult the block diagram which gives the component information in a clear way. This is discussed in section 4.5.

5.2.1 Balance tank

Data

The process begins with the raw product in the balance tank, which has a volume of 500 litres. A level measurement is used to calculate the volume of the product (LT01), while a conductivity sensor is present but not used for this purpose (CT01).

5.2.2 Centrifugal pump PA

Data

There is a pressure gauge before and after this pump. The one in front is PT21, located before the balance tank, and the one behind is PT22. The flow rate is given by FT01 and the motor speed is available too. Further in the datasheets, is a graph with the pump efficiency in function of the flow given.

Assumptions

The centrifugal pump's function is to pressurize the piston pump due to its minimum working pressure. Two calculation methods are possible for this pump. The first method is based on mechanical power and process measurements as shown in equation [12]. Pressure measurements are taken before and after the pump, resulting in Δp , and the flow rate $\dot{V}$ is known, allowing for the calculation of the mechanical power P_{mech} required to pressurize the fluid. Here is assumed that the pressure before the balance tank is equal to the pressure before the pump PA.

$$P_{mech} = \dot{V} * \Delta p$$

[12]

The second method is based on the mechanical power of the pump using the datasheet. The datasheet contains several graphs, including power consumption as a function of flow. Since this graph is approximately linear, it can be linearly interpolated to determine power consumption at a given flow (see Appendix C or Figure 5-16). The motor referred to in the datasheets is curve A.

The pump efficiency can be derived by selecting several points on the efficiency graph in Figure 5-16. Since the considered pump follows curve A, the points are taken as the intersections of the efficiency lines and the curve A. An acceptable approximation is obtained using a poly function of the third degree, as shown in Figure 5-17. This results in a flow-dependent efficiency, but if the flow is almost zero or slightly negative, the efficiency is below zero. This is a consequence of the approximate efficiency curve and slightly negative flows. Negative values are truncated to zero to solve this problem. In addition, the power values that are out of range are also clipped.

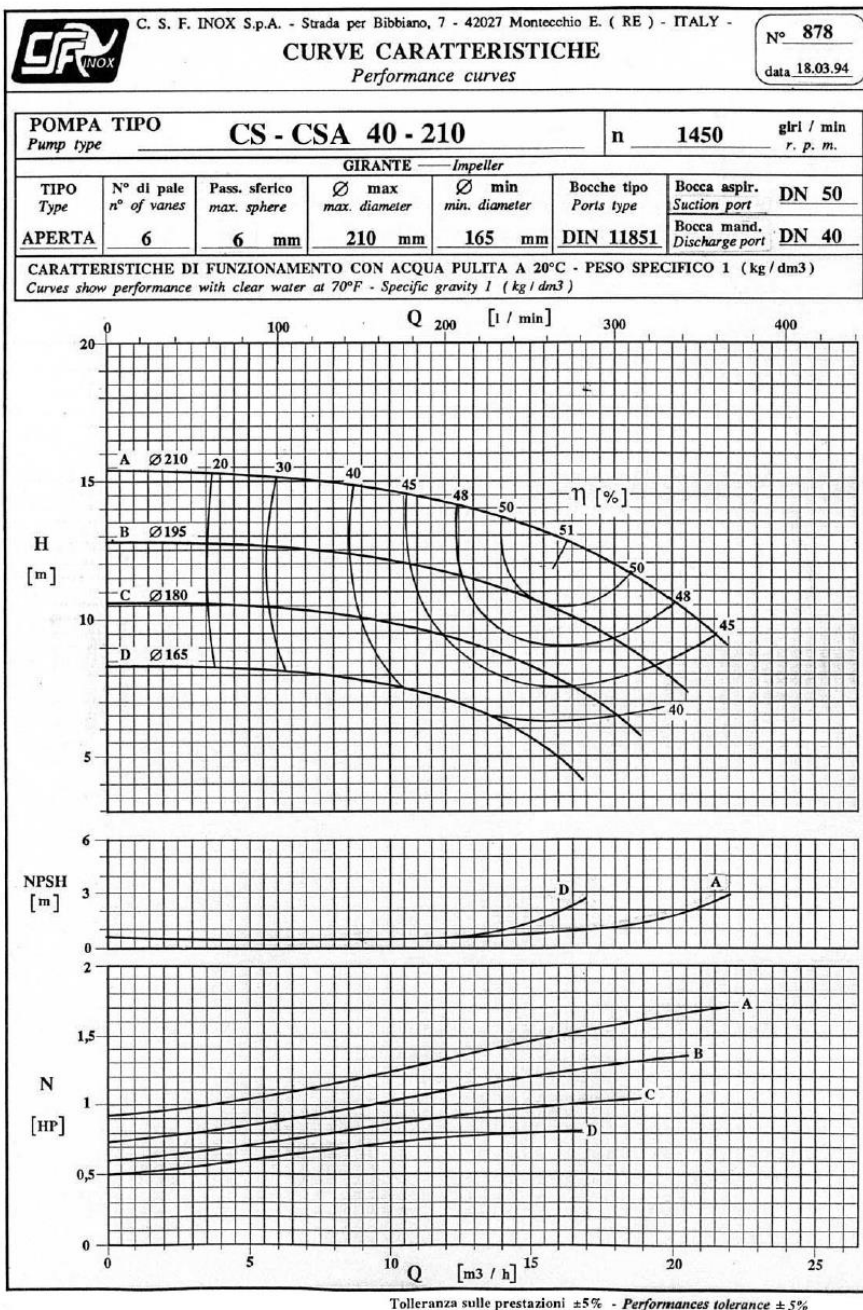


Figure 5-16: Datasheets centrifugal pump PA

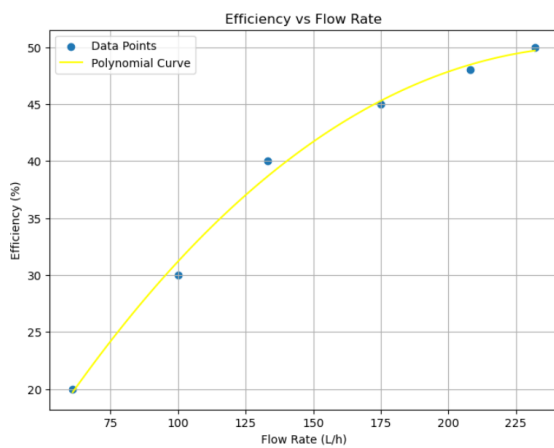


Figure 5-17: Efficiency pump PA in function of the flow

5.2.3 Piston pump

Data

The piston pump has four motors, one being the main engine. Therefore, the datasheet's electrical power consumption of 13.1 kW is consulted. The pressure (PT22) is available and the flow (FT01) as well. There are no graphs given on the datasheet.

Assumptions

The piston pump regulates system flow by volumetrically dosing the product. Calculating the mechanical energy consumption for this motor is not possible because there is no pressure measurement behind the pump. Assuming the electric power consumption is present at full production flow of 6500 L/h and that the electric power consumption is zero at a flow of 0 L/h, there can be linearly interpolated for the power using the flow. This calculation assumes that at the flow rate of 6500 L/h, the maximum power is used.

5.2.4 Condenser

Data

In the first stage, the condenser utilises the residual heat from the flash vessel to heat the product. The heat transfer of this indirect heating process can be calculated from the flow measured by FT01 and the temperature difference between TR02 and TR01.

However, it should be noted that TR measurements are not accessible in the SCADA system as they are reserved for an external logging system.

Assumptions

Since TR01 and TR02 are not available, an estimation is made to continue calculating anyway. If they become available later, they can simply be replaced. In this estimation, TR01 is kept constant at 20 °C and TR02 is a value proportional to the temperature of the condensed secreted gasses (TT09). This value is randomly chosen to be 60 %.

5.2.5 Pasteurizer

Data

In the second heating step, the pasteurizer, a similar indirect heating process occurs, but this time with steam. The temperature difference TT03 - TR02 is a measure of heat transfer that the product absorbs. However, the temperature of the drained steam is not measured, leading to absence of efficiency. The volumetric flow is given by FT01. On the P&ID is seen that this supply line is on 4 bars.

Assumptions

The steam is assumed to be held at 4 bars. This mass flow is estimated by the virtual energy meter algorithm. Since the thermal properties of the steam after the pasteurizer are not known, this heat flow cannot be calculated from the side of the steam.

5.2.6 Sterilizer

Data

The next step is the crucial sterilisation process, which involves direct steam injection. During this process, the temperature difference between TT05 and TT03 can be calculated. The product input flow

is FT01 and the mass flow of the steam is estimated by the virtual energy meter algorithm. On the P&ID is seen that this supply line is on 10 bars.

Assumptions

The steam comes into direct contact with the product, increasing the flow, which is then separated in the flash vessel. So, the flow in this part is increased. The steam is assumed to be held at 10 bars. Further calculations can be found in section 7.1.2.

5.2.7 Holding section

Data

To ensure sterilisation, the product passes through a holding section, which is a long tube with several turns. The temperature before and after this section is measured (TT05 and TT22, respectively) to calculate the energy loss using the flow (FT01) and product thermal properties. There is a steam measurement after the holding section available (PT05).

Assumptions

The heat exchange should always be negative because the product is losing energy by passing through this section. In some cases, between production batches, there are big temperature differences caused by a low flow, resulting in inaccurate calculations. To solve this problem, this heat transfer is only considered when there is production (step 330) and the positive values are clipped to zero. The product flow that is used to calculate the flow is the product flow measured by FT01 added with the steam flow in the sterilizer.

5.2.8 Flash vessel

Data

The temperature of the product with the steam is given by TT22 and the secreted steam flow temperature is given by TT09. Furthermore, there are a few turbulence measurements available, but they are not relevant for the energy calculation. Eventually, there is a level detection LT02.

Assumptions

Sterilization increases the product flow, but the remaining steam is separated in the flash vessel. The secreted flow is approximately equal to the injected steam due to the flash vessel's level detection system. Puratos suggests that the temperature of the separated steam is similar to the product temperature after the flash vessel (TT09).

5.2.9 Centrifugal pump P2

Thereafter, there is another centrifugal pump that maintains the flow through the homogenizer. It is the same concept as with centrifugal pump PA and the piston pump where P2 is similar to PA and the homogenizer is similar to the piston pump.

Data

The pressure behind the pump is known (PT23) and the flow (FT02).

Assumptions

Energy calculations must be made using the license plate data because mechanical power cannot be calculated because there is no pressure measurement before the pump. The last pressure measurement is before the flash vessel, but this is not accurate because there is an expansion. The datasheet is given in Figure 5-18. The motor referred to in the datasheets is curve A. This curve is approximated using a third-degree as shown in Figure 5-19.

In the same way as described in section 5.2.2, the flow-dependent efficiency is derived using several points on the efficiency curve. The result is shown in Figure 5-20. For negligible flows, the efficiency remains 1% and the power remains greater than zero, resulting in high energy consumption. To solve this issue the power is set to zero if the flow is negligible and the electrical power consumption is clipped down to its maximum power value. (6 kW approximated)

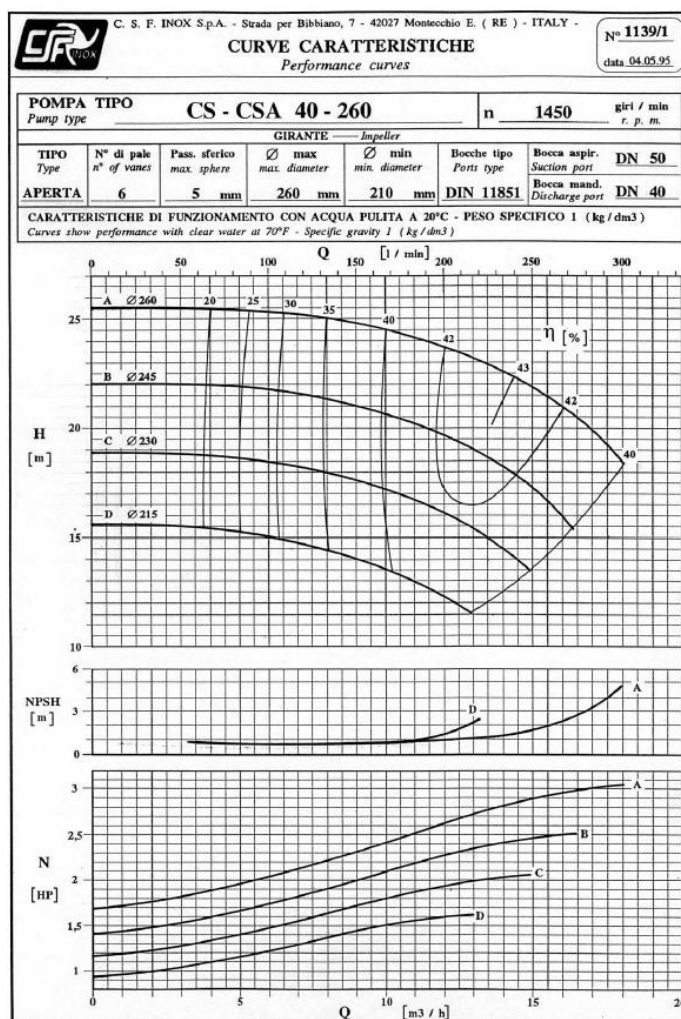


Figure 5-18: Datasheet pump P2

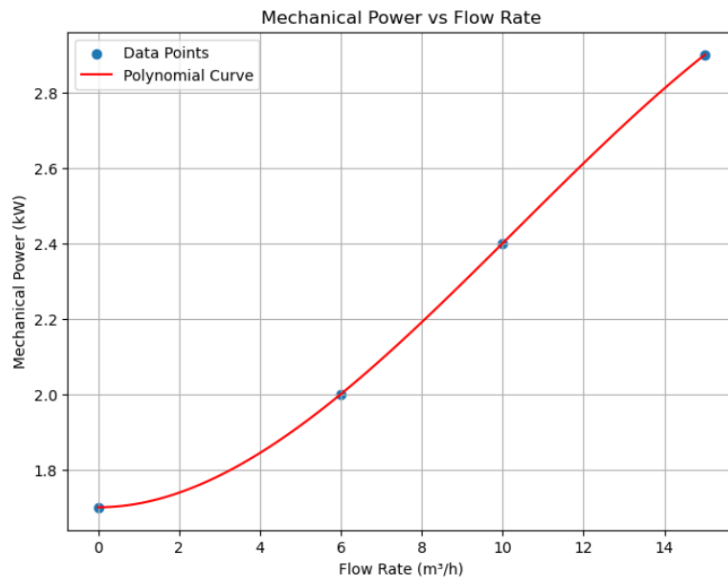


Figure 5-19: Approach of the power graph for P2

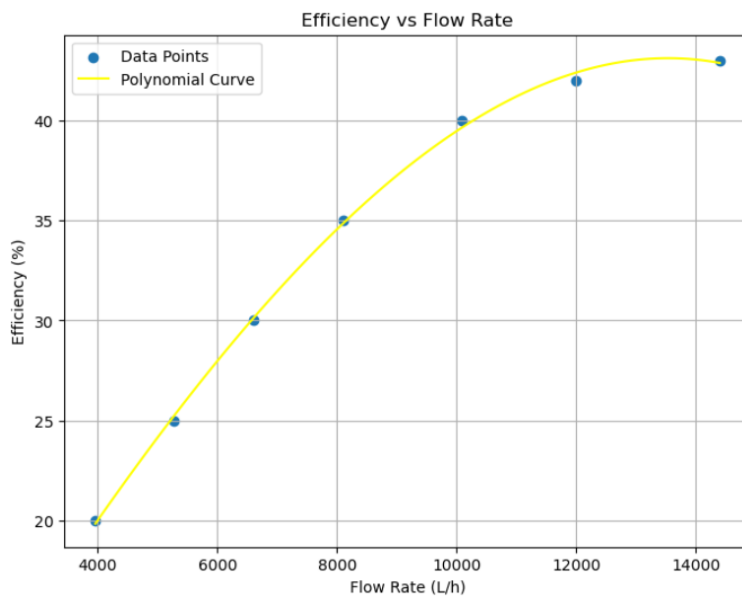


Figure 5-20: Efficiency pump P2 in function of the flow

5.2.10 Homogenizer

The homogenizer has the same concept as the piston pump and consists of multiple motors. The pumps maintain the flow by pushing it through the slit to split the fat particles equally.

Data

The electrical power consumption is 54 kW for the whole component. There are multiple measurements consisting of four pressure measurements (PT23, PT01, PT02 and PT03) and a temperature measurement (TT21). TT21 is the temperature of a fluid that cools the homogenizer because high pressures are reached but there is no further info about that process.

Assumptions

There are two ways to calculate this power consumption. The first one is by using the electrical power consumption. The problem is that there is not known when the full electrical power is present, making this method less performant. The second way of calculating this power consumption is done by multiplying the pressure elevation with the flow of sensor FT02 as in equation [12] in 5.2.2.

5.2.11 Heat exchangers

To achieve accurate calculations, six measurements are required for each heat exchanger. However, in practice, this is not always possible, and assumptions must be made. In a heat exchanger, there is always a fluid that absorbs heat and another that dissipates it. Both a flow measurement and a temperature measurement are required before and after the heat exchanger.

Data

The available data of the heat exchangers is shown in Figure 4-4 for the tubular heat exchangers and in Figure 4-5 for the plate heat exchangers in a block diagram. The measurements in orange are approximated. This is because there is no specific flow measurement available at these places. This is about the cooling flow of the second and third tubular heat exchanger and the cooling flow of the second plate heat exchanger.

The measurement TT09 or TC09 on the P&ID represents the temperature of the released gases in the flash vessel. The aforementioned P&ID can be found in appendix A. Since there is no temperature measurement of the product after this flash vessel, Puratos suggests using TT09 for this value. However, this is not a valid approach, as demonstrated in Figure 5-21. This figure shows two graphs. For the product side in the first tubular heat exchanger, TT09 (green) should be the hot temperature and TT19 (yellow) the cold temperature. TT22 is also shown, which represents the temperature after the holding section. A graph with the temperatures of the cooling product TT01 (blue) and TT02 (red) is presented below. Between 15h40 and 16h20 on the graph, the temperature difference between TT09 and TT19 is negligible, while the temperature difference for the cooling fluid is more than 60 °C. This indicates that TT09 is not a suitable measurement for the product temperature prior to this heat exchanger. It is also noteworthy that the flow of the cooling fluid at this moment is lower, but this cannot be taken as evidence of the phenomenon in question.

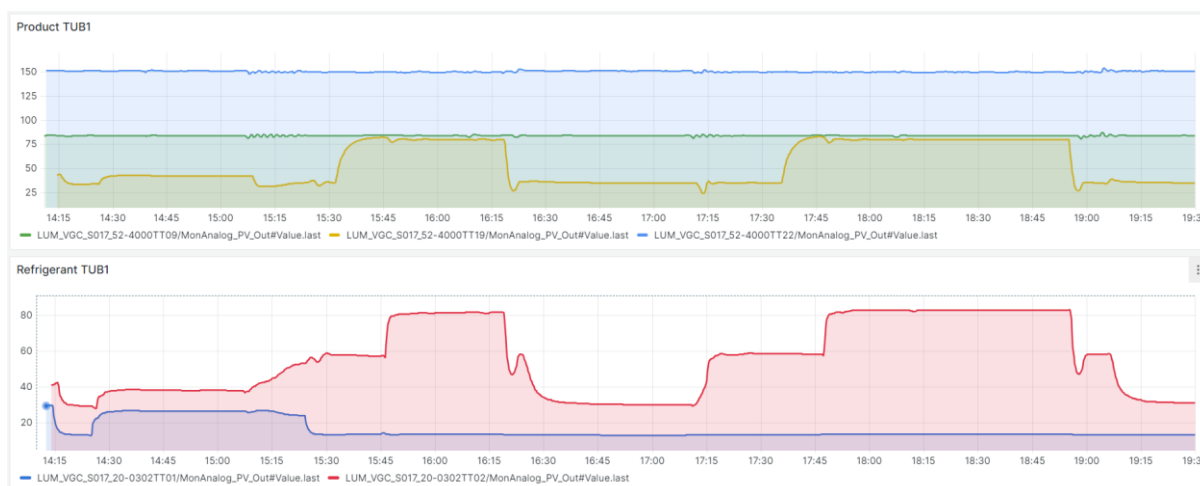


Figure 5-21: Wrong approach for tubular heat exchanger (TT09)

This approach leads to impossible power calculations, e.g., the heat that the cooling fluid receives, is greater than the heat that the product releases. This is shown in Figure 5-23. There is experimented with these results and if there is summed 30 °C with the TT09 temperature measurement, possible

values are obtained as shown in Figure 5-22. Note that the absolute value is taken for the product power.

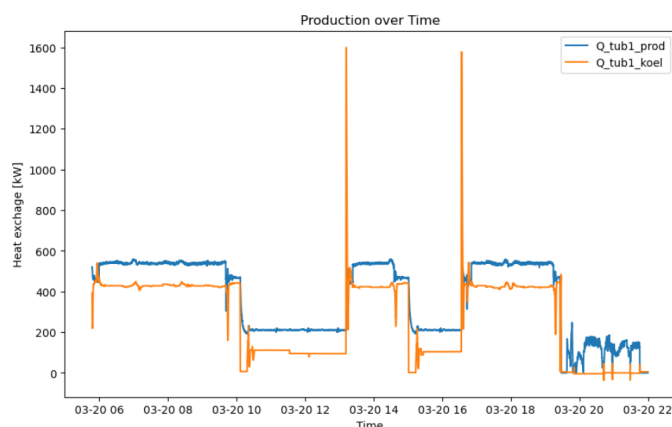


Figure 5-22: Heat exchange first tubular heat exchanger with TT09 30°C increased.

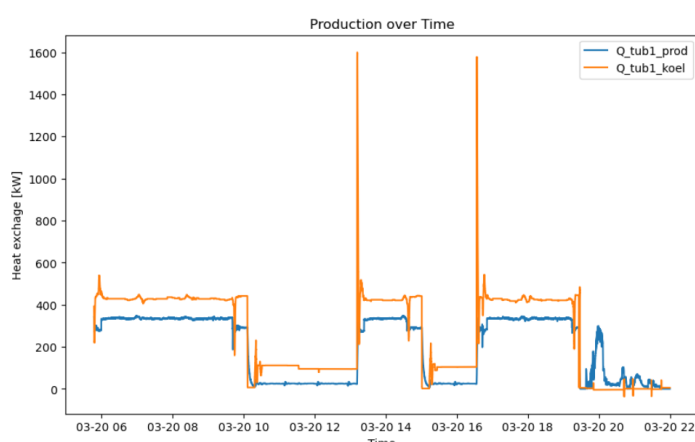


Figure 5-23: Heat exchange first tubular heat exchanger

5.2.12 Heat recuperation

This is an advanced block designed for heat recovery. It uses waste heat to heat tap water for various processes. Since this is a recent expansion of the plant, a significant amount of data is collected from this unit.

To understand the diagram shown in Figure 2-8, consider the following scenario: there is a total of 60 m³ in the process water circuit, all of which is in the cold water tank on the right side of the P&ID. When the plant is in the production phase, the heat from the product can be recovered. The technical water is heated by passing through the first plate heat exchanger, identified as "UHT Reggiani Cooling section 1", and is then collected in the hot water tank. Note that the first plate heat exchanger is parallel to the tubular heat exchanger but is not labelled as it is a recent innovation. These two heat exchangers do not necessarily operate simultaneously. When tap water is required, the hot water flows through the second heat exchanger and heats the tap water in the cold water tank. The tap water is then distributed to consumers via a ring network. If the tap water is not hot enough, it can be further heated by direct steam injection.

There is a special case when the cold water tank is at minimum level and the hot water tank is at maximum level, so there is no demand for tap water, or when the temperature in the cold water tank is too high. Then the extracted heat cannot be used, so the plate heat exchanger 20-0301HE01 is used to dissipate the heat and send it to a cooling tower.

6 DATAFLOW

This section explains how the process data is acquired. The process was time-consuming due to the difficult circumstances caused by NIS2, a directive aimed at achieving a high common level of cybersecurity across the European Union. Therefore, companies must be careful with data permissions (NIS-2 Directive, 2022).

In this chapter, there is set up a system that allows freedom in a test environment. The purpose of this system is to be safe with the original data of Puratos and to easily upload and delete the necessary calculations to a private database. This way, no errors can be made with the original process data of Puratos.

The obstacle is explained in a concise chronological format. Initially, Puratos made a part of the data available through the PI Vision platform. However, the platform permitted the export of only 3600 data points per tag, which is insufficient for the export of complete data sets. To address this issue, the data should be exported using CSV documents containing one hour of data. However, there is a possibility that some data may be lost. On 26 March, Puratos launched a new system, PI Data Link, which granted Actemium enhanced rights and facilitated the export of a greater quantity of data. Initially, the system exhibited limitations in terms of data transfer.

Much time was spent investigating more efficient methods of data acquisition. Each attempt necessitated the creation of a custom Python code due to the different formats of the data stored in the CSV file. The data then needed to be formatted and transferred to the Influx database. This is an open source time series database that Actemium uses for many customers in combination with Grafana.

The extraction of the data for this dissertation was collaborative effort with Simon Van De Velde, who is using the same data for his thesis. This section is an important part of the thesis, especially since there might be a follow-up thesis.

6.1 General

To keep the structure of the data flow clear, the diagram below is shown. It all starts with a csv export from PI Vision that is used to make calculations in Jupyter Notebook. These are uploaded to InfluxDB so it would be visible in the graphical visualization tool Grafana where the dashboards are made. This is visualised in Figure 6-1. This structure is necessary because Puratos is cautious about sharing data.

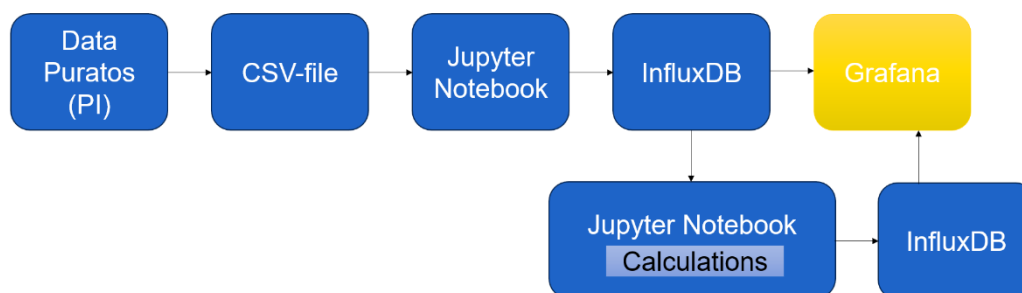


Figure 6-1: Data flow

6.2 Export to csv

There are two approaches to retrieving data. The first approach is frequently used in the first semester, but it has a significant disadvantage. The downloaded CSV file is limited to 3600 data points per file, which is problematic because some tags change every second. This causes a shortage of data in contrast to the second approach, which does not have this limitation.

The naming of the tags requires clarification since it is a large name consisting of several parts. Tags consist of:

- General naming:
\\historianaf.puratos.grp\Lummen_Cuore\VegetableCreams\UHT1\Data_Theo|
- Site naming: LUM_VGC_S017_
- Location of the process: 52-4000
- Type of measurement and number: PT01
- Type of measurement device: This can be an analog measurement by a normal sensor or a measurement of a PID controller, for example /MonAnalog_PV_Out#Value or /PID_PV_Out#Value.

6.2.1 Original approach

All the data is stored in PI Vision, a tool from Puratos, which is accessible by taking over a virtual machine (VM). The data needed for this thesis is stored in the folder Data_Theo and these tags can be plotted for various time periods. To collect this data for example a day, the tags are selected and an export to csv format is made. In Figure 6-2, the site to access PI Vision is shown and in Figure 6-3, PI Vision itself is demonstrated.

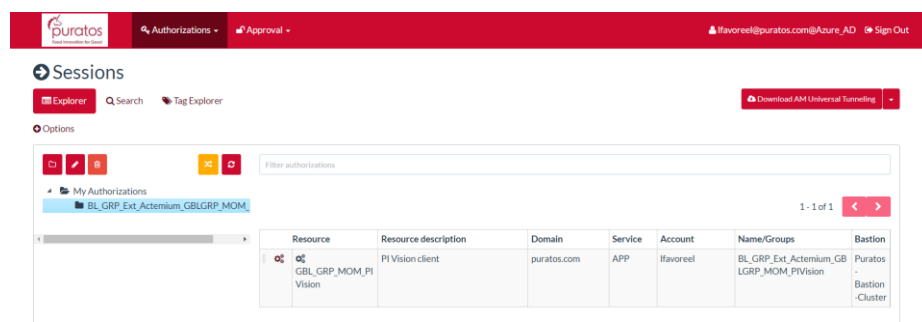


Figure 6-2: PI Vision Puratos

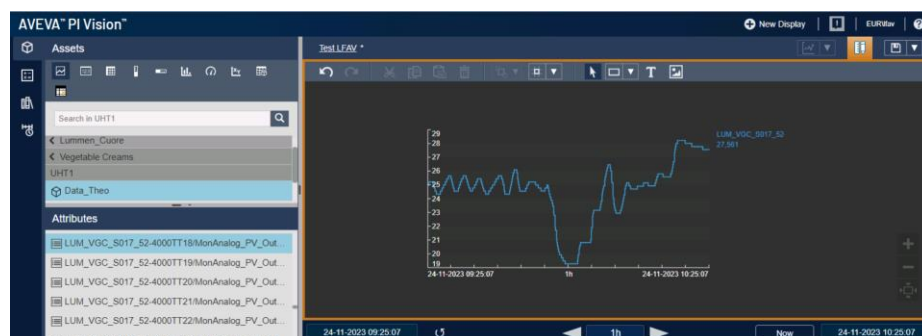


Figure 6-3: PI Vision Puratos visualisation

6.2.2 More effective approach

This approach also uses a VM to access the data. This VM has a tab in excel called 'PI Datalink' enabling it to retrieve data from the database. Then the values of the sheet should be copied to another sheet to paste it as values and save that sheet as a csv-file. This method is not limited to a certain number of data points, but if the dataset is large, the copy will be slow. These csv files are then downloaded for local access. This is done via WeTransfer.

A template is created to get the data efficiently. In the first tab of this excel template, the settings of the data export can be done. This consists of providing a list with all the tags and selecting a start and end time. This approach results in another csv structure than the original approach. The settings tab is shown in Figure 6-4.

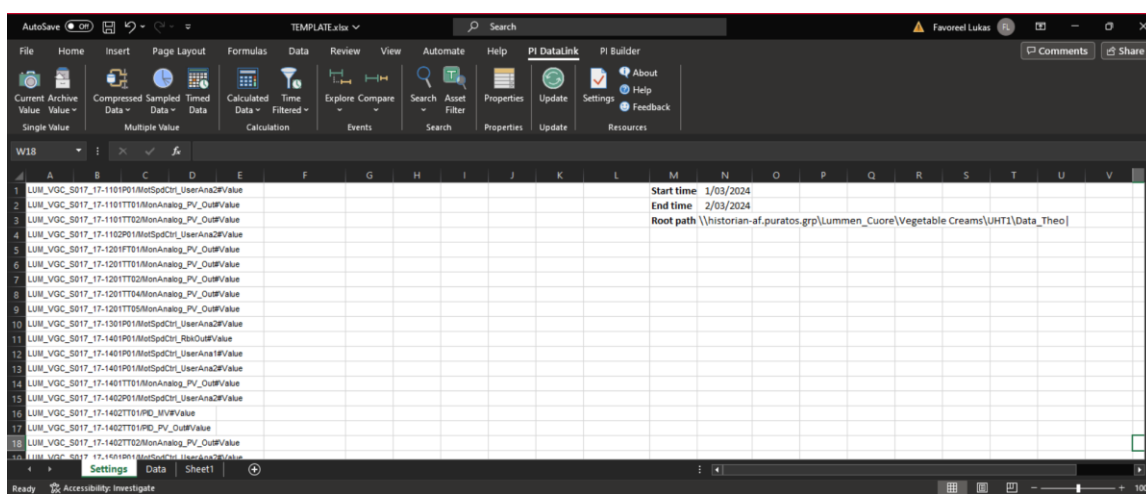


Figure 6-4: Settings of template PI Datalink

On the second tab of the Excel, the selected tags are transposed in the first two rows and are doubled in the next two rows. Each tag takes up two columns because it needs a datetime column and a value column. The individual value column for each tag is necessary because all the measurements are on random datetime; the data is not sampled. Therefore, the 'Compressed Data' function is used, this is shown in Figure 6-5 and the settings of this function are shown in Figure 6-6. The datetime received from the database is not easy to use and is formatted into a custom datetime format d/mm/yyyy u:mm:ss.

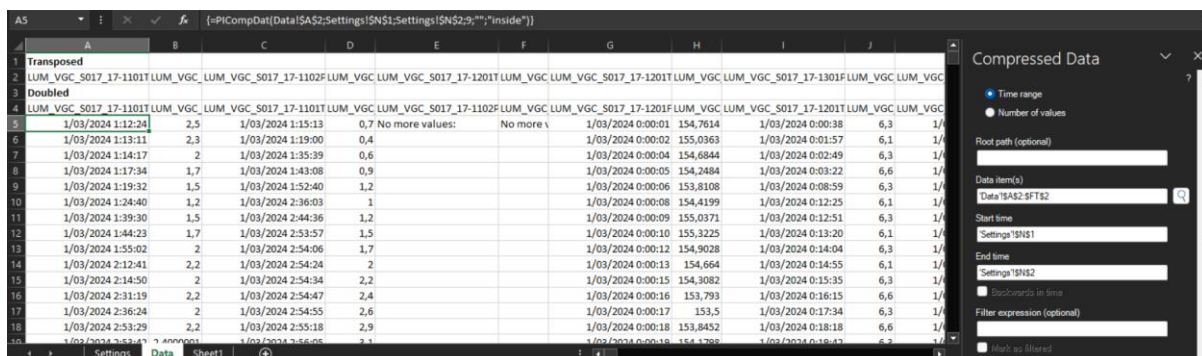


Figure 6-5: Data tab in template PI Datalink

Figure 6-6: Settings of 'Compressed Data'

6.3 Data formatting

Both approaches have different structures and require different formatting, but the data needs to be formatted in the DataFrame following the structure in Figure 6-7. While the original approach requires a rotation using a pivot command, the second approach requires the datetime columns to be combined. This is not the essence of this thesis, so it will not be explained further.

The goal is to create a Dataframe where each column is a different tag and the index is the time consisting of many rows because it includes the synchronously placed changing times of all the tags. This results in many gaps in the DataFrame because many values are unknown for the time that is not measured, but it is a constant value. These gaps can be filled with the previous value using the forward fill (ffill) command.

6]:

Data Source	LUM_VGC_S017_20- 0101LT01/MonAnalog_PV_Out#Value	LUM_VGC_S017_20- 0101TT01/MonAnalog_PV_Out#Value	LUM_VGC_S017_20- 0201LT01/MonAnalog_PV_Out#Value	LUM_VGC_S017_20- 0201TT01/MonAnalog_PV_Out#Value	LUM_VGC_S017_20- 0301T
Time					
2024-02-20 16:54:57,073013	30.370481	58.500000	64.739349	13.200000	
2024-02-20 16:54:57,67601	30.370481	58.500000	64.739349	13.200000	
2024-02-20 16:55:01,041	30.370481	58.500000	64.739349	13.200000	
2024-02-20 16:55:02,042007	30.370481	58.500000	64.739349	13.200000	
2024-02-20 16:55:03,043014	30.370481	58.500000	64.739349	13.200000	
...	...	...	...	...	...
2024-02-21 11:21:31,428009	30.370481	59.100002	64.739349	12.900001	
2024-02-21 11:21:32,439011	30.370481	59.100002	64.739349	12.900001	
2024-02-21 11:21:33,446014	30.370481	59.100002	64.739349	12.900001	
2024-02-21 11:21:34,449005	30.370481	59.100002	64.739349	12.900001	
2024-02-21 11:21:34,833008	30.370481	59.100002	64.739349	12.900001	

52364 rows x 98 columns

Figure 6-7: DataFrame structure

6.4 InfluxDB

To send data to InfluxDB, it is useful to select the desired columns to limit export time and not overload the database. Next, an InfluxDB client is created, which stores the information needed to access the database. Finally, each row of the DataFrame is written to the database using the `write_api.write()` command in a for loop that iterates over the measurements.

Accessing data from InfluxDB also implies the construction of a InfluxDB client. Then there are two useful predefined functions `Fetch_Single_Measurement()` and `Fetch_Multiple_Measurements()` respectively meaning to fetch one single tag and multiple tags. Important parameters of these functions are starting time, ending time, the address and the desired tags in a list.

The calculated values can be sent to influx the same way as described above. The difference is that no data formatting is required.

7 ENERGY CALCULATIONS

It is important to differentiate between the consumption of energy in an electrical manner, such as electricity, and the consumption of energy in a mechanical manner. In some cases, the data necessary to calculate both types of energy consumption may not be available, necessitating the selection of an appropriate approach.

In this section, the notation with the dot above the letter is used to indicate a flow. This can be mass, volume or energy per unit time. The term “specific” means that the quantity is expressed per unit mass.

The formula to calculate energy of the power is given below. The DataFrame is indexed on time and every value remains constant until the next row. So, for every row the energy E can be calculated in kWh by multiplying the constant power P_{ct} in kW with the active time ΔT_{ct} in hours as shown in [13].

$$E = \int_{t_1}^{t_2} P dt = P_{ct} * \Delta T_{ct}$$

[13]

7.1 Heat transfer

7.1.1 Indirect heat transfer

7.1.1.1 Theory

There is a lot of indirect heat transfer in UHT line 2. This means that the product is never in contact with the cooling or heating fluid. This occurs for example in the condenser, the pasteurizer and all the heat exchangers. These processes can be considered as the processes in a heat exchanger represented by the formula [14]. This and following formulas were used as seen in the thermodynamics course at Ghent University (Claessens, 2022).

$$\dot{Q} = \dot{m}_A h_1 + \dot{m}_B h_3 = \dot{m}_A h_2 + \dot{m}_B h_4$$

[14]

Here is $\dot{Q}$ the heat transfer flow between the fluids in kJ/s or W, $\dot{m}$ the mass flow of the fluid usually in kg/s and h the specific enthalpy in kJ/(kg*K). Assuming that product A is the heat-emitting fluid, where point 1 is the inlet and point 2 is the outlet of the heat exchanger, then product B is the heat-absorbing fluid, where point 3 is the inlet and point 4 is the outlet. This can be simplified by assuming that the pressure in the fluids remains the same. Note that in these formulas the heat transfer is ideal and there is no energy loss. Equation [15] shows this.

$$\dot{Q} = \dot{m}_A c_{p,A} \Delta T_{1,2} = \dot{m}_B c_{p,B} \Delta T_{3,4}$$

[15]

Since the volumetric flow of the fluids is given and not the mass flow, the density of the fluid is needed. In equation [1], ρ is the density in kg/m³ and $\dot{V}$ is the volumetric flow in m³/s. Implementing [1] in [15]:

$$\dot{Q} = \rho_A \dot{V}_A c_{p,A} \Delta T_{1,2} = \rho_B \dot{V}_B c_{p,B} \Delta T_{3,4}$$

[16]

7.1.1.2 Practical implementation

A heat exchanger always has four temperature values of which two for the cooling fluid and two for the cooled fluid. All these measurements always involve specific heat capacities but since this is a continuous flow process the temperatures of the fluid change over the heat exchanger, so do the specific heat capacities c_p and specific enthalpy.

A formula is written in Python to simplify these calculations. The function is called 'indirect_heating' and has the following structure:

```
def indirect_heating(temp_na, temp_voor, mass_flow, cp1, cp2, naam):  
    dT = temp_na - temp_voor  
    cp = (cp1 + cp2) / 2  
    df2[naam] = mass_flow * cp * dT
```

The first two arguments are the inlet and outlet temperatures, followed by the mass flow rate. Next are the specific heat capacities at the inlet and outlet of the heat exchanger. The last argument is the name that is given to the heat flow in the Dataframe. This is also the name the tag will have in Grafana, since the Dataframe will be exported to Influx.

The specific heat capacity for the heat exchanger is calculated by taking the average of the values at the beginning and end. However, this can only be done if the values vary linearly, which is not the case as shown in 5.1.3.2. Therefore, this assumption is not precise and can be improved, but this disadvantages the calculation time.

It can be demonstrated that heat transfer from a hot fluid to a cold fluid is only possible if there is a flow in the side that provides the heat towards the colder section. To achieve this, a Boolean function is used to detect the presence of flow, and this Boolean is multiplied with the thermal power that the cooling fluid absorbs.

7.1.1.3 Example of clipping

An example of this power transfer from the second tubular heat exchanger is plotted in Figure 7-1. The product gives energy to the cooling fluid, resulting in a negative power. Using this way of thinking, the power for this example can theoretically not be positive, otherwise the heat exchangers would be heating the product and thus generating energy, while they are being used to cool the product. This may be due to reverse flows outside the production steps or due to unfavorable adverse temperature differences. The solution to this problem is to clip the power values above zero.

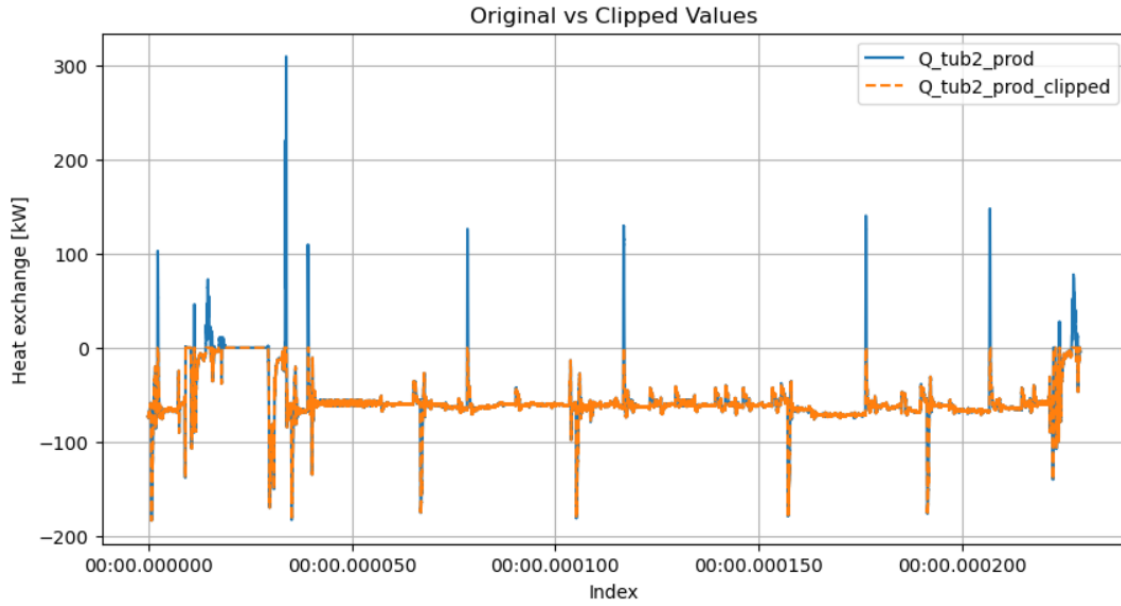


Figure 7-1: Heat transfer second tubular heat exchanger

7.1.1.4 Efficiency

The efficiency of a heat exchanger is calculated as the actual heat exchange over the optimal heat exchange according to (*Efficiency of Heat Exchanger*, 2021). This formula is shown in equation [17].

$$\eta = \frac{q_{act}}{q_{opt}}$$

[17]

Since the optimal heat exchange is difficult to calculate with the available information, the heat exchange efficiency is calculated by dividing the amount of heat absorbed by the coolant by the amount of heat released by the product, as shown in equation [18]. There are two possible ways to do this, it can be with energy or with power. If the flow is almost constant, there is not much difference between the methods, but if the flow is irregular, more significant differences are calculated. When working with power, the efficiency is calculated very often and due to process inertia, it can vary significantly. Therefore, the energies for coolant and product are calculated over a production batch.

$$\eta = \frac{E_{coolant,absorbed}}{E_{product,released}}$$

[18]

7.1.2 Direct heat transfer

The sterilizer uses direct steam injection to heat the product fast and efficiently. The following formula is applicable for unifying two heat streams (Claessens, 2022).

$$\dot{m}_3 h_3 = \dot{m}_1 h_1 + \dot{m}_2 h_2$$

[19]

In this formula is $\dot{m}$ mass flow kg/s and h the specific enthalpy kJ/kg. Both energy flows can be calculated since the steam mass flow is estimated in section 5.1.5. Remarkable values are calculated in the sterilizer as shown in Figure 7-2. The thermal power of injected steam is calculated by multiplying

the mass flow rate of the estimated steam with the enthalpy of the steam. The added thermal power to the steam is calculated by equation [19].

This large error can be caused by the steam estimation, which is based on a virtual approximation. In addition, the temperature sensor TT03 may be at a far away from the sterilizer. The error may also be caused by an incorrect value for the steam consumption value.



Figure 7-2: Comparison between both methods

7.2 Cold water production

To efficiently cool the product again in the heat exchangers, cold water is used at different temperatures. This water is heated by the product and should be cooled back again. There is a unit in charge of this cooling and this collects all the water and cools it to a temperature of less than 2 °C. In Figure 5-3, this cooling circuit is shown.

The total thermal energy transfer that needs to be removed from the water is calculated by summing up the cooling energy flows of the two stages using formula [15]. This is not the electrical power that the cooling unit consumes. This can be calculated using formula [20] according to (Claessens, 2022).

$$COP_k = \frac{Q_L}{P_{net,in}}$$

[20]

In this formula, the COP_k is the coefficient of performance of cooling, this as an alternative for efficiency. The difference between them is that the COP_k can be greater than 1 while the efficiency cannot. Further is Q_L the heat transfer that needs to be removed and $P_{net,in}$ the electrical power to keep the cooling cycle running. Since the COP_k is not known, this is estimated to be 6. This is a guess, but since it is an industrial chiller, this should be an accurate guess. The electrical power is now calculated and this can be converted to energy using formula [13].

The thermal power that is needed to cool the water is plotted and the electrical power as well in Figure 7-3.

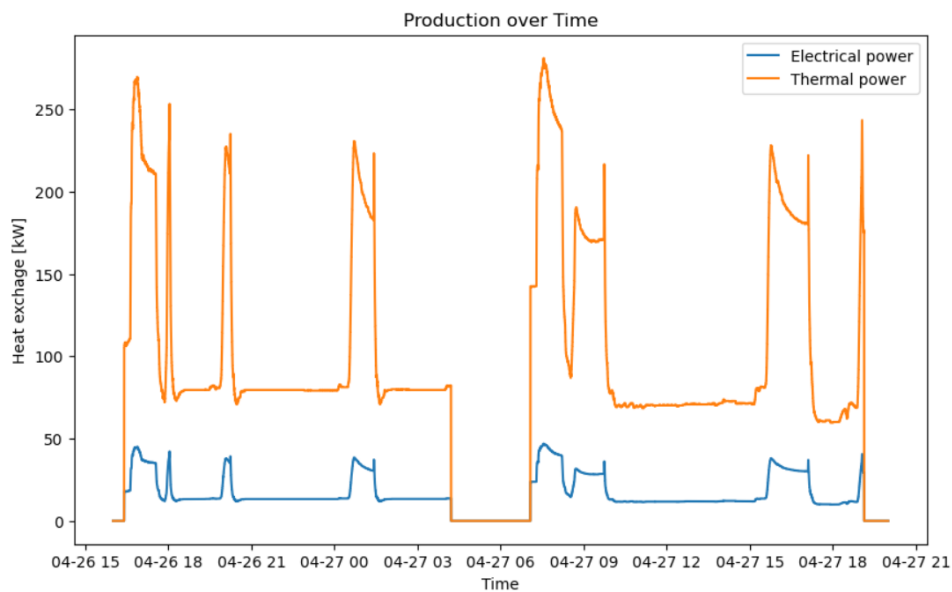


Figure 7-3: Plot of thermal and electrical power cooling unit

7.3 Steam production

The electrical steam production is calculated by multiplying the total steam measurement and the enthalpy of the steam at 12 bars. A plot is shown in Figure 7-4.

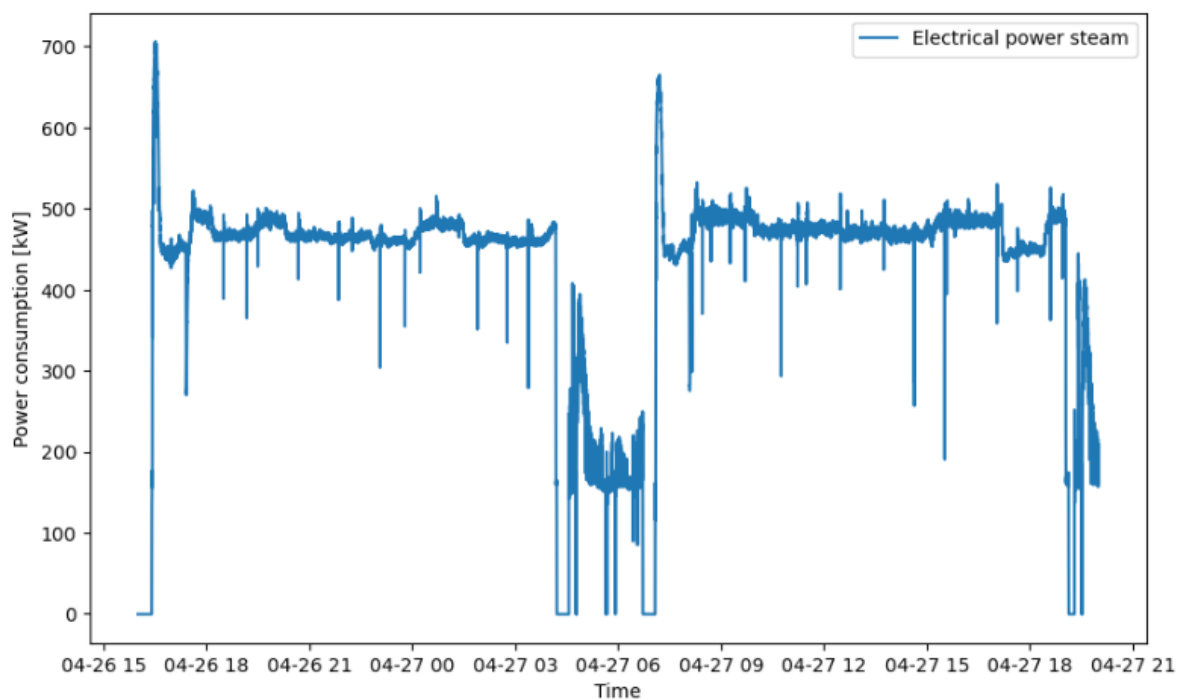


Figure 7-4: Electrical power steam

7.4 Electrical power consumption

The assumptions for the components have already been made in Chapter 5. This chapter deals with the following electrical components: two centrifugal pumps, a homogenizer, and a piston pump.

7.4.1 Centrifugal pump PA

The assumptions for this component can be found in 5.2.2. Both methods are calculated and plotted for a production interval in Figure 7-5. While the first method is rather variable because of flow- and pressure changes, the second method is more constant because the flow is controlled to a constant value. The efficiency is plotted in Figure 5-17.

The first method is assumed to be more accurate, because the pressure elevation is considered with the concurrent flow while the second method only depends on the flow, making this method less preferred. An example of the electrical and mechanical power of this pump is plotted in Figure 7-6.

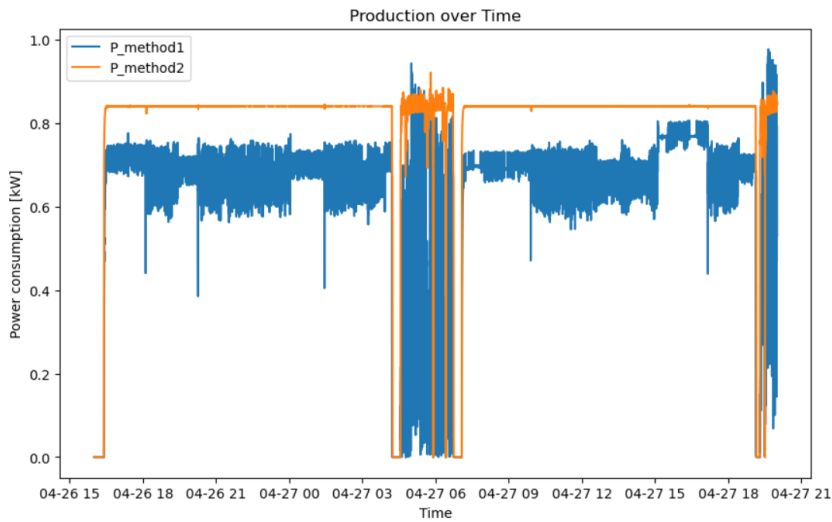


Figure 7-5: Both methods for mechanical power of pump PA

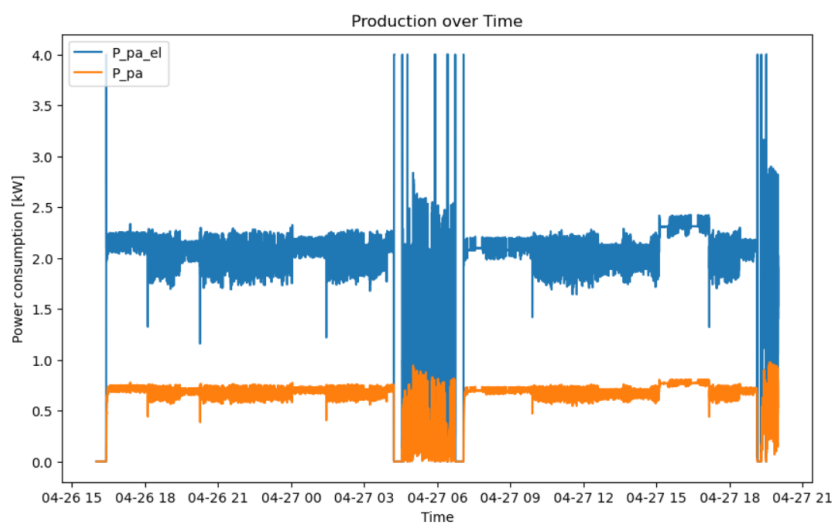


Figure 7-6: Electrical and mechanical power of PA according to method 1

7.4.2 Piston pump

Section 5.2.3 explains the calculation method. This power calculation that is shown in Figure 7-7, corresponds to the electrical power in the data sheet. Using this method, a flow variation results in a power variation. An efficiency of 80% is chosen.

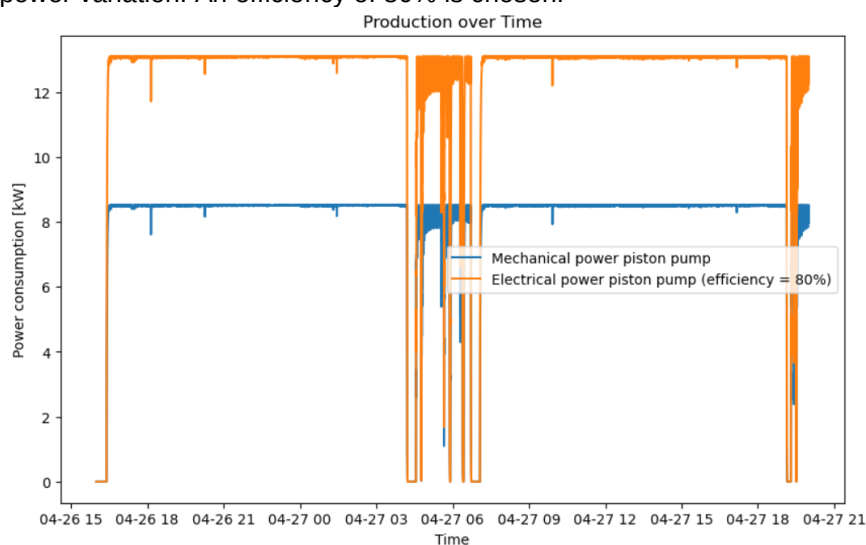


Figure 7-7: Mechanical and electrical power of the piston pump

7.4.3 Centrifugal pump P2

The curve of the mechanical power in function of the flow rate is recreated in Figure 5-19 as explained in chapter 5.2.9. In the absence of pressure sensors, this is the only acceptable method of approximation the power of this centrifugal pump. The efficiency is shown in Figure 5-20. An example of the mechanical and electrical power of P2 is plotted in Figure 7-8

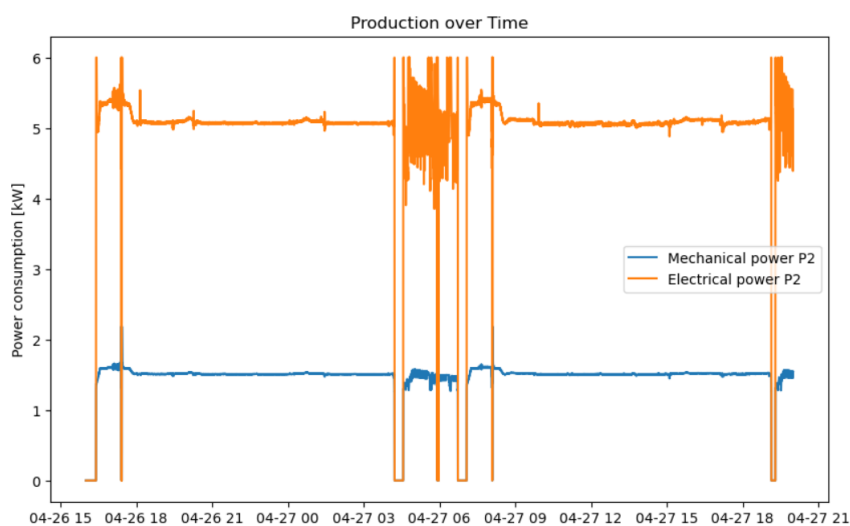


Figure 7-8: Mechanical and electrical power P2

7.4.4 Homogenizer

In section 5.2.10 the method of calculation the power of the homogenizer is explained. The results are shown in Figure 7-9. If an efficiency of 65% is taken for this component, the electrical power consumption it is about equal to the electrical power in the datasheets.

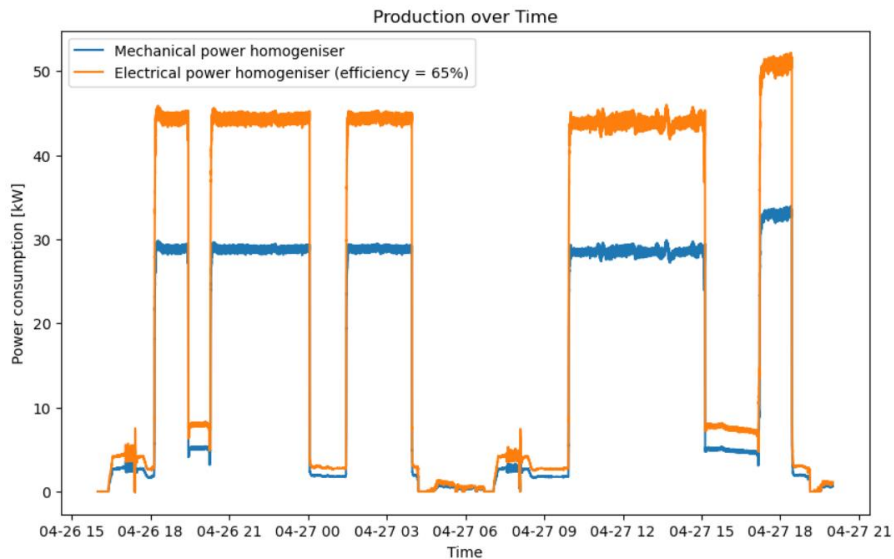


Figure 7-9: Mechanical and electrical power of the homogenizer

8 DASHBOARD

Dashboards are an easy way to get a lot of information on one screen. Applied to an energy dashboard, it provides a summary the energetic performances and relevant process values. Moreover, it allows the user to select a specific period and get all the information about a certain batch. The dashboards in this thesis are made in Grafana which is connected to the process data in InfluxDB.

The dashboards provide valuable insights into the energy consumption of Puratos' processes. Grafana differs from existing visualization tools, such as SCADA and PI Vision, in the user-friendliness, the multi-source compatibility and cost-effectiveness. The dashboards facilitate the rapid acquisition of process performance, with a particular focus on the energy. This can be accessed with a high degree of convenience, as will be explained below.

Every dashboard is equipped with a step number visualization so there can easily be seen what phase the process is in. There is also a corresponding table that gives more information about the production intervals including product name, start time, end time, duration, Unix code, type of heat exchanger and product code as shown in Figure 8-1.

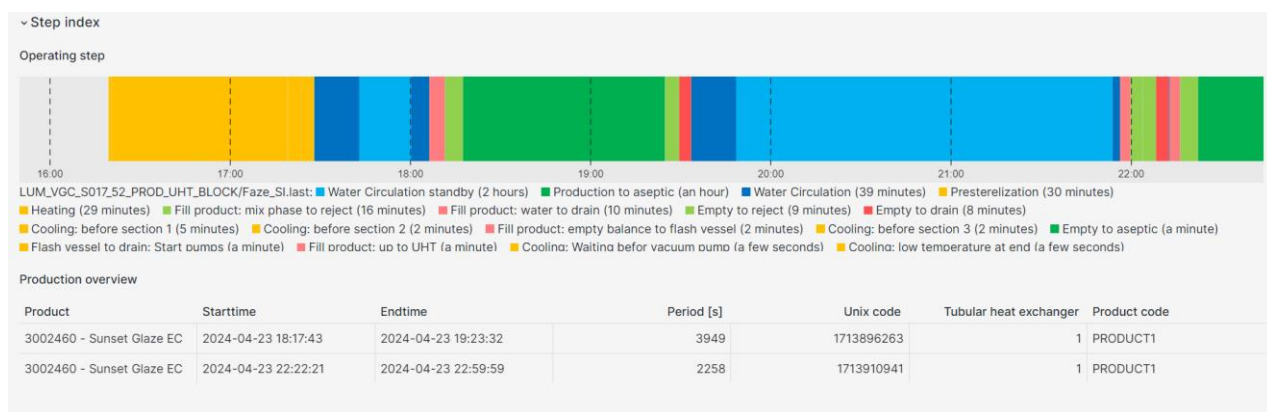


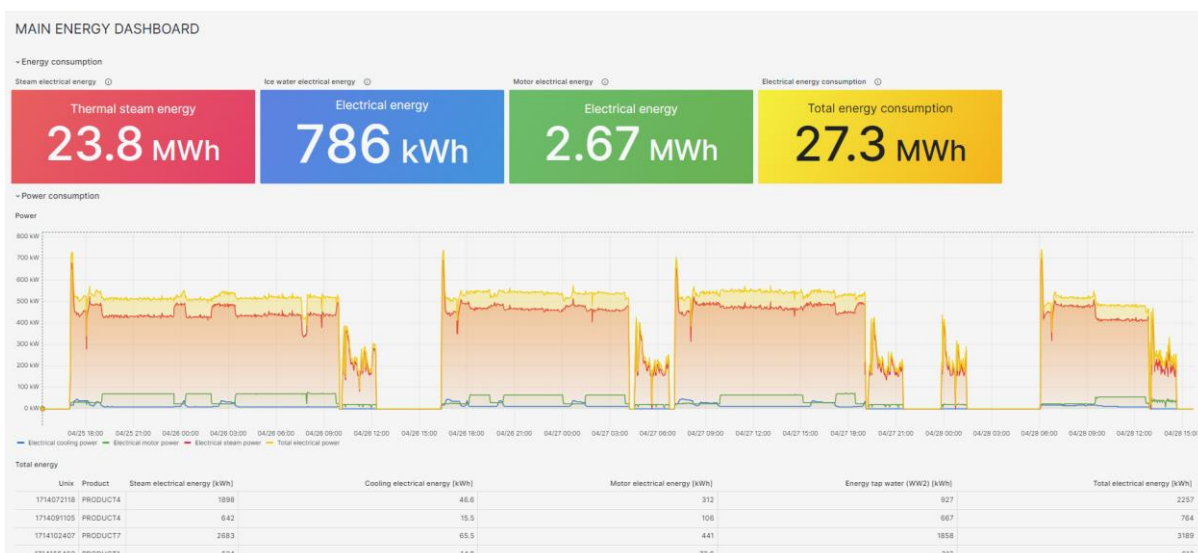
Figure 8-1: Step index with corresponding production table

8.1 Main dashboard

A variety of dashboards are interconnected by clickable links. The primary dashboard, called the "MAIN Energy dashboard," serves as the gateway to all other dashboards. It provides a comprehensive overview of energy consumption, over a selected period of time and segregated into four categories as shown in Figure 8-2. These include consumers such as steam, ice water, and electrical energy, in addition to the total power. Subsequently, a graph is presented that illustrates the power consumption over time for the selected period across the three individual categories and the total power. A table is then provided, displaying the total amounts of energy and specific energy per production batch. These are identified by a Unix code, and if further product information is required, the table in Figure 8-1 provides additional details. This method of plotting the graphs in a single figure facilitates the observation of values at the corresponding step number.

This dashboard can be accessed by the following link within the network of Actemium:

<https://grafana.masterproef.ingress.prod.esx.ltr.k8s.actemiumdev.be/d/cb18e89a-aaca-4854-b346-576db5f96bcd/main-energy-dashboard?orgId=1>



Below there is a Flowchart panel, this is a plugin for Grafana where it is possible to make a diagram in xml format dynamic. First, a figure is created using draw.io for example, to draw the whole process. This visual representation makes the process highly understandable. The advantage of this plugin is that some parts of the image can be set with a mapping for whether showing a variable or making the object clickable. Using this mapping, it is possible to get more specific information about the clicked component in an individual dashboard. For example, by clicking on the heat recuperation block, a new dashboard opens and the P&ID of that part of the process shows up. Secondly, there are boxes that show process data, but since the live data is not accessible, the last value of the selected interval is shown. The result of this panel is shown in Figure 8-3.

8.2 Heat recuperation block

The heat recuperation unit of the flowcharting panel on the main dashboard is linked with this dashboard. Since this part of the process has a P&ID, an individual flowcharting panel is given to it. The explanation on the working of this process is given in section 5.2.12.

There is given relevant data about this process such as the amount of energy that is transferred from the one fluid to the other as shown in Figure 8-4. Below that, the power consumption of those tags is given. The same colors are respected and the energy is calculated over the full selected interval.

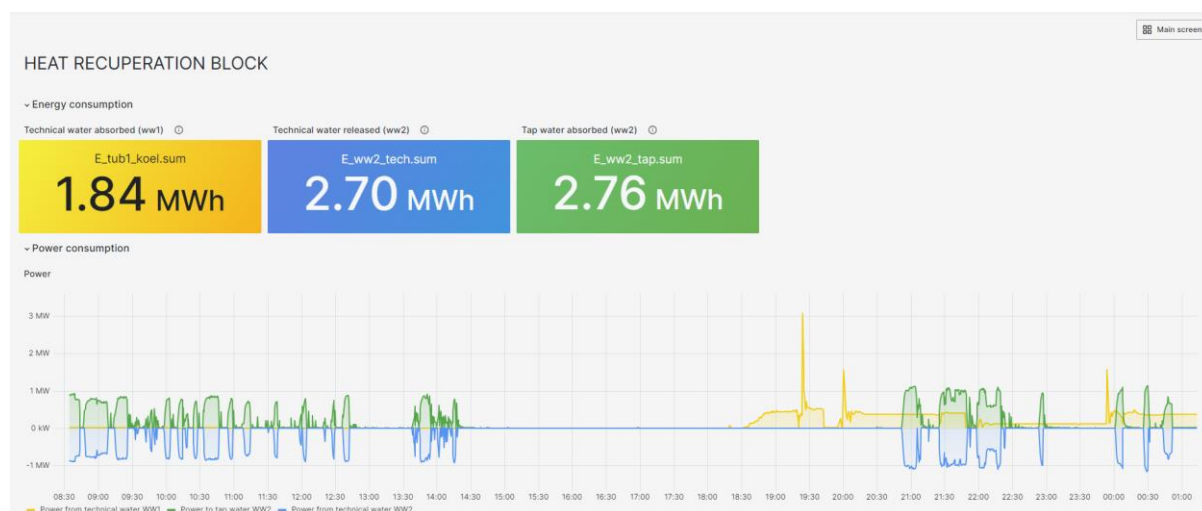


Figure 8-4: Dashboard heat recuperation (Energy)

The heat exchangers are equipped with clickable links that navigate to a more precise dashboard for that component. Since this process contains fewer components than the main process, it is possible to set more data on the screen, such as the heat transfer rate. An attempt has been made to give a different color to all the different types of measurements, for example, gray is flow, blue and red are cold and hot temperatures, yellow is power and green is pressure. Below this process overview are the relevant graphs of the tank volumes, temperatures and flows.

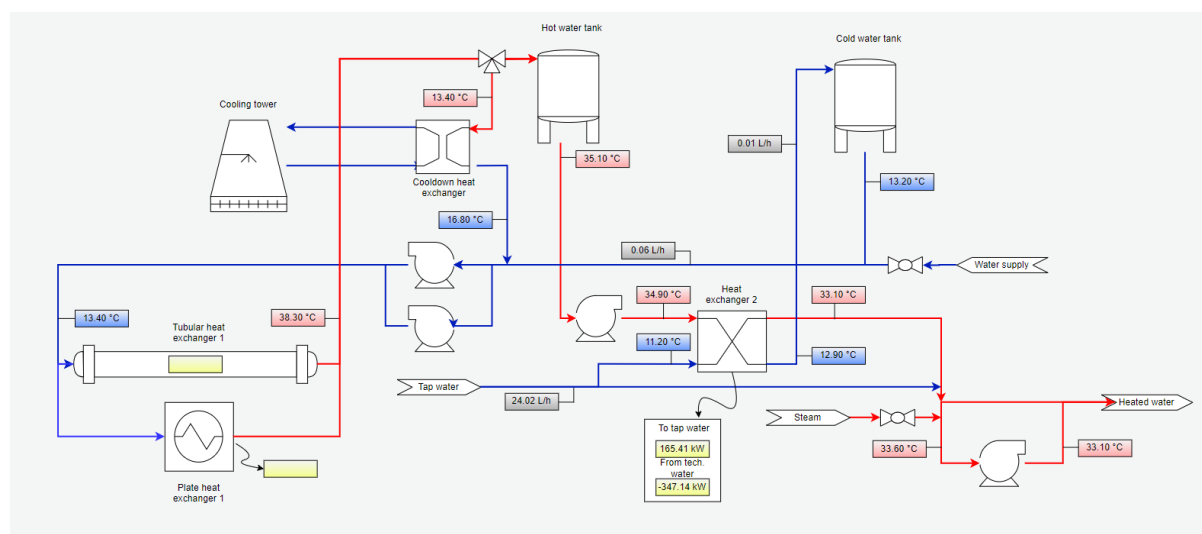


Figure 8-5: Dashboard heat recuperation flowcharting panel

8.3 Component dashboards

By way of example, two more examples of dashboards are discussed below. The others have a similar structure. For every specific dashboard, the relevant info for that component is given.

8.3.1 Centrifugal pump dashboard

This example shows the dashboard of pump PA. First, relevant constant motor parameters are shown in an info box. Next, variable motor measurements are plotted in graphs and the power and energy are also displayed. Moreover, the step index is plotted to easily navigate to the correct production moment. Other relevant measurements of this motor are speed, pressure, flow and the electrical power. This is shown in Figure 8-6.

8.3.2 Heat exchanger dashboard

The dashboard of the tubular heat exchanger is quite extensive as it consists of three different cooling stages. First, an info box is displayed with relevant info about these tubes. Next is the power graph and below is a discrete graph showing what stage the process is in. Then the cooling efficiencies are shown for the three heat exchangers with the corresponding heat transfers. This shows both the energy emitted by the product and the energy absorbed by the refrigerant. This is followed by a graph of all the relevant flow rates in this component followed by a plot with two temperature measurements of either the product or the refrigerant. This is shown in Figure 8-7.

CENTRIFUGAL PUMP PA

Electrical motor power



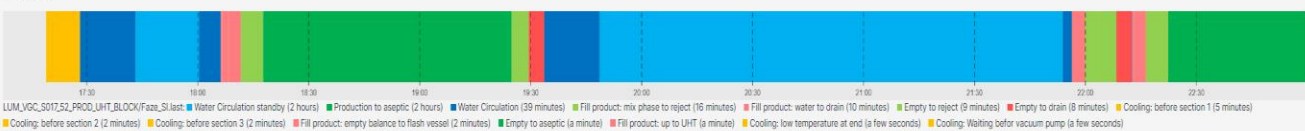
Stats

P_installed = 4 kW
N = 1450 rpm
230/400V 50/60 Hz

Electrical power



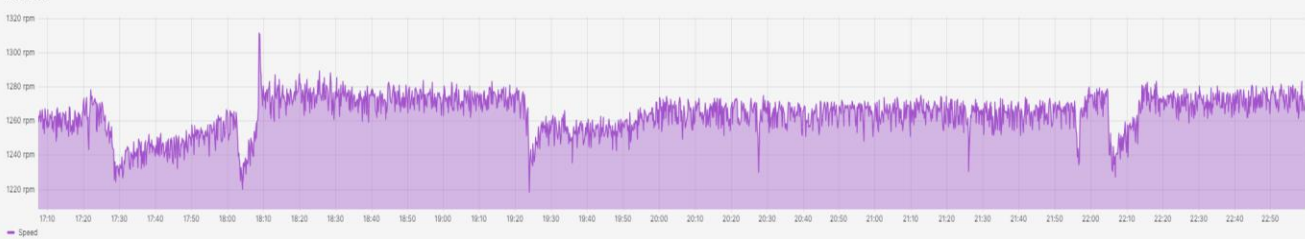
Operating step



Production overview

Product	Starttime	Endtime	Period [s]	Unix code	Tubular heat exchanger	Product code
3002460 - Sunset Glaze EC	2024-04-23 18:17:43	2024-04-23 19:23:32	3949	1713896263		1 PRODUCT1
3002460 - Sunset Glaze EC	2024-04-23 22:22:21	2024-04-23 22:59:59	2258	1713910941		1 PRODUCT1

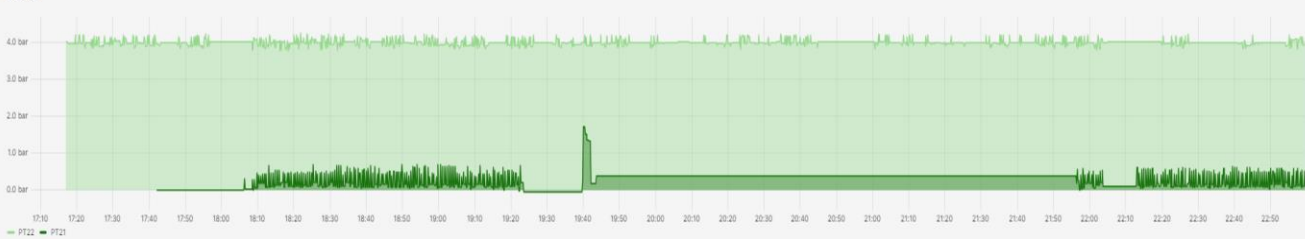
Motorspeed



Motor efficiency



Pressure



Flow

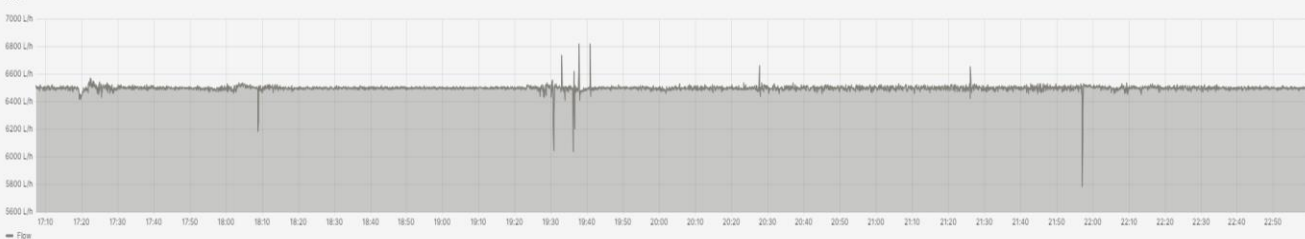
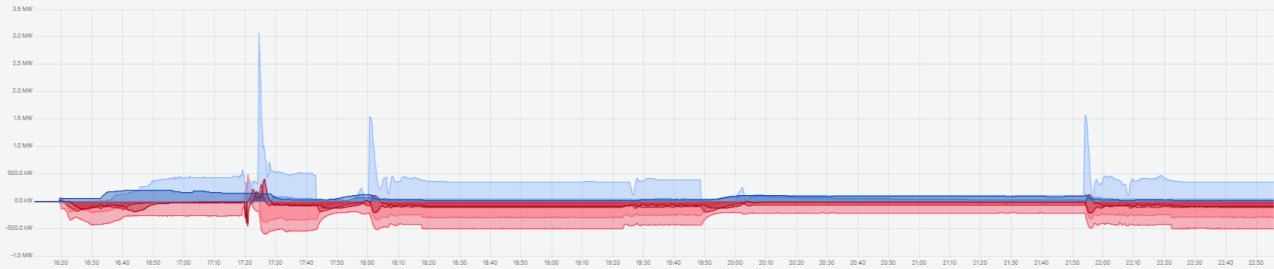


Figure 8-6: Dashboard centrifugal pump PA

TUBULAR HEAT EXCHANGERS

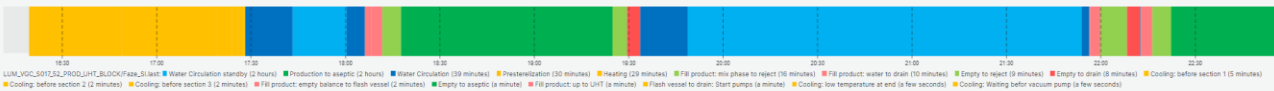
Heat transfer

Electrical power



Process overview

Operating step



Production overview

Product	Starttime	Endtime	Period [s]	Unit code	Tubular heat exchanger	Product code
3002460 - Sunset Glaze EC	2024-04-23 16:17:43	2024-04-23 19:23:32	3949	1713896263	1	PRODUCT1
3002460 - Sunset Glaze EC	2024-04-23 22:22:21	2024-04-23 22:59:59	2258	1713910941	1	PRODUCT1

Energy stats

Efficiency TUB1



Efficiency TUB2



Efficiency TUB3



Heat exchanger efficiency

Unit	Product	TUB	Efficiency TUB1 [%]	Efficiency TUB1 possible [%]	Efficiency TUB2 [%]	Efficiency TUB3 [%]
1713896263	PRODUCT1	1	124	72.2	35.0	20.3
1713910941	PRODUCT1	1	124	72.1	35.4	20.5

Energy released from product

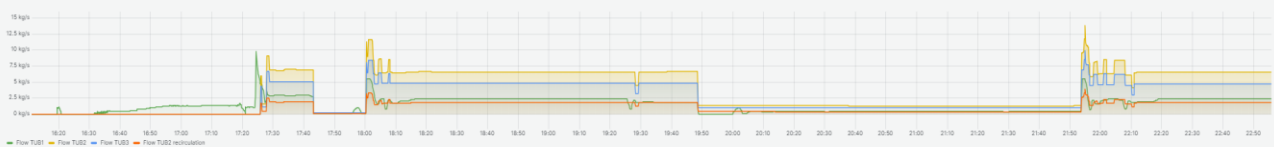
Unit	Product	TUB	Product (TUB1) [kWh]	Product (TUB1) possible [kWh]	Product (TUB2) [kWh]	Product (TUB3) [kWh]	Energy release by product (TUB) [kWh]
1713896263	PRODUCT1	1	319	548	112	99.1	332
1713910941	PRODUCT1	1	181	310	63.4	56.3	188

Energy recuperated from product with coolant

Unit	Product	TUB	Coolant (TUB1) [kWh]	Coolant (TUB2) [kWh]	Coolant (TUB3) [kWh]	Energy recuperated [kWh]
1713896263	PRODUCT1	1	395	39.2	20.1	247
1713910941	PRODUCT1	1	224	22.4	11.6	155

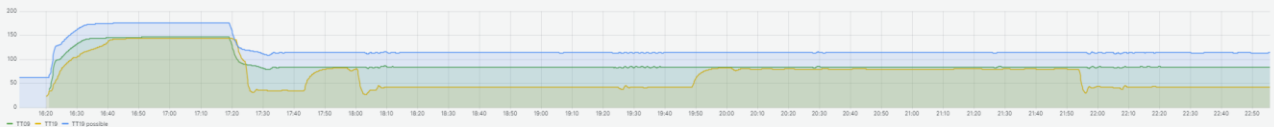
Flow

Flows



Temperature

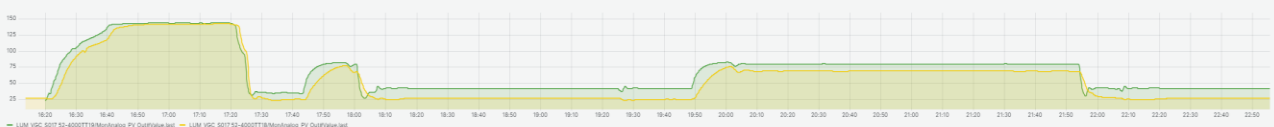
Product TUB1



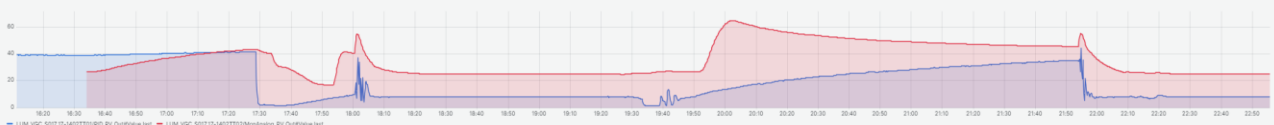
Refrigerant TUB1



Product TUB2



Refrigerant TUB2



Product TUB3

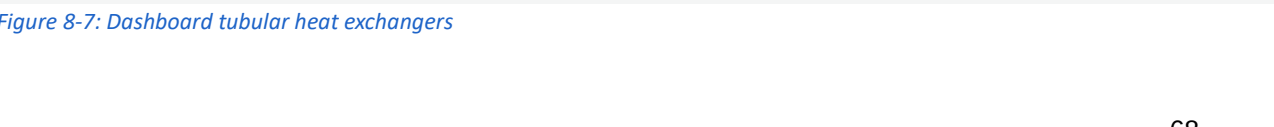


Figure 8-7: Dashboard tubular heat exchangers

9 SWARM PLOTS

Swarm plots are a way to visualize data in a compact manner. The objective of this kind of plot is to gain insight into the energy consumption per recipe and the variability of energy consumption for the same batch. There are several possibilities for plotting and interpreting these plots. In this case, the energy and the specific energy per product have been chosen for plotting. The energy for a product is not particularly meaningful because the different batches have different duration times, which depend on the volume of the tank connected with the balance tank.

Since the data of all necessary measurements are only available from April 22, 2024, the results of the calculations are also available from this date. This results in a smaller time range, so the variability of consumption can be considered less in this thesis.

These plots are made with python and so they cannot be displayed on the Grafana dashboards. For the future, it would be useful to plot those graphs on the dashboard too with a plugin.

9.1 Energy

Figure 9-1 illustrates an example of a swarm plot. The total energy is plotted on the vertical axis, while the recipe is plotted on the horizontal axis. Each point represents the total electrical energy that is required for a given batch of that product. This allows for the batches to be compared in terms of their energy, thereby providing greater insight into costing. Since batches have various durations, this is less meaningful.

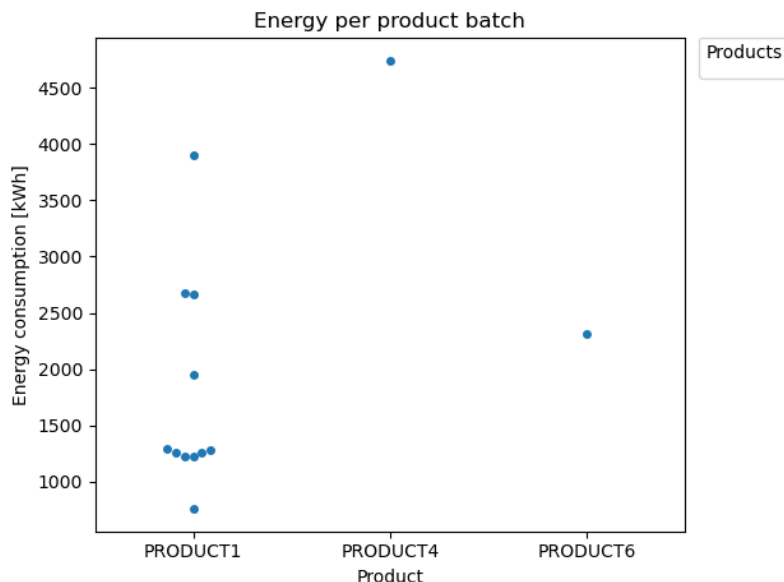


Figure 9-1: Energy per product batch

9.2 Specific energy

Figure 9-2 shows another example of a swarm plot. This time, the total specific energy is plotted on the vertical axis, while the recipe is plotted on the horizontal axis. This allows for the products to be

compared in terms of their specific energy, thereby providing greater insight into the associated costs. Furthermore, the variability per product is visible.

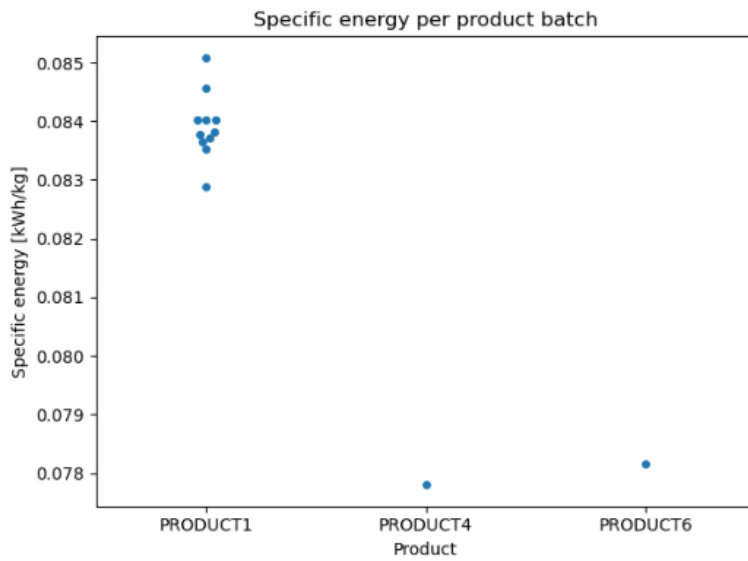


Figure 9-2: Specific energy per product batch

9.3 Classification

More information about the production batch can be displayed than just the same color for each batch, such as the energy and specific energy plots. Different colors can be used to distinguish the type of heat exchanger and the energy source. Finally, a plot of the run IDs is displayed.

9.3.1 Type heat exchanger

Another way to gain insight into the product costs is to use color to indicate the type of heat exchanger used, as shown in Figure 9-3. Since the plate heat exchanger has not been used since the new steam measurement of 24/04, random values are added to the plot to have an idea of how it should look like.

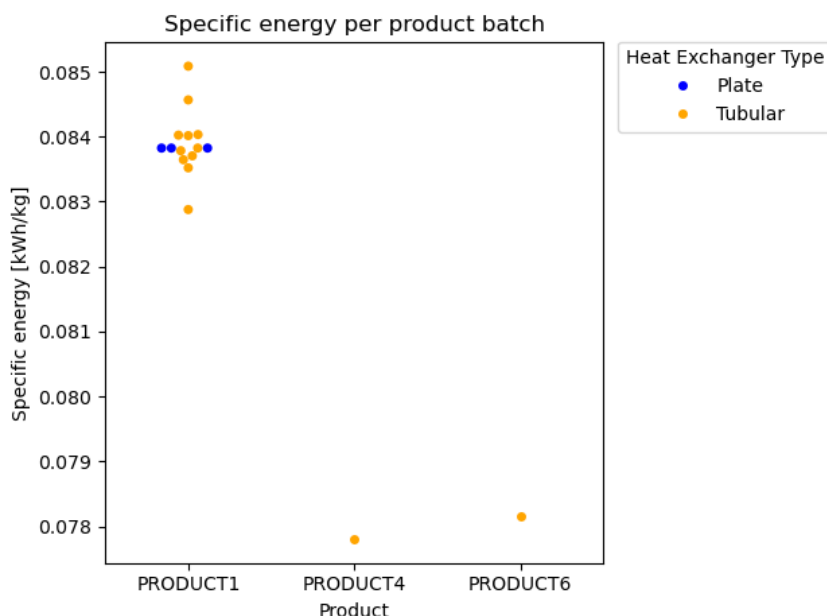


Figure 9-3: Specific energy per product batch (Type heat exchanger)

9.3.2 Energy source

Additionally, another swarm plot is displayed in Figure 9-4, where each color represents an energy consumption type including electrical steam energy, electrical motor energy and electrical cooling energy. This is split up per product. Another idea is to split up by production time, but due to a lack of data accessibility, this breakdown by period is difficult. There might be a difference if the same batch is produced in the winter or summer, but this data is not available for all the tags.

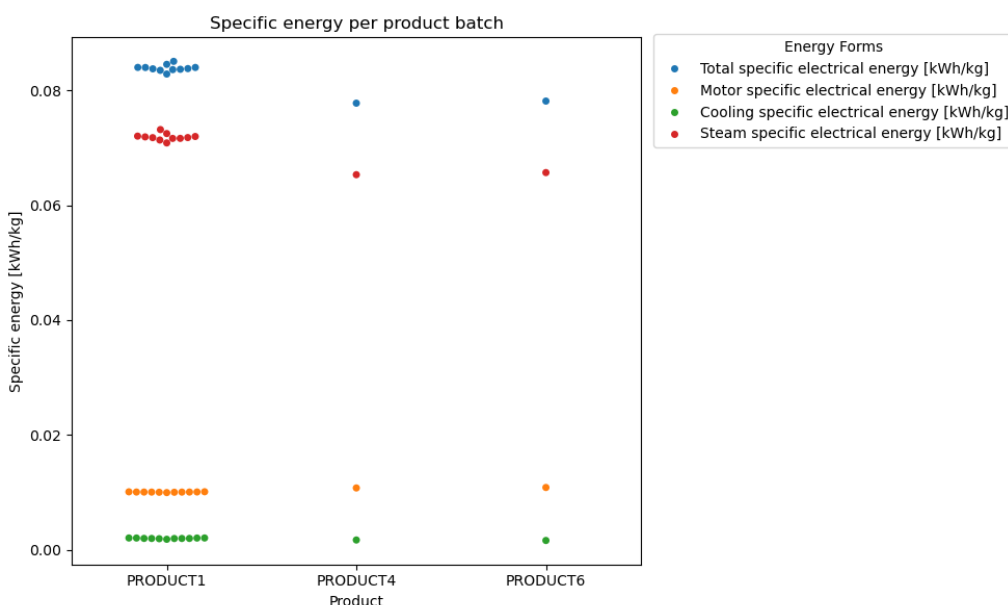


Figure 9-4: Energy per product batch (Energy source)

9.3.3 Identification

Eventually, an attempt is made to give every dot a run number in Figure 9-5. Since there are many dots at one place, the numbers cannot be read. The purpose of this identification is to see the run number of the outliers so they can be examined further.

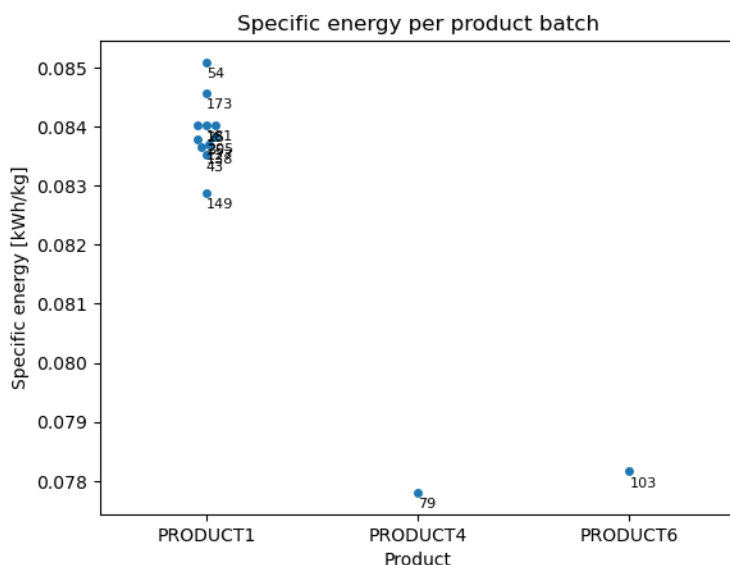


Figure 9-5: Specific energy per product batch (Identification)

9.3.4 Heat recovery

In this example, shown in Figure 9-6, the specific recuperated energy per production batch is displayed in a swarm plot. The color coding shown in Figure 9-3 allows the type of heat exchanger to be displayed. This provides insight into which product and heat exchanger combination works better. It should be noted that these results are significantly variable, as there can only be energy recuperated if there is consumed tap water. In order to facilitate a valid comparison, it is essential that the same quantity of tap water is consumed in each instance. Moreover, there should be more data to make appropriate conclusions for this heat recovery.

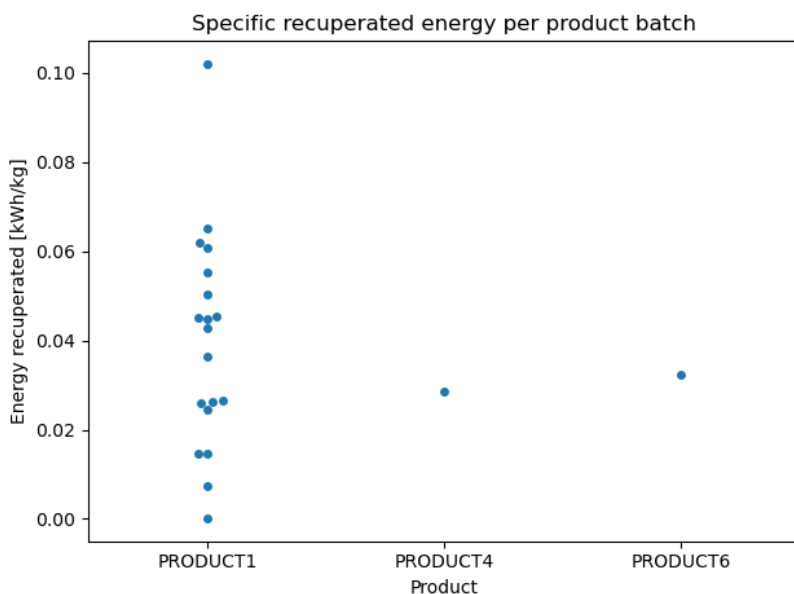


Figure 9-6: Recuperated specific energy swarm plot

10 ENERGY BASELINE

This chapter explains the concept of the energy baseline and applies it to the UHT process. The results are then presented in the form of energy graphs and performance indicators.

10.1 Concept

The theoretical approach aims at reducing energy consumption by suggesting better process configurations. There is a structured method to calculate the energy baseline (EnB) as shown in Figure 10-1 according to IEE (2016).

The first step is to identify the system boundaries. This means defining which processes are considered. This can be the production step itself, but there are many other preparatory and subsequent steps that also have a share in the energy consumption. The second step is to list the energy sources for each process under consideration. This could be electricity for pumps and motors, or gas for heating. By separating the energy sources, the individual contribution of each source to the total consumption can be accurately determined. The next step is to select the time period. This should be chosen carefully because weather and temperature play an important role in energy consumption. In winter, for example, all products should be heated more to ensure the same sterilization as in summer. Since the line is used to produce different recipes, this consumption should be grouped by recipe, as some different recipes lead to different energy consumption. The fourth step is to define and consider the relevant variables and drivers. This involves listing all the factors that affect energy consumption, which can be variables such as outside temperature, recipe, resource quality and production volume. The impact of each factor is assessed on the scale of energy consumption. Finally, the energy performance indicators are calculated. The general term for these indicators is Key Performance Indicators (KPI). When these indicators are energy based, they are called EnPI's and it's important to define which of them are relevant to the production process under consideration. They give a quantitative index of the energy performance and for the UHT process specifically, energy consumption per production unit or energy consumption per batch are examples.



Figure 10-1: Pillars energy baseline (IEE, 2016)

An energy baseline encompasses all the energy used by a site during its production processes. With the implementation of an energy monitoring system and improvements, it's likely that the energy baseline will decrease. This reduction enables precise measurement of the energy savings achieved.

This concept is illustrated in Figure 10-2 as described by Tanguay (n.d.). The figure provides an example comparing the measured energy baseline before and after the improvement.

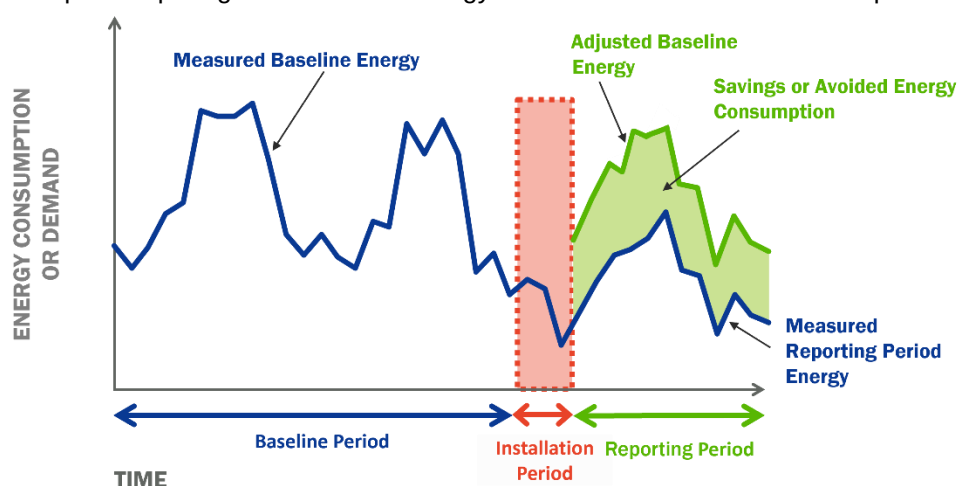


Figure 10-2: Energy Baseline according to (Tanguay, n.d.)

EnPIs are used for a variety of purposes. Primarily, they are used to effectively measure and evaluate the energy performance of a site. This can be used to identify opportunities for savings and to determine cost savings. It can also be used to experiment with different resources to compare their energy performance. There are many other benefits to improved EnPIs. For example, there is a more detailed report on energy consumption. Instead of just the total kWh used, it can be broken down by component. It is also possible to perform predictive maintenance if it is seen that the component is operating below its capacity.

There are some drawbacks, such as the investment, the cost of sensors and setting up a data flow system, but with this information, problems can be identified much faster. If the right optimizations are made, the investment is quickly recouped. Since this thesis works with data from an acquisition system, these last disadvantages are irrelevant (*FINAL-EnPIs_brochure.Pdf*, n.d.).

10.2 Applied to this process

The big goal is to compare two different production periods and see what the difference is between production with the tubular heat exchanger and the new optimized plate heat exchanger. Puratos has seen in other processes that this new type is more efficient, but this can be calculated using before and after production data.

10.2.1 System boundaries

First, the boundaries of the process are considered according to the IEE roadmap. The focus is only on the UHT process, but as this process consists of several stages described in chapter 4.1, it can be considered as several processes. For example, there are different products in the tubes such as water, untreated vegetable cream, acids and bases. The last two are part of CIP. The real improvement of the plant should be in production step 330, which attracts the most attention.

10.2.2 Energy sources

The second step is to identify the energy sources. This process has four major energy streams that contribute to the energy baseline. These are water cooling, steam production, electricity consumption, and tap water heating using heat recovery.

In this process, water at low temperature is needed to cool down the product efficiently from its high temperature. The first energy source is the energy needed to cool down this water. The thermal heat that should be removed can be calculated by the temperature difference and the flow. Eventually, the electrical consumption of the cooling unit can be estimated as in section 7.2.

The second energy source is the steam energy, which is a big consumer in this process since the product is heated intense using this steam. This is calculated in section 7.3.

Since there is not as much data available for each pump, the best way to calculate the mechanical and electrical consumption should be considered. Fewer pumps have data about torque and current available, while other just have rotor speed. This results in a third source of energy, which is the electrical motor energy. These calculations are done in section 7.4.

Something that contributes to the energy baseline, but in an adverse way, is the heating of the tap water in the heat recuperation unit. The heat released from the product plays a meaningful role in heating the tap water used throughout the site for applications such as CIP and pre-processing steps.

10.2.3 Period

Normally, EnB should be considered over a much longer time period than is possible in this thesis. Typically, this period is one year to allow for annual patterns such as weather variations or production levels (Doherty, 2021). Doherty suggests that measuring one year before and one year after the improvement allows for consideration of influencing factors and provides a long enough period for reliable analysis.

Puratos always tries to produce the same product for successive batches, as this does not involve cleaning the whole line. Therefore, they try to have several productions with the same production time following each other. In order to compare the production of two different batches in an approximate way, they should take the same amount of time. Therefore, it is necessary to find a production of the same recipe where in the first case the tubular heat exchanger is used and in the second case the plate heat exchanger is used. During this work, the plate heat exchangers are used at irregular intervals to test them. Moreover, the variation of the outside temperature plays a role in the energy consumption, so it is necessary to look for a batch of the tubular heat exchanger close to the plate heat exchanger to minimize this effect.

10.2.4 Drivers and variables

The recipe determines the energy consumption for a part because other products have different thermal properties, but by comparing per recipe, this can be eliminated. Weather is another variable that can be eliminated by looking at two batches on the same day. Finally, production volume can be eliminated by working with specific energy.

10.2.5 Performance indicators

Interesting performance indicators are parameters such as energy consumption per liter per recipe. In addition, this can be split up per energy stream.

An interesting EnPI in the heat recuperation block is the amount of energy that can be recovered relative to the total amount of exerted energy.

Another interesting EnPI can be the actual consumption of a component has relative to its maximum consumption. This shows whether the capacity can be increased.

10.3 Practical approach

The main goal is to plot the two power consumption graphs to see how much energy is being saved. This is not obvious because there are many factors to consider. The calculation is done in Jupyter Notebook and the data can be sent to InfluxDB for visualization.

The DataFrame is split by keeping only the power and energy values within the specified production interval. This results in a collection of smaller DataFrames. Next, a breakdown by product is performed. This is done by product because all products have different thermal properties and are therefore more difficult to compare. The Python code will therefore provide a plot for the entire selected time interval by energy category and by product, as shown in Figure 10-3, Figure 10-4, Figure 10-5, Figure 10-6 and Figure 10-7. Here, only the plots for product 1 are displayed. In each plot, the powers of an energy type are plotted for the different runs for a product. These have different lengths and can be compared by length and size.

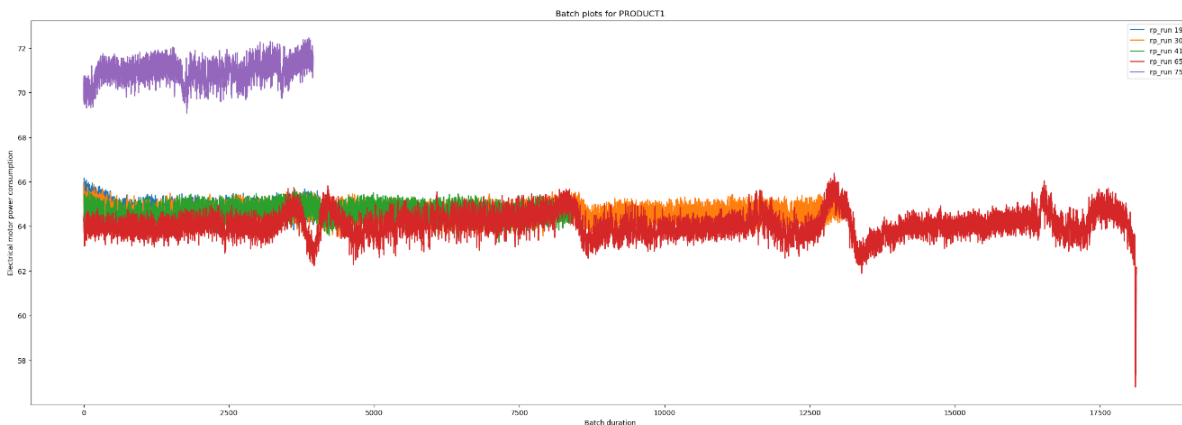


Figure 10-3: Electrical motor power trends for product 1 during production

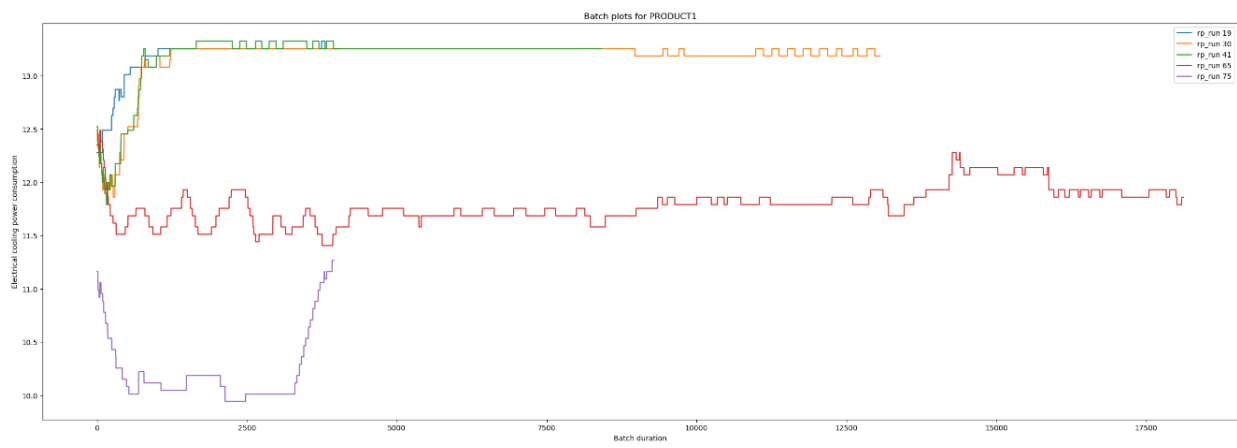


Figure 10-4: Electrical cooling power trends for product 1 during production

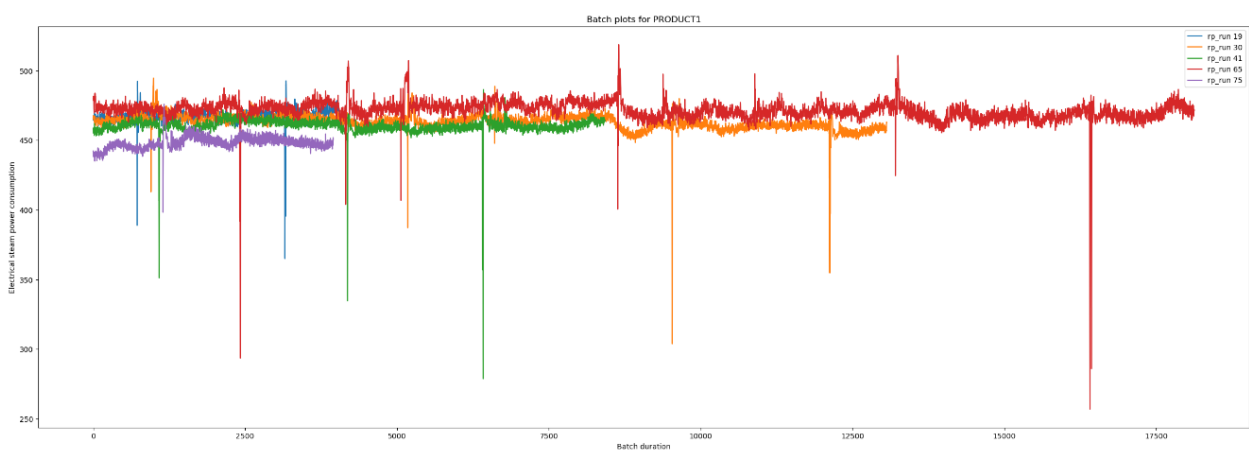


Figure 10-5: Electrical steam power trends for product 1 during production

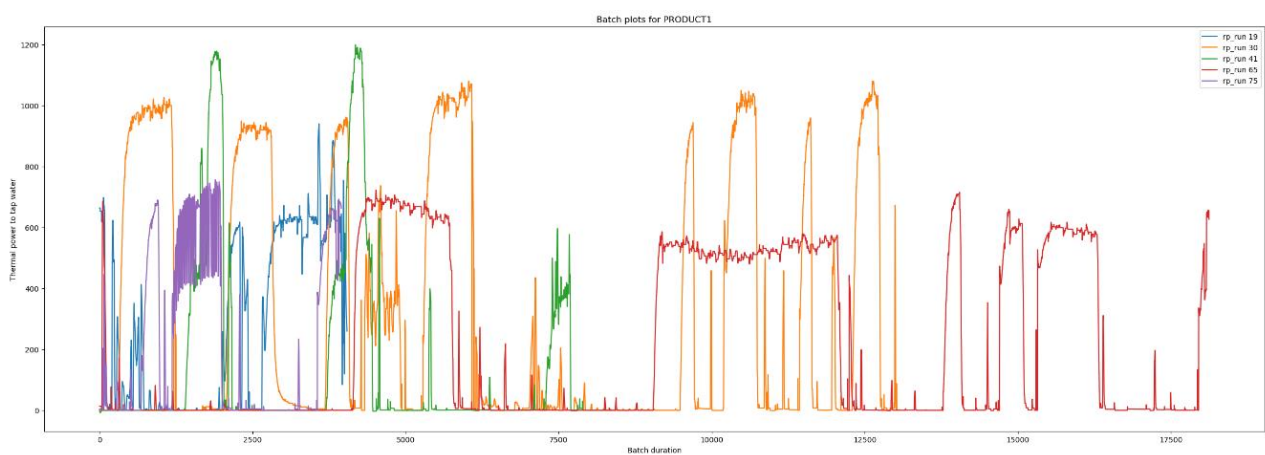


Figure 10-6: Thermal power to tap water for product 1 during production



Figure 10-7: Total electrical power trends for product 1 during production

By converting the power values to the corresponding energy values, it is possible to determine the efficiency of a particular batch. Table 10-1 and Table 10-2 below, provide an example of total energy by category. These tables give for each batch the identification, the product code and the relevant energy consumption. Since production can have variable length, the total energy does not provide a clear indication of efficiency. However, it is preferable to examine the energy per kilogram of product produced. These tables clearly show the breakdown by energy category and allow batches to be compared and, for example, an ROI to be calculated.

Table 10-1: Summary of total energy (Grafana)

Total energy					
Unix	Product	Steam electrical energy [kWh]	Cooling electrical energy [kWh]	Motor electrical energy [kWh]	Energy tap water (WW2) [kWh]
1714155460	PRODUCT1	524	14.8	73.6	312
1714163088	PRODUCT1	1680	47.8	238	1152
1714181754	PRODUCT1	1077	30.8	153	319
1714212268	PRODUCT1	2373	59.4	327	1053

Table 10-2: Summary of total specific energy (Grafana)

Total specific energy					
Unix	Product	Steam specific electrical energy [kWh/kg]	Cooling specific electrical energy [kWh/kg]	Motor specific electrical energy [kWh/kg]	Total specific electrical energy [kWh/kg]
1714155460	PRODUCT1	0.0721	0.00203	0.0101	0.0842
1714163088	PRODUCT1	0.0718	0.00204	0.0102	0.0840
1714181754	PRODUCT1	0.0715	0.00205	0.0102	0.0837
1714212268	PRODUCT1	0.0737	0.00184	0.0102	0.0857

10.4 KPI and EnPI

Eventually, two possible energy performance indicators that are earlier discussed are shown in a swarm plot. The examples presented are for three distinct products, two of which have only one production batch. This does not provide an accurate representation of the products in question.

10.4.1 Utilization ratio

KPI that shows the utilization rate of the motors can be shown in a swarm plot too (Figure 10-8). This is calculated by computing the actual consumption relative to the maximum electrical consumption. Note that for the piston pump, the utilization rate is 100 %, this is because the power is calculated based on the electrical consumption of the motor since there was no further information.

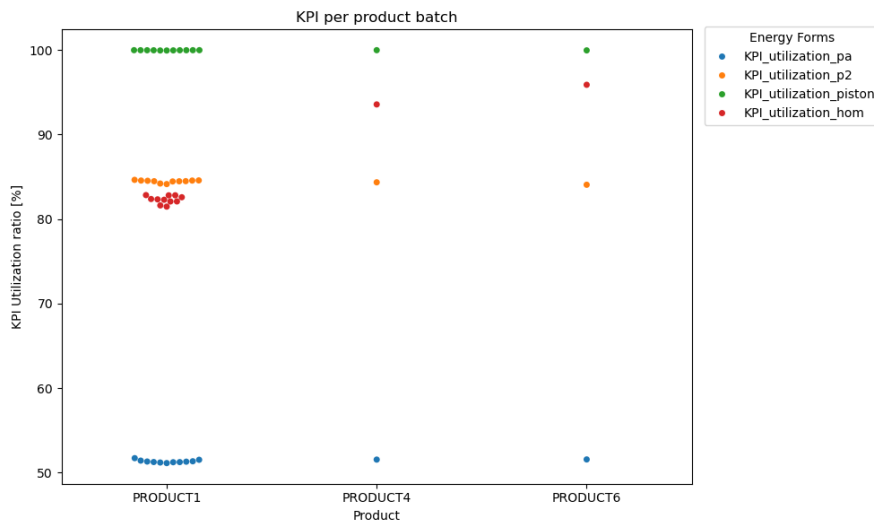


Figure 10-8: KPI utilization rate of the motors

10.4.2 Heat recuperation ratio

The second relevant indicator is the heat recuperation KPI. This shows the amount of energy that can be recuperated during the production step relative to the total energy that the product exerts. This is shown in a swarm plot in Figure 10-9 with each point representing a batch. This KPI varies a lot and depends on the control and need for preheated tap water.

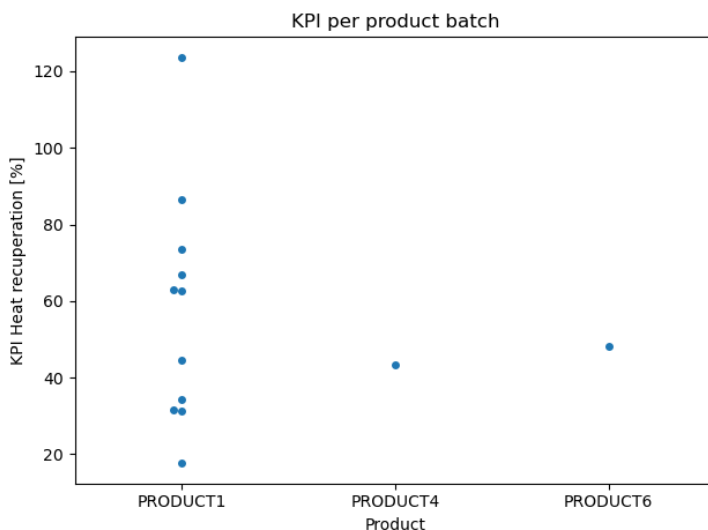


Figure 10-9: KPI heat recuperation

10.5 Process optimization

All the work done so far has focused on describing and accurately mapping the current state of the process to gain more insight into energy consumption. This detailed understanding of the process under consideration allows the virtual comparison of different scenarios before implementing them in practice.

In practice, this can be achieved by adapting the Python code to reflect the modified scenarios, mapping relevant efficiencies and energy performance indicators (EnPIs), and comparing them to the original situation. It is important to note that such optimizations require extensive process knowledge.

One potential optimization, for example, is improving the cooling efficiency. Once the power that the product releases is determined, more efficient cooling can be achieved by composing the elements that contribute the cooling. This can be done using a hypothetical cooling flow rate in a new, hypothetical heat exchanger with better cooling efficiency. If the calculated thermal cooling power is equal to the original cooling power with a lower electrical consumption, it should be further investigated.

Although this specific aspect is not elaborated on in the thesis, it provides a promising direction for future work, either by Actemium or in a follow-up thesis.

11 CONCLUSION

This thesis is a feasibility study of reporting process data into a virtual energy monitoring system with a focus on electrical and thermal consumption. Prior to this thesis, all the data collected from the field was only functional for process control, but this thesis wanted to change that. It aimed to make this data more useful by computing it further into a virtual energy monitoring system to have an idea of the energy consumption.

The first step is to gather a lot of information about the process under consideration. This is done by studying the operating principle and the components. With this information, the theoretical formulas are derived and the calculations are made. Many comparisons between methods are made to find the most correct approach. Note that this step depends on the considered process and if others want to try this on a different process, process knowledge about that process needs to be gained. Once all the relevant power and energy values have been calculated, meaningful indicators such as efficiencies and KPI's are calculated, which have economic and ecologic relevance. The next step is to visually interpret the energy consumption by plotting it on a swarm plot and establishing the energy baseline. Finally, all this information is presented on dashboards.

The aim of this work is not only to create an energy monitoring system for a specific process to gain insight into energy consumption, but also to inspire others that it is possible to create a low budget energy monitoring system. Methods and tools that are useful for this type of system are given.

Sometimes errors and unexplained issues occurred in the results. This may be due to certain conversion errors in the calculations or a lack of process info causing certain things to be overlooked, but this does not take away from the purpose of this thesis. Instead of using the error values, an acceptable value is then taken to continue calculating with in order to still have possible results and show the possibilities. These obstacles do show that theoretically calculating such a process is quite complex.

Beforehand, the approach was to be able to compare tubular and plate heat exchangers. Afterwards, this turned out not to be possible because the plate heat exchanger was not yet frequently used. The code is written in the sense that no more modification is needed to be made to this compare both types. In addition, a plot was also created with fictitious data from the plate heat exchanger comparing both types.

There were some issues where communication with the client of Actemium, Puratos, encountered difficulties. Initially, minimal info on the process was given, but gradually more and more info was required to perform the calculations. Working in collaboration with an external company without a responsible person causes time delays on Q&A's.

This conclusion ends with possible extensions of this master's thesis.

Real time process data

To access the data, one must first download the CSV file. However, this approach has the disadvantage of lacking real-time data capabilities. A more optimal solution would be to develop a program that directly links the Puratos database to the Influx Database, which is utilized in this context. The Grafana dashboard can be configured to refresh at a specified interval, such as five seconds, ensuring that the presented data remains current.

More data, less simplifications

At certain critical locations, the availability of measurements or process information is limited. This necessitates the making of assumptions, which introduces an error. With the accumulation of additional assumptions, the error becomes significant and no longer provides a representative picture of the actual energy consumption.

The greater the amount of available information, the more accurately everything can be calculated without the necessity of additional assumptions. An illustrative example is a temperature measurement taken after the flash vessel. This is an important temperature because from this point onwards, the product will be cooled and this energy can be recovered.

UHT 1

The same energy calculations could be performed for UHT line 1, which is a similar line but produced by Tetra Pak instead of Reggiani. Such an approach would permit a comparison of the two lines, thereby facilitating the identification of the relative strengths and weaknesses of each plant. It would be of interest to determine the specific energy differences between the two lines, which could be indicated by appropriate KPIs.

Critical energy point optimization

A process optimization and calculation could be proposed to improve the process from an energetic perspective, so that it becomes visible where excessive energy is consumed. Using more theoretical calculations based on new component statistics, the energy saved can be predicted. Eventually, the return of investment (ROI) can also be calculated. An example that has already been worked out quite well is the consumption of the plate heat exchanger.

SUSTAINABILITY REFLECTION

The world is changing dramatically, so investments must be made to stay within planetary boundaries. As industry plays a major role in climate change, it is important to reduce emissions and energy consumption as much as possible.

The European Commission has set targets with the objective of achieving a more sustainable society (*Sustainability - European Commission*, n.d.). These targets include several areas of action, such as the circular economy, climate-neutral economy, eco-design, and energy labelling. While this Master's thesis focuses primarily on theoretical feasibility studies related to energy consumption, it is aligned with sustainability principles, although it does not comprehensively cover all the goals set by the European Commission.

The thesis intersects with certain areas of action highlighted by the European Commission, in particular the pursuit of a climate neutral economy. Achieving climate neutrality requires a deep understanding of energy consumption patterns within processes. Going forward, it's imperative to increase this understanding and use it effectively, especially in times of energy abundance.

Another approach to making life more sustainable is the Sustainable Development Goals (SDG's), which have been established by the United Nations (SDGs, 2017). These SDG's consist of 17 separate goals, which were set in 2015 with the aim of being achieved by 2030. The following text shows how this master's thesis contributes to the achievement of these goals.

SDG 7: AFFORDABLE AND CLEAN ENERGY

It is clear that a significant portion of the electricity generated today is produced using environmentally destructive methods. Consequently, it is crucial to utilize energy in a prudent manner and to endeavor to recover as much as possible. The findings of this thesis facilitate the introduction of potential optimizations and a comprehensive picture of all energy consumption in terms of cooling, motors and steam production has been delineated. Furthermore, an endeavor has been made to utilize the electricity consumed as effectively as possible through the utilization of a heat recuperation block. This process is designed to reuse the residual heat of the product as much as possible by preheating tap water with it. In addition, this process allows for the determination of capacities, energy consumption, and associated efficiencies with the objective of minimizing the loss of heat. Another example of recuperating excess heat is the first heating stage of the product in the condenser, caused by the dissipated steam.

SDG 9: INDUSTRY, INNOVATION AND INFRASTRUCTURE

This master's thesis contributes to SDG 9 by improving infrastructure and industry practices for a sustainable future. It focuses on understanding energy use in an industrial factory, with a particular emphasis on the complex UHT process. By analyzing each part of this process, the thesis lays the groundwork for making industrial operations more sustainable and efficient, promoting inclusive growth and access to markets, particularly for small businesses in developing countries. The use of tools such as the Grafana dashboard facilitates the accessibility of data, thereby supporting the sharing of knowledge and the expansion of internet access in underdeveloped regions. By placing an emphasis

on sustainability, innovation, and inclusive development, this thesis contributes to the advancement of a more equitable and resilient industrial landscape, in alignment with the objectives set forth in SDG 9.

SDG 12: RESPONSIBLE CONSUMPTION AND PRODUCTION

By using existing process data stored in a historian database, the research attempts to develop an innovative solution to minimize energy consumption. This process data will be used to calculate electrical energy consumption, resulting in greater awareness of the amount of energy being consumed. With this knowledge, inefficient consumers can be quickly identified and replaced with more efficient ones. It can be argued that this virtual energy monitoring system provides a basis for implementing optimizations.

A good example of this is heat exchangers. It is an attempt to recover more energy from the hot fluid and make the overall efficiency of the process visible so that more optimizations can be made. The efficiencies are calculated for the two different types and can be compared.

REFERENCES

Apv-homogenizer-used-with-uht-us.pdf. (n.d.).

Boyd International. (n.d.). *A short guide on the UHT processing industry and equipment*. Retrieved 25 March 2024, from https://www.boydinternational.com/resources/uht-processing/index.php?fbclid=IwAR3hP9u4ZbtygGErXKCEZWDQZHoDGN-056hMZ9CD8KnSrYB9mk0_chgFT5w

Claessens, T. (2022). *E702080A - Warmte- en stromingsleer*. UGent.

CSI. (2019, June 5). *What is Clean-in-place (CIP)*. Central States Industrial. <https://www.csidesigns.com/blog/articles/what-is-clean-in-place-cip>

Datta, N., Elliott, A. J., Perkins, M. L., & Deeth, H. C. (n.d.). *Ultra-high-temperature (UHT) treatment of milk: Comparison of direct and ind...*

Doherty, A. (2021, April 29). What Are Energy Baselines (EnB)? *Hark*. <https://harksys.com/blog/what-are-energy-baselines-enb/>

Efficiency of Heat Exchanger: Description and Formula | Linquip. (2021, February 14). <https://www.linquip.com/blog/efficiency-of-heat-exchanger/>

Eisner, M. D. (2021). Direct and indirect heating of milk – A technological perspective beyond time–temperature profiles. *International Dairy Journal*, 122, 105145. <https://doi.org/10.1016/j.idairyj.2021.105145>

FINAL-EnPIs_brochure.pdf. (n.d.).

Hendren, N. (2022). *Steam Tables (.xlsx, .csv, .json)*. LearnChemE. <https://learncheme.com/student-resources/steam-tables/>

Hu, J., Sari, O., Eicher, S., & Rija Rakotozanakajy, A. (2009). Determination of specific heat of milk at different fat content between 1°C and 59°C using micro DSC. *Journal of Food Engineering*, 90(3), 395–399. <https://doi.org/10.1016/j.jfoodeng.2008.07.009>

Hyfoma. (2016). *Pasteuriseren, steriliseren, UHT - Safe Food Factory*. https://www.safefoodfactory.com/nl/knowledge/25-pasteuriseren-steriliseren-uht/?fbclid=IwAR195p2DYGqN5OELW11JS2b1aB-7ZJeu9I_hOpGQLSfpe0TDLWV6LmfFrrE

IEE. (2016, May 22). *The Importance of Setting an Accurate Energy Baseline – IEE*. <https://ieeegypt.org/the-importance-of-setting-an-accurate-energy-baseline/>

Instructions for use and maintenance uht block_6.500 s.n.1928_Puratos_Lummen_REV.01_2021.pdf.

(n.d.).

Laboratories, M. (2022, January 11). MycoScience—What Is Sterilization In Place? *MycoScience*.

<https://mycoscience.com/what-is-sterilization-in-place/>

Lucidchart. (n.d.). *Wat zijn Piping & Instrumentation Diagrams?* Lucidchart. Retrieved 25 March 2024,

from <https://www.lucidchart.com/pages/nl/wat-zijn-piping-instrumentation-diagrams>

Neologic Engineers. (n.d.). *What Are Aseptic Storage Tanks, and What Are the Benefits of It?* Neologic

Engineers. Retrieved 25 March 2024, from <https://www.neologicengineers.com/blogs/what-are-aseptic-storage-tanks-and-what-are-the-benefits-of-it.php>

NIS 2 Directive. (n.d.). Retrieved 28 March 2024, from <https://www.nis-2-directive.com/>

Savree. (n.d.). *Plate Heat Exchanger (PHE) Explained—saVRee—saVRee*. Retrieved 25 March 2024,

from <https://savree.com/en/encyclopedia/plate-heat-exchanger-phe>

SDGs. (2017, February 1). Sdgs. <https://www.sdgs.be/en/sdgs>

Sustainability—European Commission. (n.d.). Retrieved 27 April 2024, from [https://single-market-](https://single-market-economy.ec.europa.eu/industry/sustainability_en)

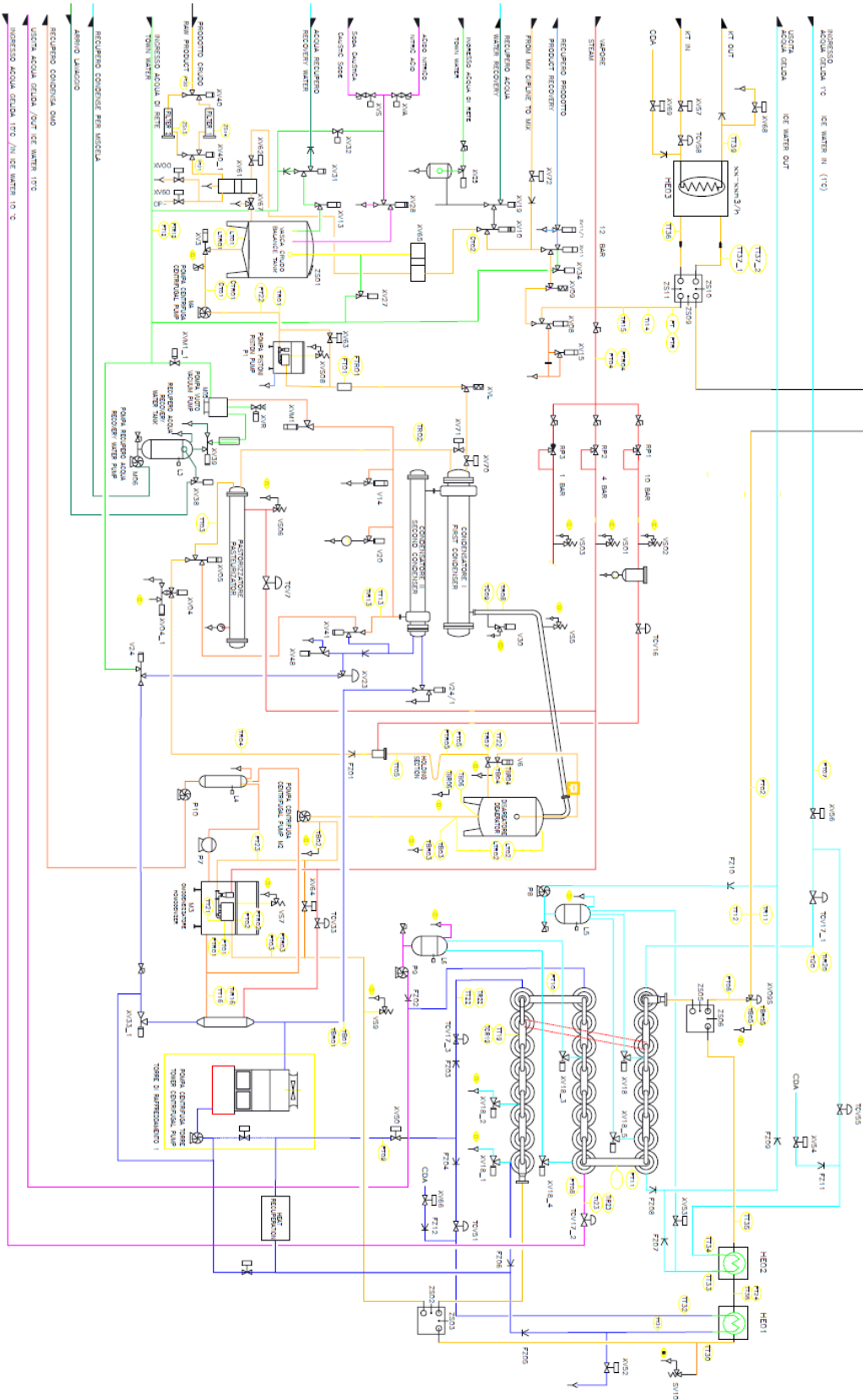
[economy.ec.europa.eu/industry/sustainability_en](https://single-market-economy.ec.europa.eu/industry/sustainability_en)

Tanguay, D. (n.d.). *International Performance Measurement and Verification Protocol (IPMVP)*.

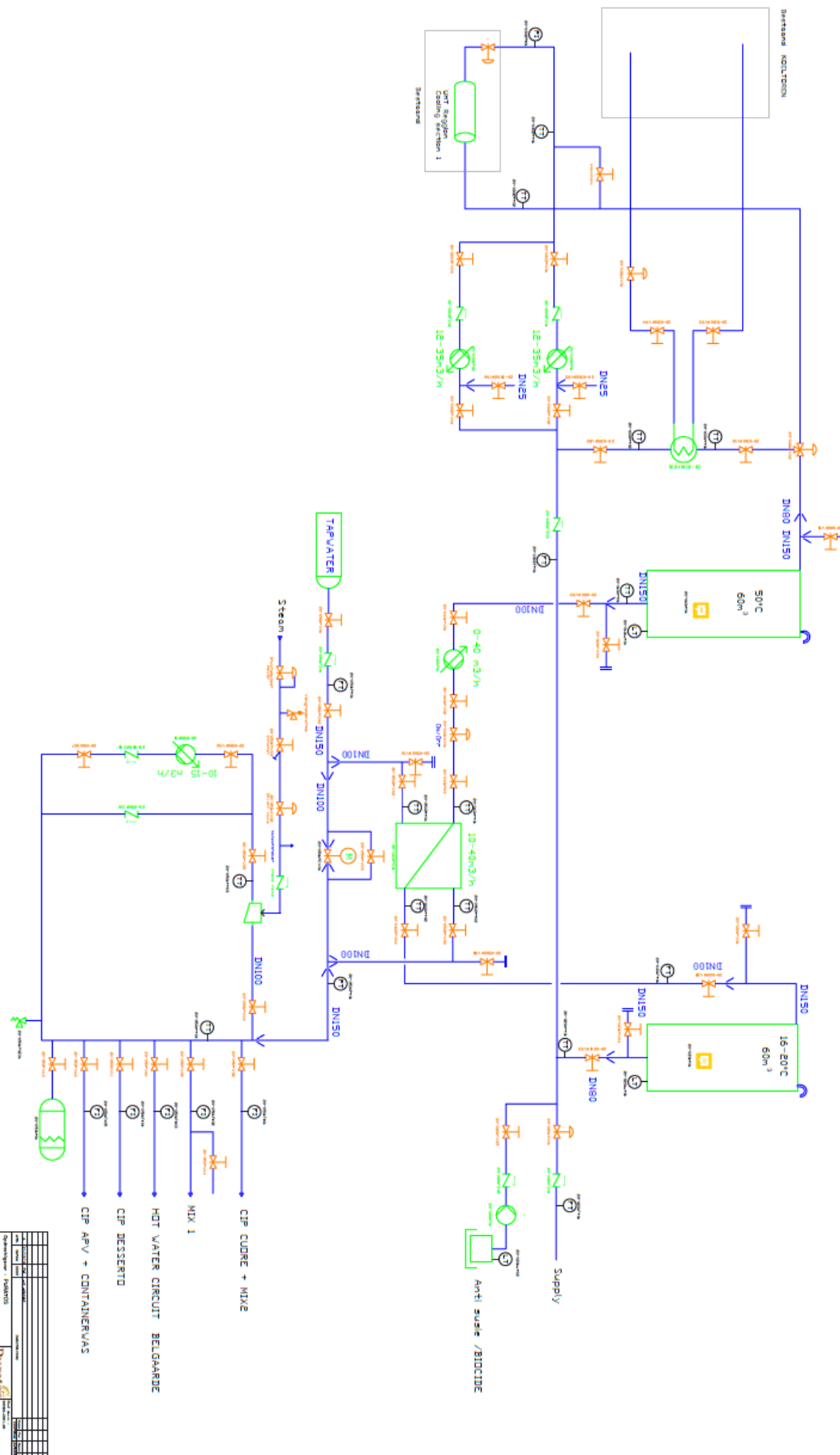
Efficiency Valuation Organization (EVO). Retrieved 29 March 2024, from <https://www.evo-world.org/en/products-services-mainmenu-en/protocols/ipmvp>

APPENDICES

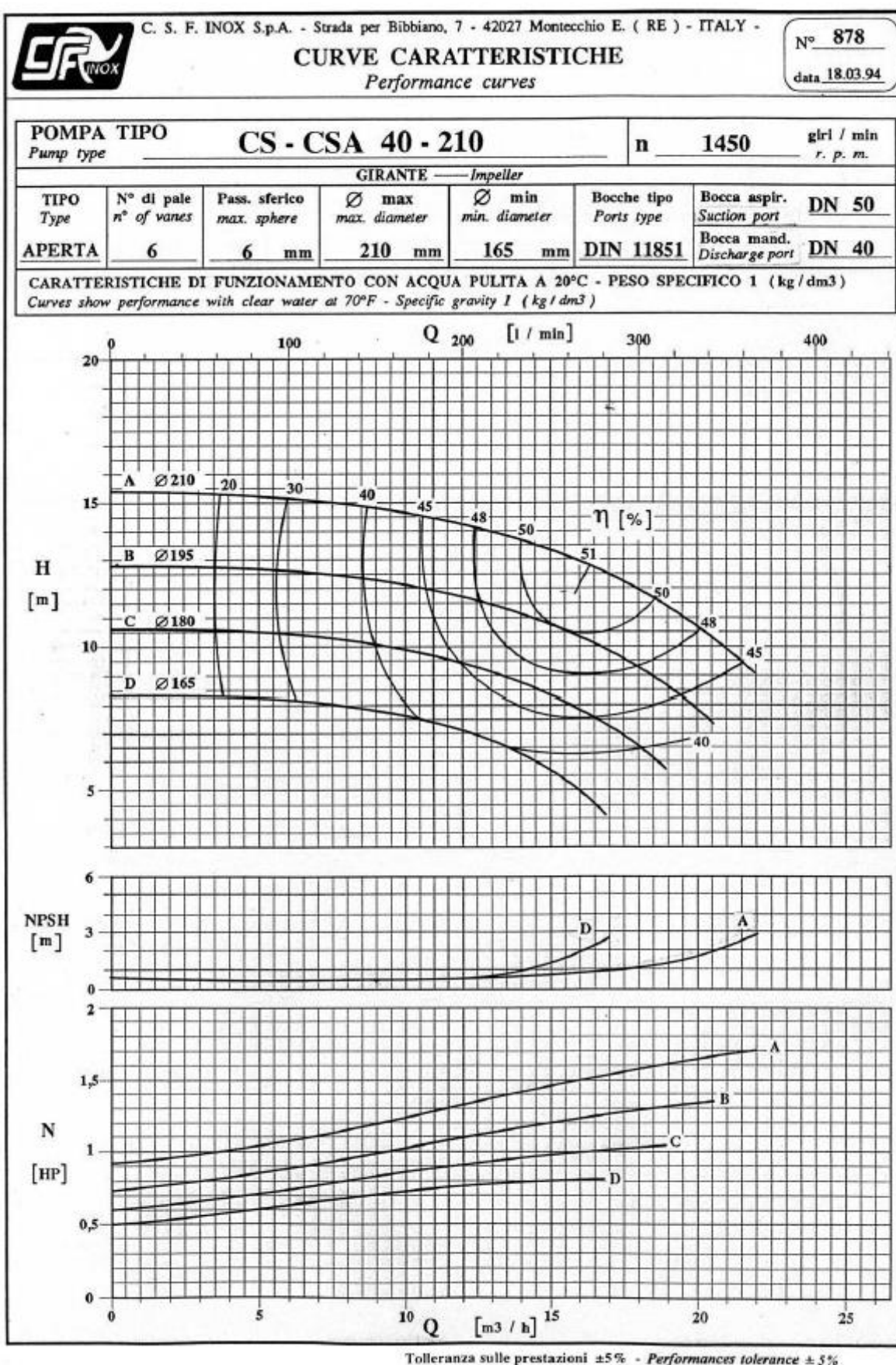
A. P&ID UHT process



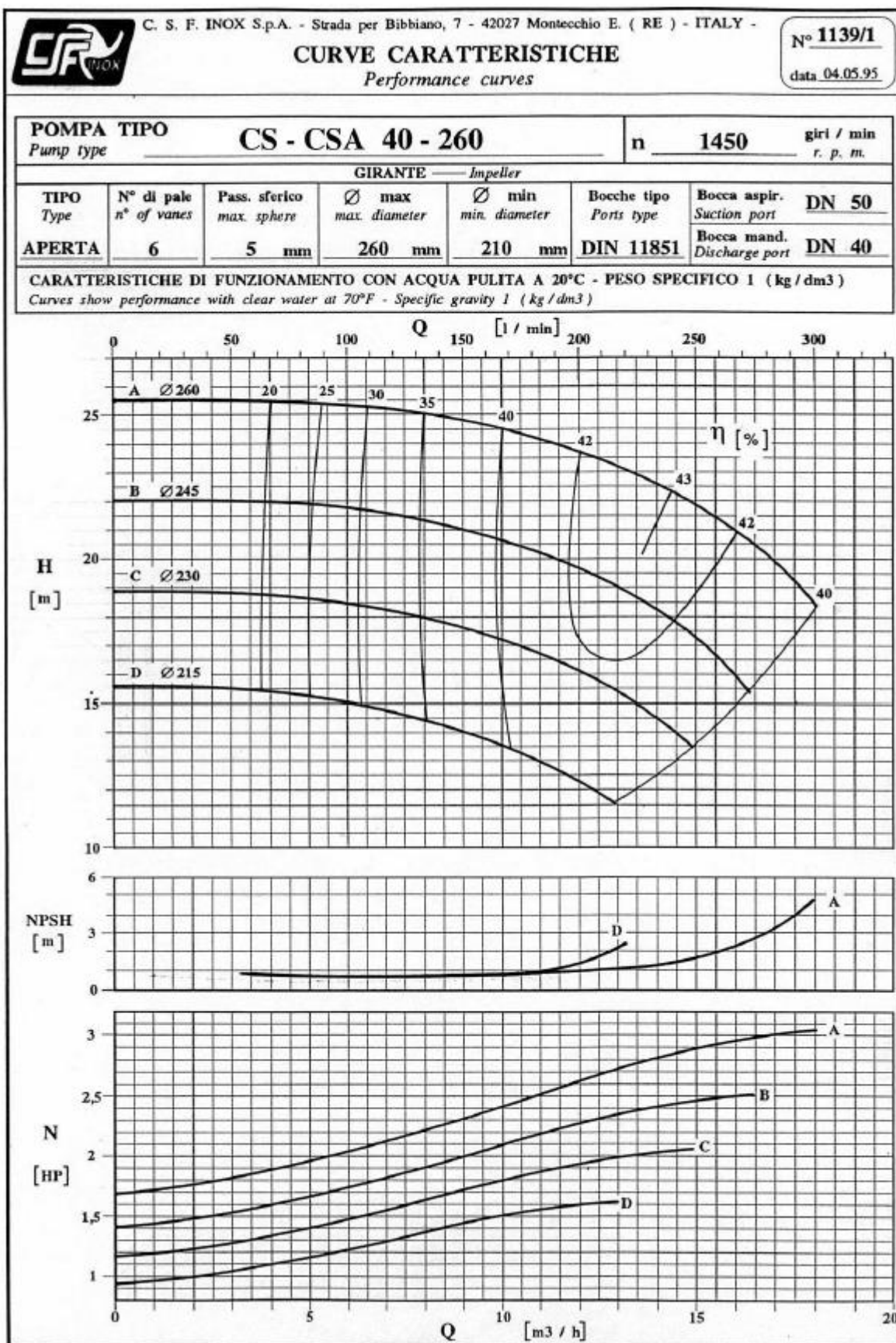
B. P&ID heat recuperation block



C. Datasheet pump PA



D. Datasheet pump P2



E. Shared folder link

The following link will take you to a shared Google Drive. The Python code is not included in this folder as it contains confidential information, but can be obtained by emailing lukas.favoreel@gmail.com for academic purposes or by contacting Actemium for private purposes.

Link: https://drive.google.com/drive/folders/17_QLu0v8p6u45DIBKN-xObGobOwMNhOi?usp=sharing