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Energy, Exergy and Advanced Exergy Analysis of a Milk Processing Factory

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Abstract

Energy, exergy and advanced exergy methods were used to analyse a milk powder production facility. While a conventional energy analysis is used to map the energy flows and to suggest possibilities for process integration through pinch analysis, an exergy analysis identifies the locations and magnitudes of thermodynamic irreversibilities. The advanced exergy analysis determines the real potential for thermodynamic improvements by dividing the exergy destruction into its avoidable and unavoidable parts, which relate to technological limitations, and into its endogenous and exogenous parts, which present the interactions between the different sub-systems. This analysis was based on factory data with which the complete production line (milk treatment, evaporators and dryers) and the utility systems were modelled. The results show the potential for optimisation and a comparison of the applicability of the different methods to the dairy industry. The pinch analysis and energy mapping showed that the potential for heat integration was small. The exergy analysis revealed the gas burner and spray dryer caused most exergy destruction, while the heaters had low exergy efficiencies. The advanced exergy analysis found the evaporators to have a high share of avoidable exergy destruction. However not all results from the advanced exergy analysis were practical.

Keywords: Energy efficiency, Exergy analysis, Advanced exergy analysis, Process integration, Pinch analysis, dairy Industry

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Nomenclature

cp	Specific heat capacity, kJ/(kg K)
$\dot{E}$	Exergy rate, kW
e	Specific exergy, kJ/kg
$\dot{H}$	Enthalpy rate, kW
h	Specific enthalpy, kJ/kg
$\dot{m}$	Mass flow rate, kg/s
$\dot{Q}$	Heat rate, kW
s	Specific entropy, kJ/(kg K)
T	Temperature, °C
$\dot{W}$	Power, kW
y^*	Exergy destruction ratio, -

Abbreviations

A	Air in spray drying section
AF	Air to fuel
AP	Air to product
B	Gas boiler
C	Cream treatment section
CU	Cold utility
DM	Dry matter
E	Product/ Component in evaporation section
EV	Evaporation
H	Component in milk treatment section
HU	Hot utility
LHV	Lower heating value
M	Milk treatment section
MER	Minimum energy requirement
MT	Milk treatment
MVR	Mechanical vapour recompression
P	Product in spray drying section
R	Component in cold utility section
RM	Refrigeration cycle
S	Component in spray drying section
SD	Spray drying
TVR	Thermal vapour recompression
U	Component in hot utility section
VE	Vapour in evaporation section

Greek letters

α	Carbon atoms, -
β	Hydrogen atoms, -
λ	Air to fuel equivalence ratio, -
χ	Molar fraction, -
ΔT	Temperature difference, K
ε	Exergy efficiency, -
ε^*	Modified exergy efficiency, -
η	Energy efficiency, -
μ	Chemical potential, -

Subscripts

0	Environmental state
00	Dead state
Conc	Concentrate
D	Destruction
Di	Diffuser
e	Exergy
F	Fuel
in	Inflow
is	Isentropic
k	Component
min	Minimum
N	Nozzle
out	Outflow
P	Product
sat	Saturation
Stoich	Stoichiometric
tot	Total

Superscripts

AV	Avoidable
EN	Endogenous
EX	Exogenous
Q	Thermal
UN	Unavoidable
W	Work

1. Introduction

An increase in energy efficiency of the industrial sector would significantly reduce the greenhouse gas emissions caused by the burning of fossil fuels and the production costs associated with energy use. The production of dairy products, such as milk powder and cheese, is a major industrial sector in Denmark and Europe, It is also one of the most energy-intensive industries within the food sector [1]. Denmark has a high share of agricultural products in their overall exports, of which 20 % of the agricultural exports are dairy products. A total of 4.7 billion kg of raw milk are processed in 61 production plants, resulting in export revenues of 1.8 billion Euro [2]. Several scientific and engineering methods exist and are under continuous development, which target the the determination, quantification and prioritisation of possible energy savings in complex and large-scale industrial processes. The potential for an increased energy efficiency of the dairy production processes, which are in Denmark often already highly integrated, still exists. As shown by [1], the energy use per amount of final dairy product has steadily decreased in France, Germany, the Netherlands and UK. Also large differences were observed amongst countries, indicating that a more energy efficient production is possible. Masanet et al. [3] further shows several energy efficiency opportunities which could be considered to be implemented in dairy factories. The aim of the present work was to identify this efficiency potential by applying and assessing different thermodynamic methods. The applied methods were based on energy analysis, exergy analysis and advanced exergy analysis, as well as pinch analysis.

Van Gool [4] investigated the use of exergy in the design and analysis of industrial processes, also comparing the exergy method to conventional thermodynamic analyses. The discussion implies that exergy analysis in the design of a process often shows losses already known. However, exergy analysis also determines the efficiency of the process, which in combination with the losses determine the improvement potential. The work by McKenna [5] analysed a glass furnace using energy and exergy analysis and a mechanical paper making process using pinch analysis. The discussion of the methodologies shows that the energy system often determines the applicable methodology. In the case of exergy analysis it was possible to differentiate between exergy losses and destruction, as well as highlight the areas on which to focus for improvements. These focus areas were however similar to the ones obtained from the energy analysis. One important issue raised by McKenna [5] was the high share of unavoidable exergy destruction in many processes, such as combustion, which resulted in low exergy efficiencies.

For the dairy industry in particular, several studies were conducted in the last years. These studies primarily analysed the milk processing [6, 7] or focused on the drying process [8]. Quijera and Labidi [6] and Quijera et al. [9] evaluated and optimised the integration of solar thermal technologies in the processes of cheese and yoghurt manufacturing, using the pinch and exergy methods. An exergy analysis for the pasteurisation process of milk was performed by Fang et al. [7], where an optimisation of the process was also included. Most recently, Yildirim and Genc [10] performed an exergy analysis of a milk powder production system, consisting of a single stage evaporator and a spray dryer. Srinivasan et al. [11] analysed an Indian milk powder plant using exergy analysis with the main aim being a comparison of two energy efficiency scenarios. The suggested energy efficiency measures increased the exergy efficiency of the overall system, in particular the pre-heaters were improved. The general usefulness of exergy as an analysis tool for the dairy industry was discussed by Vidal et al. [12]. A milk powder production facility in New Zealand was used as case study and analysed for the purpose of investigating the usefulness of exergy methods. The analysis was based on component-wise product input/output states, for which an exergy analysis was conducted. The authors concluded that exergy might be useful to design and optimize different units of operations within dairy processes. The exergy losses of flavoured yoghurt production were determined by Sorgüven and Özilgen [13], and the production of other ingredients than milk was also included from a cumulative exergy perspective.

Several exergy analyses were conducted for different systems within the food industry and a study by Trägårdh [14] used exergy as a quality factor. Most relevant for this work were articles on drying and evaporation technologies, such as Marnoch et al. [15] who performed an exergy analysis of broccoli drying. A review of exergy analyses of drying processes was done by Aghbashlo et al. [16]. Dincer and Sahin [17] proposed a new thermodynamic model for drying processes based on exergy analysis. Evaporation in food processes was discussed by Leo [18] for the processing of citrus fruits. Balkan et al. [19] analysed a three-effect evaporator for fruit juice processing applying exergy analysis. Winchester [20] analysed the modelling and operation of falling film evaporators at the example of a dairy plant. Most recently Zhang et al. [21] compared a five-effect evaporator to a three-effect evaporator with mechanical vapour recompression for milk concentration. The latter only used one third of the energy compared to the conventional five-effect one. Much of the literature on evaporation with thermal and mechanical vapour recompression technologies focused on sea water desalination. For instance Choi et al. [22] did an exergy analysis of thermal vapour recompression evaporators, suggesting new designs and operating parameters.

The exergy destruction occurring in a given component depends on its characteristics and is also impacted by the performance of the other components present in the system. The common exergy analysis has some barriers to show the real recoverable losses, which can be identied by an advanced exergy analysis [23, 24]. The method of advanced exergy analysis is described in detail in the literature and has been applied to many different systems, such as refrigeration machines [25] and combined cycle power plants [26]. In addition, advanced and conventional exergy analyses have been applied to an industrial plant in two studies [27, 28] for the production of rubber. These analyses document the benefits of carrying out an advanced exergy analyses, as the improvement priorities can be ranked based on exergy destruction.

The published works until now have shown that the application of different methods for analysing industrial processes, components and utilities can reveal optimisation potentials and allows the comparison of different alternatives. However, it is also noted in the literature that many of these advanced methods are not applied in industrial practice. Rosen [29] states that exergy is often not utilised in industry as the method may be considered inconvenient or complex and the results as difficult to interpret and utilize. An overview of the application of possible methods and a comparison of the outcomes, would give a better understanding of the practical applicability of the methods for process analysis and additional information which could be obtained compared to normal engineering methods. For dairy production systems in particular, several analyses have been performed in the past as shown above. No study applied advanced exergy analysis on a food production processes, nor where the interactions between the utility systems and the production system analysed using advanced thermodynamic methods. Investigating these relations would give additional insights in the process, optimisation opportunities and present a basis for changes in the utility systems.

The aims of this study were to: (i) determine the energy improvement potential and inefficiencies of an integrated milk powder production line using energy and exergy methods, (ii) study the interactions of the system by applying the concept of advanced exergy analysis and (iii) compare the different methods for the analysis of inefficiencies and improvement potentials in industrial processes. The focus was the application of exergy and advanced exergy methods, while comparing the results to energy analyses applied in the consultancy and process integration. The conclusions drawn from performing the different analyses were compared amongst each other. The comparison included a discussion of the applicability of the second law methods in industrial practice and identifying challenges occurring in their application. The comparison was performed qualitatively, based on the required modelling effort, level of detail, assumptions, experience and the main improvement suggestions obtained from each method. The work took origin in Bühler et al. [30], where an advanced exergy analysis of the production steps milk treatment and evaporation was performed.

The article is organised as follows. First the case study and the approaches for modelling the dairy system are introduced in Section 2.1. This is followed by an introduction to the applied methodologies (Section 2) and the results of the analyses (Section 3). Finally the methodologies are compared in the discussion and conclusions are drawn.

2. Methods

In the following the methods applied in this work are described. The work is based on the modelling of a case study which is first introduced, together with the modelling approach and assumptions (Section 2.1). This is followed the description of the methods used for the case analysis (Section 2.2).

2.1. Case Study and System Modelling

The case study was conducted for a large dairy factory producing primarily milk powder. Both the production line and the utility system were included as shown schematically in Figure 1. The modelled milk processing line was part of several parallel production lines, representing all major production steps. The processing line consists of the following subsystems:

(i) Separation of raw milk into skimmed milk and cream alongside with thermal treatment of the two products (pasteurisation)
(ii) Mixing of skim milk with additives, homogenisation and high temperature treatment
(iii) Preheating of the mixture and evaporation of water in multi-effect evaporators
(iv) Drying of the milk concentrate in spray and fluidised bed dryers

Each subsection has fixed set points (temperature, pressure and dry matter content), and can be operated individually. The three first subsections are similar and are located in the same production unit, implying that the dairy factory can be split into three sections (milk treatment, evaporation and drying) which are used in the following.

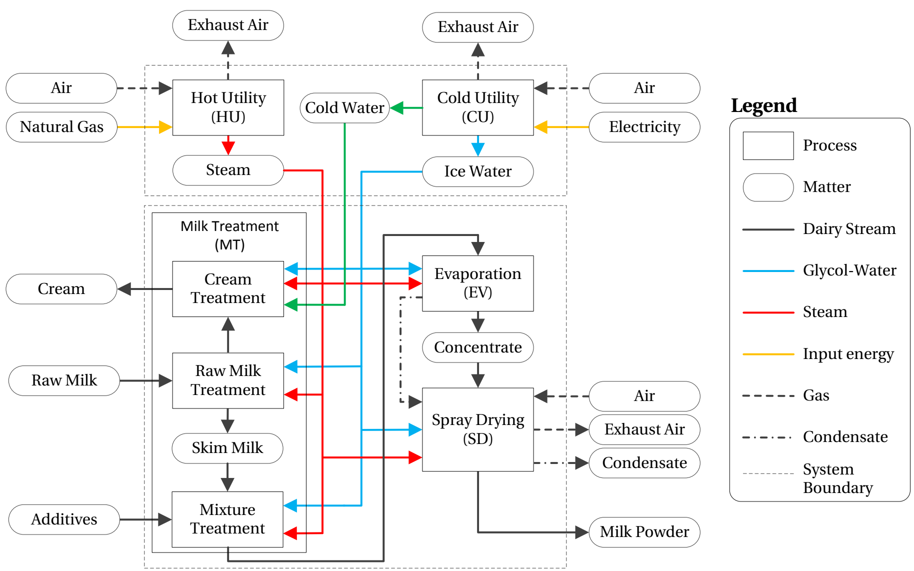


Figure 1: Dairy processing line for the production of milk powder with the main manufacturing units and materials.

2.1.1. *Production*

The studied milk processing system is shown schematically in Figure2, where the main components and states are shown. The incoming raw milk is heated to the separation temperature at 50 °C, where the raw milk is separated into cream (C1) and skimmed milk (M3) by means of a centrifuge. The skimmed milk and cream are then pasteurised (at 75 °C and 85 °C, respectively) and cooled down to 5 °C, first by a regenerative heat exchanger and secondly with the cold utility. The skimmed milk is further enriched and standardised with additives (i.e. vegetable fats, sugars, vitamins and minerals). The resulting mixture is pasteurised and cooled down a second time. In the evaporation section (Fig.

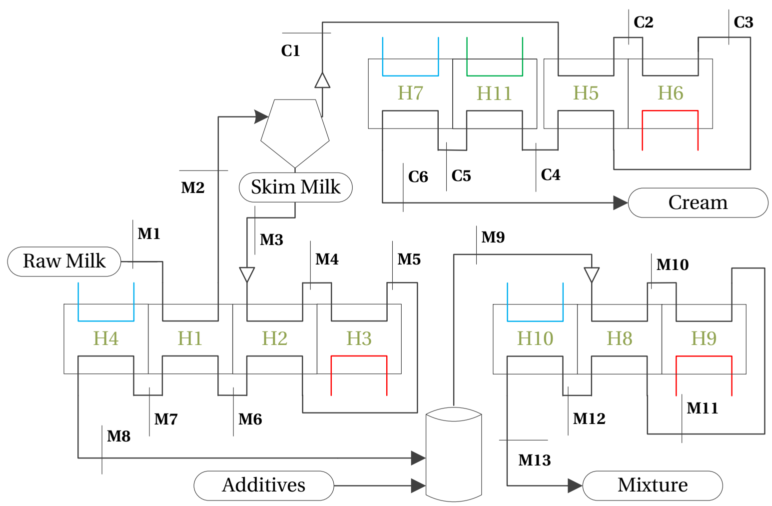


Figure 2: Milk treatment section for the pasteurisation, pre-concentration and mixing of milk and cream. The state points for milk (M) and cream (C) can be found in Appendix B and components are enumerated starting with H.

3) the mixture is heated to up to 85 °C in one regenerative step and one with externally supplied heat. The evaporation of milk first takes place in one single stage evaporator with mechanical vapour recompression (MVR) at 75 °C where the dry matter (DM) content is increased from 15 % to 35 %. The DM content is further increased to 52 % in one three-effect evaporator with thermal vapour recompression (TVR) at an evaporation temperature of 67 °C in the first step. After the concentrate is preheated to 75 °C, it is injected into the spray dryer by an atomiser. The remaining water is removed in the spray drying system to achieve a DM content of 95 %, as shown in Fig. 4. The air for the spray dryer requires a temperature of 210 °C. This is achieved by first heating the air with condensate from the evaporators, followed by a steam heater. The powder leaving the spray dryer is further treated in an external fluidised bed dryer, where primarily the milk powder is cooled and correct product consistency is achieved. After the fluidised bed dryer a dry matter content of 97.5 % of the product is obtained. The drying air is filtered in a cyclone, to recover milk powder, and in a last stage in a bag filter before leaving the system.

2.1.2. Utility

In addition to the production line the utility system is further included in the analysis. The heating demand is covered by steam at 25 bar supplied from a natural gas fired boiler (Fig. 5a). This pressure level is chosen to supply the

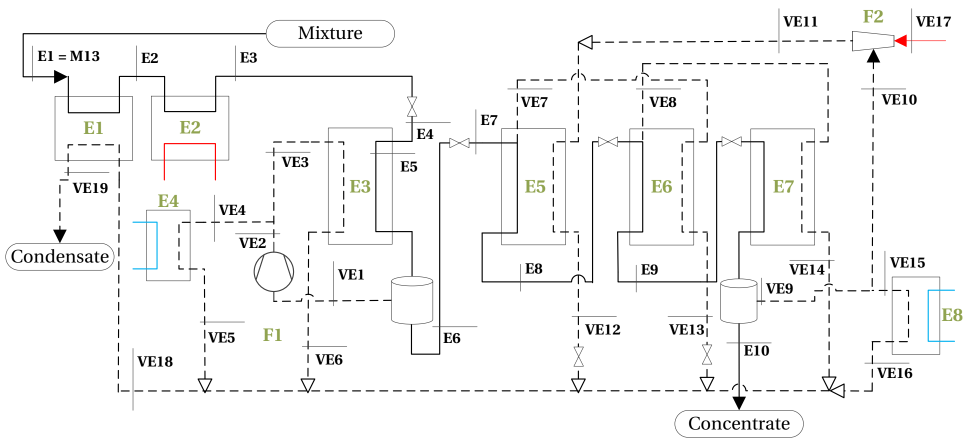


Figure 3: Evaporation section for the production of milk concentrate. The state points for product (E) and vapour/ condensate (VE) can be found in Appendix B and components are enumerated starting with E or F.

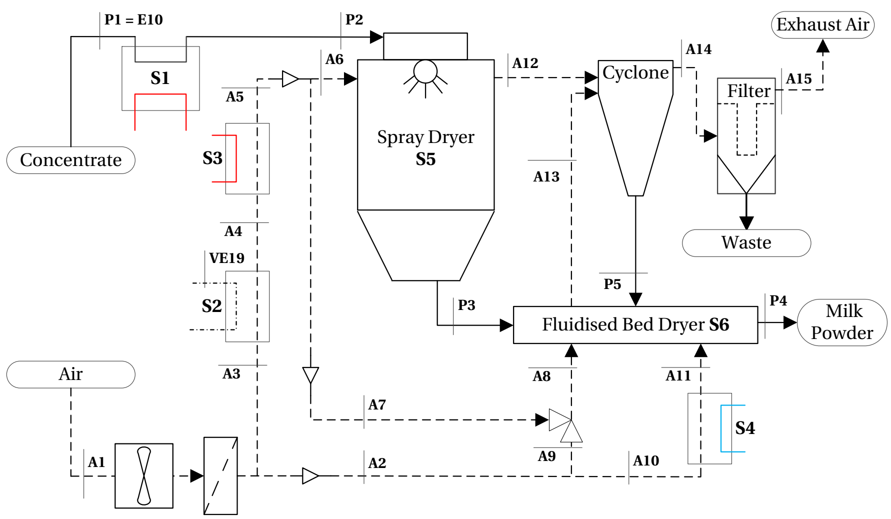
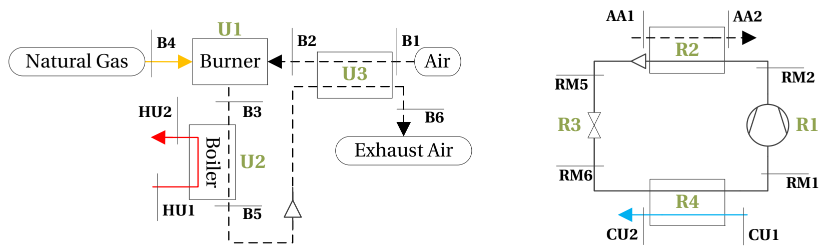


Figure 4: Drying section for the production of milk powder. The state points for the product (P) and air (A) can be found in Appendix B and components are enumerated starting with S.

highest temperature in the system with saturated steam. The combustion gases enter a boiler and are afterwards used to preheat the combustion air. Other systems may use the exhaust gases for feed- or makeup water preheating. The cooling demand is provided by ice water, an ethylene glycol-water mixture, with glycol content of 30 %. The ice water is supplied by an ammonia refrigeration system, which can be seen in Fig. 5b. The set-point for the ice water is 2.5 °C. All state points of the utility can be found in Appendix B.



(a) Hot utility

(b) Cold utility

Figure 5: Natural gas boiler with economiser for the hot utility supply and refrigeration cycle for cold water supply. The state points for the hot utility (B) and cold utility (RM) can be found in Appendix B and components are enumerated starting with U and R.

2.1.3. Model assumptions

The process modelling built upon the real operation parameters and conditions of the production line, as found in process data and from on-site measurements. The following assumptions were taken. The processing line produces different products that are pasteurised at different temperature levels, and they have varying dry matter contents after the mixing unit, depending on the milk additives. The input feed was modelled as a representative mixture with a composition corresponding to the use of skimmed milk and additives. The number of evaporation steps and their division in the MVR and TVR depends, amongst others, on the product mixture. In this work the most common set-up was chosen. It consists of a single-effect MVR and a three-effect TVR. The heat losses from process components, such as heat exchanger, were neglected. The start-up behaviour of the produciton lines and cleaning in place (CIP) were not included in this work. The reader is referred to [31], where a detailed technical description of the technologies, componenents and processes used in the production of milk powder is presented. The work by [32] gives an extensive description of the evaporation with vapour compression in single and multiple stages for salt water desalination.

The heat exchangers were modelled with energy balances, based on the streams inlet and outlet enthalpies and mass flow rates.

$$\dot{m}_{\text{hot}}\left(h_{\text{hot,in}} - h_{\text{hot,out}}\right) = \dot{m}_{\text{cold}}\left(h_{\text{cold,out}} - h_{\text{cold,in}}\right) \tag{1}$$

If a dairy stream was present at either side of the heat exchanger, the specific heat capacity of the milk was used, which was found as described in Section 2.1.4. For the pasteurisation, for example, the heat requirement was found as:

$$\dot{Q}_{\text{milk}} = \dot{m}_{\text{milk}} \frac{c_{p\,\text{milk,in}} + c_{p\,\text{milk,out}}}{2}\left(T_{\text{milk,out}} - T_{\text{milk,in}}\right) \tag{2}$$

The evaporators were modelled following Eq. 3, where the condensation of the steam takes place on the hot side.

$$\dot{m}_{\text{hot}}\left(h_{\text{hot,in}} - h_{\text{hot,out}}\right) = \dot{m}_{\text{conc,out}} h_{\text{conc,out}} + \dot{m}_{\text{vapour,out}} h_{\text{vapour,out}} - \dot{m}_{\text{conc,in}} h_{\text{conc,in}} \tag{3}$$

The entrainment ratio for the ejector used in the TVR was found based on Granryd et al. [33], where η_{N} and η_{Di} are the isentropic efficiencies of the nozzle and the diffuser, respectively.

$$\frac{\dot{m}_{\text{VE,10}}}{\dot{m}_{\text{VE,17}}} = \sqrt{\left(\eta_{\text{N}}\eta_{\text{Di}}\right)\frac{\left(h_{\text{VE17}} - h_{\text{VE10,is}}\right)}{\left(h_{\text{VE11,is}} - h_{\text{VE10}}\right)}} - 1 \tag{4}$$

The isentropic efficiency of the compressors in this work was defined as in Eq. 5 at the example of the MVR.

$$\eta_{\text{is}} = \frac{\left(h_{\text{VE2,is}} - h_{\text{VE1}}\right)}{\left(h_{\text{VE2}} - h_{\text{VE1}}\right)} \tag{5}$$

The air requirement for the spray dryer and fluidised beds were found based on the data from the factory. A fixed air to product ratio, AP, was used.

$$\dot{m}_{\text{A16}} = \dot{m}_{\text{P3}}\text{AP} \tag{6}$$

The burner U1 in the hot utility was modelled by assuming a complete combustion of methane with excess air as shown in the stoichiometric equation Eq. 7. An air to fuel ratio, AF, was chosen as to obtain an excess air ratio, λ, of 1.67 and a combustion gas temperature of 1325 °C. This was achieved by the mass and energy balances below.

$$\text{CH}_4 + 2\lambda(\text{O}_2 + 3.76\text{N}_2) \longrightarrow \text{CO}_2 + 2\text{H}_2\text{O} + 2\lambda\text{N}_2 + 2(\lambda - 1)\text{O}_2 \tag{7}$$

$$\lambda = \frac{\text{AF}}{\text{AF}_{\text{Stoich}}} \tag{8}$$

$$\dot{m}_{\text{B2}} = \dot{m}_{\text{B4}}\text{AF} \tag{9}$$

$$\dot{m}_{\text{B3}} h_{\text{B3}} = \dot{m}_{\text{B2}} h_{\text{B2}} + \dot{m}_{\text{B4}} h_{\text{B4}} \tag{10}$$

The enthalpy h_{B4} was set to the heating value of methane. The water content of the inlet air was set equal to ambient air while the one of the flue gases was found based on the stoichiometric equation. During the normal operation, no condensing of the flue gases occurred, it was necessary to account for the possibility of water condensation in the combustion air pre-heater for the cases described in the following Sections.

The refrigeration unit was based on a simple vapour compression cycle using Ammonia (R717) as a refrigerant. The compressor was modelled analogue to Eq. 5 with an isentropic efficiency of 0.75. The evaporator was split into two parts, one for evaporation and one for super-heating. The condenser was split into a cooling, condensing and sub-cooling region. It was assumed that there is 1 K sub-cooling and super-heating respectively. The valve was, in the energy model, considered with a constant enthalpy.

$$h_{\mathrm{RM5}} = h_{\mathrm{RM6}} \tag{11}$$

2.1.4. Dairy properties

The composition of the product flow throughout the system is changing, as separation and evaporation processes take place. This impacts the thermal properties, i.e. heat capacity, of the dairy flows. Based on the correlations and milk composition given [34], the heat capacity of the different milk products was found as a function of the composition (fat, protein, carbohydrates, ash and water) and temperature. An overview of the milk compositions used in this production line can be found in Appendix A.

2.2. Analysis

The analysis of the dairy factory consists at first of a conventional energy mapping and analysis which could be applied in the consultancy using factory data and measurements without any modelling. These types of energy mappings were observed at a project partner. Secondly, the pinch analysis is shown, as a more advanced method for energy efficiency within the industry. Thirdly the methods for exergy and advanced exergy analysis are presented as applied to the dairy plant model.

2.2.1. Energy Mapping

The energy mapping, as often used in consultancy, consists of the process analysis and the determination of all relevant components, mass flows and temperatures. This analysis is also the starting point for all other methods, however this mapping usually centres around the components with a high steam or ice water use, i.e. heaters and coolers. The other methods require more detailed analyses, resulting in the process information shown in Section 2.1.

The overall aims of the energy mapping are to (i) establish an overview of the energy use in the factory, (ii) find inefficient components and (iii) locate possibilities for energy efficiency improvements, while requiring a minimum amount of data and modelling effort. These aims were achieved by establishing the heating and cooling demands for all components. This was done by using the annual mass flows, which were known to a high accuracy based on the production volumes. Furthermore, the temperature differences, which were obtained from the Piping and Instrumentation Diagrams (P&ID) and, if necessary and available, measurements, were required for the energy balances. Performance indicators, which were obtained from data sheets and other reference factories, were also used for components with none of the above data being sufficient to determine the energy use. Based on this information the temperature difference over the product side for each heater and cooler was calculated and compared to reference values from experience. If the temperature differences appeared higher than what was typically feasible, while also accounting for the energy prices, extensions of the heat transfer area were recommended. By accounting for all thermal energy uses, their distribution by temperature was investigated to find overlaps between heating and cooling demands, which could indicate the possibility for process integration.

2.2.2. Pinch Analysis

Process integration techniques are powerful tools that aim at minimising the use of external energy utilities (e.g. heating by a boiler or cooling by a refrigeration cycle) by maximising internal heat recovery and possibly adjusting the process parameters. The most well-known method is named pinch analysis and was developed by Linnhoff and Flower [35] in the 80's for designing heat exchanger networks in chemical processes. It was also applied to industrial sites, as discussed in Smith [36] and Klemeš [37], and to dairy factories, e.g. by Atkins et al. [38]. The heating demand of these is much higher than the cooling demand, because of the significant drying needs [1].

The pinch method can be subdivided into four steps: (i) data extraction, similar to or based on the energy mapping (ii) definition of a minimum temperature difference, which sets the heat transfer potential between two streams in a given heat exchanger; (iii) evaluation of the maximum internal heat recovery and minimum utility demands (setting thermodynamic targets) and (iv) proposing system improvements by means of a re-design of the heat exchanger network (retrofit) or integration of processes such as cogeneration and heat pumping.

2.2.3. Energy Analysis

The energy analysis of the model was based on the 1st law of thermodynamics. For an open system, energy can be transferred in and out of the system with streams of matter, heat and work. In this work the changes in kinetic and potential energies were not consider. This implies that the energy balance in steady-state conditions, on a rate form, can be expressed as follows:

$$\sum_{\text{in}} \dot{H}_{\text{in}} - \sum_{\text{out}} \dot{H}_{\text{out}} + \sum_{k} \dot{Q}_k - \dot{W} = 0 \tag{12}$$

$$\sum_{\text{in}} h_{\text{in}} \dot{m}_{\text{in}} - \sum_{\text{out}} h_{\text{out}} \dot{m}_{\text{out}} + \sum_{k} \dot{Q}_k - \dot{W} = 0 \tag{13}$$

2.2.4. Exergy Analysis

The exergy of a system can be defined as the maximum work that can be performed by a system when it is brought into equilibrium with its reference environment. Exergy is thus only conserved when all processes occurring in the system are reversible. Unlike energy, exergy can be destroyed and is not conserved. A system, which is in thermal and mechanical equilibrium, meaning having the same temperature and pressure, with the environment is in the 'restricted dead state' [39]. The system is in 'dead state' if it is also in chemical equilibrium.

This thermodynamic concept is built on the 1st and 2nd law of thermodynamics, reflecting that all transformations are irreversible in nature and generate entropy. The exergy destruction of the system under study is defined as the difference between the in- and outlfowing exergy, and can be derived from the previous relations as:

$$\sum_{\text{in}} \dot{E}_{\text{in}} - \sum_{\text{out}} \dot{E}_{\text{out}} + \sum_{k} \dot{E}_{k}^{Q} - \dot{E}^{W} = \dot{E}_{D} \tag{14}$$

$$\sum_{\text{in}} e_{\text{in}} \dot{m}_{in} - \sum_{\text{out}} e_{\text{out}} \dot{m}_{\text{out}} + \sum_{k} \dot{E}_{k}^{Q} - \dot{E}^{W} = \dot{E}_{D} \tag{15}$$

The specific flow exergy of a stream of matter consists of physical, chemical, kinetic and potential components. Excluding the kinetic and potential components, the specific exergy can be expressed as follows:

$$e = \left[(h - h_0) - T_0\,(s - s_0)\right] + \left[\sum_{j} (\mu_{j0} - \mu_{j00})\,\chi_j\right] \tag{16}$$

The first part of Eq. 16 describes the physical exergy, which is the maximum useful work that can be extracted from the stream when it is brought to thermal and mechanical equilibrium with the environment. The second term, which is the chemical exergy, is the maximum useful work that can be extracted from the stream when it is brought from the environmental state (denoted with the subscript 0) to the dead state (denoted with the subscript 00). In the system under study, no chemical reactions take place with the exception of fuel combustion. The changes of chemical exergy associated with mixing and separation are negligible in comparison with the variations of physical exergy. The changes in chemical exergy, except for the fuel conversion processes, are therefore not considered in the present study. The specific chemical exergy of the gaseous fuel is approximated based on Moran [40] by Eq. 17. The parameters α and β represent the number of carbon and hydrogen atoms in the fuel, respectively. The chemical exergy of the combustion gases is further found using the standard chemical exergy [41].

$$e_{\text{fuel}}^{\text{CH}} = \left(1.033 + 0.01698\frac{\beta}{\alpha} - \frac{0.0169}{\alpha}\right) \text{LHV} \tag{17}$$

The exergy product $\dot{E}_{P,k}$ and exergy fuel $\dot{E}_{F,k}$ of the component k are defined based on the component function and are calculated from the exergy streams at the inlet and outlet. The exergy efficiency can therefore be defined using Eq. 18 and further the exergy destruction ratio can be defined by Eq. 19.

$$\varepsilon_k = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}} \tag{18}$$

$$y_{D,k}^{*} = \frac{\dot{E}_{D,k}}{\dot{E}_{D,\text{tot}}} \tag{19}$$

The most frequent components in the studied system were heat exchangers, which operated above the environmental state. In this case, the product exergy is usually defined as the increase of exergy related to the heating of the cold process streams [39]. Several heat exchangers in the system also operated across the environmental state. As their exergy products and fuels were not trivial, they also had to be considered. If all streams crossed the environmental state, the product exergy was defined as the sum of the exergy streams at the outlets and the fuel as the sum of exergy at the inlets. If all streams were below the environmental state, the exergy difference of the hot steam was the product and the difference of the cold stream the product. Exergy losses were further considered when a stream crossed the system boundary. Exergy losses, as can also be seen in Figure 1, were the exhaust gasses from the hot and cold utility, the dryer and condensate from the evaporators.

The dead state in this work was defined as being the ambient pressure (1 bar) and at a temperature of 15 °C. For water this corresponds to an enthalpy of 63.08 kJ/kg and a specific entropy of 0.224 kJ/(kg K). The choice of the dead state temperature was made to account for the Northern European climate and comparability with other studies [30, 42]. Erbay and Koca [8] analysed the impact of dead-state temperature on the exergy efficiency of a spray drying process. While increasing dead state temperature reduced the exergy efficiency, it had negligible effects on the possible range considered in this work.

2.2.5. Advanced Exergy Analysis

A conventional exergy analysis cannot assess the real potential for optimising a given system, as the conventional method disregards the mutual interdependencies of the system components and technological limitations [25, 43]. Advanced exergy analysis addresses these drawbacks by dividing the exergy destruction into its unavoidable and avoidable parts, and into its endogenous and exogenous parts.

The splitting into unavoidable and avoidable exergy destruction is done in order to take into account that some of the exergy destruction cannot be prevented. There are physical and economic constraints, e.g. limitations on the maximum possible isentropic efficiency of a real compressor, which limits the optimisation potential [44]. The optimisation of the system should thus focus on improving components with a high rate of avoidable exergy destruction. The rate of exergy destruction is divided into two parts for the k-th component, the avoidable part $\dot{E}_{D,k}^{\mathrm{AV}}$ and the unavoidable one $\dot{E}_{D,k}^{\mathrm{UN}}$.

$$\dot{E}_{D,k} = \dot{E}_{D,k}^{\mathrm{AV}} + \dot{E}_{D,k}^{\mathrm{UN}} \tag{20}$$

The unavoidable exergy destruction is defined as the remaining exergy destruction when the component of interest is designed for highest thermodynamically possible performance and economically feasible limit. The value for the unavoidable exergy destruction is obtained by Eq. 21.

$$\dot{E}_{D,k}^{\mathrm{UN}} = \dot{E}_{P,k} \left(\frac{\dot{E}_{D,k}}{\dot{E}_{P,k}} \right)^{\mathrm{UN}} \tag{21}$$

Following [23] the modified exergy efficiency ε_k^* was used to describe the avoidable exergy destruction in the kth component.

$$\varepsilon_k^* = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k} - \dot{E}_{D,k}^{\mathrm{UN}}} \tag{22}$$

The exergy destruction can further be split into endogenous and exogenous parts. The endogenous part of the exergy destruction $\dot{E}_{D,k}^{\mathrm{EN}}$ of the k-th component is the exergy destruction of this component at its current efficiency when all the other system components operate in an ideal way. The exogenous part of the exergy destruction $\dot{E}_{D,k}^{\mathrm{EX}}$ within the k-th component is related to the irreversibilities imposed on the component by the other components present in the system.

$$\dot{E}_{D,k} = \dot{E}_{D,k}^{\mathrm{EX}} + \dot{E}_{D,k}^{\mathrm{EN}} \tag{23}$$

$$\dot{E}_{D,k}^{\mathrm{EN}} = \dot{E}_{P,k} \left(\frac{\dot{E}_{D,k}}{\dot{E}_{P,k}} \right)^{\mathrm{EN}} \tag{24}$$

The real operating conditions shown in Table 1 and minimum temperature differences found in Appendix B, were the ones found at the factory. Existing improvement opportunities of the system components are the avoidable conditions, which can be obtained with technically and economically feasible changes. They are shown in the second column in Table 1 and for heat exchangers, based on the fluids, in Table 2. The values for the heat exchanger, compressors, ejectors and valves were based on systematic assumptions, taking values reported in the literature into account [45, 28, 24]. The values for AP and AF in the unavoidable conditions were chosen so that the process can realistically still take place, considering the materials (flame temperature) and air temperature. The theoretical conditions, expressing the thermodynamically ideal conditions are given in the last column of Table 1. For heat exchangers the theoretical minimum temperature difference is 0 K. The theoretical value of AF is equal to the stoichiometric air to fuel ratio for a complete combustion of methane. The theoretical values for the air to product ratio of the SD and FB were chosen, so that the air had sufficient heat to absorb the water, while there was no condensation taking place throughout the system (relatively humidity below 1).

The theoretical system is usually simulated with either a constant exergy product or fuel [43]. However, in this case it was not practical as the actual product of the overall system was hardly definable in a thermodynamic sense. For example, the pasteurisation and cooling of streams was required, but the streams were after these operations in the same thermodynamic state. Additionally, there were different sources of fuel, as well as internal heat recovery loops, which could not be kept constant. The simulations were thus performed with a varying fuel and product relating the endogenous exergy destruction to the one of the real system using Eq. 24.

Table 1: Real, unavoidable and theoretical operating conditions of components in the production line.

Component			Real	Unavoidable	Theoretical
F1	Compressor	η_{is}	0.75	0.95	1
F2	Ejector	η_N, η_{Di}	0.92	0.95	1
S5	Spray Dryer	AP-Ratio	16.5	15	11.25
S6	Fluidised Bed	AP-Ratio	0.93/ 1.65	0.80/ 1.50	0.67/ 0.55
U1	Burner	AF-Ratio	30	20	17.2
R1	Compressor	η_{is}	0.75	0.95	1
R3	Valve	η_{is}	0	0	1

Table 2: Unavoidable minimum temperature differences in heat exchangers based on fluids.

$\Delta T_{\mathrm{min}}^{\mathrm{UN}}$ in [K]	Evaporation	Water	Milk	Cream	Concentrate	Air
Condensation	1	1.5	2	2.5	3	4
Water	1.5	2	2.5	3	3.5	5
Milk	2	2,5	3	3.5	4	6
Cream	2.5	3	3.5	4	4.5	7
Concentrate	3	3.5	4	4.5	5	8
Air	4	5	6	7	8	10

3. Results

In the following the results obtained with each method are first presented, followed by a summary of the main outcomes and a comparison of the methods. The analysis of the results generally aims at finding inefficiencies or improvement potentials in the system and to find the minimum demands, meaning the minimum in externally supplied heat and cooling.

3.1. Energy mapping

The energy mapping approach resulted in an overview of the components with heating and cooling demands (Table 3) and a visualisation of the heating and cooling requirements at different temperatures (Figure 6). The use of thermal energy was identified as shown in Table 3 which allows to evaluate (i) the optimal degree of regeneration and (ii) the evaluation of product set-points. As the heaters in the MT section are preceded by a regenerative heat exchanger, the temperature difference of the product (T_{out} -T_{in}) over the heater can give an indication of its performance when the temperature difference is compared to other factories. It is thus possible to evaluate the degree of regeneration. Similar, heaters at modern dairy factories can have temperature differences of 3 K to 5 K for milk streams. Comparing these values to the ones found in Table 3, the investigation of increasing the heat transfer area could be justified. The higher temperature differences could also be a result of fouling on the plates and should be checked. The fouling layer is only removed if the proper cleaning chemicals and techniques are used [3].

Based on the tables and process flow charts, also some set-points can be questioned. The requirement of cooling the skim milk to 5 °C before adding additives and then heating it again might not be necessary during the whole production. Finding such possibilities based on the information collected during the energy mapping requires some level of previous experience.

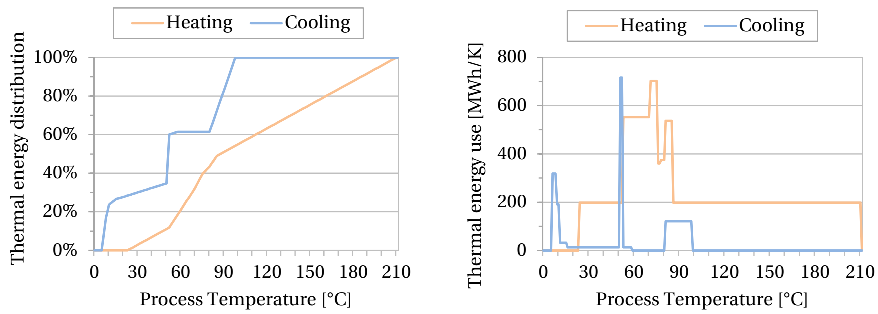
Table 3: Results of the energy mapping for the identification of improvement potentials.

	Equipment	Medium	Stream	T_{in} [°C]	T_{out} [°C]	$\dot{m}$ [10^6 kg/yr]	Energy Use [MWh]	
Heating:							Steam	Gas
MT	HEX	Skim Milk	M4	70	75	134.8	749	-
MT	HEX	Cream	C2	77	85	15.1	113	-
MT	HEX	Mixture	M10	80	85	147.4	814	-
EV	HEX	Mixture	E2	75	85	147.4	1,626	-
EV	MVR/ 3TVR	Concentrate	E4	52	75	42.8	7,321	-
SD	HEX	Concentrate	P1	52	75	42.8	829	-
SD	HEX	Air	A4	23	210	709.4	37,033	-
Cooling:							IW	CW
MT	HEX	Skim Milk	M7	8	5	134.8	442	-
MT	HEX	Cream	C5	23	5	15.1	230	-
MT	HEX	Mixture	M12	10	5	147.4	-	794
MT	HEX	Cream	C5	58	23	15.1	466	-
EV	Condenser	Water	VE4	98	80	3.7	2,179	-
EV	Condenser	Water	VE15	52	50	2.5	1,406	-
SD	HEX	Air	A10	15	8	70.6	138	-

In Figure 6 the distribution of thermal energy use over the process temperature ranges is shown for heating and cooling demands. From these two figures, it was possible to obtain an indication of, if there were in general possibilities for process integration. There was for instance a cooling demand at around 90 °C which could substitute some of the heating demand (Figure 6b). Also between 30 °C and 60 °C, a small cooling demand for the cream was found. The majority of the product cooling however, occurred at temperatures below the ones for the required heat supply and there was in general a considerably higher heating demand.

The large temperature gaps between the utility and heaters on the process sides suggest the use of other heat production methods, such as cogeneration or heat pump units.

The applied energy mapping approach was to some degree similar to the pinch analysis presented in the next section. The main differences were the number of components and the level of detail (in particular with respect to the evaporators). From the energy mapping it was not possible to find the optimal degree of integration and neither targets including the minimum temperature differences in the system. There was also no strict methodological approach for



(a) Cumulative (b) Profile

Figure 6: Results of the energy mapping for the heating and cooling demands in the processes.

the analysis, but it was rather based on the individual's experience.

3.2. Process Integration

3.2.1. Pinch Analysis

A pinch analysis of the dairy factory was performed to first calculate the minimum energy requirements of the plant. Figure 7 shows the small composite curves for the theoretical streams. The heat load, at which the hot and cold composite curves overlap, can be integrated by means of a heat exchanger network. The largest heating demand then corresponds to the evaporation needs at 75 °C (horizontal part of the cold composite curve), followed by the air heating for the drying of the milk products (cold composite curve above 85 °C). The external cooling demand is negligible, amounting to 0.24 $\mathrm{MJ/kg_{product}}$. The pinch point is located at 20 °C, meaning now external cooling is required above and no external heating below this temperature. The minimum heating demand is around 19 $\mathrm{MJ/kg_{product}}$ without considering vapour re-compression. When considering the existing degree of integration at the dairy factory, in particular the vapour re-compression in the evaporators, the grand composite curve (Figure 8) can be used to analyse the system. There were no self-sufficient pockets present, meaning that possibilities for internal heat recovery were minimal. The integration of heat pump units through TVR and MVR units is common practice in dairy factories. Water recovered as steam is compressed, either mechanically (MVR) or with high-pressure steam (TVR). The heat that can be recovered from the steam condensation is then used for driving the evaporation process in the same process unit. This allows a close match of the temperature profiles on the hot and cold sides (Figure 8). It eliminates the need for external heating within the evaporation section, besides the steam (about 0.3 MJ/kg of product) and electricity (about 0.2 MJ/kg of product) demands for driving the TVRs and MVR. The remaining heating demand, which consists of the heat demand for air heating and concentrate preheating, represents less than 33 % of the original demand.

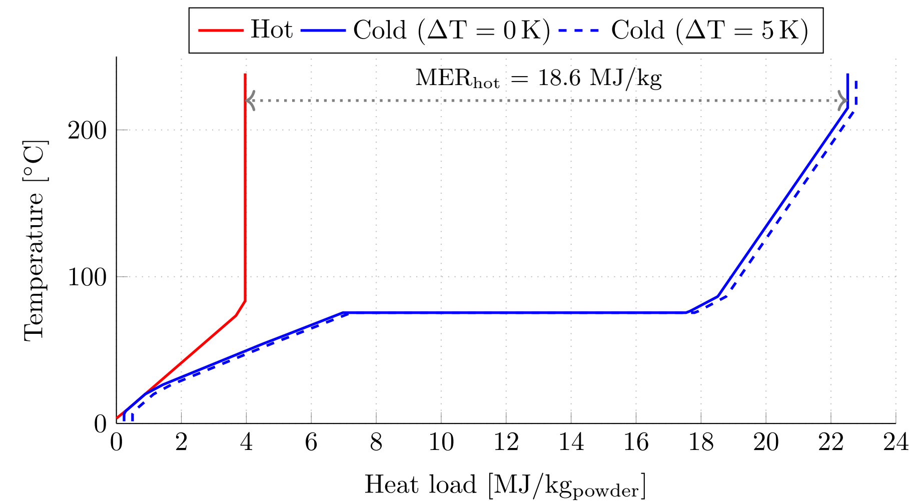


Figure 7: Composite curves of the dairy facility, without vapour re-compression and different heat recovery approach temperatures (ΔT).

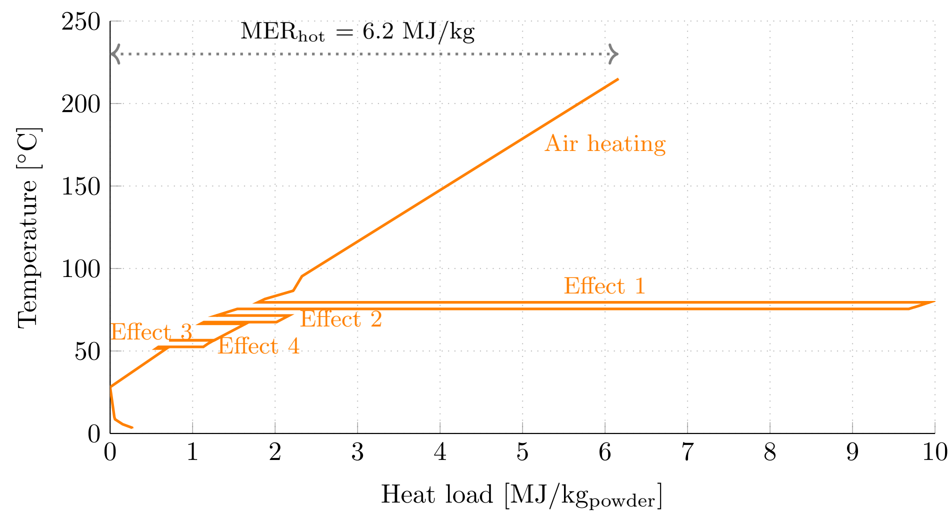
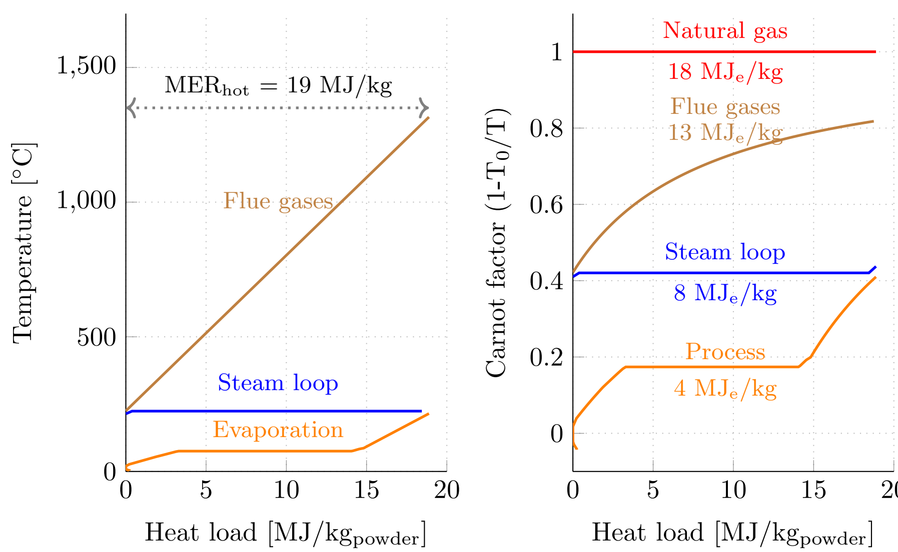


Figure 8: Temperature-heat profiles of the dairy facility, with vapour re-compression (TVR and MVR)

3.2.2. Carnot and Utility Pinch Analysis

The pinch analysis further allows the analysis of the current utility system and its integration with the factory. The heat load is covered with steam produced by natural gas combustion and cascaded from more than 1300 °C to less than 250 °C. The steam loop was designed to cover the highest process temperature in the dairy system as shown in Figure 9a.

By plotting the Carnot composite curves [46], the thermodynamic, technological and utility requirement can be analysed. The factory has an exergy demand of only about 4 MJ per kg product. It is satisfied by converting about 18 MJ of natural gas, with about 5 MJ destroyed in the combustion process, and 9 MJ in the heat transfer. The integration of a cogeneration unit would be beneficial from an exergy perspective because of the low to moderate temperature levels for the remaining heating demand. The heat present in the exhaust gases at high temperature can be converted into power, while low-pressure steam can be generated to fulfil the process heat demand. Electrification to satisfy these demands is a promising alternative from an environmental perspective, since there would not be any further need of natural gas, and electric heaters are characterised by a high energy conversion efficiency.



(a) Energy basis (b) Exergy basis

Figure 9: Temperature-heat profiles of the dairy factory with the hot utility, without vapour re-compression, on an energy basis (left) and exergy basis (right)

3.3. Exergy Analysis

The results of the exergy analysis are shown schematically in Figure 10 as a Grassmann diagram for the main exergy flows and production sections. In Table 4 to 7 the detailed results are reported. From Figure 10 it can be seen that the highest exergy destruction occurs in the hot utility, followed by the SD and EV sections. The exergy loss was small compared to the exergy destruction, but exceeds the exergy content of the dairy products from each section. The main sources of losses are the HU, CU and SD sections. The losses are primarily from exhaust gases from the combustion and drying process, as well as air used in the condenser of the CU. A small exergy loss is present in the condensate from the air preheating in SD facility. Losses in the HU and from the condensate could be reduced by increasing heat transfer in the air pre-heater U3 and S2, while reducing the losses from the drying air and condenser could be achieved by process integration. For the EV section it can also be seen in Table 5 that the

Table 4: Results of the exergy analysis of the milk treatment (MT) section.

Unit	$\dot{E}_{F,k}$ [kW]	$\dot{E}_{P,k}$ [kW]	$\dot{E}_{D,k}$ [kW]	ε_k [%]	$y^*_{D,k}$ [%]
H1	113.0	94.6	18.4	83.7	8.7
H2	125.7	114.7	11.0	91.3	5.2
H3	89.3	35.5	53.8	39.8	25.4
H4	6.9	3.9	3.0	56.6	1.4
H5	17.6	15.4	2.2	87.7	1.0
H6	13.3	6.0	7.4	44.7	3.5
H7	2.5	0.7	1.8	27.8	0.9
H8	338.0	289.0	49.0	85.5	23.1
H9	94.6	43.0	51.6	45.5	24.3
H10	11.2	6.0	5.2	53.5	2.5
H11	11.1	2.3	8.8	21.0	4.1
Total	-	-	212.1	-	100

Table 5: Results of the exergy analysis of the evaporation (EV) section.

Unit	$\dot{E}_{F,k}$ [kW]	$\dot{E}_{P,k}$ [kW]	$\dot{E}_{D,k}$ [kW]	ε_k [%]	$y^*_{D,k}$ [%]
E1	334.7	236.4	98.2	70.7	11.3
E2	195.7	86.1	109.6	44.0	12.6
E3	2695.0	2508.0	187.1	93.1	21.5
E4	142.7	8.0	134.7	5.6	15.5
E5	291.4	240.4	50.9	82.5	5.8
E6	149.2	125.1	24.0	83.9	2.8
E7	126.7	110.4	16.3	87.1	1.9
E8	50.9	2.6	48.3	5.2	5.5
F1	291.1	234.3	56.9	80.5	6.5
F2	369.9	224.6	145.3	60.7	16.7
Total	8-	-	871.4	-	100

steam ejector (F2) has three times more exergy destruction than the MVR (F1), while more water is evaporated in the MVR. The replacement of the TVR with an MVR could be beneficial from an exergy perspective as there is less exergy destruction in the compressor, while evaporating more water in this step. The replacement of the steam ejector becomes even more relevant if improvements in the HU are performed as suggested in the previous section.

Table 6: Results of the exergy analysis of the spray drying (SD) section.

Unit	$\dot{E}_{F,k}$ [kW]	$\dot{E}_{P,k}$ [kW]	$\dot{E}_{D,k}$ [kW]	ε_k [%]	$y^*_{D,k}$ [%]
S1	95.9	33.0	62.9	34.5	1.5
S2	26.0	6.7	19.3	25.7	0.5
S3	4535.0	2667.0	1869.0	58.8	44.9
S4	2.0	0.5	1.5	25.0	0.0
S5	3036.0	839.9	2196.0	27.7	52.7
S6	23.5	5.4	18.1	22.8	0.4
Total	-	-	4166.8	-	100

Table 7: Results of the exergy analysis of the hot and cold utility section.

Unit	$\dot{E}_{F,k}$ [kW]	$\dot{E}_{P,k}$ [kW]	$\dot{E}_{D,k}$ [kW]	ε_k [%]	$y^*_{D,k}$ [%]
U1	15243	10006	5236	65.7	58.4
U2	9032	5422	3610	60.0	40.3
U3	501	387	114	77.2	1.3
Total HU	16254	6822	8960	42.2	100
R1	306	247	59	80.5	27.6
R2	120	30	90	24.5	42.0
R3	16	0	16	86.9	7.6
R4	101	61	41	60	19.7
Total CU	306	61	208	19.8	100

Considering the exergy destruction ratio for each production section, more than 90 % of the exergy destruction occurs in the HU (62.1 %) and SD section (28.9 %). The milk treatment and CU sections each contributed with 1.5 to the exergy destruction. Here the steam heating of drying air (S3), as well as the burner (U1) and boiler (U2) have the highest exergy destruction. The combustion of natural gas and heat transfer from the high temperature combustion gases to the steam loop have low exergy efficiency. The regenerative heat exchangers and evaporators typically have a high exergy efficiency, above 80 %. On the contrary, heaters and coolers generally have low exergy efficiencies. The steam ejector was further found to have a low exergy efficiency, compared to the compressors, while causing more than 16 % of the exergy destruction in the EV section. This further indicates a replacement or reconfiguration opportunity.

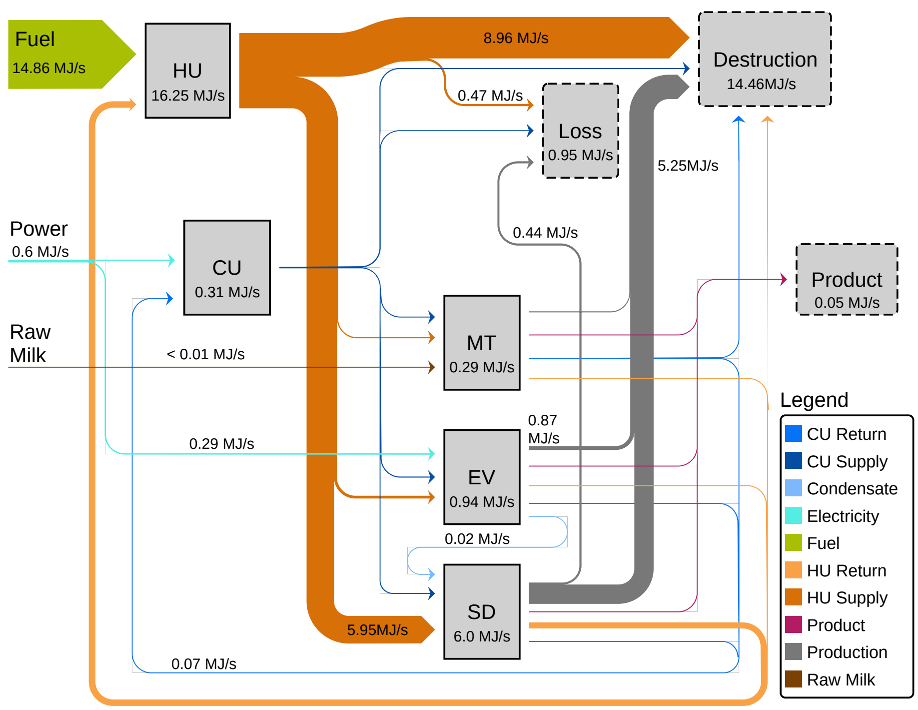


Figure 10: Grassmann diagram for the main exergy flows in the system.

Within the CU, a low exergy efficiency is obtained in the condenser (R2) due to the fixed temperature increase of 10 K in the heat sink. This temperature difference could be increased and be made usable, thus reducing the exergy destruction and loss. In this component, 40 % of the exergy destruction from the CU occurs. The burner and boiler in the HU, both have an exergy efficiency of around 60 % while the air preheater (U3) achieves 77 %. The air preheater, however, has a negligible share of exergy destruction compared to the other two components. On the other hand, this share becomes relevant on a system level. There are several possibilities to reduce the exergy destruction. Increasing the heat transfer, as well as matching the temperatures in the heaters and coolers, would decrease the exergy destruction in those production components. However, the highly integrated nature of the system, could move some of the exergy destruction to other parts of the factory.

The Grassmann diagram, presented in Figure 10, shows the cumulated exergy flows associated with the production sections of the dairy factory as introduced in Figure 1. The values represent the inputs and outputs, as well as the exergy destruction of each sections based on Tables 4 to 7.

From Figure 10 it is possible to obtain the total values for the dairy system. The milk powder production facility has a total exergy input of 15.46 MW, which to a large extent originates from the chemical exergy of the fuels, an exergy destruction rate of 14.46 MW and exergy losses of almost 0.95 MW from primarily exhaust air. With these values an exergy efficiency of less than 1 % is obtained. The product, as shown in Figure 10, is however very small. This product only contains the exergy content of the milk stream after each section. Defining an overall product for the system is difficult, as each production step gives a value to the product without being necessarily thermodynamically describable. One main product of the system is however the removal of water from the milk. Despite another part of exergy being used for the thermal treatment, the evaporation accounts for the majority of the exergy use and destruction. If only the evaporated water would be considered as the product, the total system would obtain an exergy efficiency of 35 %. The hot utility supply with steam has an exergy efficiency of 46 % and CU supply with ice water has an exergy efficiency of 22 %.

3.4. Advanced Exergy Analysis

Unavoidable and avoidable exergy destruction. The split into unavoidable and avoidable exergy destruction, shows that for the heaters, which had a low exergy efficiency, more than 50 % of the exergy destruction is avoidable (Table 8). The evaporators show a similar share of avoidable exergy destruction as shown in Table 9. The exergy destruction in the HU (Table 11) could be improved by increasing the combustion temperature and decreasing the minimum temperature difference in the boiler and preheater. However, the results show a negative avoidable exergy destruction in all HU components. This is caused by a decreased exergy efficiency through the unavoidable conditions enforced in the other components. For instance, as the condensate (HU1) into the boiler arrives at a lower temperature due to all components operating at unavoidable conditions, the flue gases are cooled down considerably in the boiler (U2). This leads to less preheating at a lower temperature, decreasing the exergy efficiency of the preheater (U3) and of the burner (U1) under unavoidable conditions.

The spray drying section (SD) itself has only a small share of avoidable exergy destruction, which is however large compared to the other sections. The air heater and spray dryer both have high absolute avoidable exergy destruction obtainable from reducing air flows and increasing heat transfer. Considering the dairy sections of the system, considerable amounts of exergy destruction are avoidable. These could be accomplished by primarily increasing the heat transfer of the heat exchangers. The real conditions in the compressors and the current spray dryer would have a lower exergy destruction if more efficient technologies would be implemented.

Endogenous and exogenous exergy destruction. The division into endogenous and exogenous exergy destruction shows that the exergy destruction in the heaters H6 and H9 is fully exogenous. This is due to that the regenerative heat exchangers determine the degree of exergy destruction within these components. The regenerative heaters thus have a high share of endogenous exergy destruction, as improvements in the heaters and coolers have no impact on their performance and the inlet conditions at one site are often set-points.

The MVR evaporator (E3) and the first step TVR evaporator (E5), both have a high share of endogenous exergy destruction. Improvements in the other components, i.e. compressor and ejector, only have a small impact on the temperature levels on the condensing site. However, the 2nd and 3rd step of the TVR (E6 and E7) have a higher share of exogenous exergy destruction. The inefficiencies in the preceding steps increase the exergy destruction e.g., due to lower evaporation temperature.

The air preheating with condensate from the evaporators (S2) has a negative exogenous exergy destruction, and in addition the part of endogenous exergy destruction is considerably higher than the real one. Improving the efficiency of the other components reduces the potential for heat transfer in S2. This reduces the total exergy destruction in S2, but also decreases the exergy efficiency, leading to the high endogenous and exogenous values. Similar to this component, the exergy destruction in the HU and in the CU is caused by other components. Optimising the components in the production causes some of the exergy destruction to be shifted to utilities.

It can further be observed, when taking the whole system analysis into account, that improvements on the production site will often have a negative impact on the utility site. This is evident when considering the negative avoidable and exogenous exergy destruction in the utility. So far, improving the heat transfer and matching the temperature of the utility to the production, would increase exergy destruction in the utility. It would thus be necessary to change the current system, to one which benefits from such changes. This could be a heat pump or cogeneration , where lower supply temperatures can increase the overall efficiency.

3.5. Comparison

At this point a summary and comparison of the main outcomes and suggestions of the methods from the results obtained with the different methods is done. With the energy mapping as presented in section 3.1, it can be shown that

- The regenerative heat transfer before the heaters in the MT section could be increased. This result can however only be obtained if engineering experience with similar systems is present.

Table 8: Results of the advanced exergy analysis of the milk treatment (MT) section.

Unit	$\dot{E}_{D,k}^{UN}$ [kW]	$\dot{E}_{D,k}^{AV}$ [kW]	ε_k^* [%]	$\dot{E}_{D,k}^{EN}$ [kW]	$\dot{E}_{D,k}^{EX}$ [kW]
H1	5.7	12.7	88.2	-0.5	18.9
H2	6.5	4.5	96.2	11.0	0.0
H3	46.7	7.1	83.3	53.8	0.0
H4	2.1	0.9	82.0	2.5	0.4
H5	1.0	1.1	93.2	2.2	0.0
H6	6.3	1.1	84.6	0.0	7.4
H7	1.0	0.8	45.3	0.7	1.1
H8	28.4	20.6	93.3	49.0	0.0
H9	45.0	6.5	86.8	0.0	51.6
H10	3.7	1.5	79.6	0.0	5.2
H11	6.9	1.9	55.5	7.2	1.6

Table 9: Results of the advanced exergy analysis of the evaporation (EV) section.

Unit	$\dot{E}_{D,k}^{UN}$ [kW]	$\dot{E}_{D,k}^{AV}$ [kW]	ε_k^* [%]	$\dot{E}_{D,k}^{EN}$ [kW]	$\dot{E}_{D,k}^{EX}$ [kW]
E1	51.6	46.6	83.5	85.6	12.7
E2	95.5	14.1	85.9	105.8	3.8
E3	45.9	141.2	94.7	184.7	2.4
E4	10.3	124.4	6.0	52.9	81.8
E5	37.9	13.0	94.8	49.1	1.9
E6	2.1	21.9	85.1	11.8	12.2
E7	1.9	14.4	88.5	10.4	6.0
E8	4.1	44.2	5.6	13.8	34.5
F1	10.0	46.9	83.4	61.2	-4.3
F2	162.4	-17.1	-	159.0	-13.7

Table 10: Results of the advanced exergy analysis of the spray drying (SD) section.

Unit	$\dot{E}_{D,k}^{UN}$ [kW]	$\dot{E}_{D,k}^{AV}$ [kW]	ε_k^* [%]	$\dot{E}_{D,k}^{EN}$ [kW]	$\dot{E}_{D,k}^{EX}$ [kW]
S1	46.8	16.1	67.2	51.6	11.3
S2	14.4	4.9	57.6	605.9	-586.6
S3	1383.0	486.0	84.6	1849.9	19.1
S4	1.1	0.4	57.2	1.5	0.0
S5	2089.0	107.0	88.7	2196.0	0.0
S6	16.9	1.2	82.1	15.1	3.0

Table 11: Results of the advanced exergy analysis of the hot and cold utility section.

Unit	$\dot{E}_{D,k}^{UN}$ [kW]	$\dot{E}_{D,k}^{AV}$ [kW]	ε_k^* [%]	$\dot{E}_{D,k}^{EN}$ [kW]	$\dot{E}_{D,k}^{EX}$ [kW]
U1	5675	-439	-	7008	-1772
U2	3652	-42	-	3934	-324
U3	1677	-1563	-	7610	-749
R1	10	49	83.4	65	-6
R2	57	33	47.0	79	12
R3	16	0	-	16	0
R4	15	26	-	40	1.6

- The possibility of integrating the cooling demand for cream and in the condensers, with the air heating should be further analysed.

These results are however highly dependent on the experience of the engineer. For the evaporators, the heating demand was found using the technical documentation, no suggestions for improvement can be made through the mapping. Here it again required experience to judge if the evaporators should be replaced or extended.

Using pinch analysis the following main observations of the system were made:

- The minimum energy requirement for heating of at the factory was determined to be $19\,\mathrm{MJ/kg_{product}}$ and $6.2\,\mathrm{MJ/kg_{product}}$ if vapour re-compression is considered.
- The theoretical heat demand on an exergy basis found using the Carnot composite curves was found to be $4\,\mathrm{MJ/kg_{product}}$
- Internal heat recovery has a small potential, as the processes are also integrated. The utilisation of free steams, e.g. from the exhaust gases of the boiler and dryer could be further investigated.
- Use of co-generation unit to decrease exergy destruction in the utility could be justified by considering the low temperature heating demand.

The exergy analysis has revealed several inefficient components, with respect to exergy destruction and exergy losses. From this the following suggestions were made.

- The exergy flow into the components of the production accumulates to $7.3\,\mathrm{MJ/kg}$ in the existing system.
- Prioritise reduction of exergy destruction in hot utility and spray drying section, as they represent a high share of the total exergy destruction
- Evaluation of potential for recovering exergy losses from spray dryer and cold utility, as here the highest exergy losses were found

- Evaluate possibility to replace TVR with an MVR, as the steam ejector has a a high rate of exergy destruction relative to the evaporation effect.

By implementing and performing an advanced exergy analysis, the system was analysed in detail and some of the results from the exergy analysis could be further specified. The overall results are:

- High share of avoidable exergy destruction in heaters and evaporators, where smaller temperature differences should be implemented.
- Improvements in production section will increase exergy destruction in the utility. New utility systems (e.g. heat pumps or co-generation) should be considered.
- Improvements in the spray dryer, e.g. better sealing, insulation and increased product diffusion, should be analysed. Spray dryer has a high absolute value of exergy destruction and a high share of endogenous exergy destruction.

The results of the different analyses are overall coherent. The pinch analysis determined a high optimisation potential by improving the utility system, which is supported by a high share of exergy destruction. The advanced exergy analysis gives some additional insight, when it comes to the component level and the interactions between production and utility. The pinch analysis however, already presents a starting point for the selection and optimal placement for a new utility and for creating an improved heat exchanger network.

The exergy analysis on the other hand showed some potential for heat recovery and reduced exergy loss, which was not directly evident from the pinch analysis and energy mapping. It was further shown that there is a potential for increasing the exergy efficiency of the components. This will not always translate into a reduced energy use. An advantage of the splitting into avoidable and unavoidable exergy destruction is that the possible improvements are directly quantified and become comparable across the system.

As several of the conclusions from all methods could be made by experienced engineers based on the initial process data, the quantification of the potential improvements is an important merit of the methods. The pinch analysis quantifies an overall target for the whole system, while the exergy analysis quantifies the thermodynamic 'inefficiencies', which may not be fully avoidable in practice. The energy mapping does not quantify optimisation potentials, but qualitatively describes improvement options.

The analysis using the energy mapping or the pinch analysis require relatively minor efforts once the all data is collected. Creating the GCC is however not as easy as the diagrams and tables for the energy mapping. Performing the exergy analysis requires more efforts, as each component has to be modelled. The advanced exergy analysis requires in additional several model evaluations, which makes it less practical, and the definition of unavoidable/ theoretical states, which makes it more theoretical.

4. Discussion

The studied system is subject to several degrees of uncertainty as some assumptions towards the production and utility had to be done. It was assumed that the operation is constant, however cleaning intervals and batch production can occur. Considering these elements, the pinch analysis could have varying results but the complexity of the problem can increase. Only the production of one product type was considered, as well as only one production line was modelled. In reality the products are different, changing the set-points, and parallel production lines increasing the complexity of interconnected systems. Despite the system being simplified to some degree, the model and results are more detailed than reported in the literature so far.

With respect to the dairy industry, Becker et al. [47] used process integration to find opportunities for heat pump integration in a cheese factory and to improve the methodological approach. By using this process integration, similar to the one in this work using the Carnot scale, considerable cost and CO_2 savings were possible. The method by Quijera and Labidi [6], which combined pinch and exergy to determine the best solar thermal process integration, compares the different solar fractions of the utility in exergy terms. It was found that using only solar energy has a lower exergy efficiency than a natural gas boiler, as the full exergy content of the solar radiation was used. An economic or exergoeconomic analysis is though necessary to find the optimal configuration, as also in this case if a heat pump or cogeneration system was used. Erbay and Koca [48, 8] who performed an exergy and exergoeconomic analysis of a spray dryer for cheese powder production, found that heaters have the highest exergy efficiency of up to 89 %, which is in line with this work. It was further found that the spray dryer itself operates best with a high inlet air temperature and low outlet air temperature. A comparison of the results with the following studies can only be indicative, as not all assumptions and state points are given and different configurations of the systems were used. The results obtained by [10] for the milk spray drying system show that the evaporator is by far the component with the highest rate of exergy destruction. This is contrary to the findings in this work, where the spray drying system has the highest share of exergy destruction. The reason for the difference is that the system used by Yildirim and Genc [10] is single stage evaporator operating solely on fresh steam. The inclusion of multi-effect evaporators with MVR and TVR can thus significantly reduce the exergy destruction of the system. The spray dryers analysed, also have different drying temperatures. The exergy efficiency of the spray dryer in this work is comparable to the one found by Srinivasan et al. [11], who used similar temperatures. The vapour re-compression, presumably using a fan, has a lower exergy efficiency than the MVR and TVR in this work. This is probably due to the much higher outlet temperature of the re-compressed vapour.

4.1. Exergy and advanced exergy analysis in industrial practice

Exergy analysis has been previously used as a tool for the analysis of industrial (food) production system [16, 27, 12, 8, 30, 14, 10, 7, 15]. As part of this work a complete production system including the utilities was modelled and an advanced exergy analysis of the system was performed. The conduction of an exergy analysis in addition to the normal energy analysis of the system, requires a complete thermodynamic model of the production system. This is often not available from industrial practice, where simpler spreadsheet calculations are used. The inclusion of an exergy analysis requires only minor model additions to the thermodynamic model. However, the implementation of the unavoidable and theoretical conditions, is connected with major challenges. There are many set-points in the production which cannot be modified as they are set to ensure product quality, which consequently results in components which operation cannot be justified from a thermodynamic perspective. This is in particular the case for the pasteurisation units, which have heat the fluid to the given set-point temperature. This requires the finding of workarounds which are sometimes distanced from the actual system. For instance it was not possible to enforce the theoretical conditions in all of the components of H1 to H4, as the unbalanced regenerative heat exchanger would violate the 2nd law of thermodynamics. In the theoretical conditions it was thus necessary to keep a minimum temperature in H3.

Due to the theoretical nature of the split into unavoidable and avoidable, but i.e. into endo- and exogenous conditions, only some of the results are significant for industrial practice. However, it becomes evident that improvements should be targeted to the regenerative heat exchangers and evaporators, where the exergy destruction was found to be both avoidable and endogenous.

As it was shown through the advanced exergy analysis, there are strong interdependencies between improvements in the production and increasing exergy destruction in the utility system. The advanced exergy analysis could be extended to determine the other components contributions to the exogenous exergy destruction in one component. However, the practicability of performing such an analysis will be challenging, as well as the engineering relevance to rigidly defined production steps in the dairy could be questionable. For a complete change of the utility system however, several advantages can be found using exergy analysis, as it clearly shows that a large fraction of the fuel is destroyed and that the exergy destruction may increase with improvements in the production system.

The results show several improvement possibilities. However, it is unclear if those can be implemented in practice. If for instance the unavoidable temperature differences in the heaters and coolers were implemented, the residence time in those components could increase. This would have unwanted effects on the product quality. When advocating measures to the owners and staff of the factory, the reasoning of the suggestion is also important. One possible barrier found for the implementation of cost-efficient energy efficiency measures is the form and credibility of information [49]. It will be challenging to communicate to staff at the production site, the results on a basis of an advanced exergy analysis. Here, other methods can have an advantage.

4.2. Comparison of methods

The basis for the application of all methods is to retrieve the required process layout and data. This becomes very time consuming in most cases, as all applied methods require detailed information for each process step and stream. The dairies however measure only certain set-point temperatures, which can vary based on the final product, and have primarily importance for the product quality and not energy use. Finding this information is comparable for each method, however the model for exergy analysis requires more accurate data. Small unbalances in temperatures and flow rates, in e.g. estimates, may have only small impact on a pinch analysis, but have to be eliminated for a complete thermodynamic model. The energy mapping approach has a focus only on the components with actual energy use from the utility and some simplifications with data sheet information are made, which reduces the work load. The impact on uncertainties in the different approaches should be investigated in future works.

Performing the exergy analysis requires only small additional efforts with respect to the model. The definition of the products and fuels is often difficult or not relevant for many components, but requires thorough consideration if useful results are to be obtained. The next level, splitting the exergy destruction into unavoidable and avoidable, was done with reasonable efforts. However, it requires time to implement new conditions, without violating product set-points, in a inflexible system like dairy treatment. The results however are useful to obtain a quantification of the real improvement potential. In the last step, splitting the exergy destruction into endo- and exogenous, the flexibility of the model has to be increased to allow the theoretical conditions. Furthermore, the number of simulations of the systems is equal to the number of components, increasing the computational time. Though the results are difficult to communicate and some might have no practical relevance, a good understanding of the interactions within the system are obtainable.

The communication of the results to non scientific personal might however be easiest with pinch analysis. The presentation of the results as shown in Figure 6 can be easily understood, as the "pockets" within the curve show the direct integration potential. The visualisation in form of composite curves, can be a useful tool too, but the interpretation requires knowledge about the method.

The practical feasibility of the obtained improvement potentials requries further a technical and economic feasibility analysis. Here a heat exchanger network could be established using the pinch analysis as basis or using mathematical programming [50]. A natural continuation of the exergy analysis would be to perform an exergoeconomic analysis [51] or, considering the advanced method, an advanced exergoeconomic analysis [44].

The input data to the model were further associated with a degree of uncertainty. The impact of these uncertainties on the results of the different methods, in particular when analysing specific improvement opportunities, should be considered in future work.

5. Conclusion

In this work a milk powder production system consisting of a milk treatment, evaporation and spray drying section together with the utility system supplying heat and cooling to the production was analysed. The aim of the work was to analyse the system and find optimisation potentials, using different methods. Furthermore, the applied methods, i.e. energy analysis, pinch analysis, exergy and advanced exergy analysis, were compared and the applicability for industrial practice discussed.

The energy analysis, focusing on the main components, was the first step in defining the system. From this basic analysis, first improvement potentials were found, which however rely strongly on the availability of previous experience. On the other hand, these findings are expected to be easy to communicate to non-scientific staff. Using the pinch analysis the theoretical MER was found, as well as the utility system was analysed. The production system is already highly integrated and improvements are merely possible. However, the modification of the utility to consist of a cogenaration or heat pumps, seems to be an optimisation options.

By performing the exergy analysis several components with a high exergy destruction, such as the hot utility and air heater, were identified. Furthermore, the exergy losses from the utility and spray dryer were quantified, with respect to potential to perform work. The advanced exergy analysis allowed to further refine the results. The heaters and coolers were found to have a high share of avoidable exergy destruction, which was however found to be to a large degree endogenous. Despite the split into unavoidable and avoidable exergy destruction appearing relevant to the system analysis in itself, a split into endo- and exogenous exergy destruction be also be performed. The latter is however connected with modelling challenges due to set-points.

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Appendix A. Dairy composition

Table A.12: Composition of the diary products for the different states based on [34].

	State [-]	Protein [kg/kg]	Fat [kg/kg]	Carbonhydrate [kg/kg]	Ash [kg/kg]	Water [kg/kg]
Raw Milk	M1	0.035	0.035	0.049	0.007	0.874
Skim Milk	M3	0.035	0.001	0.051	0.008	0.905
Cream	C1	0.035	0.290	0.034	0.000	0.641
Mixture	M9	0.049	0.003	0.087	0.011	0.850
Concentrate I	E6	0.128	0.007	0.187	0.028	0.650
Concentrate II	E8	0.153	0.009	0.224	0.034	0.580
Concentrate III	E9	0.172	0.010	0.251	0.038	0.530
Concentrate IV	E10	0.194	0.011	0.283	0.043	0.470
Milk Powder I	P3	0.347	0.019	0.507	0.077	0.050
Milk Powder II	P4	0.356	0.020	0.520	0.079	0.025

Appendix B. Thermodynamic state points

Table B.13: Thermodynamic state points for the cold utility section (CU).

State [-]	$\dot{m}$ [kg/s]	T [°C]	p [bar]	h [kJ/kg]	e [kJ/kg]	s [kJ/(kg K)]
RM1	1.3	-4.5	3.5	1459.0	172.9	5.70
RM2	1.3	108.1	12.2	1697.0	364.7	5.87
RM3	1.3	31.5	12.2	1487.0	332.7	5.25
RM4	1.3	31.5	12.2	348.6	271.3	1.51
RM5	1.3	30.5	12.2	344.0	271.1	1.50
RM6	1.3	-5.5	3.5	344.0	258.3	1.54
RM7	1.3	-5.5	3.5	1456.0	173.1	5.69
AA1	172.9	15.0	1.0	31.3	0.0	6.83
AA2	172.9	25.0	1.0	41.5	0.2	6.75
IW1	33.0	9.3	1.0	34.4	0.2	N/A
IW2	33.0	-2.5	1.0	-9.1	2.0	N/A

Table B.14: Thermodynamic state points for the milk treatment section (MT).

State [-]	$\dot{m}$ [kg/s]	T [°C]	p [bar]	cp [kJ/(kg K)]	e [kJ/kg]
M1	11.9	7.0	1.0	3.87	0.4
M2	11.9	50.0	1.0	3.89	7.7
M3	10.7	50.0	1.0	3.96	7.8
M4	10.7	70.0	1.0	3.97	18.5
M5	10.7	75.0	1.0	3.97	21.8
M6	10.7	55.0	1.0	3.96	10.1
M7	10.7	8.0	1.0	3.94	0.3
M8	10.7	5.0	1.0	3.94	0.7
M9	11.7	5.0	1.0	3.80	0.7
M10	11.7	80.0	1.0	3.84	24.5
M11	11.7	85.0	1.0	3.85	28.2
M12	11.7	10.1	1.0	3.80	0.2
M13	11.7	5.0	1.0	3.80	0.7
C1	1.2	50.0	1.0	3.31	6.5
C2	1.2	77.0	1.0	3.33	19.5
C3	1.2	85.0	1.0	3.33	24.5
C4	1.2	58.1	1.0	3.31	9.7
C5	1.2	23.0	1.0	3.29	0.4
C6	1.2	5.0	1.0	3.28	0.6

Table B.15: Thermodynamic state points for the evaporation section (EV).

State [-]	$\dot{m}$ [kg/s]	T [°C]	p [bar]	h [kJ/kg]	e [kJ/kg]	s [kJ/(kg K)]
E1	11.7	25.0	1.0	95.2	0.6	N/A
E2	11.7	74.9	1.0	287.5	20.9	N/A
E3	11.7	85.0	1.0	326.8	28.2	N/A
E4	11.5	75.0	0.4	287.8	21.1	N/A
E5	11.5	75.0	0.4	287.8	21.1	N/A
E6	5.0	75.0	0.4	251.8	18.5	N/A
E7	5.0	67.0	0.3	224.5	14.1	N/A
E8	4.3	67.0	0.3	214.8	13.5	N/A
E9	3.8	56.0	0.2	172.3	9.0	N/A
E10	3.4	52.0	0.1	152.2	6.4	N/A
VE1	6.5	75.0	0.4	2635.0	422.9	7.68
VE2	6.5	98.5	0.5	2679.0	459.0	7.71
VE3	6.2	98.5	0.5	2679.0	459.0	7.71
VE4	0.3	98.5	0.5	2679.0	459.0	7.71
VE5	0.3	80.0	0.5	334.9	26.7	1.08
VE6	6.2	80.0	0.5	334.9	26.7	1.08
VE7	0.7	67.0	0.3	2621.0	375.3	7.79
VE8	0.5	58.0	0.2	2605.0	318.9	7.94
VE9	0.4	52.0	0.1	2595.0	279.6	8.04
VE10	0.3	52.0	0.1	2595.0	279.6	8.04
VE11	0.6	127.3	0.5	2736.0	469.3	7.87
VE12	0.6	72.0	0.3	301.4	20.8	0.98
VE13	0.7	67.0	0.3	1291.0	172.0	3.89
VE14	0.5	58.0	0.2	507.6	46.5	1.61
VE15	0.2	52.0	0.1	2595.0	279.6	8.04
VE16	0.2	52.0	0.1	217.7	9.1	0.73
VE17	0.4	239.0	25.0	2848.0	1021.0	6.35
VE18	8.5	81.7	0.5	422.3	43.1	1.32
VE19	8.5	38.4	0.1	160.9	3.7	0.55

Table B.16: Thermodynamic state points for the spray drying section (SD).

State [-]	$\dot{m}$ [kg/s]	T [°C]	p [bar]	X [kg/kg]	h [kJ/kg]	e [kJ/kg]	s [kJ/(kg K)]
P1	3.4	52.0	1.0	-	152.2	6.4	N/A
P2	3.4	75.0	1.0	-	221.0	16.2	N/A
P3	1.8	81.0	1.0	-	155.4	12.6	N/A
P4	1.8	40.0	1.0	-	76.5	2.0	N/A
P5	0.1	40.0	1.0	-	76.5	2.0	N/A
A1	64.4	15.0	1.0	0.00643	31.3	0.0	5.73
A2	8.1	15.0	1.0	0.00643	31.3	0.0	5.73
A3	56.3	15.0	1.0	0.00643	31.3	0.0	5.73
A4	56.3	23.3	1.0	0.00643	39.8	0.1	5.76
A5	56.3	210.0	1.0	0.00643	231.2	47.5	6.26
A6	55.7	210.0	1.0	0.00643	231.2	47.5	6.26
A7	0.6	210.0	1.0	0.00643	231.2	47.5	6.26
A8	3.1	55.0	1.0	0.00643	72.0	2.6	5.86
A9	2.5	15.0	1.0	0.00643	31.3	0.0	5.73
A10	5.6	15.0	1.0	0.00643	31.3	0.0	5.73
A11	5.6	8.0	1.0	0.00643	24.2	0.1	5.70
A12	57.3	78.1	1.0	0.03435	169.4	8.4	6.18
A13	8.7	38.4	1.0	0.00748	57.8	0.8	5.82
A14	66.0	73.0	1.0	0.02888	149.6	6.6	6.11
A15	66.0	73.0	1.0	0.02888	149.6	6.6	6.11

Table B.17: Thermodynamic state points for the hot utility section (HU).

State [-]	$\dot{m}$ [kg/s]	T [°C]	p [bar]	h [kJ/kg]	e [kJ/kg]	s [kJ/(kg K)]
B1	8.6	15.0	1.0	31.3	0.0	5.72
B2	8.6	204.4	1.0	225.4	45.1	6.24
B3	8.9	1325.0	1.0	1913.0	1129.0	8.47
B4	0.3	15.0	1.0	52530.0	51979.0	N/A
B5	8.9	224.4	1.0	457.1	110.0	6.96
B6	8.9	63.4	1.0	269.3	53.4	6.50
HU1	6.7	214.4	25.0	917.9	209.3	2.47
HU2	6.7	239.0	25.0	2848.0	1021.0	6.35