JOURNAL OF FOOD, CULINARY, AND NUTRITION

RESEARCH ARTICLE

Pinch Analysis of Heat Exchanger Networks in A Simulated Milk Pasteurization Plant

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ABSTRACT

The dairy industry depends on milk pasteurization to achieve both product safety and nutritional value through its controlled heat treatment process. However, due to substantial energy usage, finding new methods which will boost operational efficiency is required. The research investigates the Heat Exchanger Network (HEN) of a conventional milk pasteurization facility through pinch analysis to minimize energy usage and production expenses. A High Temperature Short-Time (HTST) pasteurization system was simulated in *SuperPro Designer* v9.0 using data obtained from an existing plant with a capacity of 4,500 kg per hour. The hot and cold stream interactions were then analyzed using *HINT* v2.2 to find the pinch points and help redesign the heat recovery system. The analysis resulted in two enhanced HEN configurations which became *Alternative A* and *B*. The analysis showed *Alternative B* provided the optimal solution between heat recovery and cooling demand requirements which would result in $2,200 annual utility cost savings. The $427,000 capital requirement may extend the payback period but its success depends on particular factors which include local energy expenses and operational efficiency. The research demonstrates that pinch analysis provides essential value for dairy processing operations because it helps improve energy efficiency and enables better sustainable decision-making.

KEYWORDS: *Milk pasteurization plant, Pinch analysis, Heat exchanger network, Process simulation*

Introduction

Milk pasteurization plays a crucial role in the dairy industry by ensuring that milk is safe to drink through the removal of harmful bacteria while preserving its nutritional value. The 19th century method developed by Louis Pasteur now operates as an advanced thermal system which implements modern energy-efficient dairy processing techniques (Ayou *et al.*, 2022; Ayou & Coronas, 2024; Indumathy *et al.*, 2022; Liu *et al.*, 2020). The global increase in dairy product consumption makes pasteurization an essential process for maintaining milk safety and quality (OECD, 2024; Tina & Chiruvella, 2023). Nevertheless, the method is energy-intensive and improvements in its efficiency and ecological profile are required (Nadtochii *et al.*, 2018; Oğuz & Yener, 2019).

Contemporary techniques of milk pasteurization consist of raising the milk to precise temperatures for predetermined times and then chilling it swiftly. The processing methods for standard procedures include High-Temperature Short-Time (HTST) and Ultra-High Temperature (UHT) which kill pathogenic bacteria while maintaining the nutritional and functional properties of milk (Bousbia *et al.*, 2021; A. P. Lee *et al.*, 2016; Suksangpanomrung *et al.*, 2024; Sun *et al.*, 2023). The pasteurization process of milk depends on heat exchangers to perform efficient heat transfer operations between hot and cold streams. Although the concept of these heat exchangers is quite common, advancements in heat recovery and energy efficiency can enhance their performance and cut ongoing expenses.

Received:
16/10/2025

Accepted:
03/11/2025

Published:
30/11/2025

The pasteurization process requires precise temperature management because heat transfer plays an essential role in the entire operation. Plate and tubular heat exchangers are critical components and are responsible for the high transfer of thermal energy from pasteurized milk to farm raw milk. The pasteurization process generates substantial heat which often gets lost resulting in significant energy waste (Łšmieja *et al.*, 2018; Mahar *et al.*, 2019). Industries can reduce their energy losses by implementing pinch analysis with process integration which optimizes heat recovery systems for better total system performance.

The process optimization method of pinch analysis determines system minimum energy requirements through temperature and heat flow pattern evaluation. The data allows engineers to develop an optimized Heat Exchanger Network (HEN) which will reach its highest energy efficiency level and boost plant operational performance (Mailaram *et al.*, 2023; Rogério *et al.*, 2023; Walden *et al.*, 2023; Yushkova & Lebedev, 2023). The research method works to decrease outside energy consumption in milk pasteurization facilities while making their operations more environmentally friendly. Previous works have demonstrated the potentiality of pinch analysis in several industries, but with greater diffusion in the chemical one, it shows versatility and applicability for energy-intensive processes (Alhanif *et al.*, 2020; Mailaram *et al.*, 2023; Yushkova & Lebedev, 2023).

In this context, most efforts for the optimization of heat recovery in milk pasteurization plants have involved either reconfiguring existing HENs or introducing new heat recovery equipment, such as economizers. Economizers preheat incoming cold streams by capturing waste heat from hot streams, reducing energy consumption and improving thermal efficiency. The systems fail to achieve their energy-saving potential because their economizers do not receive proper configuration (J. H. Lee *et al.*, 2018; Trojan & Granda, 2018; Zhu *et al.*, 2016). The use of pinch analysis techniques for milk pasteurization plant optimization would create better energy efficiency which would generate major financial advantages and environmental sustainability improvements. This study redesigns the HEN of a conventional milk pasteurization plant using pinch analysis, considering simulations carried out in *SuperPro Designer* v9.0 and thermal integration analysis by *HINT* (Heat Integration) v2.2 software. That means maximizing the heat recovery in order to achieve higher energy efficiency and lower utility operational costs. This work will apply process integration principles to optimize thermal performance of the plant and provide a concrete framework that can be used in the implementation of energy-saving innovation within the dairy industry.

Method

This study presents analysis methods regarding the optimization of the HEN of the conventional milk pasteurization plant using pinch analysis. The methodology starts with the process description, in which the general configuration and operational parameters are defined to attain a basic understanding of the pasteurization process. It is followed by the identification of streams, which categorizes and characterizes all hot and cold streams by collecting necessary data such as inlet and outlet temperatures, mass flow rates, and heat capacities for accurate energy analysis. The identification of streams enables the creation of composite curves which show thermal stream interactions and identify areas where energy recovery can occur. The next procedure is pinch point determination, by using the Grand Composite Curve to determine the critical temperature that will fix the maximum achievable heat recovery. The redesign of the HEN will be done by proposing an optimized configuration based on the findings of pinch analysis for maximum energy efficiency at minimum operational costs.

Process Description

This study designed a milk pasteurization plant using *SuperPro Designer*. The simulation of an entire process would generate actual stream data which could be obtained from operating conditions to create a realistic foundation for subsequent pinch analysis. The design adapted from the previous study (Tomasula *et al.*, 2013), that developed models for different pasteurization techniques which could replace traditional milk pasteurization methods. The used process flow sheet in this study is a fluid milk model HTST pasteurization with full homogenization. These values are based on milk pasteurization plant production capacity at 4,500 kg/hour, operating at 7,920 hour a year, or approximately processes 39,420 tons/year of milk, nonetheless, it still leaves possibility for scaling-up without drastic changes in the main key processes. The simulation model included essential parameters which accurately represented actual plant operations through proper definition of flow rates and temperatures and heat capacities.

To construct a representative model of milk, a stock mixture was formulated within the *SuperPro Designer* environment. This stock mixture comprised specific mass percentages of individual components as shown in Table 1.

Table 1. Components of milk stock mixture.

Component	Mass percentage (%)
Minerals (as Calcium phosphate)	0.7
Casein	2.7
Lactose	4.9
Triglycerides	3.9
Water	87.2
Whey	0.6

Physical and aqueous properties of these components were obtained from previous studies (Tomasula *et al.*, 2013), which established that the simulated milk maintained characteristics matched those of industrial milk pasteurization with the plant operates through system which is described in Figure 1.

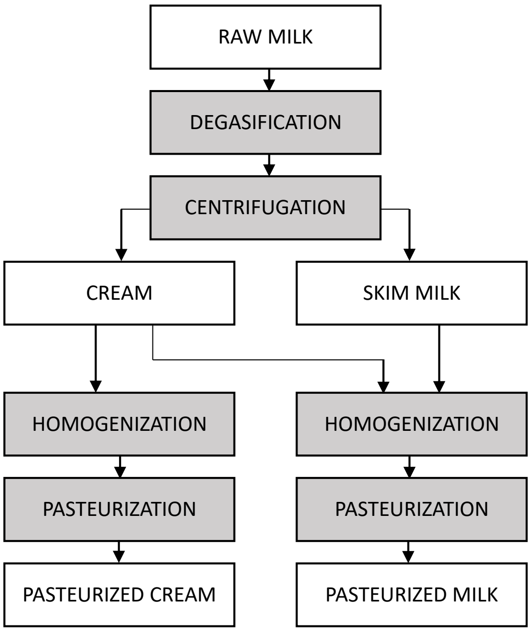

Figure 1. Stages of milk pasteurization process.

The system starts by processing raw milk during its first stage of operation. Initially, the raw milk is pumped from the reception tank to a chiller, where it is rapidly cooled to 3.3°C (276.5 K) in order to preserve its quality and prevent microbial growth. The stabilization process of milk at this stage becomes essential because it creates conditions for successful milk processing operations.

The milk, after cooling, is sent to the big storage tank for continuous supply to the next steps of pasteurization. The raw milk undergoes preheating through economizers before degassing at 60°C (333.2 K) to remove air bubbles which could affect processing operations and product quality. Degassing of milk is as important as avoidance of defects due to oxidation and also ensures efficient thermal transfer in subsequent heat treatment steps (Harwood *et al.*, 2020; Hummel *et al.*, 2024).

After degassing, the milk is fed into a centrifugal separator where it is separated into two main streams: cream and skim milk. This separation is based on the difference in density between milk fat globules (cream) and skim milk and is conducted at 40°C (313 K). Further, depending on the required fat content of the final product, a certain amount of cream is returned to the skim milk flow. The standardization process guarantees that all production batches will have the same product specifications for fat content and texture and Indonesian milk fat content will stay at 3.0% (BPOM, 2023).

High-pressure homogenizers perform homogenization on standardized milk and cream to achieve fat globule size reduction and uniform distribution in the liquid matrix (Shao *et al.*, 2023). This step prevents fat separation and the eventual formation of a cream layer in both products and therefore improves their physical stability and sensory properties.

The homogenized milk and cream are then separately pasteurized by means of the HTST method of pasteurization. In HTST, milk and cream are rapidly heated to 72.3°C (345.5 K) and held for some time; this time is long enough to fully inactivate the most heat-resistant enzymes and microorganisms yet short enough to minimize the thermal inactivation of nutritional and organoleptic properties (Lim *et al.*, 2019).

Finally, the pasteurized milk and cream are cooled down rapidly to their respective storage temperatures by several economizers and chilling systems. This is a very important step in order to inhibit microbial proliferation and preserve product freshness. The chilled milk and cream products move to dedicated storage tanks which keep them in perfect state until they reach their final packaging stage for distribution.

Stream Identification

The first step in pinch analysis involves the identification of streams from all relevant hot and cold streams in the milk pasteurization plant. The process needs measurements of both inlet and outlet temperatures and mass flow rates and heat load for all streams. The hot streams are those above the pinch that need to be cooled, while the cold streams are those below the pinch that need to be heated. The streams need definition through their essential properties which include supply temperature and target temperature and mass flow rate and heat capacity for future energy analysis and optimization work.

The supply and target temperatures of each stream, together with its specific heat capacity in the form of heat flows, were summarized in a detailed stream table that forms the basis for constructing composite curves and locating the pinch point. The heat flow for each stream is calculated through application as shown in equation (1).

$$\dot{Q} = \dot{m} \cdot C\_p \cdot \Delta T \qquad (1)$$

Where:

$\dot{Q}$: heat flow (J/s·K)
$\dot{m}$: mass flowrate (kg/s)
C_p : specific heat capacity of fluid (J/kg·K)
ΔT : temperature change (K)

The *HINT* software requires heat flow data in kW/K so the original J/s·K values for Q̇ need conversion.

Construction of Composite Curves

In order to facilitate the construction of these curves, the *HINT* software has been used in this study. The first step requires gathering all necessary thermal information from the stream table which includes inlet and outlet temperatures and mass flow rates and specific heat capacities (Cp) and heat flow (Q̇) values for all hot and cold streams. This data is converted into a computer-readable format and input into the *HINT* software to generate both hot and cold composite curves. The hot composite curve represents the cumulative heat availability of the hot streams, while the cold composite curve shows the cumulative heat demand of the cold streams. The curves enable identification of both overlapping and missing areas which show where heat recovery can occur and what are the absolute minimum heating and cooling needs of the system.

The T-Q diagram shows energy flows in pasteurization through hot and cold composite curves which *HINT* software generates. The heat load of streams at similar temperature ranges gets stacked to create two continuous profiles which show heat release (hot composite) and heat absorption (cold composite).

To develop the Grand Composite Curve (GCC), the hot and cold curves are combined, and the temperature differences between the streams are analyzed. The GCC establishes both the pinch point and minimum temperature difference (ΔTmin) which serve as vital elements for Heat Exchanger Network (HEN) optimization and heat recovery maximization.

Food Neophobia Test on Ethnic Food

The validated Indonesian version of FNS was subsequently tested to measure the neophobic level of respondents on specific ethnic foods. The questionnaire was adjusted by changing the term “ethnic food” into the specific name of the dish. To include the familiarity factor of the respondents, two of the least and two of the most familiar ethnic foods were selected by 50 university students by giving a familiarity rank among ten ethnic foods that were provided to respondents. Since there are many ethnic foods in Indonesia, previously, ten ethnic foods were subjectively selected by the researchers based on their popularity in certain regions, namely *coto Makassar, sayur umbut rotan, pempek Palembang, ayam betutu, saksang, papeda, saren, belalang goreng, sate ulat sagu*, and *soto kerbau*. Eventually, the measurement of food neophobia levels of the respondents particularly on the four ethnic foods was performed by other 100 students randomly chosen among students’ population.

Pinch Point Determination

The pinch point appears as the point where hot and cold composite curves reach their minimum distance without touching each other which indicates the optimal temperature for heat recovery. The minimum temperature difference (ΔTmin) at this point serves as a vital design parameter which determines the best placement for heat exchangers to achieve maximum energy transfer with minimal energy waste.

The *HINT* software helped researchers establish a minimum temperature difference of 5 K which they used to divide streams into two thermal zones. The researchers used this value to establish thermal boundaries which divided the system into two zones that needed external heating or cooling. The choice of 5 K ΔTmin value achieved three goals because it improved thermal efficiency by recovering more heat and it kept heat exchanger dimensions suitable for industrial applications at affordable costs (Mandalagiri *et al.*, 2021; Rezeka *et al.*, 2017). The streams located above the pinch point require heat exchangers because they contain excess heat which helps decrease external cooling needs. The streams below the pinch point require additional heating because they contain heat deficits.

The *HINT* software allows for precise identification of these thermal regions, enabling effective isolation of hot and cold stream interactions. The software defines exact boundaries between these zones through its enforcement of the fundamental rule, “no heat transfer across pinch” principle, which blocks heat transfer at pinch points to maximize energy recovery.

Redesigning the Heat Exchanger Network

The last stage of the pinch analysis process consists of designing the HEN for the most heat recovery according to the established pinch point. The new structure of HEN is designed to exchange heat between the hot and cold streams so as to reduce external utilities. Specifically, this consists of the assignment of heat exchangers to exchange heat respecting pinch limits, avoiding heat transfer violations to take place.

The redesigned HEN is expected to perform analyses on the potential for reductions in energy consumption and operational costs as well as improvements in thermal efficiency. The redesigned HEN will also take advantage of the principles of pinch analysis to promote the existence of a more resource-efficient system that can meet production demands with a reduced emissions profile (Kazantzi *et al.*, 2019; Tan & Foo, 2017).

Nonetheless, there are some limitations on cost analysis which was performed for this study. An economic evaluation was conducted using the Economic Evaluation Report feature of SuperPro designer, regarding mostly Fixed Capital Investment (FCI) and the annual utility cost.

The calculation of FCI requires the addition of Total Plant Direct Cost (TPDC) and Total Plant Indirect Cost (TPIC) and Contractor's Fee & Contingency (CFC). TPDC, which is the Total Plant Direct Cost, covers all physical aspects, including equipment acquisition, equipment installation, process piping, instrumentation, insulation, electrical systems, buildings, yard upgrades, and auxiliary facilities associated with plant construction and operation. TPIC, or Total Plant Indirect Cost, are costs associated with engineering and construction activities supporting the project that are not directly related to the physical infrastructure. The Contractor’s Fee & Contingency (CFC) fund covers both the costs of contractor work execution and additional funds for unexpected project expenses. The FCI results from adding these three components because it shows the complete capital expenses needed for project execution according to equation (2).

$$FCI = TPDC + TPIC + CFC \tag{2}$$

Where:
FCI : Fixed Capital Cost (US$)
TPDC : Total Plant Direct Cost (US$)
TPIC : Total Plant Indirect Cost (US$)
CFC : Contractor’s Fee & Contingency (US$)

Besides the main process streams in the milk pasteurization process, four distinct utilities play critical roles in maintaining thermal balance and ensuring product quality. Std Power for powering up general equipment, medium-pressure (MP) steam for heating processes, cooling water stream which functions as a cooling medium, and glycol stream in the chilling stages of both raw milk and final products, reducing temperatures to 3.3°C (276.3 K). Therefore, annual utility costs including usage of these utilities are shown in Table 2.

Table 2. Cost of milk pasteurization plant utilities.

Utility	Unit Cost (US$)	Ref. Units

Std power	0.10	kW·h
MP steam	12.00	MT
Cooling water	0.05	MT
Glycol	0.35	MT

The simulation analysis excluded labor expenses because the study determined they had no impact on the results. The cost analysis serves as a useful starting point but it makes an assumption that HEN redesign will not impact the established fixed labor expenses from industrial operations. Operator salaries in standard industrial operations function as fixed costs because they stay unchanged when equipment arrangements or process improvement methods are implemented (Ramanathan *et al.*, 2022; Rogoff, 2014). The economic evaluation assesses FCI and annual utility expenses but omits changes in labor-related expenses from its analysis.

Results and Discussion

Conventional Milk Pasteurization Plant HEN Performance

The design and simulation of a conventional milk pasteurization plant were conducted using *SuperPro Designer*, incorporating modifications based on the model proposed in previous study (Tomasula *et al.*, 2013). This model included equipment configurations and stream flows is as shown in Figure 2.

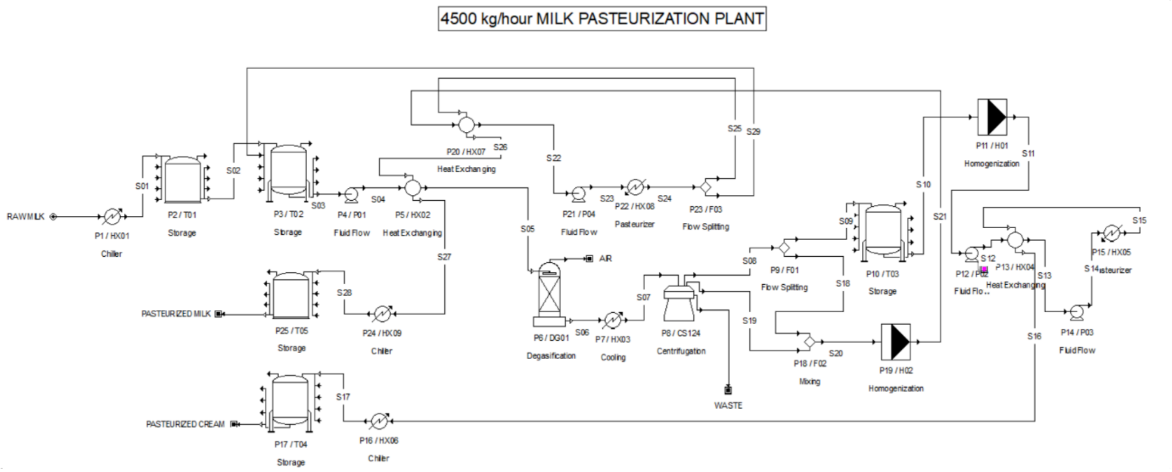

Figure 2. Modified plant flow simulation of conventional milk pasteurization plant.

Conventional milk pasteurization plant design has applied economizers to preheat raw milk or cream using excess heat from pasteurizers. However, in broad outline, HEN performance in this conventional milk pasteurization plant reveals possibility of more heat recovery. This inefficiency is particularly evident in the use of a cooler before the centrifugation process.

In the conventional design, twelve process streams were identified, comprising seven hot streams and five cold streams. From this simulation, the parameters of each stream were collected and compiled into a stream table, as shown in Table 3. The system requires five operational parameters to function properly which include stream input origin and equipment identification and code and stream temperature classification and supply temperature (Ts) and target temperature (Tt) and heat transfer rate (Q̇).

Table 3. Conventional milk pasteurization plant process streams.

No	Input	Equipment & code	Type	Ts (K)	Tt (K)	Q (kW/K)

1	Raw Milk	Chiller HX01	Hot	298	276.3	43.34
2	S04	Economizer HX02	Cold	277	331.5	43.74
3	S06	Cooler HX03	Hot	331.5	313	40.78
4	S12	Economizer HX04	Cold	336.7	342.9	40.37
5	S14	Pasteurizer HX05	Cold	343	345.3	40.37
6	S15	Economizer HX04	Hot	345.3	341.7	39.97
7	S26	Economizer HX02	Hot	314.7	282	39.97
8	S16	Chiller HX06	Hot	282	276.3	39.97
9	S21	Economizer HX07	Cold	336.7	358	2.25
10	S22	Pasteurizer HX08	Cold	358	363	2.25
11	S25	Economizer HX07	Hot	363	318.1	2.25
12	S27	Chiller HX09	Hot	318	276.3	2.25

According to the stream table as shown in Table 2, the system includes nine heat exchangers: three economizers, four coolers/chillers, and two heaters (pasteurizers). The economizers function as heat recovery components which extract heat from Stream No. 2 to Stream No. 7, Stream No. 4 to Stream No. 6, and Stream 9 to Stream No. The system operates at 11 by converting pasteurization heat waste into useful energy. The conventional HEN heat exchangers consume 238,927 kWh of Std Power and 1,359 MT of MP steam and 111,335 MT of cooling water and 162,631 MT of glycol for their operations. The heat exchangers in the conventional HEN use 238,927 kWh of Std Power and 1,359 MT of MP steam and 111,335 MT of cooling water and 162,631 MT of glycol for their operations. The distribution shows that glycol refrigerant serves as the main refrigerant which indicates that the conventional design in Figure 3 heavily depends on chiller operation.

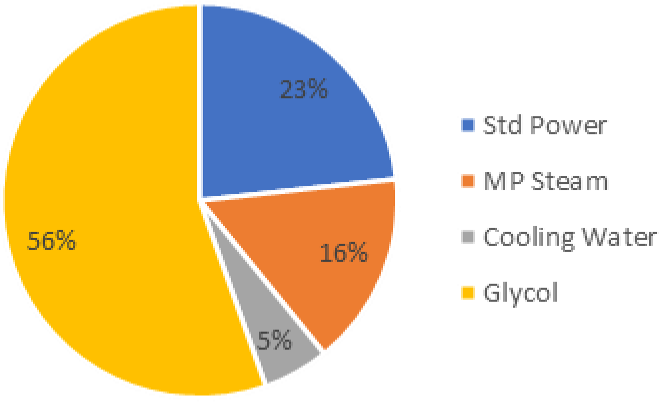

Figure 3. Utility usage ratio of conventional milk pasteurization plant.

The analysis required two subsequent steps which began with creating a composite curve and determining the pinch point for the system through *HINT* software grid diagram development. The streams, their properties, and the HEN for the conventional milk pasteurization plant, were visualized and organized, as a grid diagram, illustrated in Figure 4.

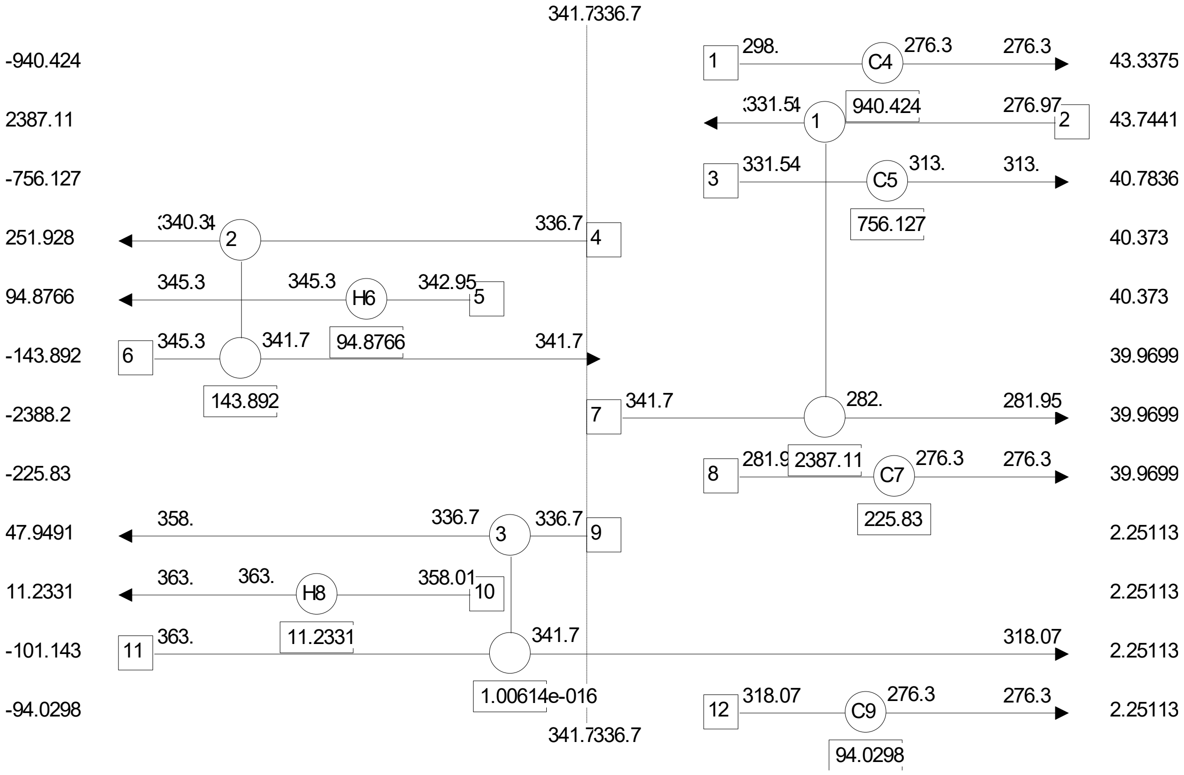

Figure 4. Grid diagram of conventional milk pasteurization plant HEN.

All streams and their corresponding heat exchangers were connected appropriately within the system. The calculations between *HINT* and *SuperPro Designer* showed minimal variations which did not affect the final analysis results. Notably, the *HINT* software provides automated calculations that identify the temperatures above, below, and at the pinch point, the determination of this pinch point temperature will be further explained later.

By determining the pinch temperature at 5 K, the minimum energy requirements for the hot and cold utilities were calculated to be 214.146 kW and 2070.69 kW/year, respectively. The temperature range in the system spans from the highest point of 363°C to the lowest point of 276.3°C, with each stream having its own distinct heat flow. This data was utilized to construct the composite curve, as shown in Figure 5.

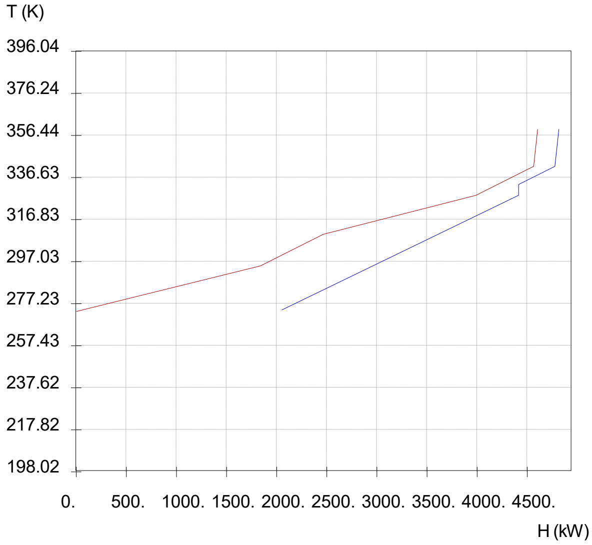

Figure 5. Composite curve of conventional milk pasteurization plant.

The system energy interactions became visible through the detailed GCC which was created from the generated composite curve. From the GCC, it is evident that the pinch point temperature, representing the critical balance between the hot and cold utilities at the minimum temperature difference (ΔTmin), is 339.2 K as shown in Figure 6.

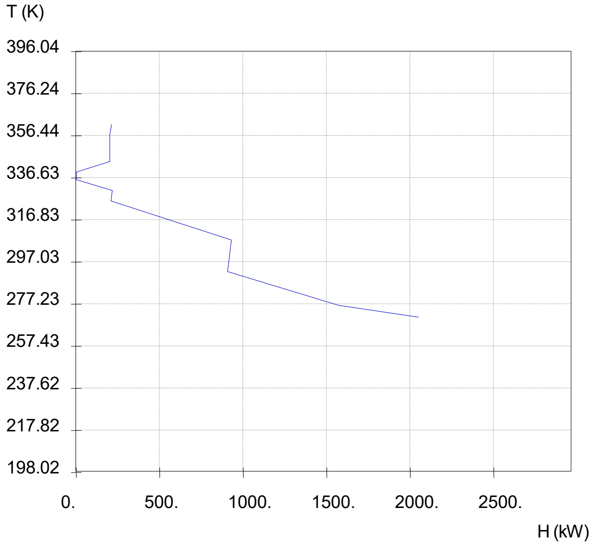

Figure 6. GCC of conventional milk pasteurization plant.

The analysis data including stream parameters and heat exchanger configurations and thermal interactions will enable the development of a new HEN design for the milk pasteurization plant. The redesign process will improve energy recovery and system efficiency through its maintenance of existing processing equipment flow which preserves the current production system structure.

Redesigned Milk Pasteurization Plant HEN

Before redesigning the HEN, a detailed analysis of the main stream table, as presented in Table 2, was conducted to identify all relevant hot and cold streams within the conventional milk pasteurization plant. The research identified seven distinct streams through chemical element and thermal property analysis which revealed that all streams contain identical chemical elements and thermal properties. The redesigned HEN will achieve better thermal performance and operational flexibility through its three separate streams. Therefore, the revised main stream table, which represents the thermal interactions in the milk pasteurization plant, is presented in Table 4.

Table 4. Identified milk pasteurization plant main process streams.

No	Type	Ts (K)	Tt (K)	Q (kW/K)
1	Hot	298	276.3	43.34
2	Cold	277	331.5	43.74
3	Hot	331.5	313	40.78
4	Cold	336.7	345.3	40.37
5	Hot	345.3	276.3	39.97
6	Cold	336.7	363	2.25
7	Hot	363	276.3	2.25

Two alternative HEN layouts for the milk pasteurization plant have been designed using the data from the main stream table to address the inefficiencies observed in conventional HEN. The redesigned configurations receive names *Alternative A* and *Alternative B* for comparison purposes in Figure 7. The three layouts show different methods to combine streams which reduce utility consumption for better pasteurization energy performance.

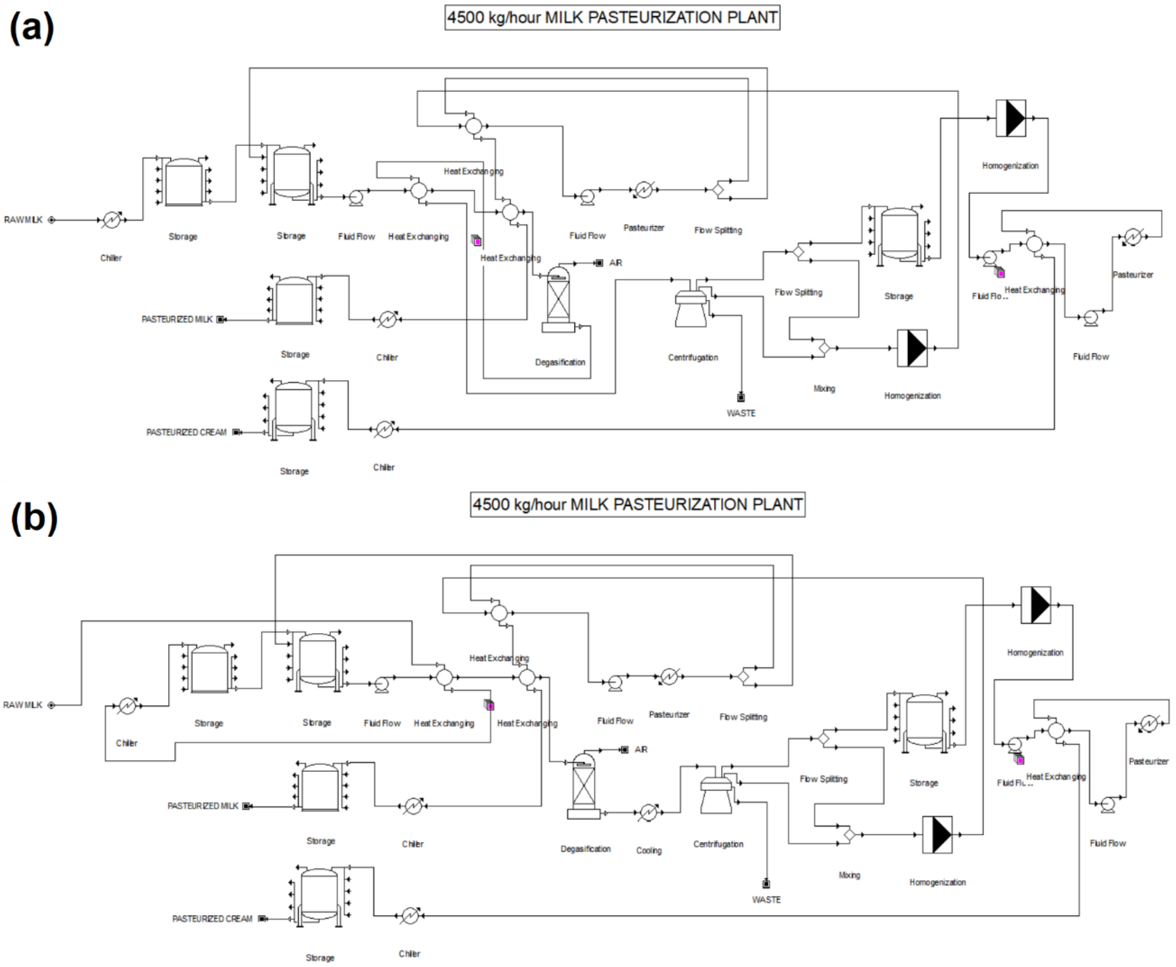

Figure 7. Redesigned HEN of milk pasteurization plant simulation: *Alternative A* (a) and *Alternative B* (b).

Alternative A HEN Performance

Alternative A was primarily designed to eliminate the need for a cooler immediately following the degassing process. In the conventional design, the cooler was responsible for reducing the temperature of the degassed milk before it proceeded to the centrifuge. The intermediate cooling process required additional energy consumption while creating an unrequired thermal process. The heat recovery process in *Alternative A* achieved optimization through direct connection of degassed milk to an appropriate economizer which enabled temperature control without requiring external cooling. The system uses this method to reduce heat transfer while achieving better energy extraction performance. The streams and the HEN for *Alternative A*, were visualized and organized, as illustrated in Figure 8.

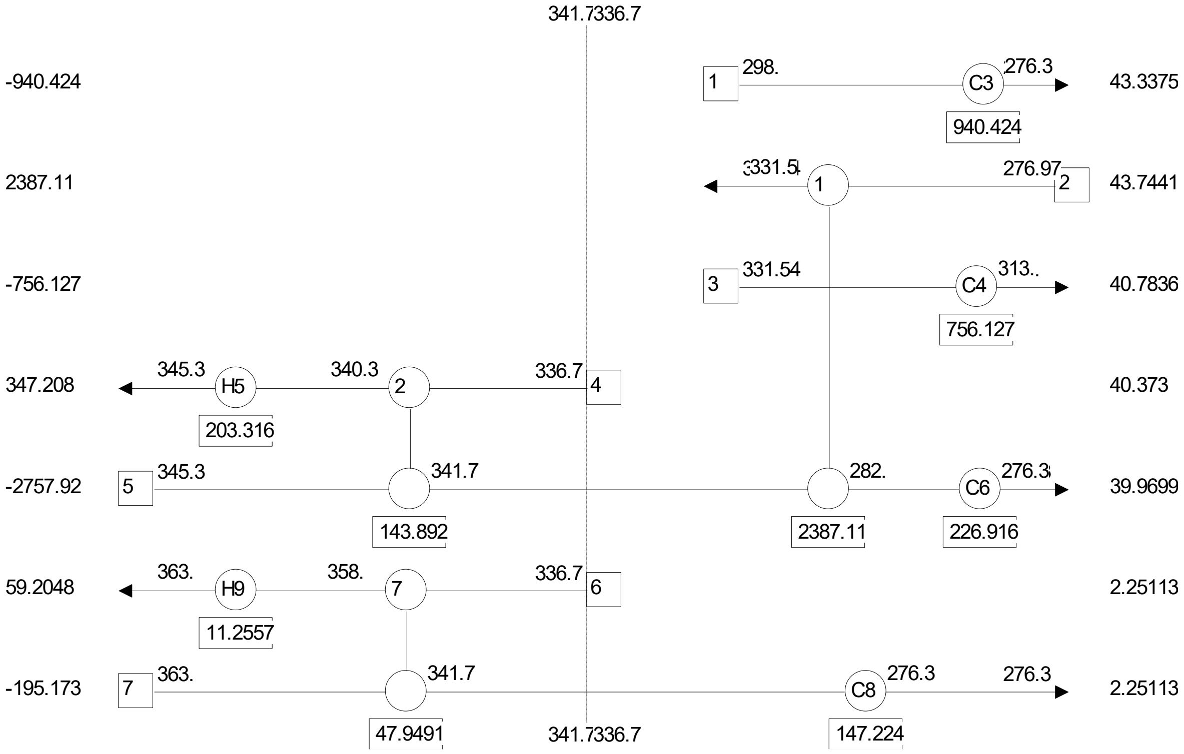

Figure 8. Grid diagram of milk pasteurization plant HEN *Alternative A*.

However, the analysis reveals that *Alternative A* does not result in significant changes in overall heating and cooling duties, as composite curves, compared to the initial design. While the cooler after degassing was removed, the cooling duty of chillers increased as there was no intermediate cooling step before the milk proceeded to the centrifugation process. The network shows increased thermal load distribution because the system transitioned to a new thermal load pattern. The system became simpler after removing the cooler but the overall utility consumption did not reach its maximum potential. The utility consumption ratio patterns for *Alternative A* are illustrated in Figure 9.

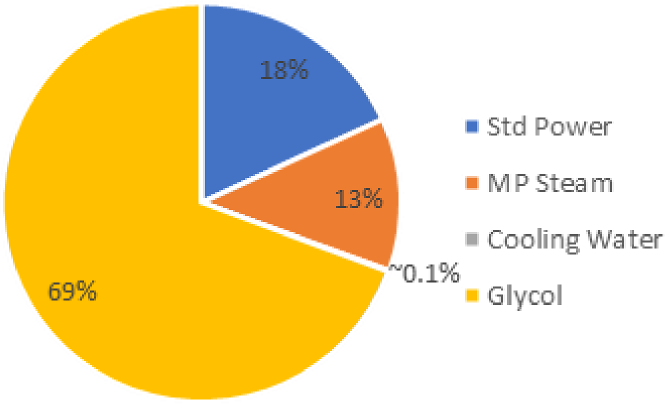

Figure 9. Utility usage ratio of Alternative A milk pasteurization plant.

This is even more evident when looking at the usage of each utilities shows that Std Power usage is 238,927 kWh of Std Power, 1,359 MT of MP steam, 2,865 MT of cooling water, and 260,944 MT of glycol.

Alternative B HEN Performance

The chiller system under *Alternative A* faced operational problems because of high glycol consumption which led to increased power consumption and higher operating costs. To address this, *Alternative B* was developed with a redesigned HEN that focuses on reducing the chiller duty needed to cool raw milk. The new system improves internal heat recovery because it allows hot pasteurized milk to transfer more heat to incoming cold raw milk which decreases cooling needs while keeping products at safe temperatures. The storage raw milk passes through an economizer which combines it with room-temperature streams to achieve partial temperature adjustment before additional processing steps. The process enables stage temperature differences to become more similar which results in better energy performance and decreased need for outside cooling systems. The new configuration needs additional capital investment for its expanded heat exchange section but it produces a better-balanced operation with enhanced efficiency and sustainability. The streams and HEN for *Alternative B* were shown as grid diagram illustrated in Figure 10.

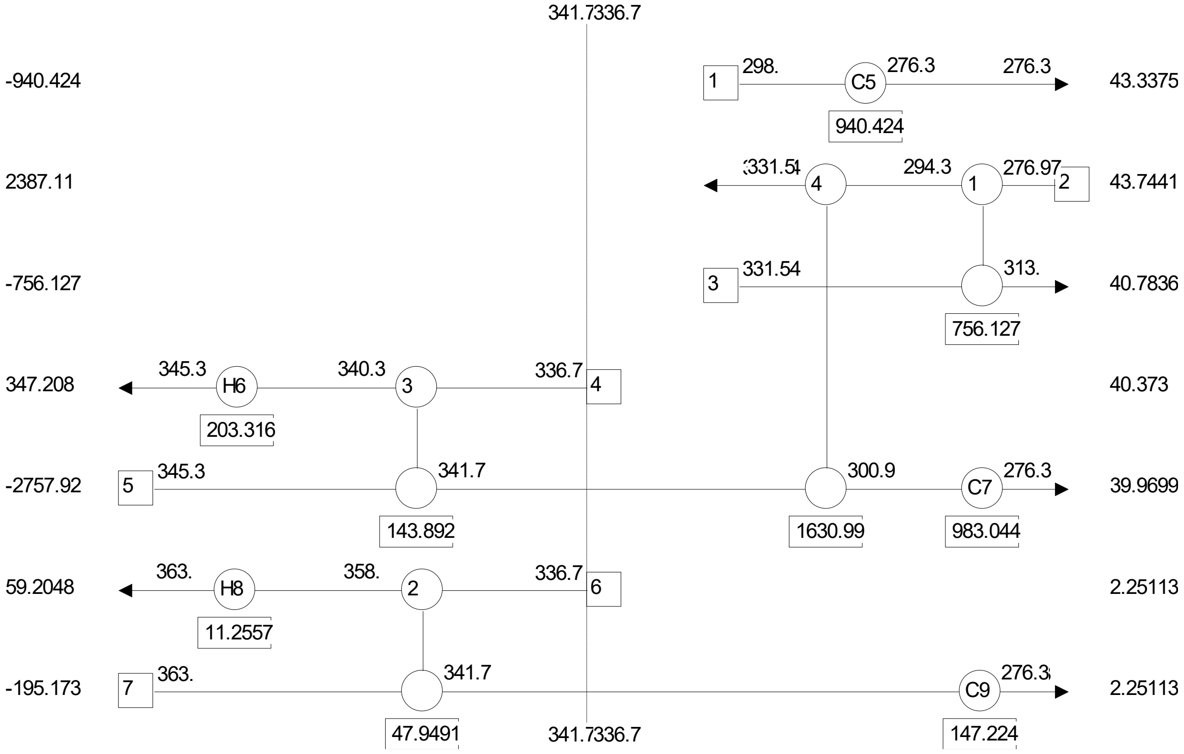

Figure 10. Grid diagram of milk pasteurization plant HEN Alternative B.

Alternative B produces results identical to *Alternative A* while keeping total heating and cooling needs unchanged. To minimize chiller (glycol) usage, excess heat is efficiently transferred through an economizer between raw milk streams before and after storage. The analysis showed that adding a cooler before the chiller becomes unnecessary because 25°C cooling water effectively lowers the temperature to match the final product temperatures which reach 25°C after multiple economizer stages for pasteurized milk and pasteurized cream. Specifically for pasteurized cream, while the addition of a cooler before the chiller is technically possible, it is generally not recommended due to the low flow rate of the stream, which does not economically justify the capital investment in an additional heat exchanger. Std Power consumption of *Alternative B* is at 238,927 kWh, MP steam at 1,359 MT, cooling water at 119,365 MT, and glycol at 155,197 MT, lower than both HEN of conventional plant design and *Alternative A*. The utility consumption ratio patterns for *Alternative B* are illustrated in Figure 11.

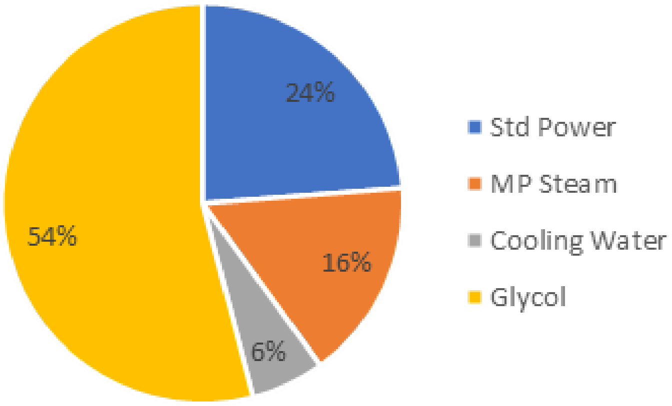

Figure 11. Utility usage ratio of *Alternative B* milk pasteurization plant.

Cost Analysis

FCI and annual utility cost analysis of these HEN reveals distinct outcomes for the conventional design, *Alternative A*, and *Alternative B*, especially in terms of heating and cooling expenses. Different HEN designs, each defined by distinct intermediate temperature targets, directly influence the required heat exchanger surface area needed to achieve optimal thermal exchange. The different design configurations produce various FCI values because of these design differences. Table 5 presents a comparison of the FCI among the conventional design, *Alternative A*, and *Alternative B* in the milk pasteurization plant. The TPDC, TPIC, and CFC are shown for each design.

Table 5. Comparison of costs and FCI between conventional, Alternative A, and Alternative B milk pasteurization plant designs.

Design	TPDC (in 000's US$)	TPIC (in 000's US$)	CFC (in 000's US$)	FCI (in 000's US$)
Conventional	3,637	2,182	873	6,692
Alternative A	3,692	2,215	886	6,793
Alternative B	3,869	2,322	929	7,119

The conventional design requires $3,637,000 for TPDC and $2,182,000 for TPIC and $873,000 for CFC which leads to a total FCI of $6,692,000. *Alternative A* shows a minimal rise in investment through its $3,692,000 TPDC and $2,215,000 TPIC and $886,000 CFC which results in a total FCI of $6,793,000. The system performance improved because thermal optimization changes were made by removing the cooler after degassing operations.

Alternative B requires the most investment because its total project development cost (TPDC) reaches $3,869,000 and its total project implementation cost (TPIC) amounts to $2,322,000 and its construction facility cost (CFC) equals $929,000 which results in a final construction investment (FCI) of $7,119,000. The higher costs in *Alternative B* result from the combination of economizer integration and thermal stream optimization improvements which work to reduce chiller operation and enhance total energy performance.

On the other hand, for annual utility cost. The two alternatives achieve their primary cost reductions through lower utility consumption and reduced need for specific utilities and better heat recovery performance because of economizer installation.

The thermal pathway in *Alternative A* became simpler because the degassing stage cooler was completely taken out which removed all unneeded cooling steps between stages. The modification eliminates duplicate equipment while creating an optimal energy transfer system through the HEN.

Alternative B uses an integrated system which decreases chiller needs through enhanced heat exchange between raw milk streams during storage and pre-storage times. The system design reduces thermal demands on the chiller system which leads to better energy performance.

This effect becomes even more pronounced when considering the significantly higher cost of glycol refrigerant compared to cooling water. Therefore, while maximizing heat recovery through additional economizers can enhance energy efficiency, it may not always translate into economic benefits, especially when the overall heating and cooling duties remain largely unchanged between the conventional design and the proposed alternatives.

Table 6 presents a comparative analysis of utility usage and annual utility costs among the conventional, *Alternative A*, and *Alternative B* designs for a milk pasteurization plant. The table shows how four essential utilities are used by the system along with their corresponding expenses for Standard Power (Std Power) and Medium-Pressure Steam (MP Steam) and Cooling Water and Glycol.

Table 6. Comparison of annual utility cost between conventional, *Alternative A*, and *Alternative B* milk pasteurization plant designs.

Design	Utility	Usage (kWh or MT)	Annual Utility Cost (US$)
Conventional	Std Power	238,927	23,893
	MP Steam	1,359	16,307
	Cooling Water	111,335	5,567
	Glycol	162,631	56,921
		Total	**102,687**
Alternative A	Std Power	238,927	23,893
	MP Steam	1,359	16,307
	Cooling Water	2,865	143
	Glycol	260,944	91,330
		Total	**131,673**
Alternative B	Std Power	238,927	23,893
	MP Steam	1,359	16,307
	Cooling Water	119,365	5,968
	Glycol	155,197	54,319
		Total	**100,487**

The conventional design shows glycol as its most expensive utility component because it makes up 56% of the total yearly utility expenses. The high cost stems from the fact that chiller systems depend on glycol refrigerant which costs more than cooling water.

The HEN optimization in *Alternative A* through degassing stage cooler removal results in higher glycol usage at 260,944 MT while decreasing cooling water consumption to 2,865 MT. The system now requires more glycol refrigerant which leads to a total annual utility expense of US$131,673.

Alternative B shows a better distribution of utility benefits in its design. The system achieves a glycol consumption of 155,197 MT through enhanced heat transfer between raw milk streams before and after storage and uses 119,365 MT of cooling water. The total annual utility cost for this design amounts to US$100,487 which represents the minimum value among the three options.

The results show *Alternative A* achieved thermal pathway simplification but it led to higher operational expenses because of its high glycol consumption. *Alternative B* provides the best utility balance through its design structure which reduces costs while maximizing both energy efficiency and financial performance.

The increase in FCI from one alternative to the next shows that while there is a potential cost saving by the operation of *Alternative B* due to improved heat recovery and utility efficiency, the capital cost is higher. The results clearly bring out the trade-off between the capital and operational benefits in the long-term optimization of HEN designs for milk pasteurization plants.

However, with the FCI difference of approximately US$ 427,000 between the conventional design and *Alternative B*, chasing an annual utility cost saving of US$ 2,200 does not seem to be very economically viable. The process of achieving these savings would take longer than the standard operational benefits period. Research studies demonstrate that pinch analysis requires sensitivity analysis because economic factors together with heat recovery and thermal efficiency limitations affect managerial decisions which produce different analysis results (Bakar *et al.*, 2017; Kumar *et al.*, 2024; Mohammad Rozali *et al.*, 2016).

The cost structure remains highly dependent on local economic factors which affect both energy expenses and raw material prices and exchange rates. The economic feasibility of *Alternative B* depends on specific local factors together with project costs which vary between different regions.

Conclusion

The results of this study indicate that the conventional milk pasteurization plant design, modeled using *SuperPro Designer* and *HINT* simulations, is already relatively efficient. However, improvements can still be achieved through the two proposed alternatives. *Alternative B* stands as the better choice because it reduces chiller system and glycol usage burden through optimized heat recovery strategies instead of removing the cooler completely as *Alternative A* does.

The main goal of pinch analysis continues to optimize heat recovery but this research demonstrates that operating expenses from utilities affect both process management choices and different system configuration options. Notably, although *Alternative B* demonstrates the lowest annual utility cost at US$100,487, it also incurs a higher FCI compared to the conventional design.

The simulation shows better preference for *Alternative B* because conventional chiller operations consume most energy while this alternative provides operational efficiency and extended cost savings through its higher initial investment. However, when comparing the FCI difference of around US$427,000 between the conventional design and *Alternative B*, it is clear that the annual utility cost savings of US$2,200 may not provide a strong economic rationale. The extended recovery period for these savings reduces operational benefits so complete capital investment versus utility savings evaluations must be performed during HEN optimization planning.

Future research needs to develop cost estimation models through sensitivity analysis which will predict financial results when economic conditions change. The implementation of hybrid optimization methods which unite capital expenditure with operational performance optimization provides a stronger approach to deploy sophisticated HEN designs for milk pasteurization systems.

Acknowledgements

The author expresses sincere gratitude to Universitas Katolik Soegijapranata Program Profesi Insinyur (PPI) for providing valuable insights into engineering design, and to the Food Technology Department for their guidance and expertise in food plant operations and processing systems.

Conflicts of Interest

The authors state there's no conflict of interest in the writing of this article.

Author Contributions

GJS conducted the experiment and calculations, NIP reviewed the design and manuscript. All authors agreed to the final version of this manuscript.

Ethical Statement

Ethical statement is not necessary for this research.

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Cite this article: Sanyoto, G.J. & Putri, N.I. (2025). Pinch Analysis of Heat Exchanger Networks in A Simulated Milk Pasteurization Plant. *Journal of Food, Culinary, and Nutrition*, 2(1), 1-19.