Modelling of dynamic thermal loads in industry

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ABSTRACT: The rise in global energy consumption, and consequent increase in the extraction and use of resources, has negative impacts on the environment. Many industrial sectors depend on fossil fuels to obtain energy and, during its burning, large amounts of gaseous effluents are emitted into the atmosphere. The environmental and economic concern has motivated the research for new methodologies that promote the energy efficiency maximization in the industry, in order to reduce the primary energy consumption and the gaseous emissions. The interiorization that maximizing energy efficiency benefits the planet's sustainability promotes the establishment of measures for greenhouse gas emissions reduction, energy efficiency increase and renewable energies use. The use of software tools allows industrial sectors to explore new measures for monitoring and optimizing their processes, even when it comes to small companies such as those in the food and beverage industry. In order to better understand the software support options available to companies in this industry, a study was carried out to identify tools for modelling dynamic thermal loads (batch processes). Among the analysed tools, the pinch analysis methodology-based PinCH software was selected. Its characteristics were explored and tested with some academic examples referring to continuous and discontinuous industrial processes with potential for energy integration. At the same time, an industrial unit included in the Portuguese meat and meat related products sector was characterized. Even though it was not possible to apply the PinCH software's methodology to the respective process, the energy recovery potential was still identified.

KEYWORDS: Energy efficiency, Heat recovery, Pinch Analysis, Modelling, PinCH software, Industrial cases.

1. INTRODUCTION

The rise in the world's energy consumption is deeply connected with the worldwide human population growth. To face the basic needs of a growing population involves an increasingly higher global energy consumption due to the high and continuous energy input required by modern industrial production techniques (Klemeš et al., 2011).

A feature that the most varied industrial sectors have in common is the fact that their energy input is fundamentally dependent of fossil fuels (which are non-renewable natural resources) such as coal, oil and natural gas (U.S. Energy Information Administration, 2016).

Such industrial dependence, in addition to the resource depletion problem that it originates, also has a negative impact on the environment caused by the associated gas emissions that will inevitably take place during the combustion of fossil fuels (the major energy conversion used). Apart from not assuring any type of environmental sustainability, the waste associated with the inefficient use of energy (i.e., with high energy losses) and resources generates high production costs which can be avoided (Fernández et al., 2012).

It is of extreme relevance that the industrial processes, or the respective energy systems, be designed to function with the highest efficiency possible by promoting the minimum consumption of both energy and materials. Such systems should also use low-level consumptions and recycle the waste of previous processes in order to lower the energy or materials consumption in other processes that requires them. This concept is sometimes called "industrial symbiosis" (Klemeš et al., 2011).

The maximization of the global energy efficiency of a process results in the reduction of both the fossil fuels consumption and the gas emission that their combustion would implicate. Energy efficiency can be achieved through process integration. This technique takes advantage of the thermal potential of each process as a way to allow the optimization of the utilities' consumption (fluids, external to the processes, which directly exchange heat with the processes streams) (Relvas et al., 2002).

According to Klemeš et al. 2011, the efficiency of energy supply is substantially improved when cogeneration (the use of CHP – Combined Heat and Power – systems) is applied. The theoretical foundations that support the use of cogeneration techniques are simply related with the use given to energy in the form of heat, which would otherwise end up wasted. If one combines a system of electrical energy production with a CHP system, it becomes possible to make use of the heat for other ends, such as water heating solutions to nearby buildings.

The food and beverage industry is constantly challenged to understand its thermal energy efficiency increasing potential because product quality and flavour are essential factors in the production process. In addition, thermal energy management in these processes might be complex since most of them are batch or semi-continuous and, therefore, energy requirements may vary in time (Muster-Slawitsch et al., 2014).

More than 50% of the food and beverage industry thermal energy needs are required at low temperatures (under 100ºC). Vannoni, Battisti, and Drigo 2008 refer that, due to this need for thermal energy at low and medium temperature levels, several studies revealed the existence of high potential for renewable energy integration (especially solar thermal).

In 2015, the food and beverage industry consumed about 11% of the global industry's final energy requirement in the European Union. This is the manufacture's biggest sector in the EU and contains more than 289 000 companies, of which 99,1% are small or medium-sized enterprises that only contribute to 49,5% of the sector's turnover (Fluch et al., 2017).

Since the companies in this sector do not have the dimension or the financial power to invest in complex analysis, the need for tools capable of analysing the energy requirements' effects, under conditions of variation over time, is identified (Muster-Slawitsch et al., 2014).

The diversity of production processes in the food and beverage industry and the wide variety of produced products hinders the development of tools capable of modelling the industrial units. Most foods have highly complex compositions and their properties may change irreversibly during the industrial process. Under these conditions, the struggle in modelling processes increases because it is difficult to predict food's properties and, consequently, their behaviour depending on the operation conditions (Bon et al., 2010).

Considering this, five objectives are proposed for the development of this thesis:

1) To make a detailed study concerning the already available tools for modelling thermal loads, with a preference for the ones that allow the evaluation of dynamic loads (batch processes);
2) To approach and analyse a case study, involving a concrete and real business contact with a company from the food sector;
3) To apply an energy process integration analysis tool for discontinuous processes to the industrial case study, in order to better understand the energy recovery potential in the selected company;
4) To present the optimization measures/solutions identified by the tool, as well as the associated costs;
5) To analyse the impact that different production scenarios have on the company's energy recovery potential and costs.

2. METHODOLOGY

For an industry to be sustainable, it is necessary to seek the increase of profits while trying to reduce both the consumption of resources and the generation of waste. These are the main goals of a sustainable industry. Process integration in the industry is a systematic approach used in the design and / or optimization of productiion processes. It represents a set of varied techniques that aim to develop new sustainable strategies for the design and functionality of the industrial unit.

These techniques can be applied to projects made from scratch or in already installed plants, in simple or complex processes (continuous or discontinuous) (Relvas et al., 2002).

Foo et al., 2017 define process integration as a "*holistic approach to design and operation that emphasizes the unity of the process*".

Nowadays, energy integration is recognized as one of the broadest areas of use in process integration. In addition, most of the methods developed to date, applicable to different areas of process integration, resulted from studies based on energy systems (Relvas et al., 2002).

The importance of energy integration in industry is indisputable and that is why it should be increasingly explored. Although there are several methodologies, Pinch Analysis has been the most outstanding technique in this area since it has already proven to be highly applicable to industrial processes.

2.1 Pinch analysis

The Pinch Analysis is a technique that is fundamentally based on the first two laws of thermodynamics and has been increasingly used in industrial processes due to its simplicity of application. The use of this methodology has the purpose of obtaining a new heat exchanger network (HEN) for processes, so that after the energy integration it is possible to achieve financial savings, increase heat recovery and reduce external utilities consumption.

The Pinch Analysis is composed mainly of two stages: a pre-project targeting phase, in which objectives are set and, later, a design phase, where the heat exchanger network is designed. Since data collection and validation is the first activity in any analysis, it precedes the two stages mentioned. This activity is quite important because it serves as the basis for energy integration.

In an industrial process, there are enthalpic needs that must be satisfied, since the process streams may need to be heated or cooled. These are the situations where it is necessary to resort to external utilities in the process (Fernandes et al., 2016).

2.2 Continuous and discontinuous processes

The production processes used to produce final products will always depend on the needs and characteristics of a certain industry. This way, the industry can choose to produce in a continuous or discontinuous (by using batches) way. The difference between these two types of processes is not always clear, in the sense that, many times, big and continuous industrial units include single units that operate in a discontinuous way. Nevertheless, if there are only one or two discontinuous operations in an industrial unit with large production outputs, that process is still considered continuous. Likewise, many batch processes, which are discontinuous, include one or two units which operate continuously.

On one hand, continuous processes are generally used when the annual production is very high which, for example, is the case of the high-scale heavy industries, such as the petrochemical industry. They are characterized for having all their operations running 24 hours a day, seven days a week. The industrial unit works in a constant way throughout almost the whole year, only stopping production to perform the annual maintenance of the equipment. Production can also be interrupted in case of an unexpected malfunction or breakdown which might jeopardize the entire process (Douglas, 1988).

On the other hand, discontinuous processes have their main phases of production operating in a discontinuous way. This means that some properties change over time, such as the heat, the temperature, the concentration and the flow mass involved in the processes. The vast majority of discontinuous processes are composed of both discontinuous and semi-continuous phases. The semi-continuous phases operate continuously, but their work schedule is programmed to have periodic interruptions.

2.3 Energy integration in batch processes

The conventional pinch analysis already proved it could reach excellent results, concerning the energy integration of continuous processes. The reality is that in discontinuous processes (in which properties change over time), the energy integration can become more complicated. This is due to the tendency for the sources and the heat sinks to be available only at different time intervals. This requires different types of mathematical methods and models for the energy integration to be reached, once the heat recovery depends on both the temperature and the time. Since these processes are time-dependent, it is important to have all production well scheduled and defined, as a way to achieve financial efficiency. Scheduling is a sequential order of many production operations. Basically, it defines the sequence by which each operation is performed as well as the time intervals in which each one of them is inserted. Production scheduling is, indeed, absolutely relevant when one deals with energy integration and represents a quite useful tool to lower energy consumption in discontinuous processes (Fernández et al., 2012).

In a discontinuous process, the energy integration can assume a direct or an indirect mode, depending on the form of how heat is exchanged between the process streams. One verifies the existence of direct energy integration when, in any specific time interval, the process streams exchange heat directly (Chaturvedi and Bandyopadhyay, 2014). This heat recovery mode requires very strict scheduling conditions, as a way of guaranteeing both the necessary product quality and process energy efficiency (Fernández et al., 2012).

On the other hand, the indirect heat exchange becomes very complicated when there is a need to transfer heat from a certain time interval to another one. On these conditions, the heat from the hot streams is transferred to a heat transfer medium, which is then heated and stored until the moment it is steered towards cold streams, which in turn exist in distinct time intervals. By using this approach, the heat exchange between streams that do not coexist in time is less limited, making this method less sensitive in terms of scheduling.

2.4 Gantt charts

Gantt charts work as calendars for activities. They assume the shape of diagrams and are extensively used in project management.

The usefulness of Gantt charts for production scheduling is evident, whether the chart is produced manually or using an algorithm or heuristic. They present very helpful information that facilitates communication between analysts and users. Mainstream Gantt charts usually display the tasks to be performed, when and for how long the tasks should be performed, the equipment required for each specific task and when the equipment's inactivity periods occur (Wilson, 2003).

Even when considering the simplest discontinuous processes, the use of Gantt charts is extremely useful. It allows to verify that it is quite common to exist a low equipment utilization. This means that there are several moments in which the equipment is inactive, many times referred to as dead times.

One of the objectives of discontinuous processes is precisely to reach high levels of equipment utilization. If some units of the process for the production of one batch are already inactive, namely the initial ones, it is not necessary to wait for the first batch to be finished so as to have the second batch's production started. This way of achieving higher rates of utilization is called batch overlapping, in the sense that more than one batch, in different phases, coexists in the process at any given time (Smith, 2005).

2.5 Available tools for modelling dynamic thermal loads

Process integration, modelling and problem optimization in chemical and industrial engineering are, in most cases, complex and time-consuming tasks, which require a big amount of data processing. The use of certain software, specifically programmed for these fields of knowledge, are essential to obtain new solutions in an expeditious manner. The tools used by the industry not always correspond to simple data processing computer applications (software), in which the user only needs to insert a certain amount of data to obtain a set of results. There are some tools which aim is to support the user with problem modelling. In other words, some tools can be best described as programming languages which solve a set of equations defined by the user and considering a set of parameters also defined by the user (Hon Loong Lam et al., 2011).

Although there are many tools for modelling industrial processes, not all gather the necessary conditions or characteristics that allow them to be applied to discontinuous processes. Among the tools that allow the modelling of dynamic thermal loads (discontinuous processes) stand out the programming languages gPROMS and CHEMCAD and the software tools SOCO, PinCH (version 3.0), GREENFOODS branch concept, BATCHES and Aspen Batch Process Developer. However, considering the characteristics and the applicability of the identified tools, one verifies that the computer applications are probably the better-positioned solutions to allow the industry to reach its energy-related objectives. Programming languages have some limitations regarding its features and capabilities when compared to computer applications.

Both BATCHES and Aspen Batch Process Developer are software tools that take too long to come up with solutions because both make detailed energy and mass balances for all the simulated batches. Another negative feature that both present is the fact that they do not consider possible equipment failures, delays, work shifts patterns, inactivity for equipment maintenance, vacations, etc. Therefore, these two software tools are not the most advisable for scheduling industrial units that produce several products (Petrides et al., 2014).

Taking these limitations into account, it is concluded that perhaps SOCO, PinCH 3.0 or GREENFOODS branch concept are the best software tools to support the user with energy and economic efficiency. As an initial selection criterion, it was given priority to open source tools and/or available to IST or ISQ. Once the considered three best tools fit within these criteria, the possibility of obtaining them was investigated. Among the three tools, only PinCH 3.0 and GREENFOODS branch concept were possible to obtain. At a later stage, it was decided to use pinch analysis methodology-based PinCH (version 3.0) software to work the data of this dissertation.

3. INDUSTRIAL CASE STUDIES

The purpose of this chapter is to present a detailed study about an industrial company that meets the necessary conditions for the application of the pinch analysis used by the PinCH software. With the objective of producing a study using real data, a company from the food and beverage industry was contacted and face-to-face interaction was carried out. The mentioned company is part of the Portuguese meat and meat related products sector. This company will be henceforth referred to by the name “CarneMestra” (not its true name) for confidentiality purposes.

Unfortunately, the data provided by the "CarneMestra" does not meet all the necessary conditions for a pinch analysis. Therefore, it was necessary to complement this chapter with the inclusion of a second case study. In this sense, an adaptation/recreation of a case study included in the learning tutorials of PinCH software was performed in order to clearly expose the practical results of this tool’s application to an industry. This second case study is related to the production of nutrient salt used in the fertilizer industry.

3.1 Meat industry

“CarneMestra” is a company specialized in slaughter of pigs and meat butchering. Both the slaughter process and the meat butchering process are activities that last all morning. Since this type of industry demands high standards of hygiene and food safety, “CarneMestra” dedicates all the evening working period (the remaining time until the industrial unit shuts down its daily operations) to cleaning and sanitizing its rooms and equipment. Because of this, the hot water consumption, associated with such tasks, is very high. Nevertheless, these are essential tasks because the rooms and equipment need to be clean before “CarneMestra” can restart the whole production process on the next day.

The study concerning the company “CarneMestra” is related with the steam (produced in the company’s thermal power station) distribution circuit. To produce steam, “CarneMestra” uses one Ambitermo SBM-C2800 boiler, which works continuously. The thermal power station is the only natural gas consuming unit present in “CarneMestra”, which means that the natural gas consumption of the whole company is exclusively related with the natural gas supply to the boiler. The steam produced by the boiler is collected by a collector which, posteriorly, distributes it to two distinct production lines, simultaneously. About 70% of the steam is used for washing the equipment used during the meat butchering activities. The remaining 30% is channelled to a domestic hot water system, with the purpose of heating the water that the workers use for washing their hands. In both production lines, the vapour returns to the boiler taking the form of condensate.

The produced vapour (hot utility) is responsible for heating two cold streams. However, there are no hot streams in the previously described process, there are only heating requirements. Since no cooling requirements can be found, the opportunity of heat exchange between streams becomes impossible. Thus, the energy integration is impracticable.

Under the just mentioned conditions, it is not possible to perform a pinch analysis. Thus, the application of the PinCH software to this case will not produce relevant results.

3.2 Production of nutrient salt for fertilizers

The soil, by itself, already provides plants with the great majority of nitrogen (N), phosphorus (P) and potassium (K), the three main macronutrients they need. Nevertheless, given the great needs that the harvests present concerning these macronutrients, multiple mineral fertilizers are developed in order to supplement them.

Evaporation and crystallization are very common techniques in this industry, and their use in the synthesis of fertilizers N, P and K may have several applications. Process selection is influenced by the types of raw material, the desired quality of the final product, the physical behavior of the materials and by the specific criteria of the project. One of the different process options covered in this type of techniques is cooling crystallization. This type of crystallization is used when certain compounds, whose solubility depends on the temperature, easily precipitate in cooling crystallizers. Cooling crystallization is extremely common in mining processes for potassium chloride (KCl) production. In this case, the evaporation is used as the initial treatment to remove the sodium chloride (NaCl) present in sylvinite, the ore originally extracted (Bourgier et al., 2017).

3.2.1 Process description

In order to produce nutrient salt, used to make fertilizers with multiple nutrients (N, P and K), an industrial production unit resorts to a batch process which encompasses the following three phases: (1) dissolution, (2) evaporation and (3) cooling crystallization. Since the unit in question already resorts to the same process for many years, it was decided that it would be better to evaluate new optimization options for the process. Having in mind that the production unit already exists, one assumes that it can be already considered as fully depreciated. Thus, the only expenses incurred by the factory on an annual basis are the costs associated with the utilities' usage (operating costs).

(1) Dissolution: A reaction of dissolution occurs inside a mixing tank. In this reaction, an inorganic salt (2.5t) at room temperature is dissolved in an aqueous solvent (water), being this an endothermic process. The solvent (7t per batch) is preheated to 75ºC before it is placed inside the mixing tank in order for the water to reach a temperature that allows it, with only a small amount, to solubilize the inorganic salt. Due to the fact that there is a need of energy to dissolve the inorganic salt (endothermic reaction), the temperature of the solution at the exit of tank lowers to 55ºC.

(2) Evaporation: At the same time as the solution from the tank enters the evaporator (laterally jacketed) at 55ºC, one and a half tons (1.5t) of an additive is added to the formation of nutrient salt. The additive will prevent the precipitation from happening during the evaporation phase. After this, some steam (hot utility) is injected in the tank's side wall jacket until enough water has evaporated and the solution has reached an adequate concentration level. A total of one and half tons (1.5t) of water are evaporated, and such steam is then condensed using cooling water (cold utility). After concentrating the solution, and keeping everything dissolved, the solution is cooled with water (cold utility) through the side wall jacket, passing from 100ºC to 65ºC and is posteriorly carried to a drainage tank. The drainage tank (holding tank) is used to maintain the solution at the desired temperature (65ºC), without allowing it to precipitate, since the crystallization phase (the next one) is a continuous process integrated into a batch process.

(3) Cooling crystallization: The nutrient salt will be extracted in the form of pure crystals through the phase of crystallization, assuming that there is no coprecipitation of impurities or of the used additive. This way, no subsequent process of washing or recrystallization is needed. Before entering the crystallizer, the concentrate from the drainage tank is precooled to 19ºC (cold utility). First, two and a half tons (2.5t) of small crystal seeds are added to the crystallizer as a way to induce the formation of crystallization nuclei, on which the precipitate will later grow. The crystallization process begins after the addition of the seeds, while the recirculation cooling takes place. After this, when the nuclei are completely formed, the cooling (cold utility) is intensified to 7ºC and, at the same time, the concentrate from the drainage tank is slowly added to the crystallizer. With the objective of not exceeding the capacity of the crystallizer, and while the concentrate is added, the suspension of already formed crystals and the liquor are removed. Once the solution from the drainage tank has been fully used, the crystallization is interrupted. However, the suspension of already formed crystals and the liquor continue to be removed until the crystallizer is empty. The liquor (6t per batch) is then heated (hot utility) from 7ºC to 65ºC for further processing throughout the removal process.

3.2.2 Process data

The quantities (tonnes) per batch produced, the average specific heat values and the heat transfer coefficients for the various substances involved in the process are summarized in Table 1.

TABLE 1 - QUANTITIES PER BATCH, AVERAGE SPECIFIC HEAT VALUES AND HEAT TRANSFER COEFFICIENTS

Substances	*m (ton)*	*cp [kJ/(kg K)]*	*α [W/(m^2 K)]*
Solvent (water)	7.0	4.19	1 000
Inorganic Salt	2.5	1.50	150
Additive	1.5	1.60	1 500
Concentrate	9.5	3.25	400
Crystal suspension	3.5	2.85	250
Mother Liquor	6.0	2.85	600

The available utilities for heating and cooling process streams, referred throughout the description of the three steps of the nutrient salt production process, are specified in table 2. Steam is used as the heating source (hot utility) and is available at the saturated state. The initial and final temperatures are not specified, but rather the vapor quality. The available cold utility is cooling water from an external cooling unit.

TABLE 2 - UTILITY DATA

Utility	*Vapor (hot utility)*	*Cooling Water (cold utility)*
T_i [ºC]	x1	7
T_f [ºC]	x0	13
p [bar(a)]	4.0	2.0
α [W/(m^2 K)]	4 500	2 500
c [€/kWh]	0.075	0.025

The nutrient salt production is carried out by the batch process described previously (3.2.1). From September to July (44 weeks), the industrial unit produces three batches every day of the week (from Monday to Sunday). The operating time of each batch is seven hours and thirty minutes (7.5 hours) and during this period, each piece of equipment has the following tasks to perform:

✓ **Mixing tank**

1. Solvent pre-heating, filling (7t)
2. Salt addition, dissolving process (2.5t)
3. Emptying (9.5t)
4. Cleaning

✓ **Evaporator**

5. Filling (9,5t)
6. Addition of the additive (1.5t)
7. Solution's evaporation, condensation (1.5t)
8. Jacket's cooling
9. Emptying (9.5t)
10. Cleaning

✓ **Drainage tank**

11. Filling (9.5t)
12. Emptying (2.5t)
13. Emptying, concentrate's cooling (7t)

✓ **Crystallizer**

14. Filling (2.5t)
15. Start of crystallization
16. Crystallization, suspension's emptying (9.5t)

Through table 3 it is also possible to understand the distribution of the mentioned tasks over time.

TABLE 4 - PROCESS STEPS PER BATCH

Equipment	*Task*	*Mode*	*Start*	*Duration*
Mixing tank	1	Processing	0h00'	0h45'
	2	Postprocessing	0h45'	0h45'
	3	Postprocessing	1h30'	0h15'
	4	Postprocessing	1h45'	0h15'
Evaporator	5	Preprocessing	1h30'	0h15'
	6	Preprocessing	1h45'	0h15'
	7	Processing	2h00'	1h15'
	8	Postprocessing	3h15'	0h30'
	9	Postprocessing	3h45'	0h15'
	10	Postprocessing	4h00'	0h15'
Drainage tank	11	Preprocessing	3h45'	0h15'
	12	Preprocessing	4h00'	0h15'
	13	Processing	5h00'	2h00'
Crystallizer	14	Preprocessing	4h00'	0h15'
	15	Preprocessing	4h15'	0h45'
	16	Processing	5h00'	2h30'

To obtain a stream's average heat capacity (CP) it is necessary to multiply its mass flowrate ($\dot{m}$) by its average specific heat. In order to obtain the mass flowrate of a batch process stream, one must divide the mass of the substance in question by the time interval in which the heating or cooling requirement occurs. Thus, it is possible to calculate the $\dot{m}$ and CP values of the process streams by using the data presented in tables 1 and 3. Table 4 displays the calculated values for the hot streams (solvent and mother liquor) and for the cold ones (concentrate and vapor-condensate).

TABLE 3 - MASS FLOWRATES AND AVERAGE HEAT CAPACITIES OF THE PROCESS STREAMS

Stream	*$\dot{m}$ (kg/s)*	*CP (kW/K)*
Solvent	2.593	10.86
Mother Liquor	0.667	1.90
Concentrate	0.972	3.16
Vapor-condensate	0.333	-

*vapor's condensation enthalpy at 1 bar(a) is 2 257 kJ/kg

Based on tables 3 and 4, it is possible to create a Gantt chart (figure 1) that demonstrates the heating (blue) and cooling (red) requirements over time. This diagram allows the identification of the time intervals in which there is a cooling and/or heating requirement. These specific intervals are called Time Slices (TSs). For this mode of operation, it is only possible to recover heat directly in TS3. In the remaining TSs (TS1 TS2 and TS4) there are only heating or cooling requirements that must be satisfied with external utilities.

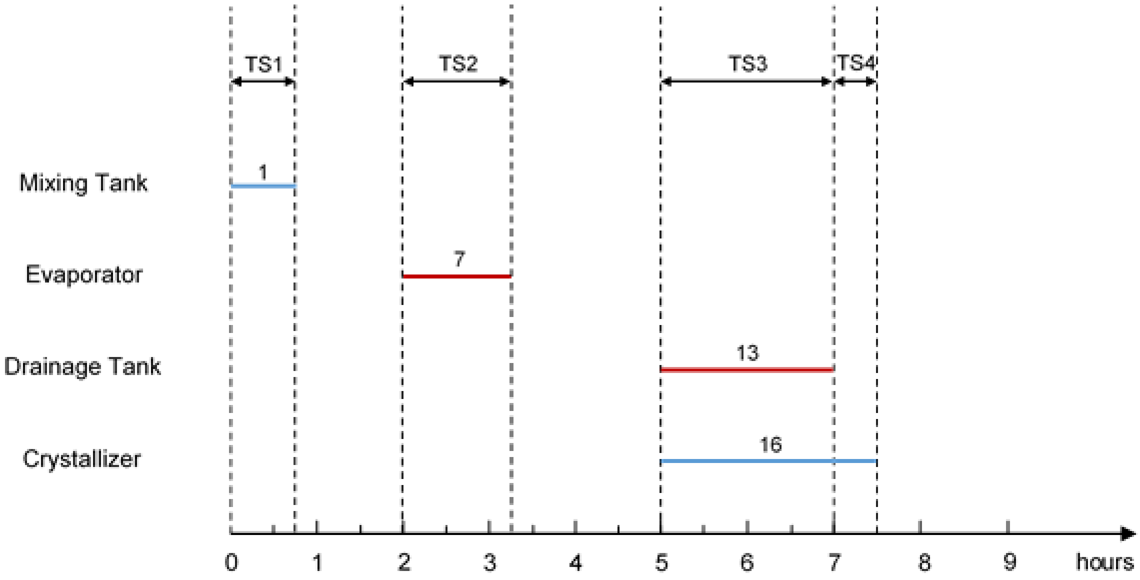

FIGURE 1 - HEATING AND COOLING REQUIREMENTS PER BATCH

The plant is already fully depreciated, so the only expenses incurred by the factory on an annual basis are the costs associated with the utilities' usage (operating costs). Table 5 shows values referring the utilities consumption and the annual operating costs associated with the production of 924 annual batches [3 (batches/day) × 7 (days/week) × 44 (weeks/year)].

TABLE 5 - UTILITIES CONSUMPTION AND THE ANNUAL OPERATING COSTS ASSOCIATED WITH THE PRODUCTION OF 924 ANNUAL BATCHES

TS	h/batch	*τ (h/year)*	$\dot{Q}_{HU}$ (kW)	$\dot{Q}_{CU}$ (kW)	C_{Op} *(€/year)*
TS1	0.75	*693*	*533*	*-*	*27 703*
TS2	1.25	*1 155*	*-*	*752*	*21 714*
TS3	2	*1 848*	*110*	*145*	*21 945*
TS4	0.5	*462*	*110*	*-*	*3 812*
Total	4.5	*4 158*	*-*	*-*	*75 174*

3.2.3 Heating and cooling requirements

Before evaluating any energy integration measures for this process, one verifies that there is a clear opportunity to reduce solvent consumption in the production of each batch. As a result, the vapor produced in the second stage of the process (evaporation) must return as condensate to the mixing tank.

Initially, the solvent would have to be preheated from 15°C to 75°C. However, by returning to the system, the condensate at 100°C is mixed with fresh water at 15°C. Therefore, it is necessary to determine the new solvent's temperature resulting from this mixing. The calculation of this temperature involves an enthalpic balance around the junction node of the involved streams (figure 2).

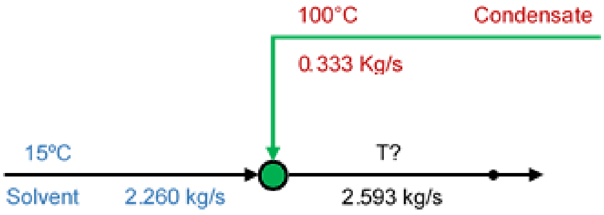

FIGURE 2 - STREAMS' JUNCTION NODE

The referred enthalpic balance that allows the determination of the unknown temperature (T? in figure 2) can be described by the following equation:

$$\Delta H1 + \Delta H2 = \Delta H3 \tag{1}$$

Once the average specific heat does not vary (water, 4.18 kJ/kg K), one obtains:

$$2.260\frac{kg}{s} \times (15°C - 15°C) + 0.333\frac{kg}{s} \times (100°C - 15°C)$$
$$= 2.593\frac{kg}{s} \times (T - 15°C)$$

By solving this equation, one determines that the new temperature is equal to 25.9ºC. As previously mentioned, the return of the condensate to the mixing tank allows a smaller consumption of fresh water in the production of each lot. Instead of 2.593 kg/s, the consumption becomes 2.260 kg/s, as displayed in figure 2. In addition, the temperature of the solvent increases from 15°C to 25.9°C, which allows the consumption of external utilities for heating the same to 75°C (temperature to enter the mixing tank) to reduce (€/kWh). This means the hot utility consumption can therefore be reduced by 18.2%.

4. RESULTS & DISCUSSION

Both the industrial processes presented in the previous chapter are amenable to improve their energy efficiency. Even though the pinch analysis is not applicable to the first case ("CarneMestra"), the recovery potential of the combustion gases emitted by the company's boiler is verified. Regarding the second case study, the software tool (PinCH) is applied and identifies new measures for energy integration in the nutrient salt production process, providing its economic evaluation as well.

4.1 Combustion gases recovery in "CarneMestra"

The boiler emits gases (during the natural gas combustion) which are being unused and are polluting the environment. This means that "CarneMestra" is not taking advantage of the gases' full potential for heating requirements, since they represent a good source of heat. The heat provided by these combustion gases can be used to heat the workshop (inside the company's facilities) air, which is normally very cold. This way, "CarneMestra" will improve its energy efficiency and reduce its ecological footprint.

4.2 Heat recovery potential

The study of the heat recovery potential in the PinCH software is carried out by the Energy Target Analysis tool (ETA). Since the costs associated with the thermal energy storage make the indirect recovery mode less preferable, the direct heat recovery potential is analysed first. The study of the indirect heat recovery potential is performed later. As a result, the heating and cooling requirements (consumption of external utilities) associated with the indirect heat recovery correspond to those that were not satisfied by the direct heat recovery.

4.2.1 Direct heat recovery

Since direct heat exchange between the process streams is only possible in TS3 (see figure 1), the minimum temperature difference (ΔT_{min}) can be optimized as a function of total cost, without influencing the remaining TSs and, consequently, the complexity of the heat exchanger network. Thus, the target results can be calculated through PinCH using the separate design tool during the targeting phase. Through the TS3 data table, PinCH identifies that the total cost is minimized for a ΔT_{min} = 10.53 K, corresponding to a pinch temperature of 59.7°C. Posteriorly, after completing the MER HEN design (the design of a network that respects the Minimum Energy Requirement and represents the Heat Exchanger Network), one identifies that with a 35 613€ investment in a new exchanger, it is possible to reduce 90 kW in both the hot and cold utility consumption. This represents a consumption decrease of 82% in hot utilities (from 110 kW to 20 kW consumed) and of 62% in cold utility (from 145 kW to 55 kW consumed). As a result, an annual saving of 166 MWh (90 kW × 10^ (- 3) × 1 848 h/year) in hot (UQ) and cold (UF) utilities can be obtained.

Considering that the investment has a 5% return rate and that it is depreciated over 7 years (corresponding to an annuity factor equivalent to 0.173), the annual cost associated with this energy integration measure is 6 161 €/year (35 613 × 0,173).

Although it is necessary to invest in a new heat exchanger, during the payoff period (7 years), there is an annual saving of 10 471 €/year. This corresponds to a 48% reduction in total annual costs.

4.2.2 Indirect heat recovery

After properly identifying the direct heat recovery potential, one verifies that there are still heating and cooling requirements to be satisfied. The indirect heat recovery potential study carried out by PinCH is based on the Indirect Source and Sink Profile (ISSP). Thus, as a result of this approach, the streams to be considered for thermal energy storage were selected. One verifies that the two streams that do not exchange heat directly ("Solvent" and "Vapor-condensate") are the ones that gather the best conditions to exchange heat indirectly. The remaining streams ("Concentrate" and "Liquor") have lower heat transfer coefficients, which makes them less suitable to exchange heat indirectly. In addition, their small amount of heat (kWh) does not justify the cost associated with the addition of new intermediate loops (ILs) and new layers in the stratified storage (SS).

For a process that already recovers heat directly, the ideal amount of heat to be considered in the storage corresponds to the total heat requirement of the "Solvent" stream (400 kWh). Under these conditions, PinCH identifies that the total cost (€/year) is minimized for a stratified storage in which the temperature of the lower and upper layers is 51°C and 93°C, respectively. Based on the loading and unloading thermal profile, PinCH estimates that the required storage unit must meet the following required characteristics:

- ✓ required volume (8 m ^ 3);
- ✓ Mass (8 t);
- ✓ Number of heat exchangers required (2);
- ✓ Total heat transfer area required (60 m^3).

According to the Pinch heat storage system savings' table, the implementation of this energy integration measure involves a storage investment of 118 601 € that is depreciated over seven years. This means an incurred annual cost of 20 528 €/year (annuity factor equivalent to 0.173). However, there is an annual reduction of 369 389 kWh/year in external utilities consumption. This means that the hot and cold utility use decreases by 81% and 38%, respectively, when compared to the process optimized only with direct heat recovery. This decrease in the use of external utilities results in a 36 939 €/year drop in operating costs (9 235 €/year in cold utilities and 27 704 €/year in hot utilities).

The costs and energy requirements of the process in the different integration scenarios mentioned (no integration, direct integration and direct plus indirect integration) are shown in the table 6.

TABLE 6 - SCENARIOS COMPARISON: (DIRECT) VS (DIRECT + INDIRECT)

	HU *(MWh/year)*	*CU* *(MWh/year)*	C_{Op} *(€/year)*	C_{Inv} *(€/year)*	C_{tot} *(€/year)*
(1*) Initial Situation*	624	1 137	75 174	0	75 174
(2) Direct Recovery	457	970	58 542	6 161	64 703
(3) Direct + Indirect	88	601	21 603	26 679	48 282
(4) Saving (1-3)	536	536	53 571	-26 679	26 892

Operating costs can be reduced by 71% if direct and indirect recovery measures are implemented. The total annual cost can be reduced by 36% during the first seven years. After this period, the investment is fully depreciated, and the total annual costs start corresponding only to the operational costs. In this way, after 15 years, the industrial unit can save:

$$(15 \times 75\,174) - (7 \times 48\,282 + 8 \times 21\,603) = \mathbf{616\,812}\ €$$

One concludes, therefore, that recovering heat directly and indirectly is the most advisable option for this industrial unit. The implementation of this energy integration measure allows a substantial reduction of 86% and 47% in the current hot and cold utilities' consumption, respectively.

4.2.3 Production scenarios analysis

This analysis serves the purpose of demonstrating the impact that different production scenarios have on the unit's heat recovery potential and total costs. This study focuses essentially on the variation of the number of batches produced per day.

Batch overlapping allows the exploring of the possibility for transferring heat directly between different batches. In this sense, when batches are overlapped, the direct heat recovery potential is considerably increased.

At present, the industrial unit produces three batches per day, each lasting seven hours and thirty minutes. To increase production, overlapping was considered by reducing the time interval between consecutive batches (Batch Cycle Duration) and increasing the number of batches per day. Thus, the following alternative scenarios were defined in PinCH's scheduling component:

- ✓ Production of 4 lots per day, each lasting five hours;
- ✓ Production of 6 lots per day, each lasting four hours;

Without changing production volume (924 batches per year), the number of work weeks can therefore decrease from forty-four (44) to thirty-three (33) in the first scenario. As a result, the direct heat recovery becomes possible in three of the four TSs (TS1, TS2 and TS3), instead of only in TS3. The annual cost associated with this mode of operation is 75 169 €/year. This value is very similar to the unit's current operating cost (75 174 €/year). Regarding the second scenario, the number of production weeks may decrease to twenty-two (22), with an additional TS being created. In this scenario, among the five existing TSs, direct heat recovery is possible in three of them (TS2, TS3 and TS4). The operating cost for this production scenario is 75 175 €/year, being therefore also similar to the current one.

Table 7 compares the current mode of operation (3 batches/day) with the two referred scenarios relatively to the direct heat recovery potential in each TS.

TABLE 7 - PRODUCTION SCENARIOS COMPARISON: POTENTIAL VS COSTS

batches	*Direct Heat Recovery Potential (kW)*							C_{Op}	C_{inv}	C_{tot}
	ΔT_{min} (k)	TS1	TS2	TS3	TS4	TS5	Total	*(€/year)*	*(€/year)*	*(€/year)*
3 batches	10,53	0	0	90	0	-	90	58 542	6 161	64 703
4 batches	40	34	34	100	0	-	168	64 270	5 383	69 653
6 batches	35	0	44	110	110	0	264	58 404	6 637	65 041

In PinCH, it is verified that the minimum temperature difference (ΔT_{min}) associated to the minimum total cost of integration is 40 K for the first scenario and 35 K for the second one. One identifies that, in relation to the current mode of operation, the heat recovery potential increases by 46% and 66% in scenarios 1 (4 lots) and 2 (6 lots), respectively. This is due to the amount of overlapping.

However, even recovering less heat, the current mode of operation is more appropriate if this energy integration measure (direct heat recovery) is to be implemented, because the total annual cost is lower than the other scenarios' cost (€ 64,703).

5. CONCLUSIONS & FUTURE DEVELOPMENTS

The absence of cooling requirements in the "CarneMestra" discussed process made it impossible to recover heat between streams, so the energy integration study had no effect. However, the company's process analysis stimulated the contact with the Portuguese industrial reality in the meat and meat related products sector. Also, the potential the boiler's combustion gases recovery was identified. The use of the combustion gases may be used to heat air which, in turn, may be useful for the heating of a workshop, which has a very low temperature.

PinCH has proven to be able to model batch processes and identify new energy integration measures for them. Likewise, it has proved to be very useful in the optimization of an academic-based industrial process, focused on the production of nutrient salt used in the composition of fertilizers.

One of the difficulties of this dissertation was the obtention of data that allowed the study of heat recovery in the Portuguese industrial context. Therefore, as future work, it is suggested the definition of a data collection plan for the methodology of the pinch analysis in batch processes.

In the future, it is also recommended to continue the exploration of the software PinCH, in order to optimize the most varied processes in the Portuguese industry. The various functionalities this tool provides, can be very useful as a support in real problems of energy efficiency decision-making. The use of this tool can also be an added value at an academic level, namely in the practical learning of energy integration concepts in this type of processes.

REFERENCES

Bon, J., Clemente, G., Vaquiro, H., Mulet, A., 2010. Simulation and optimization of milk pasteurization processes using a general process simulator (ProSimPlus). Comput. Chem. Eng. 34, 414–420. https://doi.org/10.1016/j.compchemeng.2009.11.013.

Bourgier, V., Schooley, K., Lawson, R., Technologies, W., 2017. Phosphates 2017 conference , Tampa Canola crop nutrition Phosphates market report Evaporation & crystallisation technology Applying evaporators & crystallisers to fertilizer production.

Chaturvedi, N.D., Bandyopadhyay, S., 2014. Indirect thermal integration for batch processes. Appl. Therm. Eng. 62, 229–238. https://doi.org/10.1016/j.applthermaleng.2013.09.042.

Douglas, J.M., 1988. Conceptual design of chemical processes. McGraw-Hill. https://doi.org/10.1002/jctb.280460308.

Fernandes, M.C.S., Matos, H.A., Nunes, C.P., 2016. Medidas Transversais de Eficiência Energética para a Indústria. Direcção-Geral de Energia e Geologia.

Fernández, I., Renedo, C.J., Pérez, S.F., Ortiz, A., Mañana, M., 2012. A review: Energy recovery in batch processes. Renew. Sustain. Energy Rev. 16, 2260–2277. https://doi.org/10.1016/j.rser.2012.01.017.

Fluch, J., Brunner, C., Grubbauer, A., 2017. Potential for energy efficiency measures and integration of renewable energy in the European food and beverage industry based on the results of implemented projects. Energy Procedia 123, 148–155. https://doi.org/10.1016/j.egypro.2017.07.243.

Foo, D.C.Y., El-Halwagi, M.M., Tan, R.R., 2017. Process Integration for Sustainable Industries A2 - Abraham, Martin A. BT - Encyclopedia of Sustainable Technologies. Elsevier, Oxford, pp. 117–124. https://doi.org/https://doi.org/10.1016/B978-0-12-409548-9.10032-6.

Hon Loong Lam, Klemeš, J.J., Zdravko Kravanja, Varbanov, P.S., 2011. Software tools overview: process integration, modelling and optimisation for energy saving and pollution reduction. https://doi.org/10.1002/apj.469.

Klemeš, J., Friedler, F., Bulatov, I., Varbanov, P.S., 2011. Sustainability in the Process Industry. Integration and Optimization. McGraw-Hill.

Muster-Slawitsch, B., Brunner, C., Fluch, J., 2014. Application of an advanced pinch methodology for the food and drink production. Wiley Interdiscip. Rev. Energy Environ. 3, 561–574. https://doi.org/10.1002/wene.117.

Petrides, D., Carmichael, D., Siletti, C., Koulouris, A., 2014. Biopharmaceutical Process Optimization with Simulation and Scheduling Tools. Bioengineering 1, 154–187. https://doi.org/10.3390/bioengineering1040154.

Relvas, S., Fernandes, M.C., Matos, H.A., Nunes, C.P., 2002. Grupo Nacional para a Integração de Processos (GNIP). Integr. Process. - Uma Metodol. Optim. energética e Ambient. 129.

Smith, R. (Chemical engineer), 2005. Chemical process design and integration. https://doi.org/10.1529/biophysj.107.124164.

U.S. Energy Information Administration, 2016. International Energy Outlook 2016, International Energy Outlook 2016. https://doi.org/www.eia.gov/forecasts/ieo/pdf/0484(2016).pdf.

Vannoni, C., Battisti, R., Drigo, S., 2008. Potential for solar heat in indutrial processes. IEA SHC Task 33 and and SolarPACES Task IV: Solar heat for industrial processes. Iea 1–21.

Wilson, J.M., 2003. Gantt charts: A centenary appreciation. Eur. J. Oper. Res. 149, 430–437. https://doi.org/10.1016/S0377-2217(02)00769-5.