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Increasing Energy Efficiency of Milk Product Batch Sterilisation

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Abstract

The food industry is a large energy consumer and most heat demands in food processing are low-temperature. The aim of this study is to develop and simulate innovative retrofits or redesigns that unlock the heat recovery potential of industrial batch sterilisation processes. The case study focuses on the whey cream process, although the method and results apply to similar batch sterilisation processes. The initial situation is compared to energy efficient designs based on "Energy Storage" and "Rescheduling". Using a thermodynamic model, including the control system, the dynamic behaviour is simulated. The results show a high energy saving potential of up to 83%, faster processing with up to 60% timesaving, and favourable economics for the proposed novel designs.

Nomenclature

A	Area of the Exchange Surface	m_C	Mass of Content in Storage Tank
α	Thermal Diffusivity	$\dot{m}$	Massflow
C	Heat Capacity	n	Number of
CIP	Cleaning in Place	n_d	Number of different Materials
CP	Cold Product	NTU	Number of Transfer Units
c_p	Specific Heat Capacity	PLC	Programmable Logic Controller
$c_{p,C}$	Specific Heat Capacity of Content	$\dot{Q}_{heating}$	Heat Transfer by Heat Exchangers
CS	Cold Stream	$\dot{Q}_{HT}$	Heat Transfer by Convection and Radiation
C_t	Cash Flow of Energy Savings	$\dot{Q}_m$	Heat Transfer by Massflow
d	Diameter	$\dot{Q}_J$	Heat Transfer by Heating Jacket
E	Energy	R	Ratio
I	Investment Costs	S	Solid Parts of the Vessels
In	Incoming Stream	SEC	Specific Energy Consumption
IW	Ice Water	ST	Storage Tank
HS	Hot Stream	T	Temperature
HP	Hot Product	T_{amb}	Ambient Temperature
HX	Heat Exchanger	$t_{Payback}$	Payback Time
λ	Length of Heat Conduction	out	Outgoing Stream
$m_{product}$	Mass of Product	$\dot{T}_{ST}$	Change of average Vessel Temperature

Highlights

- High energy efficiency potentials unlocked in batch sterilization along with saving of process time
- Two heat recovery designs tested including energy storage and rescheduling approaches
- Dynamic model of the system developed and applied

Keywords

Energy Efficiency, Batch Sterilization, Dairy Processing, Pinch Analysis

1 Introduction

In 2015, the food industry was the sixth largest energy consumer in Germany [1] and the fifth largest in Europe [2]. Most heat demands in food processing are low-temperature [3]. In the associated dairy and fruit juice industries, low-grade heat – below 100 °C – is used in the thermal treatment of the products [4], which is necessary for hygienic reasons [5].

Muller et al. [6] described the general approach to energy management via top-down and bottom-up-analysis for the food processing industry. In their paper, the bottom-up-approach using Pinch Analysis techniques best fits the target to identify energy efficiency measures in thermal systems. Energy optimization can be implemented at the utility level by integration of solar thermal energy [7], hot water loops in low-temperature-pinch industrial processes [8], dedicated heat recovery loops [9], and Total Site Heat Integration through to Local Integrated Energy Systems [10]. Heat pumps also provide an efficient option to utilize renewable electricity from the grid [11] with low emissions [12] or in combination with geothermal energy [13]. At the process level, previous works in the area of dairy processing include a comprehensive analysis of milk powder production [14] as well as key processes such as the evaporation system [15] and spray dryer [16]. More recent, Walmsley et al. [17] integrated the utility and process systems to further raise the level of energy efficiency.

There are many thermal unit operations such as sterilisation, cooking, and evaporating. In addition, cleaning and pasteurisation are mandatory thermal processes in this sector. Pasteurisation is used for products that range from dairy products, fruit juices, beer, pickles, sauces to meat and fish products [18]. Waheed et al. [19] reported that pasteurisation is the most energy-intensive unit operation in the processing of orange juice. Ramirez et al. [20] called it the most common thermal process in the dairy industry. In general, pasteurisation is a low-temperature process (60–100 °C) with different heating temperature and holding time combinations, assuring the reduction of pathogens to a safe level. Continuous pasteurisation of milk using plate heat exchangers (PHE) is typically conducted at 72–74 °C with a holding time of 15–30 s [21]. A cooling operation takes place after each treatment to maintain food safety and product quality. Regular cleaning of processing equipment is required in most areas leading to interruptions and semi-continuous or batch operation. In many pasteurisation processes, heat recovery systems are installed, containing a combination of the actual pasteurisation zone, a preheating and a cooling zone [21]. However, in batch processes, such as the whey cream sterilisation considered in the present study, heat recovery is uncommon because of its discontinuous character. Despite this limitation, it is possible to store the heat or improve batch sterilisation processes to enable heat recovery. Peesel et al. [22] demonstrated energy efficiency measures for batch retort sterilisation for pet food. Since sterilisation temperatures are 130 °C, the process requires steam injection. Pressurised water could be a technical alternative for this technique and has been investigated for medical applications. Weisskopf [23] developed a concept, using Pinch Analysis techniques, for indirect heat exchange via heat storage tanks in the sterilisation process of medical devices in autoclaves with pressurised water. During the cooling cycle, six tanks temporarily store the heat at different temperature levels and then preheat the water in the heating phase in 10 °C steps to 95 °C. Using this approach, energy savings of up to 60 % are possible for one cycle.

For whey cream processing, the cream is obtained by centrifugation from sweet whey and has a fat content of at least 10 % [24]. It is used to produce butter and cheese milk, among other things [25]. In the thermal treatment of whey cream compared to milk, higher temperatures and longer holding-times are required since the microorganisms are surrounded by a larger fat layer, making it more heat resistant [26]. Curing processes around 100 °C with longer holding-times are called sterilisation processes [27]. Compared to the presented examples on milk powder production [17] and pasteurisation [18], the described sterilisation batch process treats fluid product streams and uses jacketed heat exchangers in tanks. In discontinuous processes such as this batch sterilisation process, the heating and cooling requirements significantly change over time. The whey cream, initially at 20 °C, is heated up in a tank, held for 30 minutes at 95 °C, and then cooled to 6 °C. The batch sequencing of heating, holding, cooling and cleaning cycles impede direct heat recovery. For the same reason, however, large energy-saving potentials exist.

The aim of this study is to develop and simulate innovative retrofit designs that unlock the heat recovery potential of industrial batch sterilisation processes. The application focuses on the whey cream process, although the method and results apply to similar batch sterilisation processes. In this study, targets for increases in energy efficiency of thermal production processes based on Pinch Analysis are determined. The industrial status quo, as well as the modelling of the batch sterilisation process plant, are described. The results of the Pinch Analysis lead to two designs for heat recovery, considering the batch operation. Using a dynamic simulation, the two designs are evaluated regarding energy and cost efficiency as well as complexity and control flexibility.

2 Theory of Improving Energy Efficiency in Thermal Sterilisation Processes

The thermal sterilisation processes for this study operate as a batch process. Within batch processes, direct heat transfer from one product flow to another is difficult due to the timing of when the two flows are available. The concept of batch heat integration is to optimally store heat and synchronise the process flows to maximise heat recovery while balancing the need for capital investment.

2.1 Initial Design

Figure 1 describes the initial design of the process of batch sterilisation for liquid products typically found in industry. The product enters from the top and is discharged from the bottom. After a production cycle, automated cleaning via an in-tank cleaning in place (CIP) system is performed by a central supply station. The temperature of the product is controlled via a heating and cooling jacket (no direct contact or mixing). The thermal energy is supplied by the central utility system. Heat carriers are hot water (100 °C), cooling water (19 °C) and ice water (1 °C). To decrease process time, a tank group consisting of several tanks that work in parallel (e.g. four tanks).

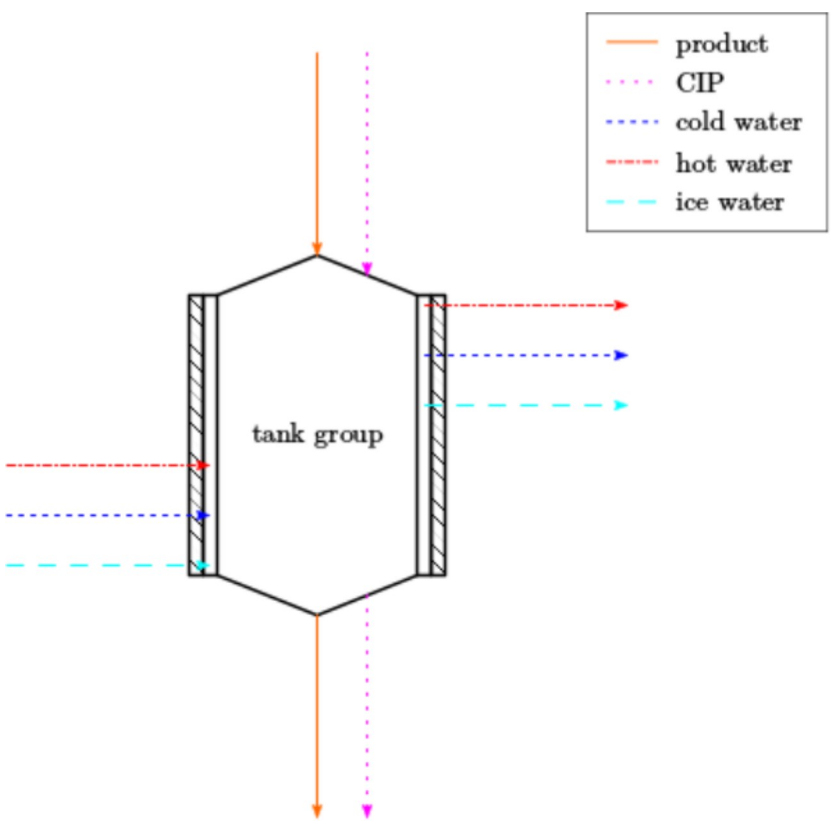

Figure 1: Flowchart of the initial process design

2.2 Energy Storage

By integrating thermal storage tanks, using water as an intermediate heat exchange medium, product and energy flows can be decoupled, as shown in Figure 2. This concept, according to the Time-Average-Model[1] [28], is based on the idea of storing the recovered heat from the process stream and storing it as warm fluid, so that it can be used again later for useful heating. In addition, a cold storage is used for the cooling purpose.

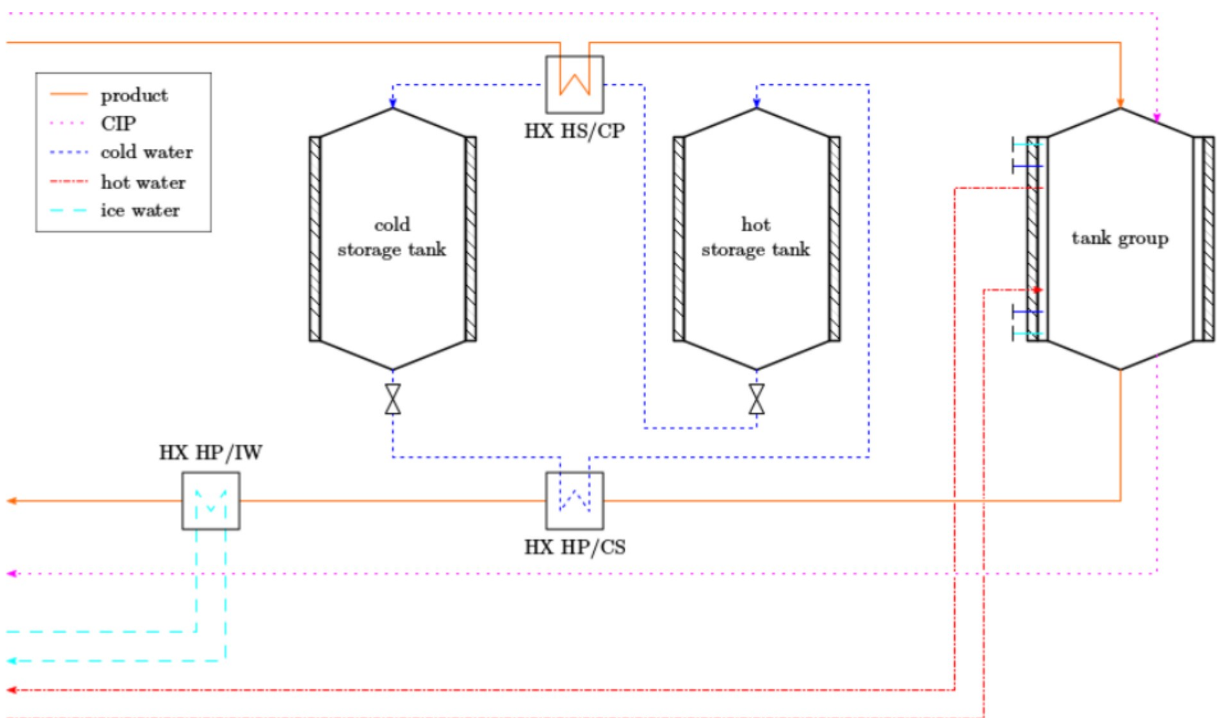

Figure 2: Process flow diagram of the plant with thermal storage

The hot tank should be kept as close to the sterilisation temperature as possible, i.e. minimum approach temperature, and the cold tank close to the cooling temperature. During the filling cycle, the whey cream is heated by water from the hot tank in a counterflow heat exchanger. The hot water is simultaneously cooled and fed into the cold storage tank. The remaining heat, required to reach the sterilisation temperature, is supplied via the jacket, by pumping hot pressurised water through it. At the end of the sterilisation cycle, the product tank can be emptied immediately. The whey cream

[1] Average heat load (dividing used energy by time) of process used as input parameter for Pinch Analysis

is cooled by two heat exchangers. The first exchanger uses water from the cold thermal storage tank, which transfers heat from the product, and then returned to the warm storage to regenerate the hot tank. The remaining cooling demand for reaching the storage temperature is covered by an ice water cooler.

This leads to the advantage that the heating and cooling not only take place inside the tank but already very effective through the heat exchangers during filling and emptying. In this way, heat can be recovered and production time can be reduced.

2.3 Rescheduling

According to the “Rescheduling” approach, the temporal sequence of the sterilisation process is changed, so that the heating and cooling requirements overlap in time. This is achieved by the fact that the filling and emptying arrangements of different tanks are matched so that heat recovery can occur. This concept follows the Time-Slice-Model [28].

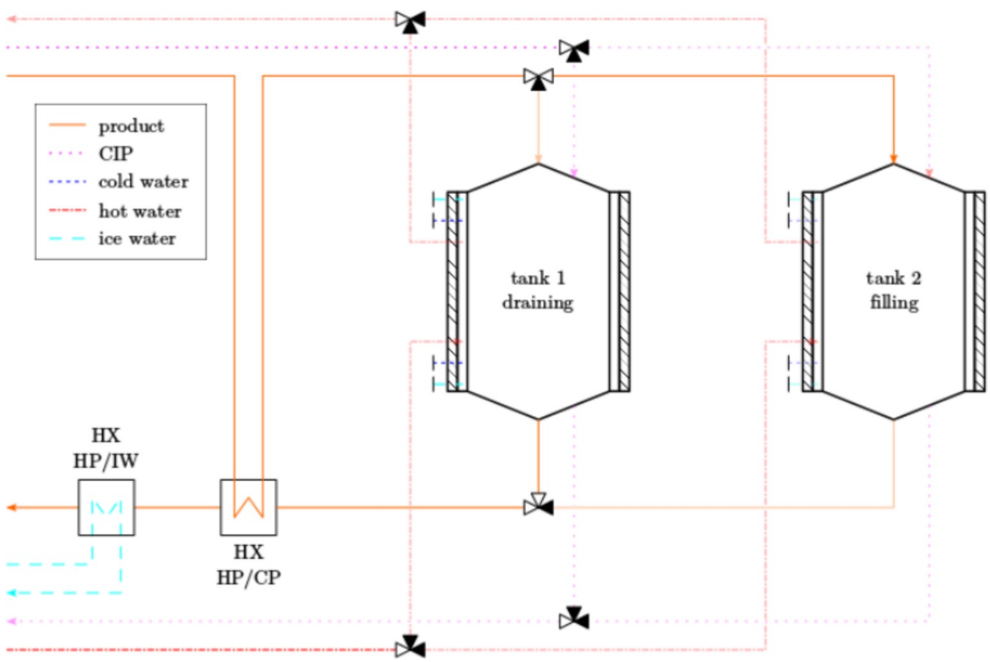

Figure 3: Process flow diagram of the plant following the “Rescheduling” approach

If beneficial, the filling of a tank may wait until another tank is ready to be drained. In the same way, the emptying may wait until another tank should be filled. By appropriate scheduling, the hot stream leaving the tank can be directly used to heat the cold stream entering another tank. The remaining heating and cooling requirements must be covered by the jacket heat exchanger in the tank and the ice water cooler.

This “Rescheduling” concept needs intelligent control to recognize the operation states of each tank and maximum energy savings as well as the physical equipment to connect the tanks using pipes, pumps and valves.

In the “Rescheduling” approach, one large tank is replaced by two smaller ones of approximately half the volume. The heat recovery rate and the production time for this concept are improved with increasing numbers of tanks each with less volume.

3 Methods

Figure 4 describes the methodical analysis and design approach applied in this retrofit and redesign study to increase the energy efficiency of thermal production processes.

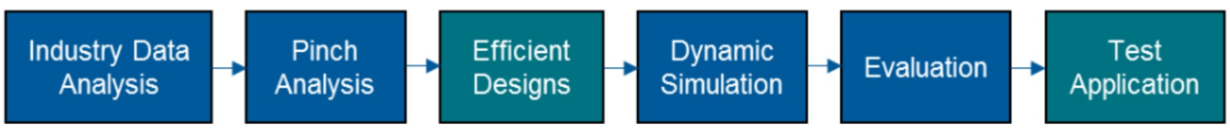

Figure 4: Methodical design approach for energy efficient industry applications

First, the process is analysed in the industry. Process flow sheets, the process sequence of the controlling and measurement data for process and energy flows are collected and summarised. The gathered data is the basis for analysing potential energy efficiency improvement.

To optimise energy efficiency, Pinch Analysis [28] invented by Linnhoff [29] is applied. Through the construction of Composite Curves, the technical optimum energy target is calculated. From there, two new design approaches are developed and worked out in flow charts.

To evaluate the dynamics of the process, MATLAB/Simulink models are developed. The physical models are based on thermodynamics and heat transfer [30]. The control sequence of the programmable logic controller (PLC) used in the current industrial installation is adopted in the MATLAB simulation. The production program that models each virtual component matches reality. The detailed description of the model is provided in section 3.1.

The results are evaluated in the technical effects on specific energy consumption (SEC), complexity and flexibility. Specific energy consumption is based on mass through-put for a single production cycle. Each thermal heat flow may be presented as a specific energy (Eq. 1-3), which may be summed to determine the total SEC (Eq. 4) as a single energy performance indicator.

$$SEC_{heating} = \frac{E_{heating}}{m_{product}} \tag{1}$$

$$SEC_{pre-cooling} = \frac{E_{pre-cooling}}{m_{product}} \tag{2}$$

$$SEC_{deep-cooling} = \frac{E_{deep-cooling}}{m_{product}} \tag{3}$$

$$SEC_{sum} = \frac{E_{heating} + E_{pre-cooling} + E_{deep-cooling}}{m_{product}} \tag{4}$$

Complexity is based on the number of components of the design and flexibility on adjustability of product mass flow.

The economic assessment is based on the concept of investable investment costs I. They are the product of yearly cash flows C_t for energy savings and the payback time $t_{Payback}$ defined by the individual organisation.

$$I = C_t \cdot t_{Payback} \tag{5}$$

Additionally payback times for a specific case are calculated and assessed in a sensitivity analysis.

3.1 Thermal Sterilisation Process Model Description

The model is implemented in MATLAB/Simulink. The physical model calculates mass balances and temperature changes and is based on thermodynamics. To compute the time-dependent behaviour of the production sequence, the control logic of the PLC from the industrial plant is transferred to the simulation code.

3.1.1 Storage Tank

Figure 5 shows the flowchart of the storage tank model. It represents incoming and outgoing mass flows of the product, heat transfer $\dot{Q}_{HT}$ through the surface and radiation from the surface. Additionally, heat $\dot{Q}_{heating}$ can be actively transferred from the jacket heat exchanger to heat up and cool down the contents of the tank. The physical model of the storage tank is based on the concept of the perfectly mixed system and simplifies the geometry to a constant surface.

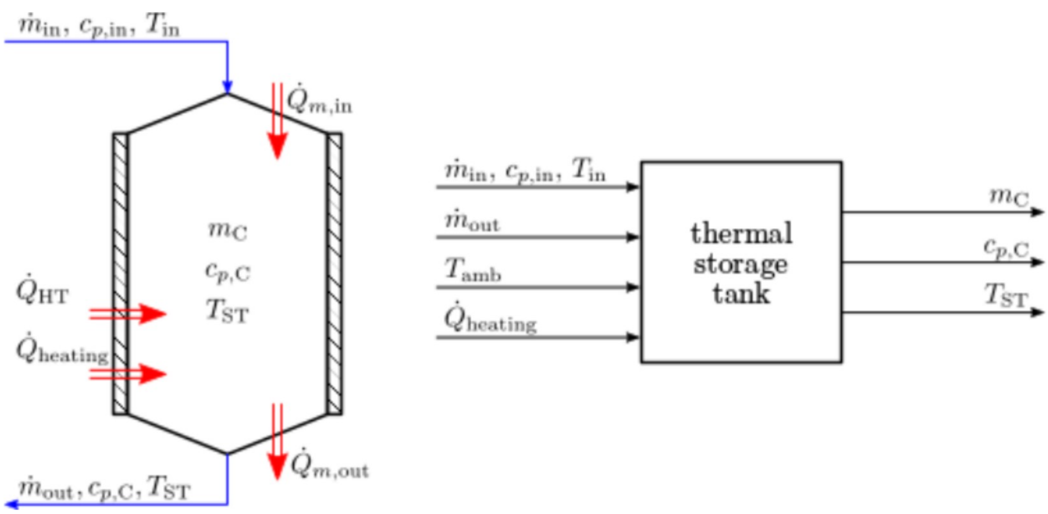

Figure 5: Process flow chart and equivalent process flow model of the storage tank

The thermal storage is calculated according to the first law of thermodynamics.

$$\frac{dE_{ST}}{dt} = \frac{dm_C}{dt} \cdot \frac{dc_{p,C}}{dt} \cdot \frac{dT_{ST}}{dt} = \dot{Q}_{ST} + \sum_{i=1}^{n_{in}} \dot{m}_{in,i} - \sum_{j=1}^{n_{out}} \dot{m}_{out,j} \tag{6}$$

First, the change of mass in the storage tank (ST), $\dot{m}_C$, is calculated. This is the difference of mass flows going in and out of the system at an instance in time.

$$\dot{m}_C = \frac{dm_C}{dt} = \sum_{i=1}^{n_{in}} \dot{m}_{in,i} - \sum_{j=1}^{n_{out}} \dot{m}_{out,j} \tag{7}$$

The heat capacity of the storage tank C_{ST} is the sum of heat capacities of the solid parts of the vessel, C_S, and the content inside the vessel, C_C. Both heat capacities can be calculated from the product of a specific heat capacity and a mass.

$$C_{ST} = C_S + C_C = m_S \cdot c_{p,S} + m_C \cdot c_{p,C} \tag{8}$$

The heat capacity of the jacket is constant, due to its solid building constant.

$$\frac{dC_S}{dt} = 0 \tag{9}$$

With the previous definition of the jacket, the change in the heat capacity is defined by the sum of the incoming and outgoing mass flows multiplied by the specific heat capacity.

$$\dot{C}_{St} = \dot{C}_C = \sum_{i=1}^{n_{in}} \left(\dot{m}_{in,i} \cdot c_{p,in,i} \right) - \ c_{p,C} \sum_{j=1}^{n_{out}} \dot{m}_{out,j} \tag{10}$$

The change of the specific heat capacity of the content of the ST $\dot{c}_{p,I}$ can then be calculated by the quotient rule for later integration.

$$\dot{c}_{p,C} = \frac{d}{dt} \frac{C_C}{m_C} = \frac{\dot{C}_C \cdot m_C - C_C \cdot \dot{m}_C}{{m_C}^2} = \frac{\dot{C}_C - c_{p,C} \cdot \dot{m}_C}{m_C} \tag{11}$$

The heat flows from and to the storage tank, $\dot{Q}_{ST}$, can be subdivided by its physical effects in the components of heat transfer to and from the environment - $\dot{Q}_{HT}$ - including thermal radiation and convective heat transfer. $\dot{Q}_m$ contains heat flow associated with the mass flow. $\dot{Q}_{heating}$ represents active heating and cooling components.

$$\dot{Q}_{ST} = \dot{Q}_{HT} + \ \dot{Q}_m + \dot{Q}_{heating} \tag{12}$$

Each physical effect is calculated separately. Heat transfer to the environment is approximated using:

$$\dot{Q}_{HT} = \frac{1}{\frac{1}{\alpha_{inside}} + \sum_{i=1}^{n_d} \frac{d_i}{\lambda_i} + \frac{1}{\alpha_{outside}}} \cdot A_{ST} \cdot \left(T_{amb} - T_{ST} \right) \tag{13}$$

$\dot{Q}_m$ depends primarily on the temperature of the mass, assuming a constant specific heat capacity.

$$\dot{Q}_m = \sum_{i=1}^{n_{in}} \dot{m}_{in,i} \cdot c_{p,in,i} \cdot T_{in,i} - c_{p,C} \cdot T_{ST} \sum_{j=1}^{n_{out}} \dot{m}_{out,j} \tag{14}$$

The change of the average vessel temperature, $\dot{T}_{ST}$, which is also the fluid outlet temperature, is calculated by quotient rule for later integration.

$$\dot{T}_{ST} = \frac{d}{dt} \cdot \frac{Q_{ST}}{C_{ST}} = \frac{\dot{Q}_{ST} \cdot C_{ST} - Q_{ST} \cdot \dot{C}_{ST}}{{C_{ST}}^2} = \frac{\dot{Q}_{ST} - T_{ST} \cdot \dot{C}_C}{C_{ST}} \tag{15}$$

By integration of the differentials the mass of the content, the specific heat capacity of the content and the temperature of the storage tank, assuming the jacket material and the fluid have the same temperature, are defined for each time step.

$$m_C(t) = m_{C,0} + \int_{t_o}^{t} \dot{m}_C(t')dt' \tag{16a}$$

$$c_{p,C}(t) = c_{p,C,0} + \int_{t_o}^{t} \dot{c}_{p,C}(t')dt' \tag{16b}$$

$$T_{ST}(t) = m_{ST,0} + \int_{t_o}^{t} \dot{T}_{ST}(t')dt' \tag{16c}$$

The initial conditions and the maximum boundary values are defined in a graphical user interface in MATLAB/Simulink.

3.1.2 Heating Jacket

The heating jacket is modelled in MATLAB/Simulink as an add-on block, that can be coupled as a heat input – $\dot{Q}_J$ – to the storage tank.

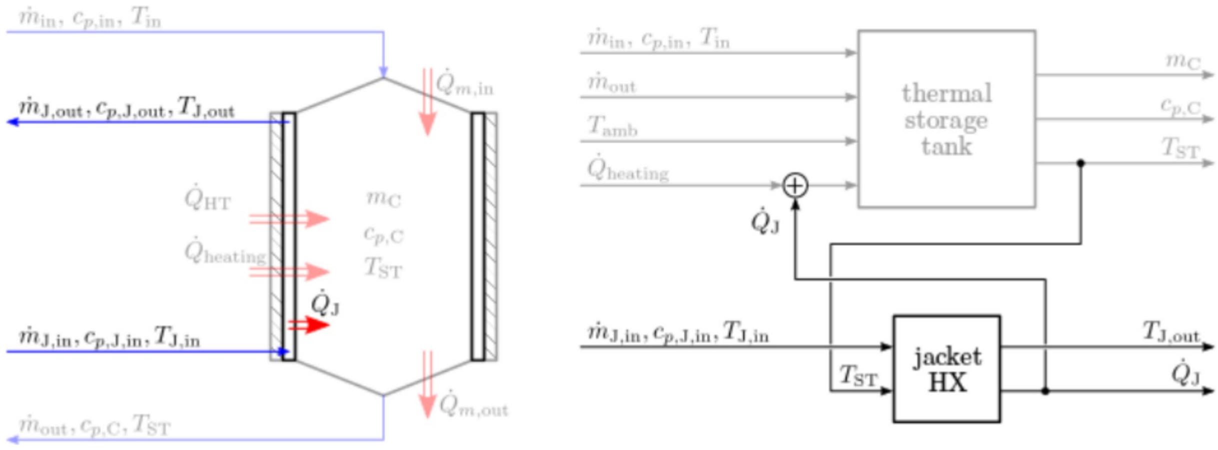

Figure 6: Flowchart of the jacket heating and equivalent process flow model. The jacket system can be coupled with the storage tank model through the interface of $\dot{Q}_J$

The energy balance of the ST is modified to include $\dot{Q}_J$.

$$\dot{Q}_{ST} = \dot{Q}_{HT} + \dot{Q}_m + \dot{Q}_{heating} + \dot{Q}_J \tag{17}$$

To calculate the heat flow transferred from the jacket to the tank, the outlet temperature of the media from the jacket must be known. If there is no mass flow, there is no heat addition and the jacket temperature is assumed to be the same as the tank temperature. In all other cases, the temperature is calculated using the counterflow P-NTU formula:

$$T_{J,out} = \begin{cases} T_{ST}, & if\ \dot{C}_{J,in} = 0 \\ T_{ST} + \left(T_{J,in} - T_{ST}\right) \exp\left(-\frac{U_J \cdot A_J}{\dot{C}_{J,in}}\right), & if\ \dot{C}_{J,in} \neq 0 \end{cases} \tag{18}$$

With mass flow, heat capacity and inlet and outlet temperatures available, the heat flow is defined using:

$$\dot{Q}_J = \dot{C}_{J,in} \cdot (T_{J,in} - T_{J,out}) \tag{19}$$

Through the coupling of the variables in Simulink, the jacket and ST are interlinked with one other.

3.1.3 Counterflow Heat Exchanger

For calculating the heat flow of the counter flow heat exchanger (Figure 7), the dimensionless temperature change P_i is calculated using the counter flow P-NTU formula. From this, the temperatures at the outlet of both mass flows are calculated. With all temperatures of the heat exchanger, the logarithmic temperature difference $T_{m,log}$ and the heat flow $\dot{Q}_{CHX}$ are computed.

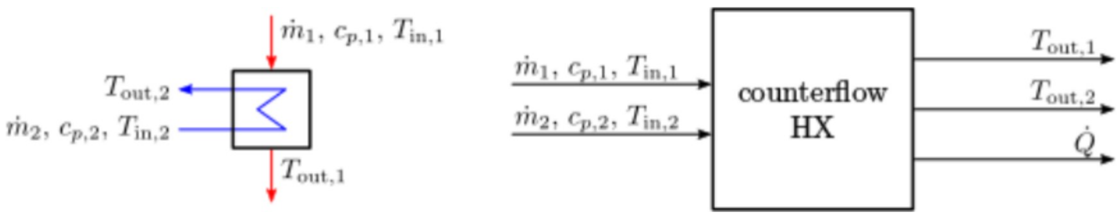

Figure 7: Flowchart of the counter flow heat exchanger (HX)

To calculate the dimensionless temperature, auxiliary numbers are necessary for the first step. The heat capacity flow rate $\dot{C}_i$ contains the mass flow $\dot{m}_i$ and the physical properties of specific heat $c_{p,i}$ of each stream.

$$\dot{C}_i = \dot{m}_i \cdot c_{p,i} \tag{20}$$

With this information, the ratio of heat capacity flow rates R_i are determined. The ratio symbolizes the capability of the streams to take heat and the corresponding effect on temperature change. If the ratio R_i equals one, the temperature change after the heat transfer is equal for both mass flows.

$$R_1 = \frac{\dot{C}_1}{\dot{C}_2}, R_2 = \frac{1}{R_1} \tag{21}$$

Number of Transfer Units (NTU) sets the physical properties of the overall heat transfer coefficient, U, and the area of the exchange surface, A, in context with the heat capacity flow rate for each stream.

$$NTU_i = \frac{U \cdot A}{\dot{C}_i} \tag{22}$$

Knowing NTU and R, the dimensionless temperature, P_i, is calculated according to the given if-statement.

$$P_i = \begin{cases} \dfrac{NTU}{1 + NTU} & if\ R = 1 \\ \dfrac{1 - \exp[(R_i - 1) \cdot NTU_i]}{1 - R_i \cdot \exp\,[(R_i - 1) \cdot NTU_i]} & if\ R\ \neq 1 \end{cases} \tag{23}$$

The outlet temperature of each stream is then calculated.

$$T_{out,1} = T_{in,1} - P_1 \cdot (T_{in,1} - T_{in,2}) \tag{24a}$$

$$T_{out,2} = T_{in,2} + P_2 \cdot (T_{in,1} - T_{in,2}) \tag{24b}$$

In the last step, the heat flow of the counter flow heat exchanger $\dot{Q}_{CHX}$ is calculed.

$$\dot{Q}_{CHX} = \dot{m}_1 \cdot c_{p,1} \cdot (T_{in,1} - T_{in,2}) \tag{25}$$

3.1.4 Control system

To simulate the virtual product flow, a control system is necessary. A condition state-based system is used, that changes state when the physical system has reached specified set points e.g. sterilisation temperature or sterilisation time. Table 1 presents descriptions for the 10 sequential states of the system from being ready to fill (0) through to heating/cooling (2 - 5) and cleaning (9). These 10 states represent one cycle of the batch process.

Table 1: Description of the states of the control system

Number	State	Description
0	Ready to fill	The storage tank is empty and clean. It is waiting for filling.
1	Filling	The tank is filled with the product until a user-defined filling level is reached. The jacket heating is deactivated.
2	In-tank heating	The filling is completed. The jacket heating is activated at its maximum heat flow until sterilisation temperature is reached.
3	Sterilisation	The sterilisation temperature is held until a user-defined time has elapsed. A hysteresis controls the heat flow of the jacket heating.
4	Cooling 1	The tank is cooled by cooling water until reaching a user defined temperature.
5	Cooling 2	The tank is deep cooled by ice water until reaching a user-defined storage temperature.
6	Ready to	The sterilisation process is complete. The tank is queued for

	drain	draining[2].
7	Draining	The product drains out of the tank until it is empty.
8	Waiting for CIP	The empty tank must be cleaned. Due to limited capacities in the central cleaning stations, the tank is registered in a queue until all predecessor processes are completed.
9	CIP	The central CIP station executes the cleaning. When CIP is finished, the process begins with the state “Ready to Fill”

4 Industrial Case Study

The initial process design is modelled and validated against real production data. This builds the energetic baseline for further comparison of energy efficiency improvements. Pinch Analysis is applied to calculate the maximum energy target. From there the energy efficient designs “Energy Storage” and “Rescheduling” are derived. With the dynamic model, the energy saving potentials are calculated.

4.1 Maximum Heat Recovery

For evaluating the maximal possible heat recovery, it is assumed that all heat flows are available at the same time. For this to be the real case, either *n* parallel processing lines of batch sterilisations processes, between which heat may freely be exchanged, or a very large amount of storage or a combination of the two approaches would be needed. For actual batch sterilisation, this is in not the case, but this simple approach helps to define an ambitious energy target.

The process consists only of two energy flows. The filling and heating as well as the cooling and draining of the product. The mass flow of filling and draining is equal and the temperatures of the starting and ending of the process are almost equal. These are very good conditions for heat recovery like in pasteurisation processes [31]. Figure 8 shows the resulting composite curve using a minimum approach temperature of 2 K with a high degree of heat recovery, very low heating demand and low cooling demand.

[2] Reasons for waiting can be: reserved lines by other product flows or missing input flows in the design of “Rescheduling”.

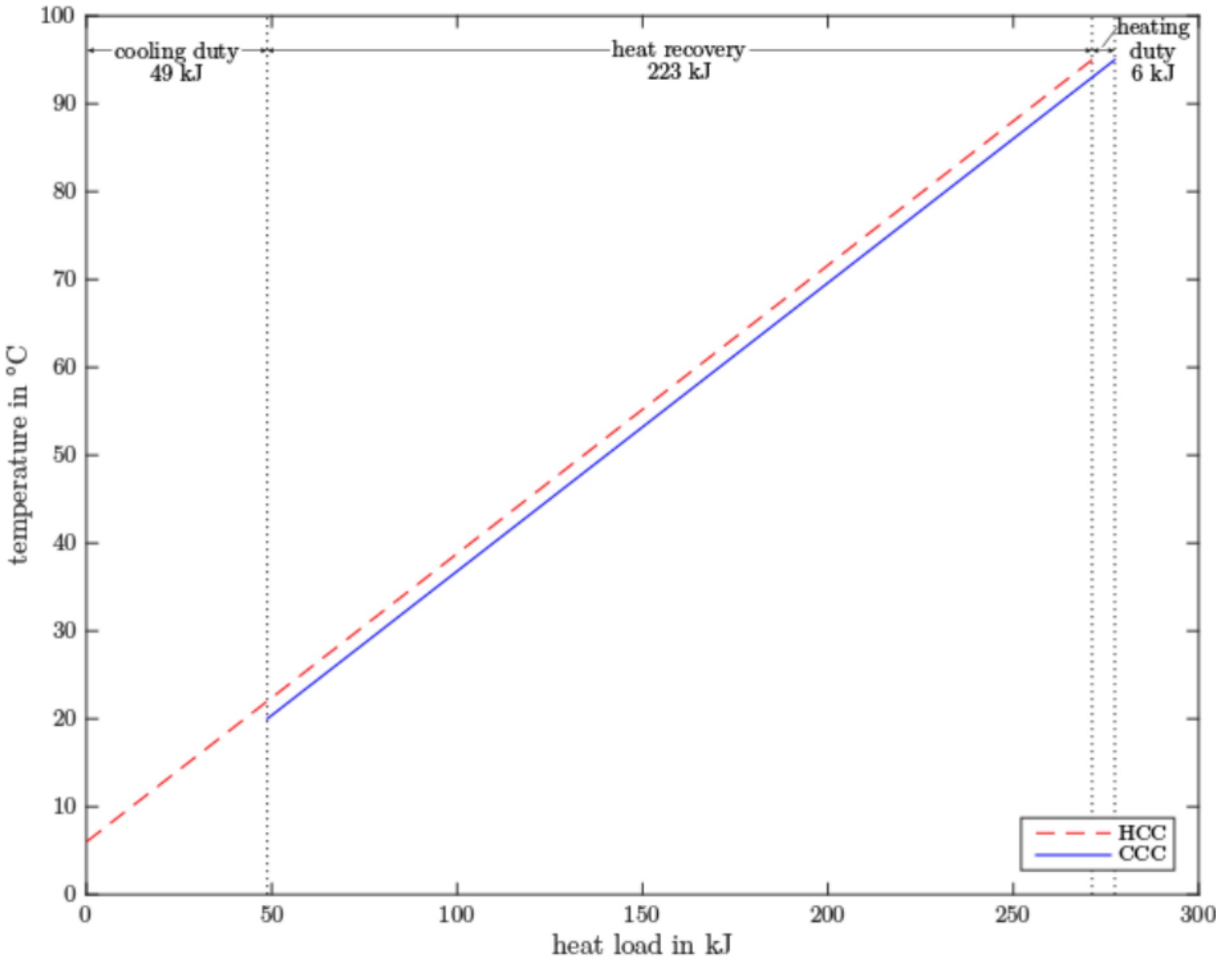

Figure 8: Composite curves of the batch sterilisation process ignoring the time-dependence of all heat flows.

One way to achieve the identified heat recovery potential is through heat storage. Alternatively, the process can be rescheduled, if allowable. This procedure is described by Kemp et al. [28]. The time-dependent heating and cooling requirements of the batch sterilisation process for whey cream, considered in this work, are shown in Figure 11. Positive values indicate heating requirements and negative values cooling requirements. It becomes clear, that they occur with a time offset.

4.2 Model Development

According to the design layouts and control strategies, the model is built. The detailed process description of the initial design and the optimized layouts are given in section 2. The modular thermodynamic models from section 3.1 are put together to describe the system mathematically. The initial design is validated against real production data.

4.3 Model Validation

Figure 9 describes the production process over time for a single tank. The process begins with an empty vessel at ambient temperature. The first step is filling. The mass increases to 3,000 kg before the heating to 95 °C begins. When the target temperature is reached, the temperature must be held for 30 min to ensure the sterilisation. The cooling is separated into two steps: cooling water for precooling and ice water for deep cooling. Due to the small temperature differences in the cooling process, it takes more than double the time as heating. After draining the product from the tank, the vessel gets cleaned before the next production starts.

Figure 9 shows the mass of the product in the tank, the temperature and the heat flow over time. Since mass and temperature are relevant in process monitoring, these are logged in the manufacturing execution system and can be evaluated for validation of the model. In Figure 9, the real production data is marked with a continuous line in blue while the simulated values are an orange dotted line. The comparison shows that the time-dependent behaviour of the system can be adequately modelled.

The heat flows are not monitored in the real production process, as these are not directly measured. As a result, only the heat flows for hot, cold and ice water from the simulation are presented.

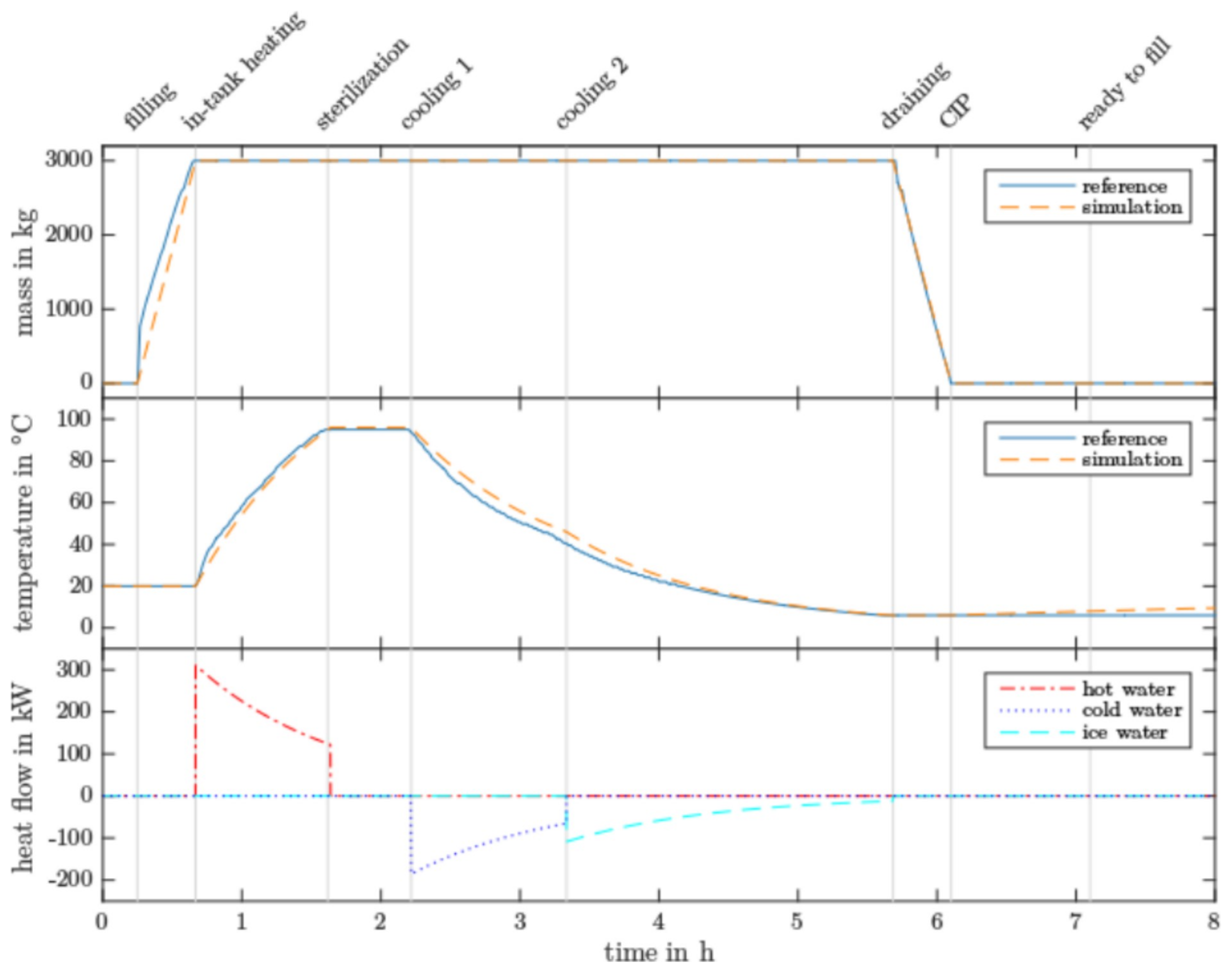

Figure 9: Time-dependent process description and validation of mass of product load, product temperature and heat flow from utilities measurement and simulation data

5 Results

The results are calculated for the three designs using the same operational scenario. The simulation time is equal for all three cases with 27.7 hours. In total, 12 tons of product are processed. The product temperature before processing is 20 °C and after is 6 °C. This setting makes the results from the energetic perspective directly comparable. The initial design is the basis that has already been validated against the measurement data from the real process.

5.1 Initial Design

In the initial design, the heating and cooling process is completely done via the jacket of the tank. At the start of the process, the tank temperature is relatively low compared to the flow temperature of the heating circuit. Figure 10 shows the temperature curves of four tanks running in parallel.

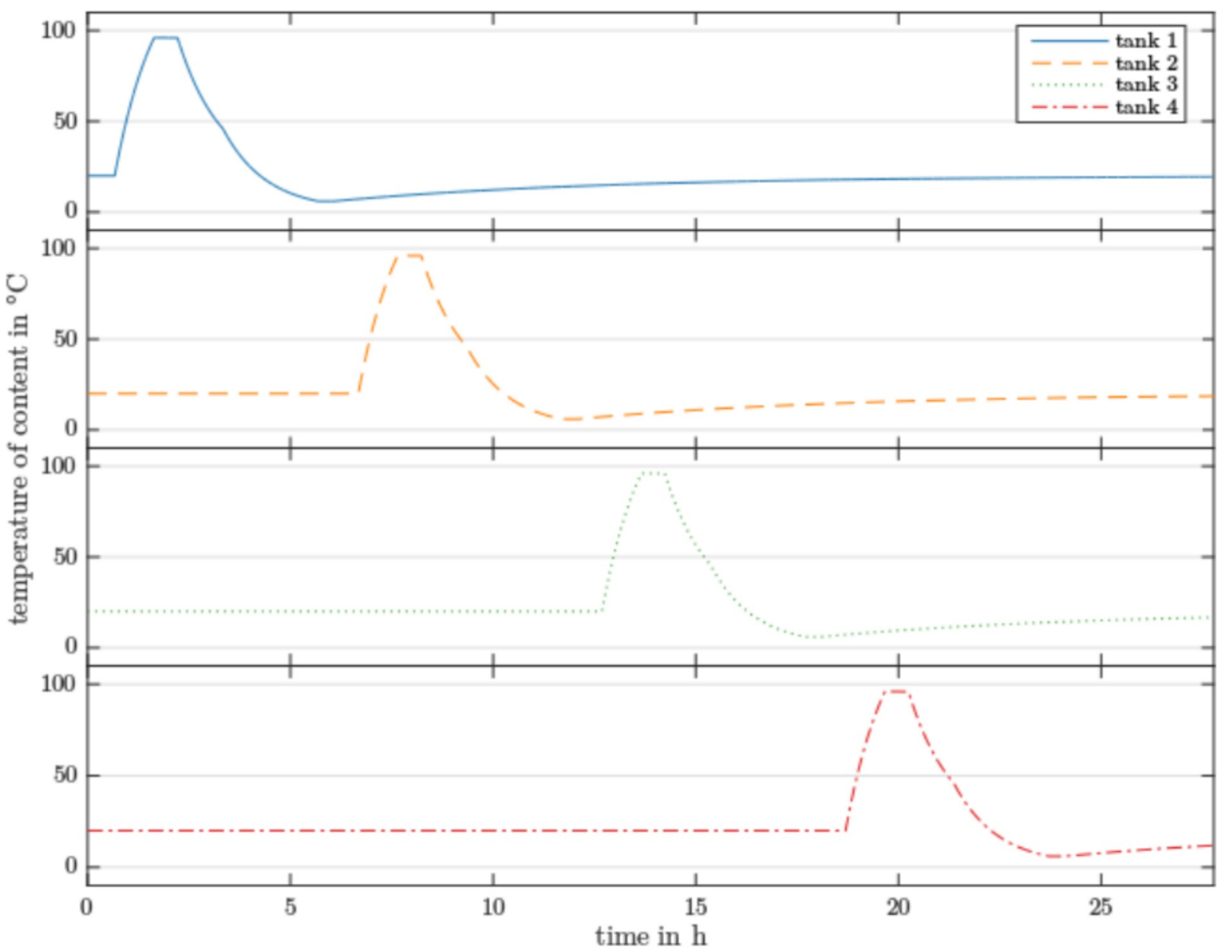

Figure 10: Temperature curve of the tanks in the initial design

The thermal heat flow, therefore, reaches its maximum at 311 kW. While the tank heating up, the driving temperature force is lowered and the thermal heat flow decreases. Figure 11 shows the time-dependent graph of the thermal heat flows. After sterilisation, the product is cooled down in two separated steps. First with cold water, that has a temperature of 19 °C. Second with ice water, that has a temperature of 1 °C. The graph of the cooling process shows the same patterns like the heating process with negative values. The reason is again the decreasing driving temperature force between the flow of the cooling circuit and the product temperature in the tank.

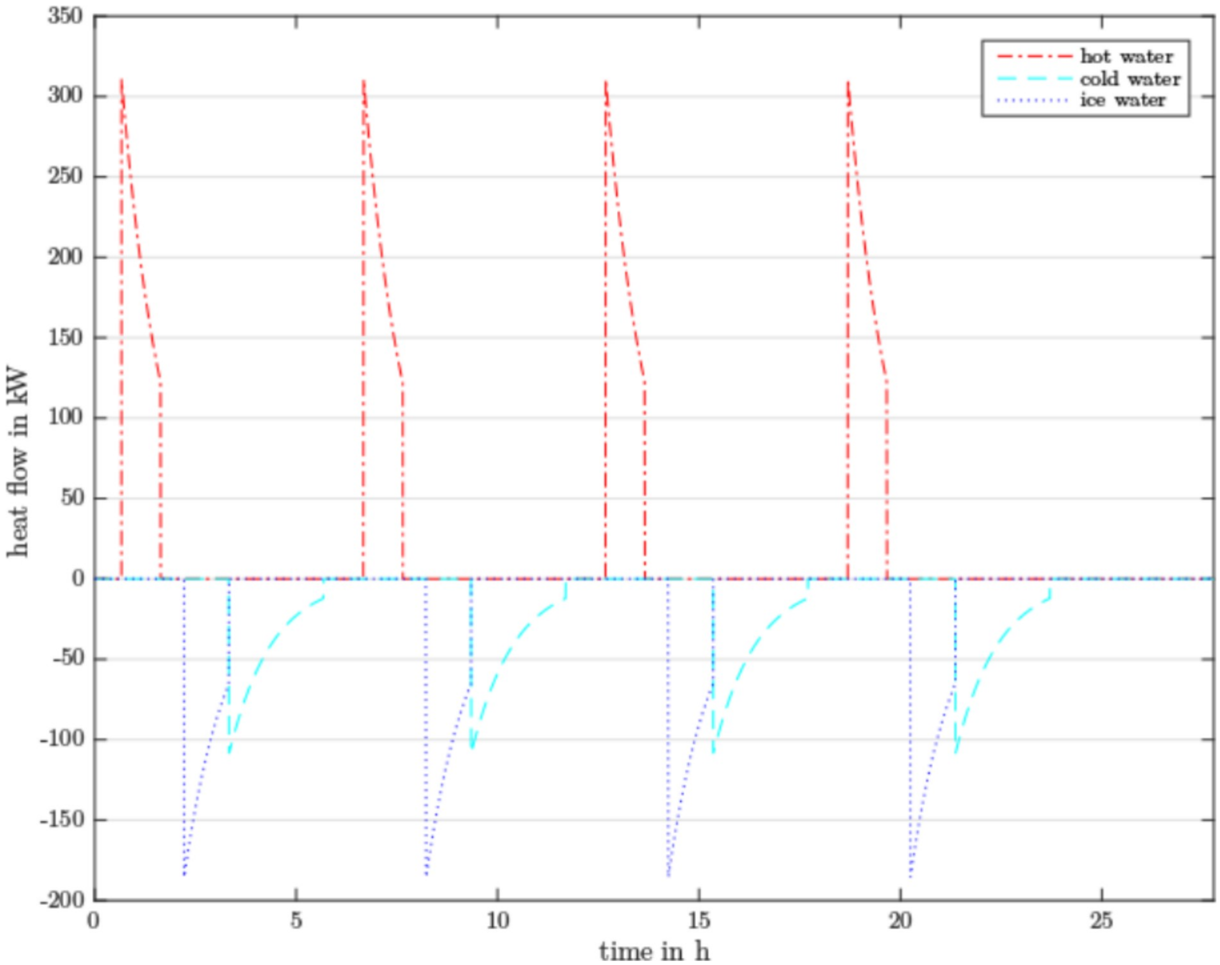

Figure 11: Time-dependent simulation results of the thermal heat flows in the initial design

For running the four batches, 24 hours are necessary. If one process is finished, cleaning is obligatory, and the next batch of 6 hours and 51 minutes can start. Through using further parallel tanks in a group, the acceleration of the process using this design is possible.

5.2 Design with Energy Storage

The description of the design with “Energy Storage” begins in the cycle within the sterilisation process. This simplifies the explanation of the storage concept. When cooling down the product after sterilisation, the energy that was brought into the process to heat up the tank to sterilisation temperature is released to the environment. In this design, this heat is recovered and stored in an additional thermal storage tank (regenerative tank). The temperature curve of the product tank is shown in Figure 12. When the processing tank is filled with product, the heat from the regenerative storage is used to pre-heat the product in a counter flow heat exchanger. During this process, the driving temperature force between product and thermal energy carrier stays constant and high. Therefore, large thermal heat flows are transferred from the heat recovery to the product that reaches 79 °C. The external heat jacket adds the remaining 16 °C. The heat flows in Figure 13 are only displayed for external heat. Due to the heat recovery, the energy demand for heating is decreased by 77%.

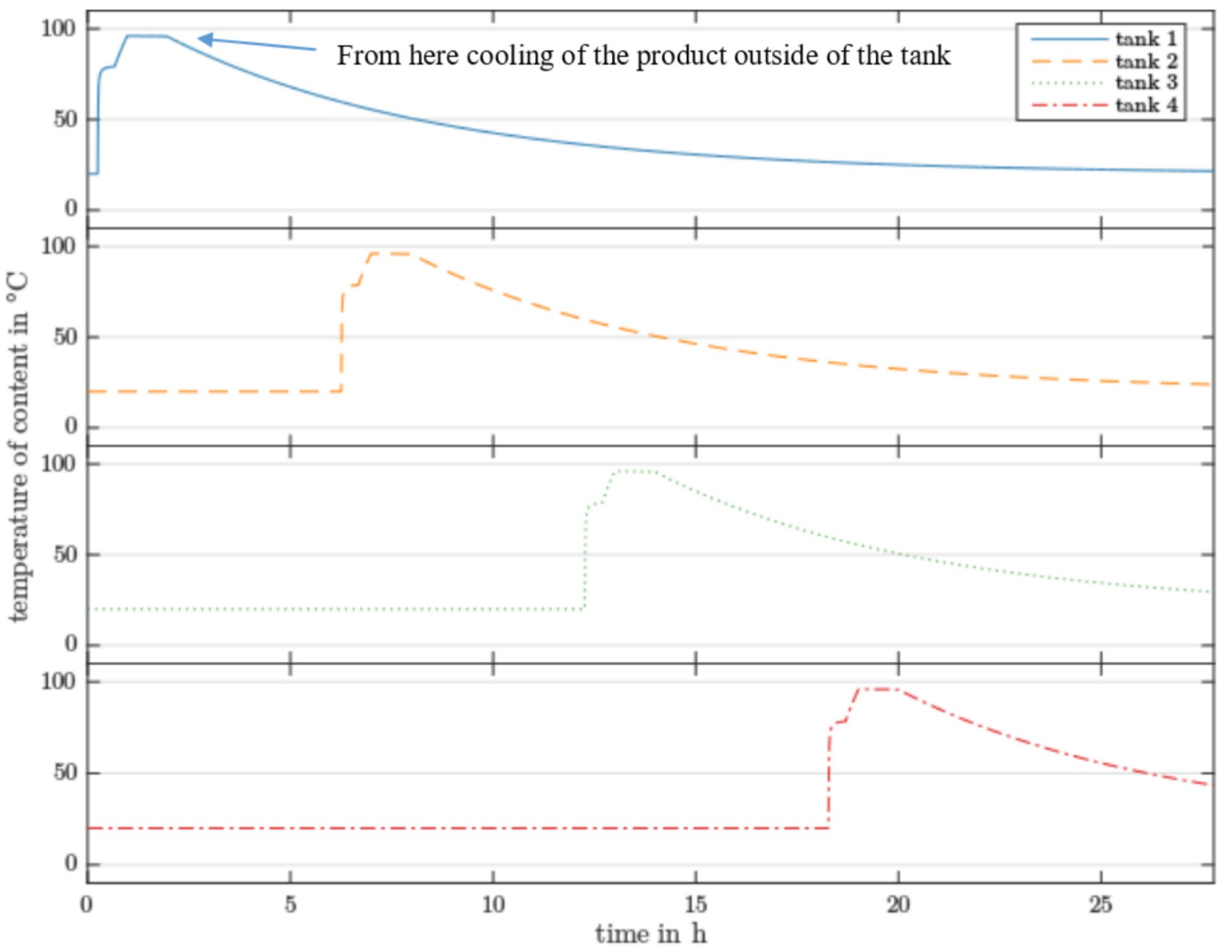

Figure 12: Temperature curve of the design using thermal energy storage

In this design, the product is cooled outside of the tank throughout an additional heat exchanger. Therefore, the temperature of the processing tank is cooled down passively against ambient temperature with a low driving force and is therefore very slow. The cooling temperature, as shown in the graph, does not have any effects on the processing of the product since the product is cooled down continuously and effective outside from the processing tank. In the first step, the product is cooled in a counterflow heat exchanger with water from the regenerative cold tank. The water, that is heated simultaneously, is piped into the hot regenerative tank. In the second step, ice water is used in a counter flow heat exchanger. A constant heat flow of 183 kW is necessary.

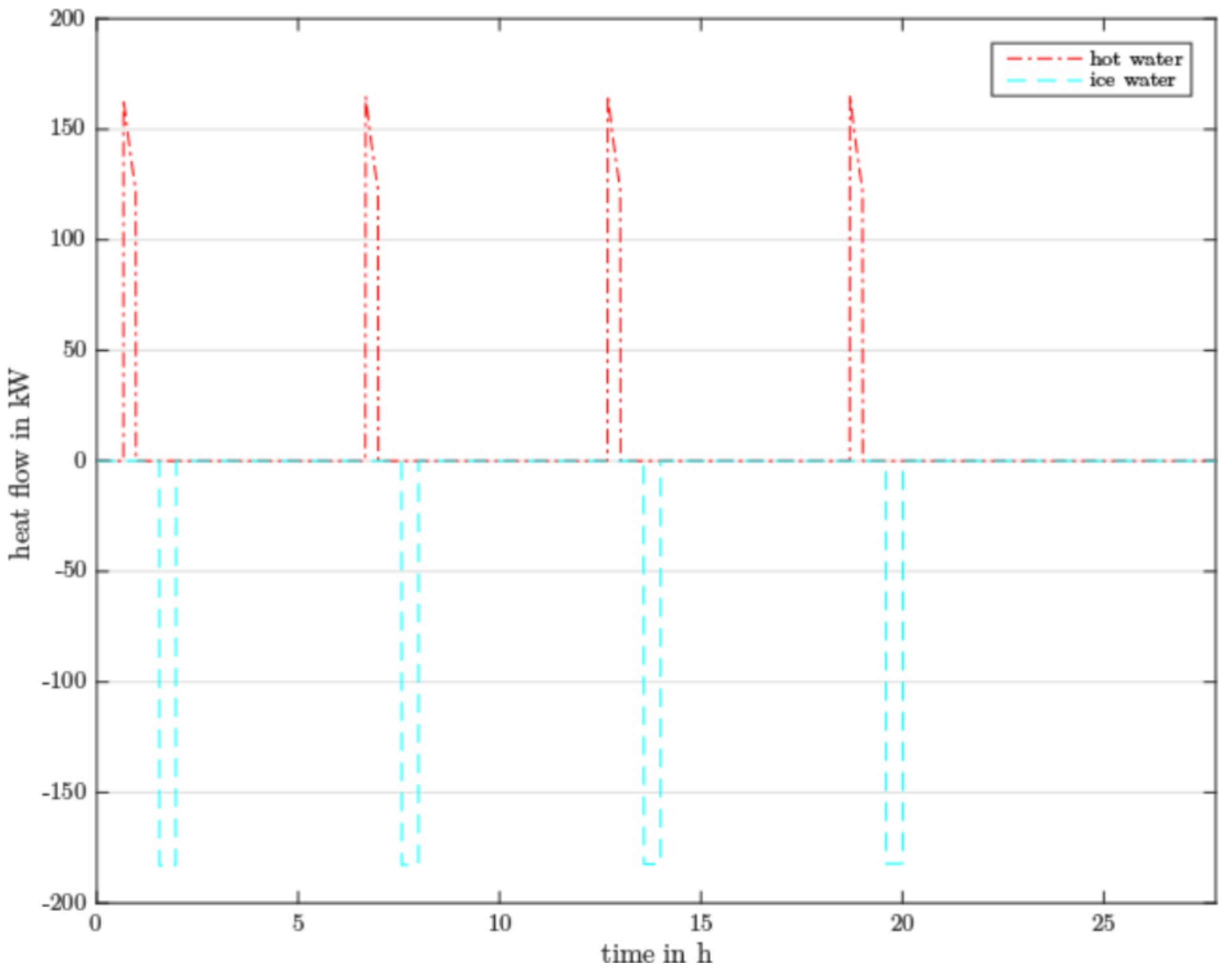

Figure 13: Time-dependent simulation results of the thermal heat flows in the design with thermal energy storage

The processing time of a single batch reduces significantly compared to the initial design. Time is reduced from 6 hours and 51 minutes to two hours and 44 minutes. Adverse to the heat recovery, an extra restriction is in the schedule of the process.

5.3 Design with Optimised Scheduling

The “Rescheduling” design does not require a thermal storage (regenerative) tank but a more advanced control strategy. Discharging of a processing tank is only possible when another batch is in the filling process. The temperature curve in Figure 14 shows a fast heating process in the counter flow heat exchanger and external heating needed for the final 2 °C of heating. The cooling is divided into two steps. First in the counter flow heat exchanger for heat recovery for pre-heating the product for the next batch. Second in a counter flow heat exchanger for deep cooling via ice water. Since the cooling of the product is external from the processing tank the tank temperature decreases against the ambient temperature. This temperature does again not affect the processing of the product.

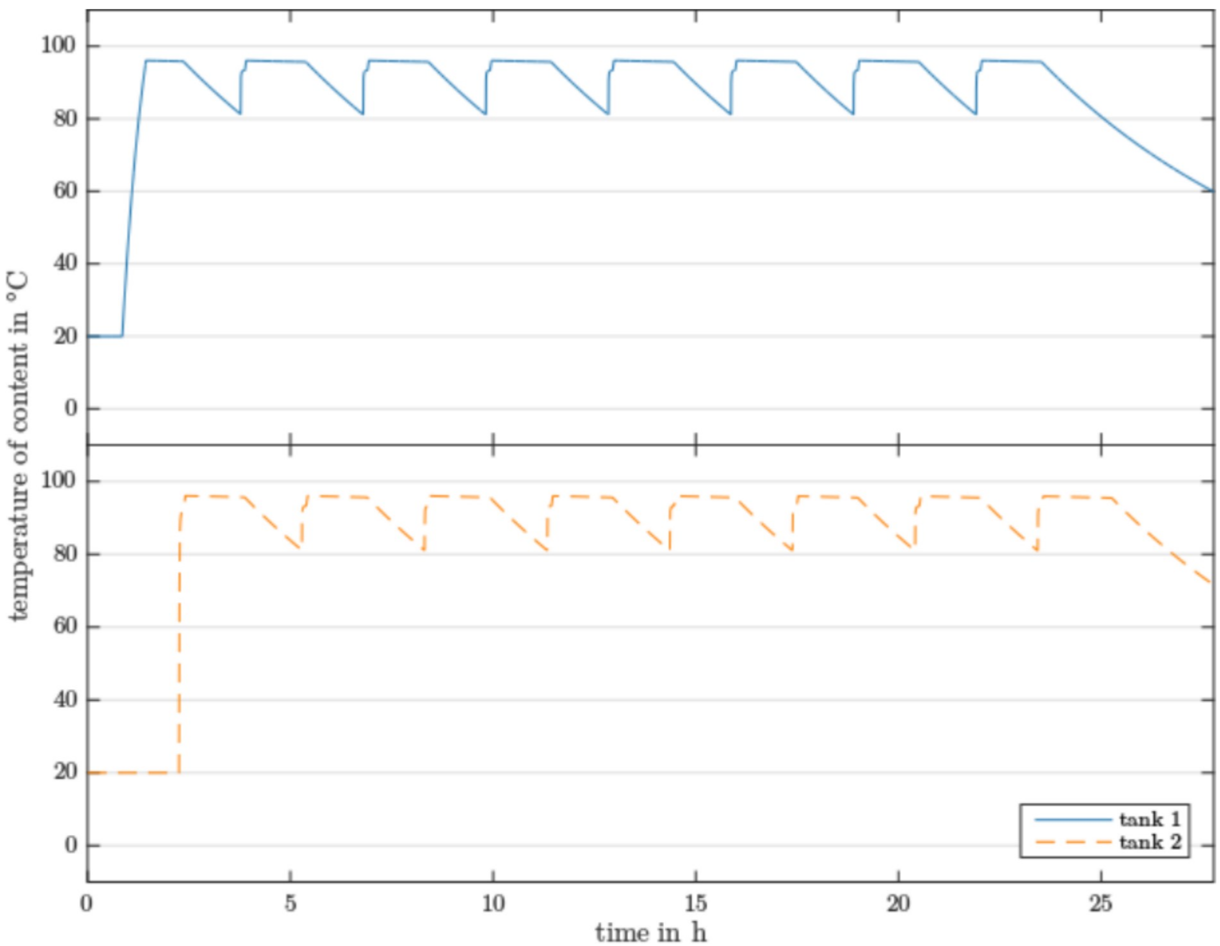

Figure 14: Temperature curve of the rescheduling design

Figure 15 shows the heat flows. Since there is no thermal storage, the start-up heating and shut-down cooling are required. The start-up and shutdown processes take the highest thermal energy flows. They can be reduced by using smaller tanks. When the heat recovery is running, only 51 kW for heating and 98 kW for cooling are required. The total heat demand is by 90 % lower compared to the initial design.

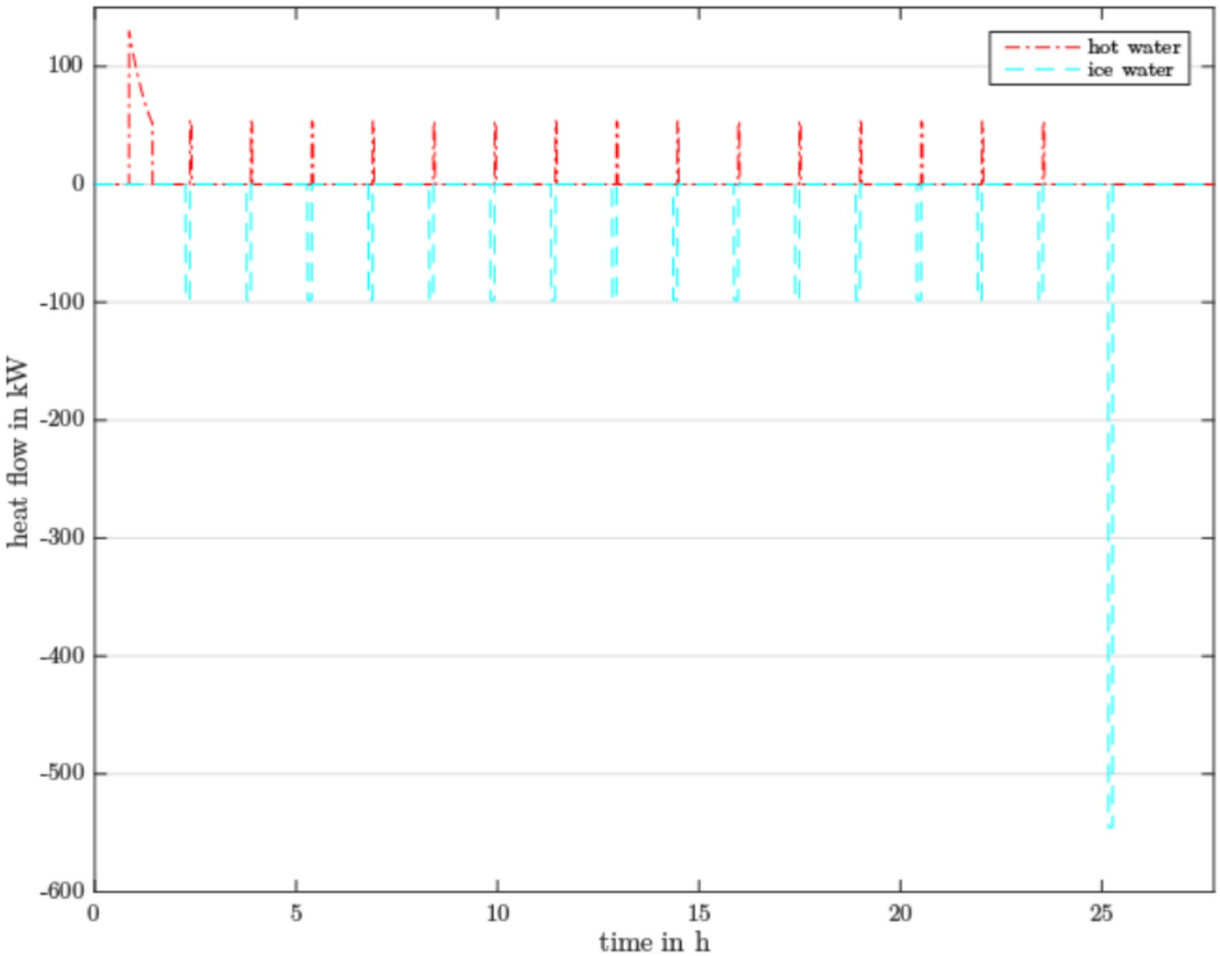

Figure 15: Time-dependent simulation results of the thermal heat flows in the design with thermal energy storage.

Figure 15 shows also that 16 batches were produced during the same time. Since the design has strong limitations on the filling and discharging, the size of the processing tanks is reduced to produce the same amount of product. Smaller equipment and batch sizes is a disadvantage as the process becomes semi-continuous and the scheme would need to be proven, in particular, that hygiene standards can be met.

6 Comparison and Discussion

The results are first compared from a technical perspective and then evaluated from the point of economic feasibility.

6.1 Technical Comparison of the Designs

For technical comparison, three assessment values have been defined. The first value is the specific energy demand. Where the thermal heat demand is related to the mass processed. This is the key figure for energy efficiency. The second and third assessment values are considering the flexibility and complexity of production planning. Within the assessment of flexibility, the process flow and the energy demand are rated on halved or doubled production throughput. Complexity rates the number of components that are necessary.

6.2 Specific Energy Demand

The specific heat demand makes the concepts directly comparable. Figure 16 lists all the results from the simulation. The initial design is the only configuration in which cold-water is needed. In the newly developed designs, this energy is transferred directly in the heat recovery. This leads to a 77% less heat demand in “Energy Storage” and 90% in “Rescheduling”.

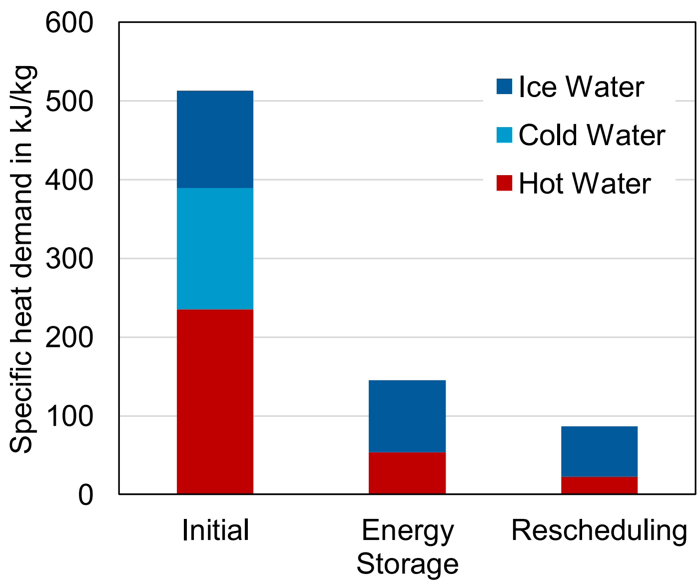

Figure 16: Specific heat demands for each design broken down by energy form

Since the designs of “Energy Storage” and “Rescheduling” are focusing on maximizing the heat recovery, they also integrate parts of the energy set free during ice water cooling in the heat demand. This leads to a 26% reduction in cooling demand in “Energy Storage” and 48% in “Rescheduling”. The concept of “Rescheduling” is more energy efficient than “Energy Storage” because there are fewer heat exchange processes and no losses during thermal storage in a tank.

Summarised the design “Energy Storage” saves 71% and “Rescheduling” 83% of the overall specific energy demand including heating and cooling.

6.3 Flexibility

Due to changes in the order situation or production process, the throughput of the product may change. Figure 17 shows the effect of doubled or halved throughput on the specific energy demand in quantified numbers. The initial design and “Energy Storage” are independent of the production volume. The “Rescheduling” design is tightly linked to the output. A processing tank can only be emptied if another is going to fill. In the case of doubled production volume, this fact does not change the energy demand. It is always enough material available to keep the flow. With halved output, the control system in the “Rescheduling” design recognises that the maximal waiting time for holding the product after processing in the tank is exceeded and it discharges the processing tank without heat recovery. Thus, there is no heat recovery potential for the next cycle. This problem is partly be answered by lower batch sizes that lead to sufficient product puffer on the input side.

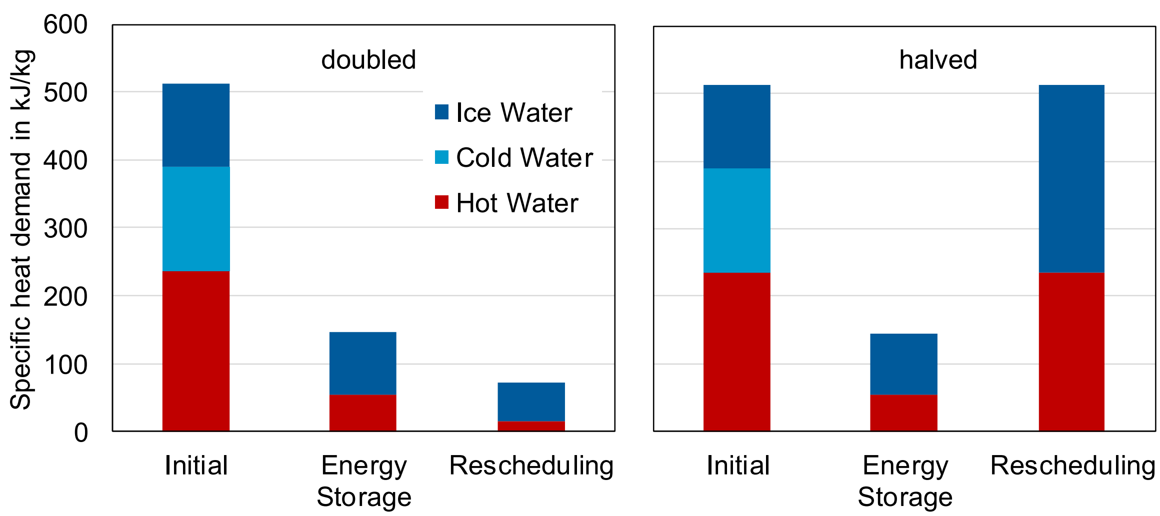

Figure 17: Specific heat demands for each design at doubled and halved production output

Summarised the initial design and “Energy Storage” are robust for variable product output where “Rescheduling” is sensitive to low volumes.

6.4 Complexity of components

For the designs with heat recovery, additional components are needed. Table 2 shows that the initial design is the simplest. It operates only with the processing tanks. The design of “Energy Storage” needs additional heat exchangers for pre-heating and pre-cooling and a thermal storage tank to bridge two productions steps. “Rescheduling” reduces the number of necessary components. Since the heat recovery takes place directly between filling and discharging of the processing tank it does not need a thermal storage tank. In contrast, the rescheduling approach requires, the substitution of one large tank by two smaller ones of approximately half the volume for a retrofit case.

Table 2: Complexity of the designs and number of additional components necessary

Design	Number		
	Initial	Energy Storage	Rescheduling
Processing tanks	2 (3.000 kg)	1 (3.000 kg)	2 (750 kg)
Thermal storage tanks	0	2	0
Sterilisation tank	0	0	2
Heat exchangers	0	3	2

The initial design is the simplest, whereas “Rescheduling” is predestined for redesign. “Energy Storage” has the highest complexity of components but is better suited for a retrofit.

6.5 Production time

It is analysed how long the tanks must be active to produce a batch of 12 t. For this purpose, the time during which the tanks are not in the state “ready to fill” is measured and summed up for the two or four tanks, respectively. The total time can be longer than the simulation time because multiple tanks can be active at the same time. Table 3 shows the results.

Table 3: Production times for each design

Design	Production time
Initial	27 h 25 min
Energy Storage	10 h 56 min
Rescheduling	9 h 39 min[3]

The “Energy Storage” and “Rescheduling” design take less than half the production time of the initial design. This is because heating and especially cooling in the tanks

[3] Equivalent tank size of 3,000 kg anticipated

consume significant time. Due to the longer production time, the initial design requires larger and/or more tanks than the other designs.

6.6 Overall Rating of Technical Results

The individual criteria of energy savings, flexibility and complexity of components cannot be compared directly. Table 4 displays the summary of the results in a simple advantage/disadvantage rating. The major target of increased energy efficiency is reached by the design of “Rescheduling”. The disadvantages of this concept are the flexibility on lowered production outputs once the hardware of the design is set and the higher cost for substitution of the sterilisation tank. Both advantages unite in the design of “Energy Storage” on costs of energy efficiency.

Table 4: Specific heat demands for each design broken down by energy form

Design	Energy efficiency	Flexibility	Complexity of components (redesign)	Complexity of components (retrofit)	Production time/rate
Initial	-	+	+	+	-
Energy Storage	+	+	-	-	+
Rescheduling	++	-	O	-	+

The most elegant design for redesigning is “Rescheduling”. The size of the tanks and space usage decreases. The trade-off with less flexibility may be solved when further decreasing the processing tank size and establishing a parallel process.

6.7 Economic Comparison of the designs

Economic comparisons are site-specific. Every plant produces different outputs and energy prices differ significantly depending on location and energy resources availability. The economic evaluation is based on a scenario that represents a typical large-scale dairy processing plant in Germany.

It processes each day two batches each 3.000 kg in the sterilisation process. The price for electricity is 80 €/MWh and for natural gas 40 €/MWh. The ammonia compression-chilling machine runs on an average COP of 4 and the gas boiler at an efficiency of 90 %. Thus, follows a hot water price of 44 €/MWh and an ice water price of 20 €/MWh. The cold water supplied by free cooling (COP = 20) has a price of 10 €/MWh.

Figure 18 shows the calculated energy saving costs that sum up at around 0.6 M€ per year.

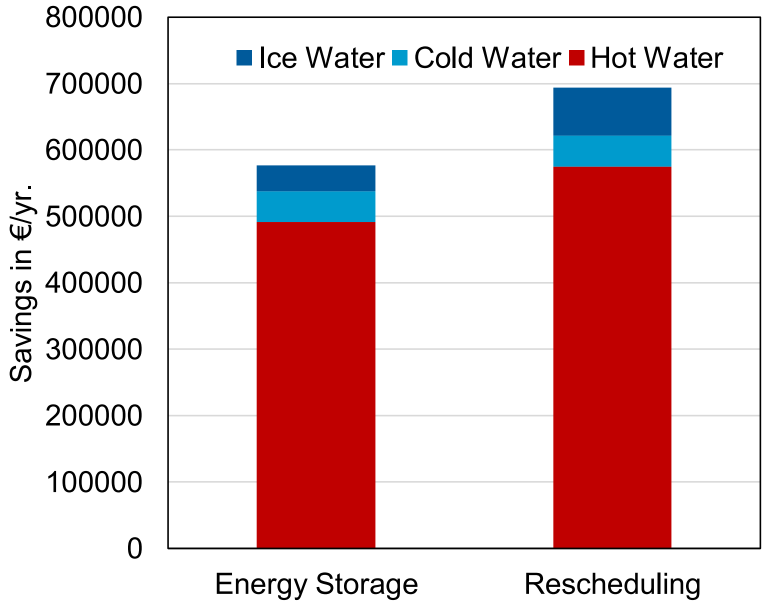

Figure 18: Savings of energy costs

The typical amortisation in industrial processing plants is two years for investments. If they have an environmental impact, the time may be extended up to three to five years. This leads to a maximum possible investment sum for this scenario between 0.97 M€ to 2.4 M€ for "Energy Storage" and 1.2 M€ to 2.9 M€ for "Rescheduling".

To realise the concepts, additional hardware components like thermal storage tanks, heat exchangers, instrumentation and piping are needed. On top of the costs for components, engineering, procurement and construction, are added.

Table 1 is giving the investment costs in each system for the redesign. The costs are taken from specific values from literature, requests from suppliers, and an industry expert. Even though using all the sources and having discussions with practitioners the costs may vary heavily by the choice of supplier, the relation to the supplier (one time or regular customer) requested quality and the existing production plant. When considering a retrofit in "Energy Storage" the costs for the tank group and pumps are omitted and implementation costs fall. For “Rescheduling” in case of a retrofit, additional dismantling costs of 50,000 € are calculated.

Table 5: Investment costs for each system for a redesign approach

Initial Design		**Energy Storage**		**Rescheduling**	
Component	**Cost in €**	**Component**	**Cost in €**	**Component**	**Cost in €**
Tank group (4 x 3,000 kg)	20,000 [32]	Tank group (4 x 3,000 kg)	20,000 [32]	Processing tanks (2 x 750 kg)	3,000 [32]
Piping and Instrumentation	61,300 [33]	Cold and hot storage tank (2 x 3 m³)	10,000 [34]	HX HP/CP	19,300 [35]
Engineering, Procurement and Construction	4,000 [33]	HX HP/IW	19,300 [35]	HX HP/IW	19,300 [35]
		HX HP/CS	19,300 [35]	Piping and Instrumentation	39,700 [33]
		HX HS/CP	19,300 [35]	Engineering, Procurement and Construction	35,500 [33]
		Piping and Instrumentation	64,300 [33]		
		Engineering, Procurement and Construction	32,900 [33]		
Sum	104,600	**Sum**	185,100	**Sum**	116,800

The uncertainty in investment costs is addressed by a sensitivity analysis. The costs are varied between 75% and 400%. The results show that even with heavily rising costs both redesigns remain economically feasible in a timeframe shorter than two years. “Rescheduling” is less sensitive to a rise in investment costs.

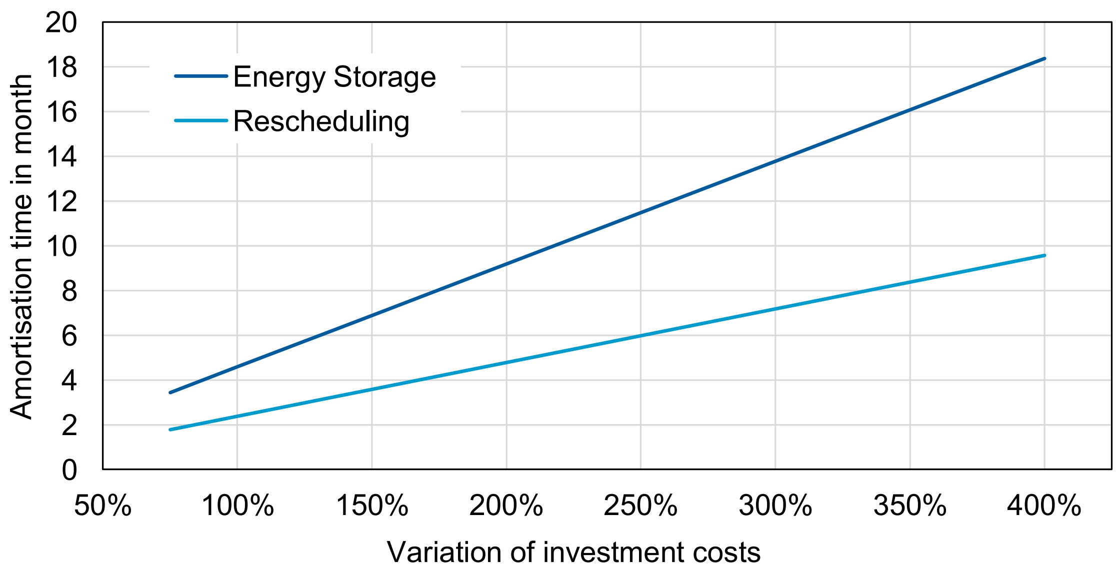

Figure 19: Sensitivity of amortisation time of "Energy Storage" and "Rescheduling" by variation of investment costs in case of redesign

When taking into account retrofit as shown in Figure 20 "Energy Storage" is slightly more cost-effective than Rescheduling. Due to the higher number of cost expensive heat exchangers and instrumentation in "Energy Storage", the retrofit only gains a slight advantage compared to Rescheduling.

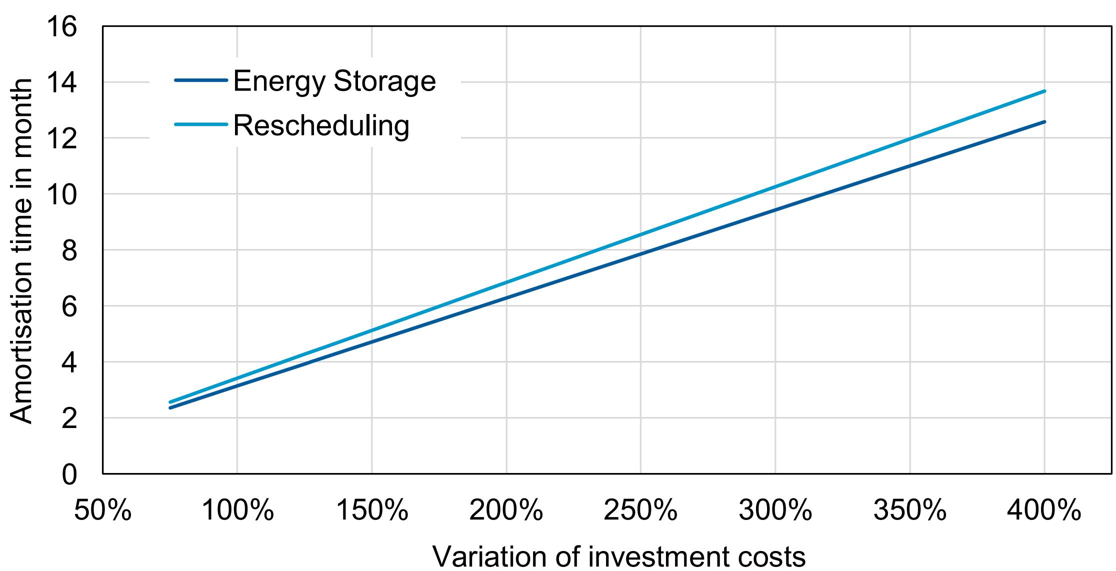

Figure 20: Sensitivity of amortisation time of "Energy Storage" and "Rescheduling" by variation of investment costs in case of retrofit

Depending on the production volume, energy prices and the limit of amortisation time, the energy efficiency measures are economically feasible within less than one-year payback time.

6.8 Limitations

The presented results show the benefits of the retrofit and redesign based on the simulation data. In reality, unforeseen events cause the disruption to product cycles and affect the availability of new product feed or a tank. These events automatically disturb the heat recovery and lead to lower energy savings as calculated.

The use of pure counterflow heat exchangers lead to a low-temperature difference and thus to high energy savings. Even though a PHE, which almost has this pure counterflow, is suitable for this process. Other heat exchangers such as tubular heat exchangers might be used for hygienic reasons. Another limitation on the heat recovery is a build-up of fouling during a process. This factor is not possible to implement into the simulation due to the complexity of geometry, flow and the chemistry of the product composition. In reality, especially the heat transfer on the product site of the heat exchanger decreases during production time, leading to lower heat flux at a given temperature difference. Extra redundant heat exchangers cause higher operating costs mainly due to increased cleaning effort rather than pressure drop and pumping. The increase in operating costs due to increased pressure drop can be neglected compared to the energy savings on thermal energy. Since the extra heat exchangers would be integrated into the CIP cycle of the sterilisation tank, an estimation of additional costs is barely predictable.

The food processing industry places high demands on product quality and safety. Therefore, fouling has to be considered carefully when using cream heat exchangers [36]. The use of tubular heat exchangers is the dairy industry standard for this application. The cleaning schedule needs to be well organized to maintain food safety. It is also common to have more than one heat exchanger to organize continuous production while cleaning in parallel. To meet these requirements, laboratory-scale testing over the entire operating range is necessary. The test application is not reported in this study but would be the last step before roll-out and implementation industry-wide.

Another strong impact on economic feasibility comes with the investment costs for the redesign and retrofit. Prices for hardware, such as heat exchangers and tanks, are assessable but costs for engineering and construction are always different. Availability of space and accessibility to the sterilisation plant affect the pipework and final design. The percentage of extra costs for person-hours and construction is therefore just an estimation and can vary drastically.

7 Conclusion

The evaluation of the newly developed design concepts showed high degrees of energy savings potential. The concept of “Rescheduling” is the most energy efficient. Reducing the specific thermal energy demand down to 10% of the initial design.

The economic assessment shows that the energy saving costs are high enough for a payback of less than one year.

In addition to the energy savings and economics, the product flow is changing with the designs. The “Initial Design” and “Storage Tanks” are both batch processes, running each batch up to 3.000 kg of product. In “Rescheduling”, a semi-continuous process is designed. Each batch will be significantly lower in product mass depending on requirements. In this example only 750 kg, 25 % of the usual batch. The process, therefore, needs to run four times as often to produce the equivalent amount of product. Since the processing time of each batch is lower through continuous heat transfer between the filling and emptying tank the same amount of time is necessary to run this four batches. With further decreasing of the batch size in the “Rescheduling” design, time-dependent problems in the control of filling and emptying are negligible.

Especially for redesigning, the “Rescheduling” design has demonstrated its energy efficiency, economic feasibility and all compromises in batch size and control strategies. Further steps will be the development of a prototype plant. ret

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References

[1] Destatis. Energieverwendung der Betriebe im Verarbeitenden Gewerbe 2015. [August 22, 2017]; Available from: https://www.destatis.de/DE/ZahlenFakten/Wirtschaftsbereiche/Energie/Verwendung/Tabellen/TabellenIndustriebranchen.html.

[2] European Union. Energy balance sheets 2015 DATA: 2017 edition. Luxembourg; 2017.

[3] Chan Y, Kantamaneni R. Study on Energy Efficiency and Energy Saving Potential in Industry from possible Policy Mechanisms; 2015.

[4] Fryer PJ, Robbins PT. Heat transfer in food processing: Ensuring product quality and safety. Applied Thermal Engineering 2005;25(16):2499–510.

[5] Law R, Harvey A, Reay D. Opportunities for low-grade heat recovery in the UK food processing industry. Applied Thermal Engineering 2013;53(2):188–96.

[6] Muller DCA, Marechal FMA, Wolewinski T, Roux PJ. An energy management method for the food industry. Applied Thermal Engineering 2007;27(16):2677–86.

[7] Quijera JA, Labidi J. Pinch and exergy based thermosolar integration in a dairy process. Applied Thermal Engineering 2013;50(1):464–74.

[8] Atkins MJ, Walmsley MRW, Morrison AS. Integration of solar thermal for improved energy efficiency in low-temperature-pinch industrial processes. Energy 2010;35(5):1867–73.
[9] Walmsley TG, Walmsley MRW, Tarighaleslami AH, Atkins MJ, Neale JR. Integration options for solar thermal with low temperature industrial heat recovery loops. Energy 2015.
[10] Liew PY, Walmsley TG, Wan Alwi, Sharifah Rafidah, Abdul Manan Z, Klemeš JJ, Varbanov PS. Integrating district cooling systems in Locally Integrated Energy Sectors through Total Site Heat Integration. Applied Energy 2016;184:1350–63.
[11] Becker H, Vuillermoz A, Maréchal F. Heat pump integration in a cheese factory. Applied Thermal Engineering 2012;43:118–27.
[12] Philipp M, Schumm G, Peesel R-H, Walmsley TG, Atkins MJ, Schlosser F et al. Optimal energy supply structures for industrial food processing sites in different countries considering energy transitions. Energy 2017.
[13] Barkaoui A-E, Boldyryev S, Duic N, Krajacic G, Guzović Z. Appropriate integration of geothermal energy sources by Pinch approach: Case study of Croatia. Applied Energy 2016.
[14] Walmsley TG, Walmsley MRW, Atkins MJ, Neale JR. Improving energy recovery in milk powder production through soft data optimisation. Applied Thermal Engineering 2013;61(1):80–7.
[15] Walmsley TG, Atkins MJ, Walmsley MRW, Neale JR. Appropriate placement of vapour recompression in ultra-low energy industrial milk evaporation systems using Pinch Analysis. Energy 2016.
[16] Atkins MJ, Walmsley TG, Philipp M, Walmsley MRW, Neale JR. Carbon Emissions Efficiency and Economics of Combined Heat and Power in New Zealand. Chemical Engineering Transactions 2017(61):733–8.
[17] Walmsley TG, Atkins MJ, Walmsley MRW, Philipp M, Peesel R-H. Process and utility systems integration and optimisation for ultra-low energy milk powder production. Energy 2017.
[18] Filipa Vinagre Marques da Silva, Paul Anthony Gibbs. Principles of Thermal Processing: Pasteurization. In: Simpson R, editor. Engineering Aspects of Thermal Food Processing. CRC Press; 2009.
[19] Waheed MA, Jekayinfa SO, Ojediran JO, Imeokparia OE. Energetic analysis of fruit juice processing operations in Nigeria. Energy 2008;33(1):35–45.

[20] Ramírez CA, Patel M, Blok K. From fluid milk to milk powder: Energy use and energy efficiency in the European dairy industry. Energy 2006;31(12):1984–2004.
[21] Bylund G, Bake K (eds.). Handbuch der Milch- und Molkereitechnik. Essen: Th. Mann; 2012.
[22] Peesel R-H, Philipp M, Schumm G, Hesselbach J, Walmsley TG. Energy Efficiency Measures for Batch Retort Sterilization in the Food Processing Industry. Chemical Engineering Transactions 2016(Vol. 52):163–8.
[23] Sommer T. B. Braun Medical AG, Werk Crissier Pinch-Analyse: Schlussbericht. Zürich; 2013.
[24] Eisenbrand G (ed.). Römpp Lexikon Lebensmittelchemie. 2nd ed. Stuttgart: Thieme; 2006.
[25] BMEL. Verordnung über Butter und andere Milchstreichfette (Butterverordnung): ButtV 1997. [August 22, 2017]; Available from: http://www.gesetze-im-internet.de/buttv_1997/.
[26] Spreer E. Technologie der Milchverarbeitung. 10th ed. Hamburg: Behr; 2011.
[27] Kessler H-G. Lebensmittel- und Bioverfahrenstechnik, Molkereitechnologie. 4th ed. München: Kessler; 1996.
[28] Kemp IC. Pinch analysis and process integration a user guide on process integration for the efficient use of energy. 2nd ed. Oxford: Butterworth-Heinemann; 2007.
[29] Linnhoff B. Thermodynamic Analysis in the Design of Process Networks [PhD Thesis]. Leeds: University of Leeds; 1979.
[30] Baehr HD, Kabelac S. Thermodynamik: Grundlagen und technische Anwendungen. 15th ed. Berlin, Heidelberg: Springer Vieweg; 2012.
[31] Bylund G. Dairy processing handbook. 3rd ed. Lund, Sweden: Tetra Pak Processing Systems AB; 1995.
[32] Inox Behälter GmbH. Inox Behälter GmbH. [June 16, 2018]; Available from: http://inox-behaelter.com.
[33] Schumm G. Price informations. Ingolstadt, Göttingen; 2018.
[34] Steinsheimer Tankhandel. Price information on energy storage tanks. Telephone. Kassel; 2016.
[35] Institut für Energie- und Umwelttechnik e.V. Preisatlas. Duisburg-Rheinhausen; 2002.

[36] Bylund G. Dairy processing handbook. 3rd ed. Lund: Tetra Pak Processing Systems AB; 2015.