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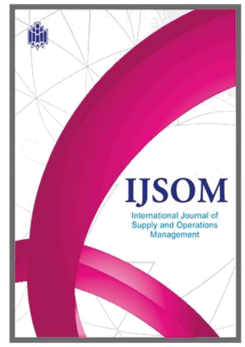

Automated Pinch-Exergy Analysis for Industrial Processes: ΔTmin Effect on Energy and Exergy Targets

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Abstract

Energy efficiency and process integration play a vital role in minimizing fossil fuel consumption and electricity demand within industrial processes. Therefore, experts have prioritized research on enhancing and promoting the thermal energy efficiency of this sector, with a specific emphasis on energy recovery and sustainability goals. Pinch analysis (PA) and exergy analysis (ExA) have been employed separately or in conjunction to optimize energy recovery and minimize the work potential losses (exergy loss).
This paper demonstrates the effectiveness of a developed algorithm that handle the impact of ΔT_{min} on energy and exergy targets in an automatic manner through a set of scripts. The scripts manipulate input data and intermediate data through loops in order to quantify and determine different energetic and exergetic quantities. The developed algorithm is testified using a literature case study in order to prove its validity. For δT_{min} in range [0,10] and step s =2, the algorithm performs the calculations for each δT_{min} in range ΔT_{min}. The obtained results include the pinch analysis parameters such as the global pinch point temperature [T_{pinch}] as well as the minimum heating and cooling requirements ([U_{hot}] and [U_{cool}]). For the scripts devoted to the exergy concept, the algorithm determines all the exergy targets (rejection, requirement and avoidable losses). As a result for δT_{min} in ΔT_{min}, the process external utilities U_{hot} and U_{cool} increased simultaneously from 6.85 and 4.39 MW to 12.2 and 9.75 MW with increment of δT_{min}, which means that the energy recovery and avoidable exergy losses reduced with respect to δT_{min}. For the exergy requirement and rejection targets, they increased simultaneously from 2.6602 and 1.3231 MW to 6.711 and 2.88 MW with δT_{min} increment, indicating the opportunity to design a system to recover work through turbine expansion. In addition to the originality of the interconnected scripts, the obtained results are in accordance with those in the literature, indicating the applicability of the developed algorithm.

Keywords: Process Integration; Algorithmic; Data Analysis; Pinch-Exergy analysis.

1. Introduction

Nowadays, the industrial sector is regarded as one of the world's greatest consumers of energy, particularly thermal energy. It has changed profoundly and diversified with recent developments. The efforts of specialists in this sector have been directed towards policies that target energy efficiency as well as the adoption and integration of green energy. These efforts are envisaged through the development of thermodynamic optimization techniques such as

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energy analysis (Xie et al., 2021). The later includes entropy analysis, enthalpy analysis as well as exergy analysis which are used to preserve the environment, better use the available resources in the current industrial installations and better design those to come. The major issues related to this sector generally concern the elimination of the inefficiencies, the minimization of the huge energy consumption by the appropriate utility targets identification and especially heat recovery in the context of the sustainability.
Heat integration (HI) concept using pinch method and exergy approach has been applied successfully in various industries. Linnhoff and J. Flower (1978) have developed the concept of pinch or pinch analysis (PA) for the first time. It offers a useful and methodical strategy for process integration and improvement (Kemp, 2011). To investigate the role of PA in various sectors, namely the building (Khalid et al., 2021; Misevičiutė et al., 2018) and industrial sectors, many works have been carried out. A significant review titled "New directions in the implementation of Pinch Methodology (PM)" was published in 2018 by Klemeš et al. (2018). The review was constructed to provide a comprehensive analysis of the methodology. In their paper, authors attempted to recognize and justify the researches' future directions and significant implementations of pinch concept. Due to its simplicity, PA is commonly used for energy consumption monitoring, heat exchange network designing (HEN) as well as energy integration opportunities. For energy consumption monitoring, Mrayed et al. (2021) applied PA to assess an existing CDU with pre-flash heating train and VDU. Taking into account the steady state simulation model, their evaluation and analysis allowed determining energy targets and possible utility savings. In terms of HEN designing, several methods have already been successfully applied with the PA-based method proving to be the most effective (Bakhtiari and Bedard, 2013). In fact, the PA-based method normally involves three stages; the first one is the targeting stage in which the maximum heat recovery is determined. The second stage concerns redesigning in order to fix the existing cross-pinch heat exchangers. Finally, the detail engineering and implementation stage which is used to estimate the project costs and control aspects. Gundersen (2013) described the heuristic-based HEN design method which has been used widely for achieving the targeted minimum utility. The most interesting review on retrofitting HEN has been discussed by Wang et al. (2021). In addition to the review contribution, they have proposed a novel framework to determine the HEN retrofit with a lower total annual cost and based on the selection of heat exchanger types and materials. PA is widely used not only for heat integration but also for optimizing power consumption and advanced utilities integration. Olsen et al. (2011) studied the integration of an organic rankine cycle (ORC) based on PA. Their investigation demonstrates the simplicity and importance of PA role to integrate advanced utilities. To ensure the appropriate placement of the ORC, authors based their research on the grand composite curve (GCC). Through the definition of an ORC and based on GCC, the equipment uses waste heat below the pinch point to produce electricity and reduce the cold utility requirements; and that reflects its correct integration. A key limitation of this research is that even with this integration, it still requires improvement in terms of economic feasibility. Recently, Sharan et al. (2017) have proposed a theorem for vapor suction position optimal location. Their contribution focuses on the development of a methodology to reduce total energy consumption through multiple-effect evaporator integration with thermo-vapor compressor and the background process. In addition to PA, thermodynamics' second law-based exergy analysis (EA) can also be used to optimize the energy systems. In fact, exergy concept measures the usefulness or quality of energy; it can be defined as the maximum amount of work that a system is able to produce as it approaches to equilibrium with a reference environment. Several publications have appeared in recent years documenting the relevance of exergy analysis and considerable attention has been paid to power generation systems. Mahian et al. (2020) made a comprehensive literature review on EA and exergoeconomic assessment of combined heat and power systems. The findings revealed that many complex configurations had not yet been investigated experimentally and proposed recommendations for further studies. The results obtained by Zueco et al. (2020) suggest that the highest priority to optimize combustion systems is given to the processes where exergy destruction or irreversibility is the most important.
The subsequent sections of this paper are structured as follows: Section 2 provides an introduction to the research background and a comprehensive literature review. Section 3 describes the methodology through a proposed algorithm based on pinch-exergy analysis, ranging from data inputs and distribution to energy and exergy scripts analysis. In Section 4 is devoted to the algorithm implementation in a case study in order to test and validate it. Section 5 presents the scripts' computational results and discussion. Finally, section 6 provides concluding remarks, a summary of the study and its perspective.

2. Literature review

PA is combined with EA to enhance energy management and consumption, especially through HEN retrofit situation. In fact, the two approaches are combined to provide ideal operating conditions and improve process structure so as to overcome the particular limits of each approach. Most of the works that have been done involve PA to consider only heat integration in order to satisfy existent energy requirement, while EA assesses and guides the potential improvements in operating conditions and industrial processes structure. Njoku et al. (2019) conducted a comparative study of the basic and combined methods. Applied on a gas-fired steam power plant, the combined PA and EA showed the degree of performance degradation more clearly with respect to design conditions. In order to foster energy efficiency for environmental sustainability, Ghannadzadeh and Sadegzadeh (2016) applied the combined analysis on ethylene oxide production process. Three stages of analysis are involved in their contribution; the first one evaluates the overall exergy loss distribution in different unit operations to visualize the exergetic process flowsheet. The second concerns the pinpoint of the main thermal exergetic inefficiency for individual unit operations and the third deals with the estimation of minimum energy requirements using PA as well as utilities selection and HEN designing. Malham et al. (2019) strengthened the combined analysis by introducing advanced optimization techniques (using Jacobian matrix concept). Their purpose is to progress from an auditing tool to a decision-making tool using EA as a way to obtain indications on the target operating conditions and modification directions. In addition to the combined analysis (PA and EA), Bühler et al. (2018) invoked the advanced exergy method to analyze a milk powder production facility. In fact, they have split the exergy destruction into avoidable exergy and unavoidable exergy using the advanced exergy analysis. The splitting is performed to determine the real potential for thermodynamic improvements. Furthermore, conventional energy and exergy analysis are used to chart and suggest process integration possibilities on the one hand, and identify the locations and the degree of thermodynamic irreversibilities on the other hand.

Many works have been carried out in the context of evaluating the impact of ΔT_{min} on energy targets and on energy and exergy targets, each with its own approach to address the issue. However, the common point among these works lies in the fact that the analysis is performed for a given value of ΔT_{min}. For another value, the calculation and analysis must be started from scratch. Consequently, data loss may include the analysis and the results of the improvement. The optimal value of ΔT_{min} in most prior analysis is determined by balancing trade-offs involving external energy demand, utility cost, heat-transfer area requirements within a heat exchanger network, and capital costs. Heggs (1989) investigates the direct impact of ΔT_{min} on energy lost in heat recovery systems. The study demonstrates that the ΔT_{min} approach is a direct measure of the heat exchanger equipment ineffectiveness. In this regard, it is feasible to eliminate any heat exchanger configurations that are incapable of fulfilling the duty requirements of the stream matches. Allen et al. (2009) provided a procedure for the heat exchanger network components (HEN). In order to determine the optimal HEN, a set of assumptions are observed, and one of these assumptions pertains to the value of ΔT_{min} that is imposed. For a given minimum temperature difference ΔT_{min}, the procedure initially employs pinch analysis to maximize heat recovery. Subsequently, a genetic algorithm (GA) is utilized to design each exchanger within the network with the objective of minimizing the total annual cost associated with it. Applied to chemical processes especially the reactor, Zhang et al. (2020) took the minimum temperature approach and both capital and utility cost as variables to conduct an efficient and optimal integration through pinch analysis. Compared with the traditional pinch analysis, the optimal ΔT_{min} is identified to be at 10 °C since the system is a threshold problem type. In their work, the reactor conversion parameter changes in interval [0.70, 0.85], and from this, the various desired optimization quantities are extracted including optimal ΔT_{min} value. The primary objective of Kaviani et al. (2022) work is to employ pinch technology to optimize energy consumption in the milk powder production process. In fact, four scenarios illustrating different approaches for connecting heat exchangers are well discussed and presented. This study takes into account for the four scenarios a value of ΔT_{min} which equals to 10°C. In the realm of recent endeavors focused on the development or application of combined pinch and exergy analysis, Hamsani et al. (2018) developed a novel numerical tool known as exergy problem table algorithm in their work. Indeed, the new numerical tool flowchart is an extension of Aspelund et al. (2007) work. The significance lies in the exploration and assessment of different energy and exergy parameters, aiming to drive forward advanced enhancements. While the study actually relies on varying values of ΔT_{min}, the process of calculating, exploring, and analyzing the results for each value is performed manually rather than in an automated fashion. Bandyopadhyay et al. (2019) have made a valuable contribution by employing pinch and exergy analysis to improve the energy efficiency of a diesel hydrotreating unit. Notably, their analysis considers a wide range of minimum allowable approach temperature (ΔT_{min}) values, spanning from 10 to 60°C with a step equal to 5. While it is accurate that the calculation is performed automatically, the key distinction lies in our algorithm's utilization of the concept of exergy, which offers a broader perspective by encompassing avoidable, unavoidable exergy losses aspects, exergy requirement as well as exergy rejection parameters. Table 1 provides a compilation of publications that consider the impact of ΔT_{min} on energy and exergy analysis for various systems.

The purpose of this work is focused on the presentation of ΔT_{min} impact on energy and exergy targets in an automatic manner through a set of scripts that constitute a properly developed algorithm (built with Python language). There are two aspects or sides to our work; the analytical side where we have performed a set of scripts that reflect the energy and exergy analysis. The interconnection between these scripts allowed us to develop a complete algorithm. The scripts manipulate input data and intermediate data through loops in order to quantify and determine different energetic and exergetic quantities. The energetical side lies in the fact that we can predict the energy and exergy targets of a range of ΔT_{min} for any case study and choose the appropriate ΔT_{min} value. Offering a straightforward illustration of energy and exergy concepts based on exergetic temperature (T^E), the developed algorithm turns out to be computationally powerful and efficient. Moreover, it facilitates the task of energy integration. In general, this work is realized in the context of automation of the CPEA concepts. The algorithm gives specialists and planners a framework to help them effectively exploit and benefit from the combined analysis tools for a given process.

Table 1. Literature review summary on ΔTmin impact and combined analysis works

Reference	Process subject	System type	Research method	Method type	Key results
Alwi and Manan (2010)	Chemical reactors	Standard and threshold systems	Pinch analysis	Graphical	New STEP method for targeting and design Multiple utilities and area determination
Ibaaz et al. (2022)	Low Temp process	Standard and threshold systems	Combined pinch And exergy analysis	Numerical and graphical	Energy and exergy target identification for the imposed value of ΔT_{min}
Bakar et al. (2016)	Chemical reactors	Standard system	Pinch and optimization	Numerical and graphical	Optimal design selection Operability and controllability targets
Lai et al. (2019)	Chemical reactors	Standard system	Pinch analysis	Graphical	Enhancement of STEP methodology Capital-energy trade-off achieving
Ebrada et al. (2014)	Brewery process	Standard system	Pinch analysis	Numerical	Reduce the brewery's energy intensity Determination of appropriate HEN
Kaviani et al. (2022)	dairy iprocess	Standard system	Pinch and optimization	Numerical	Optimize energy consumption Appropriate HEN determination
Kocaman et al. (2022)	Iron and steel process	Standard system	Pinch and optimization	Numerical	Appropriate placement and design of the ORC system based on multi-objective optimization
Njoku (2019)	steam power plant	Standard system	Combined pinch And exergy analysis	Numerical and Graphical	Magnitude of losses determination for ΔT_{min} value contributed by individual HEN components
Marmolejo-Correa and Gundersen (2012)	Reverse Brayton process	Standard system	Combined pinch and exergy analysis	Numerical and Graphical	Reduce both heat and power requirements using quality parameter and ΔT_{min} assumption values
Mehdizadeh-Fard et al. (2018)	natural gas refinery	Standard system	Combined pinch and advanced exergy analysis	Numerical and Graphical	Optimal ΔT_{min} determination through an initial value of ΔT_{min}=0°C Development of systematic framework to optimize complex HENs
Our work (2023)	Low Temp process	Standard and threshold systems	Combined pinch and exergy analysis	Numerical	Energy and exergy parameters calculations are performed automatically for a range of ΔT_{min} Reliable and efficient computational algorithm Different exergy concepts are considered

3. Methodology and Algorithm description

The proposed computation algorithm for energy and exergy targets determination is presented in this section. Several calculation variables have been implemented in the algorithm and the variable that turns out to be more important for the contribution is the minimum temperature approach ΔT_{min}. On the one hand, it is considered as a critical variable for pinch method as indicated in the literature. On the other hand, its variation demonstrates the flexibility and power of the computation algorithm. The global flowchart of the computation algorithm is summarized as shown in figure 1:

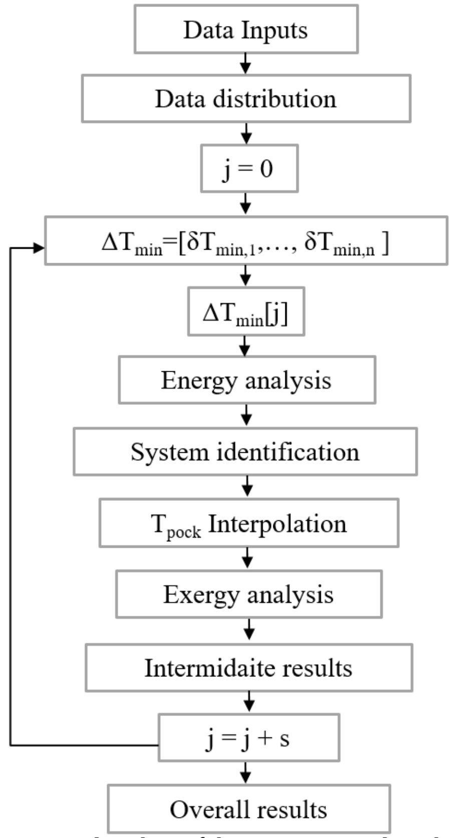

Figure 1. Flowchart of the computation algorithm

3.1. Notations

The following notations are devoted to clarify the abbreviations, data, intermediate data and variables used for describing the algorithm in this study. The abbreviations are shown in table 2, all other parameters are shown in table 3.

Table 2. Abbreviations

Abbreviations	definition
MER	Maximum energy recovery
HEN	Heat exchange network
HE	Heat exchanger
PM	Pinch method
TSI	Total site integration
PA	Pinch analysis
CCs	Composite curves
GCC	Grand composite curve

Table 2. Abbreviations (*Continued*)

Abbreviations	definition
ExA	Exergy analysis
PTA	Problem table algorithm
dim	Dimension
CPEA	Combined pinch and exergy analysis
GA	Genetic algorithm

Table 3. Parameters

Symbols	**definition**	**List**	**definition**
H	Hot stream	$Q_{stage,1}[]$	First stage cascade list
C	Cold stream	$Q_{stage,2}[]$	Second stage cascade list
$\Delta T_{min,Opt}$	Optimal minimum temperature difference	$\Delta T_{min}[]$	Minimum temperature difference list
δT_{min}	Minimum temperature difference	$\Delta Q[]$	Load variation list
Occ	Number of occurrences	$T_{interval,1}[]$	First temperature interval list
k	Number of temperatures ($k = 2n$, $n \epsilon \mathbb{N}^*$)	$T_{interval,2}[]$	Second temperature interval list
l	Indicates Req, pock or total	$Cp_{net,l}[]$	Net capacity flow rate list of l
N	Number of streams	$H_{f,2}[]$	Final enthalpy profile list
N_H	Number of hot streams	$H_{ext}[]$	External heat requirement profile list
N_c	Number of cold streams	$H_{pock}[]$	Heat recovery pocket profile list
T^E	Exergetic temperature	$H_{tot}[]$	Second enthalpy cascade stage list
$T_{in,i}$	Inlet temperature of stream i	$T^*_{interval,2}$ []	Shifted temperature interval list
$T_{out,i}$	Target temperature of stream i	$T_{pock}[]$	Pocket temperature interval list
T_{hot}	Hot stream temperature	ΔX_{req} []	Exergy requirement variation list
T_{cold}	Cold stream temperature	ΔX_{loss} []	Exergy losses variation list
T^*	Shifted temperature	ΔX_{total} []	Total xergy variation list
T^*_{hot}	Hot stream shifted temperature	$X_{pock,initial}$ []	initial exergy losses list
T^*_{cold}	Cold stream shifted temperature	$X_{req,initial}$ []	initial exergy requirement list
Cp_i	Heat capacity flow-rate of stream i	$X_{tot,initial}$ []	initial total exergy list
Cp_{net}	Net heat capacity flow-rate of stream	$X_{pock,final}$ []	Final exergy losses list
q_i	Heat load of stream i	$X_{req,final}$ []	Final exergy requirement list
U_H	Minimum hot utility	$X_{tot,final}$ []	Final total exergy list
U_C	Minimum cold utility		
$T_{h/c,pinch}$	Hot or cold pinch temperature		
$T_{pinch,process}$	Process pinch temperature		
T_{ref}	Reference temperature		
dim $T_{interval,1}$	First temperature interval size		
dim $T_{interval,2}$	second temperature interval size		

Table 3. Parameters (*Continued*)

Symbols	definition	List	definition
Dim T_{pock}	Pocket temperature interval size		
Index[]	Element index in desired list		
$X_{tot,sur}$	Total exergy surplus		
$X_{tot,def}$	Total exergy deficit		
$X_{loss,above}$	Exergy losses above the pinch		
$X_{loss,below}$	Exergy losses below the pinch		
Min X_{req}	Minimum exergy requirement		
Max X_{rej}	Maximum exergy rejection		

3.2. Data inputs and distribution

In fact, what makes the developed algorithm simple in terms of execution, is the simplified display of the results which makes it possible to understand the logic of the calculations and data analysis. For each stream, when data inputs are introduced, a specified instruction calculates the heat load (q_i) according to equation 1, then the algorithm rearranges and affects all the data to the appropriate stream as a list of four elements ($T_{in,i}$, $T_{out,i}$, Cp_i and q_i):
The first block of scripts which represents the header of the algorithm is the most crucial part for the rest of the scripts. In fact, the algorithm receives data of the studied process which is considered as process of N streams (hot and cold streams) and performs the analysis. The relevance of the algorithm's calculation depends strongly on the data extracted and received. Referring to collecting and processing data about streams, the data extraction is a very time consuming and critical step before algorithm execution. There are several methods that can be used for data acquisition either separately or in combination including process control systems, data acquisition systems, simulation models and from measurements taken directly from the plant. Figure 2 represents the script part of the algorithm header and the console window. The input data stage starts from the first line which indicates the project name (type of studied plant or industry). By specifying the number of hot and cold streams, the algorithm requests the streams data through a set of instructions. The instructions of the header algorithm script to follow start by providing the inlet temperature ($T_{in,i}$), the target temperature ($T_{out,i}$) and then the heat capacity flow rate (Cp_i) of each stream i (the order must be respected). The first results blocs in the console window represent the data distribution. This involves rearranging the data of all streams in the form of two blocs comprising hot and cold streams side information.
In fact, what makes the developed algorithm simple in terms of execution is the simplified display of the results which makes it possible to understand the logic of the calculations and data analysis. For each stream, when data inputs are introduced, a specified instruction calculates the heat load (q_i) according to equation 1, then the algorithm rearranges and affects all the data to the appropriate stream as a list of four elements ($T_{in,i}$, $T_{out,i}$, Cp_i and q_i):

$$q_i = \pm\, Cp_i\ (T_{in,i} - T_{out,i}) \tag{1}$$

Therefore, data analysis by the algorithm is done by manipulating the lists of input data and intermediate data.

```
project_name = str(input("enter the project name :"))
h = int(input("enter the HOT streams number :"))
c = int(input("enter the COLD streams number :"))
... {scripts}
    for i in range(1, h+1):
        H_i = H[(i-1) * 4:i * 4]
        print("H_"+str(i)+"=",H_i)
    for i in range(1,c+1):
        C_i = C[(i-1) * 4:i * 4]
            print("C_"+str(i)+"=",C_i)
... {scripts}
```

Results ⇒ Console

```
H_1 =[Tin , Tout , Cp, q]
H_2 =[Tin , Tout , Cp, q]
...
C_1 =[Tin , Tout , Cp, q]
C_2 =[Tin , Tout , Cp, q]
...
```

Figure 2. Scripts layout and console window display

3.3. Minimum temperature approach ΔT_{min}

In the industrial processes, engineers are aware that there is usually a trade-off (optimization problem) between energy consumption and capital investment even if pinch analysis has already addressed and allows for both energy and capital savings (not the optimal solutions but the opportunities for energy recovery and analysis). The minimum temperature approach ΔT_{min} is defined as the key parameter that affects all process variables and objectives. Otherwise, the determination of ΔT_{min} for heat transfer determines the targets for heat recovery systems. For a given value of ΔT_{min}, it automatically leads to an amount of maximum energy recovery (MER) and a well-defined quantity of external utilities (hot and cold utilities). The optimization problem lies in discussing the investment cost side concerning the heat transfer area to recover MER. Several methods are developed to establish the energy targets for a well determined value of ΔT_{min}, of which composite curves (CCs) and grand composite curve (GCC) are the main graphical methods or representations that various researches have relied on for case studies. And while the problem table algorithm (PTA) known as Linnhoff's table algorithm is the main numerical method (Linnhoff, B. and Flower, J.R., 1978). In terms of optimization, the most recognized method used to determine the optimal ΔT_{min} value is the super-targeting approach (Zhang et al., 2020; Kaviani et al., 2022). In fact, basically the ΔT_{min} optimum value is usually determined according to the classical economic criteria (Figure 3) but nothing prevents the use of global energy criteria including exergy for example and/or environmental factors. That is the main point of our developed work.
Among the data required during the data extraction phase is the ΔT_{min} value; in our case the ΔT_{min} range values. After specifying the ΔT_{min} range and the calculation steps, the interconnection between the developed scripts allows assigning each value of ΔT_{min} (for example $\delta_{min,1}$) the energy and exergy quantities in an automatic way, and that allows specialists to choose the right ΔT_{min} that is optimal for well-defined constraints (MER and minimum exergy destruction for example).

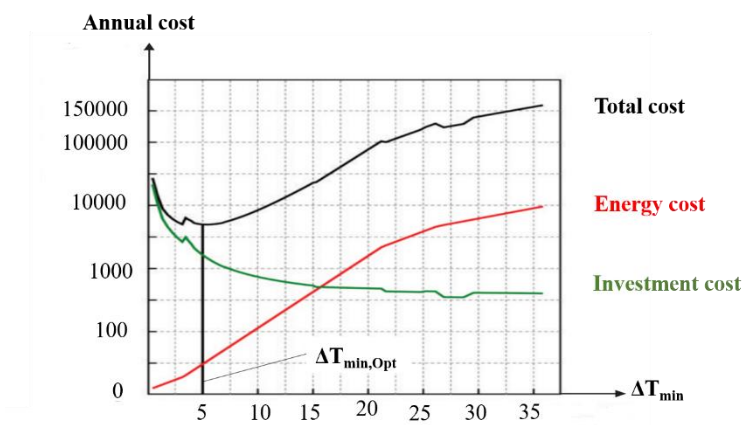

Figure 3. Trade-off between energy and investment costs

3.4. Energy analysis scripts flowchart

The first analysis part of the algorithm introduces the energy analysis with pinch concept (figure 4). Once the necessary data have been acquired, the energy scripts begin with the temperature intervals identification. In fact, through loops whatever the system type (N streams with k temperatures and k = 2n, $n \in \mathbb{N}^*$), the scripts manipulate data to build a list of temperatures, delete the occurrences and then reorder the temperature values from highest to lowest. The created list indexed by $T_{interval,1}$ represents the initial system temperature intervals with the following size:

$$dim\ T_{interval,1} = k - Occ \tag{2}$$

With, Occ = number of occurrences.

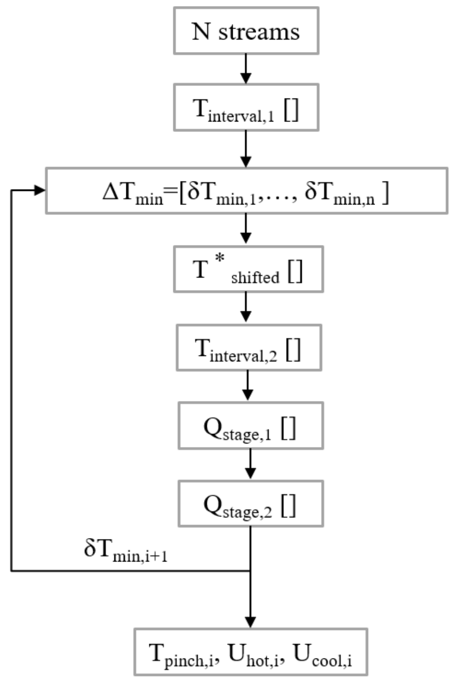

Figure 4. Energy analysis flowchart

For a δT_{min} value in the imposed range of ΔT_{min}, the algorithm calculates the shifted temperature (T^*) based on Linnhoff's law (Linnhoff, B. and Flower, J.R., 1978). A special script is used to identify the cold and hot stream temperatures simultaneously in $T_{interval,1}$, then performs the calculations according to the following equations:

$$T^*_{hot} = T_{hot} - \frac{\delta T_{min}}{2} \tag{3}$$

$$T^*_{cold} = T_{cold} + \frac{\delta T_{min}}{2} \tag{4}$$

Subsequently, the algorithm assigns all calculated shifted temperatures to a new list $T_{interval,2}$. The structure of the scripts at this stage is based on the newly created $T_{interval,2}$ list which represents the subject key to energy analysis. Temperature duplication can result from the generation of shifted temperatures, which calls for a command script to eliminate the occurrences for the second time. In this case, the size of $T_{interval,2}$ is less than or equal to $T_{interval,1}$ size (equation 5). For each interval ($[T^*_i,\ T^*_{i+1}]$) in list Tinterval,2, the first stage cascade ($Q_{stage,1}$) is performed using equation 6 and the algorithm invokes the script part that calculates the cascade second stage ($Q_{stage,2}$) according to equation 7 in which the identification of the energy system parameters is done.

$$\dim T_{interval,2} = \dim T_{interval,1} - Occ \tag{5}$$

$$\begin{cases} Q_{stage,1}[0] = 0 \\ Q_{stage,1}[j] = Q_{stage,1}[j-1] + \Delta Q[j-1] & 0 < j \leq dimT_{interval,2} \end{cases} \quad (6)$$

$$\begin{cases} Q_{stage,2}[0] = \left|minQ_{stage,1}[j]\right| \\ Q_{stage,2}[j] = Q_{stage,2}[j-1] + \Delta Q[j-1] & 0 < j \leq dimT_{interval,2} \end{cases} \quad (7)$$

With, $\Delta Q[i] = \Delta T[i] * Cp_{net}[i]$ and $i = j - 1$

The algorithm is composed of scripts that translate the path, the main and intermediate loops for data processing and analysis. The main loop that turns out to be interesting is the one that performs the calculation for all δT_{min} value in ΔT_{min} list. From the shifted temperature calculation, the algorithm resumes the computation process and displays the results in simple and understandable lists.

3.5. Energy analysis script results

At this stage, the study's objectives were carefully considered when tracing the scripts through the intermediate results manipulation and the assignment of variable lists. As with any type of application that deals with the pinch concept, the developed algorithm allows to visualize the computational results in an organized way. Moreover, the calculation of different energy quantities and pinch parameters associated to δT_{min} values, which are included in the well-defined interval of minimum temperature approach (ΔT_{min}) is well displayed without the need to insert the values one at a time. Without any computational difficulties, the algorithm performs all the instructions to come out with the energetic results such as the external utilities needed to fulfill the heating and cooling requirements. Those results are considered as the global energy criteria which the specialists can use to make the choice of a suitable and appropriate δT_{min}. For each value of δT_{min}, the algorithm generates the usual pinch-energy target values as follows:

Process pinch temperature	:	$T_{pinch,process} = T_{interval,2}[index[Q_{stage,2}[j] = 0]]$
Pinch temperature of hot streams	:	$T_{pinch,hot} = T_{pinch,process} + \frac{\delta T_{min}}{2}$
Pinch temperature of cold streams	:	$T_{pinch,cold} = T_{pinch,process} - \frac{\delta T_{min}}{2}$
Process minimum heating requirement	:	$U_{hot} = Q_{stage,2}[0]$
Process minimum cooling requirement	:	$U_{cold} = Q_{stage,2}\left[dim\,T_{interval,2} - 1\right]$

Beside the analytical results, the algorithm also calls on 'Matplotlib' library which is a comprehensive library designed to plot and create interactive data visualization. Combined with the scientific calculation library 'NumPy', a part of scripts is built and used to generate the grand composite curve (GCC) for each value of δT_{min} since it is the visualization that is more interesting in terms of energy results. In fact, GCC is the heat cascade graphical representation; it can be constructed from the composite curves (CCs) or directly based on the final energy cascade $Q_{stage,2}$. Consequently, it illustrates how the energy requirements (above the pinch point) and the extra energy that has to be released (below the pinch point) depend on temperature.

3.6. Exergy analysis

The second analysis part of the algorithm proceeds with the exergy concept. Once the necessary results have been calculated and acquired, in order to identify additional temperatures associated with the pockets and their energy, the exergy scripts begin with temperatures interpolation in which the algorithm uses the interpolation scripts. The subscript employed in this context serves the purpose of distinguishing between system types (standard or threshold system) to facilitate the identification of the studied system. This distinction allows for following the prescribed instructions and generating accurate exergy calculation results.

3.6.1. Temperatures interpolation scripts

Exergy scripts start with the interpolation of pocket temperatures. In fact, the algorithm is merely the combination and interconnection between the energy and exergy scripts. The interlinking between the two concepts begins when exergy scripts invoke the $T_{interval,2}$ and $Q_{stage\text{-}2}$ lists of energy concept. Figure 5 depicts the subscript part (a) and the grand composite curve (b) which clearly represent two pockets (one above the pinch temperature and one below). The pockets (gray areas) are algorithmically recognizable and that indicates the temperature range where recovery potential and energy demands is in balance, resulting in the dependence on external utilities requirement. Each pocket is characterized by three temperatures, the boundaries temperature and the inflection point (or more than one inflection point). As previously stated, interpolation of the additional temperatures by the algorithm is guaranteed and automatically performed by a special subscript (figure 5-a) that makes time-consuming calculations. Two possibilities are provided for each interpolated temperature and both belong to $T_{interval,2}$, either the $T_{interval,2}$[i] or undefined temperature T_{pock}[j]. The interpolation is done according to the two subsystems above and below the pinch point according to the conditions below:

Above the pinch

$$T_{interval,2}[i+n] \leq T_{pock}[j] \leq T_{interval,2}[i]$$
$$0 \leq i \leq index[T_{process,pinch}] - 1$$
$$1 \leq n < index[T_{process,pinch}] - 1$$
$$0 \leq j \leq dimT_{interval,2} - 1$$

Below the pinch

$$T_{interval,2}[i] \leq T_{pock}[j] \leq T_{interval,2}[dimT_{interval,2} - 1 - n]$$
$$dimT_{interval,2} - index[T_{process,pinch}] \leq i \leq dimT_{interval,2} - 1$$
$$1 < n \leq dimT_{interval,2} - index[T_{process,pinch}]$$
$$0 \leq j \leq dimT_{interval,2} - 1$$

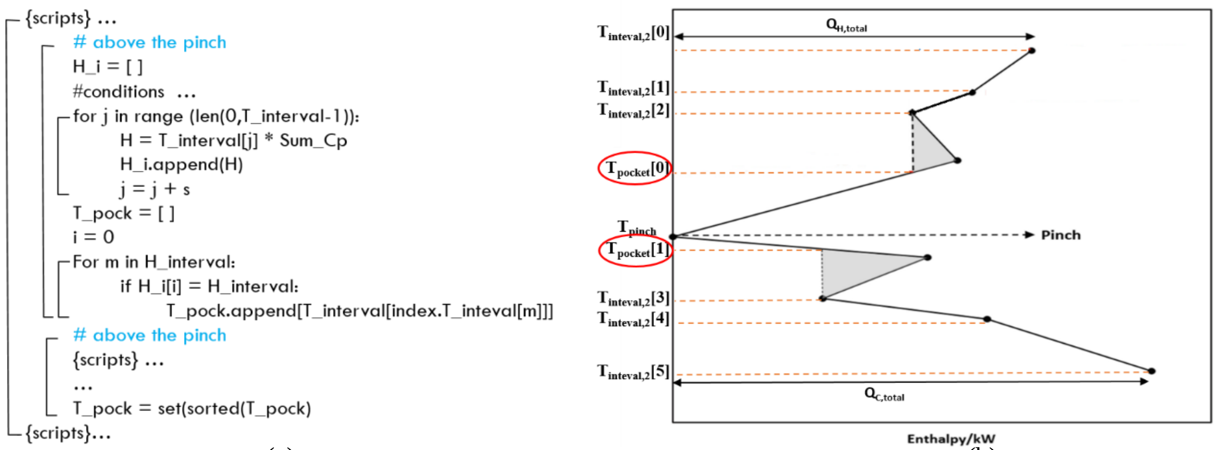

Figure 5. (a) Interpolation subscript part; (b) GCC with pockets temperatures

The algorithm creates a list of T_{pocket} so fare its dimension is greater than or equal to zero since each temperature $T_{interval,2}$[i] can induce T_{pocket}[j] except the $T_{process,pinch}$. The existence of the pockets is strongly related to the temperature allocation and distribution. Furthermore, the calculation and identification of T_{pocket}[j] is done based on energy criteria. Alternatively, T_{pocket}[j] and $T_{interval,2}$[i] characteristic lies in the fact that they have the same energy. As indicated in figure 5-b, there are 2 additional temperatures to interpolate and identify; T_{pocket}[0] and T_{pocket}[1] which have respectively the same energy as $T_{interval,2}$[2] and $T_{interval,2}$[3].

3.6.2. System identification

According to the T_{pocket} size, the first decomposition of the algorithm is done depending on the process type. For $dimT_{pocket} = 0$, the process is considered as a simple system and there are no pockets and no temperature to interpolate. In this case, by introducing the reference temperature T_{ref}, the scripts involve the second enthalpy cascade $Q_{stage,2}$ to perform the calculation of exergy parameters. For $dimT_{pocket}$ greater than zero, the process is considered as a problem with pockets and the algorithm proceeds to calculate exergy parameters for each δT_{min}. Figure 6 represents the exergy analysis flowchart for both systems; the difference between the two pathways is in the starting energy cascade. In fact, for the process considered as a system with pockets, the calculations are made based on the combination of the two temperature lists {$T_{pockets}$[] + $T_{interval,2}$[]}. Therefore, the algorithm creates a new list of well-stretched temperatures including the pockets temperatures and proceeds to the $H_{f,2}$ calculations. At this level, the script devoted to the formulation of $H_{f,2}$ refers to $T_{pockets}$ and $Q_{stage,2}$ to adjust its size so as to have:

$$dim\, H_{f,2} = dim\, Q_{stage,2} + \frac{dimT_{pockets}}{2} \tag{8}$$

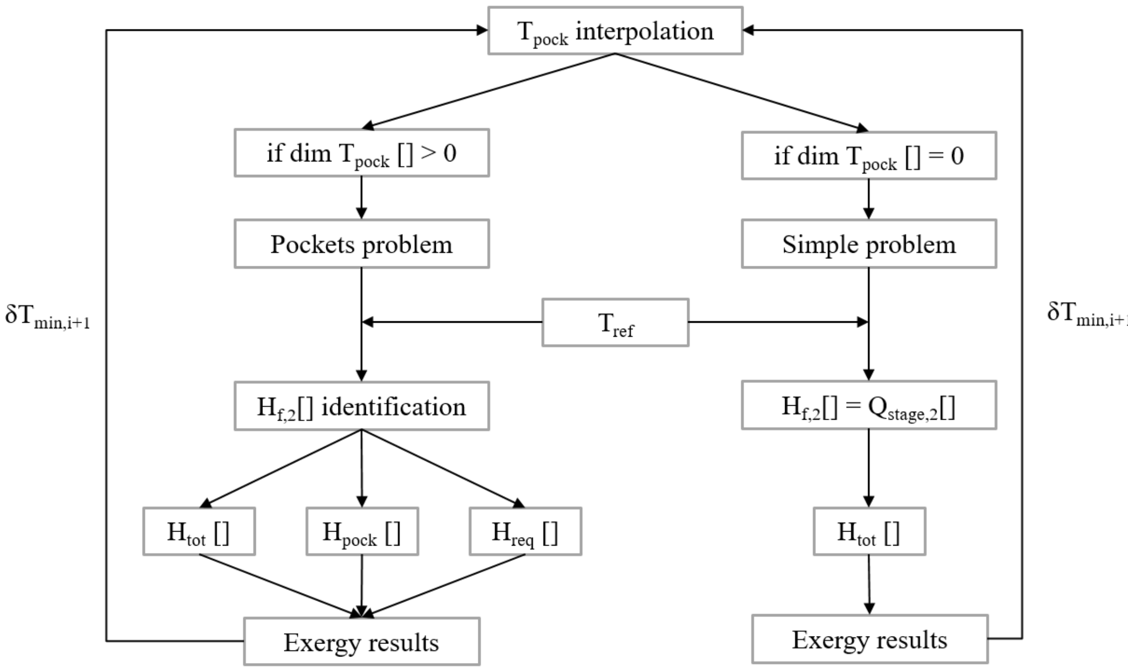

Figure 6. Exergy analysis flowchart

In order to specify the $H_{f,2}$ elements, the algorithm assigns to the temperatures of the pockets their energy and to all the temperatures that belong to the pocket the same energy. Otherwise, $H_{f,2}$ can be subdivided into two sub-lists so that one list represents the pure external heat requirements (H_{ext}[]) and the other list reflects the heat recovery pockets (H_{pock}[]); that's the difference between the two systems. The only common point between the two systems is the analysis based on the H_{tot}[] list. In order to provide more details on the analysis script at this stage, the algorithm starts by calculating the exergetic temperature (T^E) according to equation 9. The scripts devoted to that are presented in figure 7. So for each δT_{min} in range ΔT_{min}, the algorithm calls up T^E calculation script for each iteration i in range $dimT_{interval,2}+1$.

```
... {scripts}
    T_Exg = [ ]
    T_0 = int(input("insert a reference temperature : ")) + 273
    for i in range(0, len(T_interval)):
            T_ex = T_0 * ((T_interval_273[i]/T_0) - math.log(T_interval_273[i]/T_0) - 1)
            T_Exg.append(T_ex)
    T_Exg = set(T_Exg)
    T_Exg = sorted(T_Exg)
... {scripts}
```

Figure 7. Exergetic temperature scripts calculation layout

Then the algorithm performs instructions for each calculation loop and path to evaluate different exergy quantities and according to the following respective equations (10-13):

$$T^E = \left[T_{ref}\left(\frac{T}{T_{ref}} - \left(\ln\frac{T}{T_{ref}}\right) - 1\right)\right] \tag{9}$$

$$Cp_{net,l}[i] = \frac{\Delta H_l[i]}{\Delta T[i]} \tag{10}$$

$$\Delta X_l[i] = Cp_l[i] * \Delta T^E[i] \tag{11}$$

$$\begin{cases} X_{l,intial}[0] = 0 \\ X_{l,intial}[j] = X_{l,intial}[j] + \Delta X_l[j-1] \end{cases} \quad 0 < j \leq dim\ H_{f,2} \tag{12}$$

$$\begin{cases} X_{l,final}[0] = \left|X_{l,intial}\left[index[T_{process,pinch}]\right]\right| \\ X_{l,final}[j] = X_{l,intial}[j] + \Delta X_l[j-1] \end{cases} \quad 0 < j \leq dim\ H_{f,2} \tag{13}$$

And $l = req, pock\ or\ total$

3.6.3. Exergy scripts results

The algorithm exergy scripts provide necessary results for process improvement through exergy analysis. Exergy results are derived from the energy lists at the system specification level (H_{pock}[] and H_{req}[] for the pocket problem and H_{tot}[] for both systems). The scripts employ loops and sub-loops to perform the calculation of the exergy quantities list such as $X_{pock,final}$, $X_{req,final}$ and $X_{tot,final}$ (figure 8). Based on these lists, the algorithm compiles the specified exergy results that yield more information about the improvement opportunities. From the heat recovery pocket list, the algorithm determines the avoidable exergy loss $X_{loss.above}$ above the pinch temperature and the avoidable exergy loss $X_{loss.below}$ below using the instructions (14) and (15) respectively. The Minimum exergy requirement ($MinX_{req}$) and maximum exergy rejection ($MaxX_{rej}$) are determined from the pure external heat requirement list X_{req}[] according to instructions (16) and (17) and finally, the total exergy surplus and deficit target ($X_{tot,sur}$, $X_{tot,def}$) from $X_{tot,final}$ using instructions (18) and (19):

$$X_{loss,above} = X_{pock,final}[0] \tag{14}$$

$$X_{loss,below} = X_{pock,final}[dim\ H_{req} - 1] \tag{15}$$

$$Min\ X_{req} = X_{req,final}[dim\ H_{req} - 1] \tag{16}$$

$$Max\ X_{rej} = X_{req,final}[0] \tag{17}$$

$$X_{tot,sur} = X_{tot,final}[0] \tag{18}$$

$$X_{tot,def} = X_{tot,final}[dim\ H_{req} - 1] \tag{19}$$

Following the temperatures interpolation, the exergy analysis began with decomposition of the cascade second stage $Q_{stage,2}$ according to the pocket temperatures. Based on the calculation and decomposition logic, analysis results must respect a set of dependencies including equations 20 and 21, which allow approving the rigidity of the elaborated algorithm calculations.

$$Max\ X_{rej} = X_{tot,sur} - X_{loss,below} \tag{20}$$

$$Min\ X_{req} = X_{tot,def} + X_{loss,above} \tag{21}$$

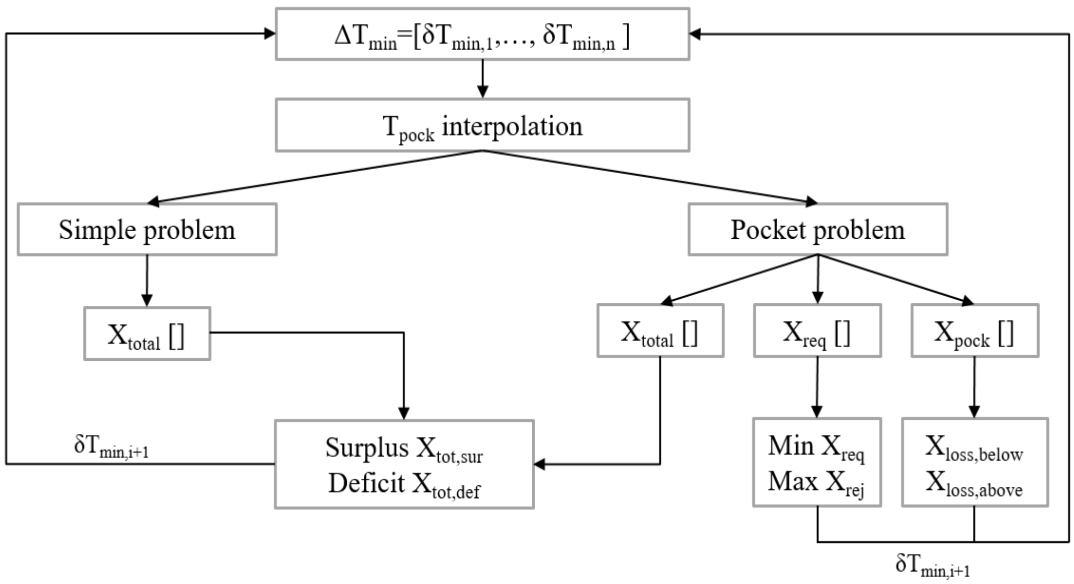

Figure 8. Exergy analysis results flowchart

4. Case study and algorithm validation

The efficiency and computational flexibility of the algorithm is illustrated through a case study adopted from Hamsani et al. (2018). The system under study is composed of four streams (2 hot and 2 cold) in which the temperatures and capacities are well acquired through one of the data acquisition techniques (table 4). From the stream temperatures, it is clear that the system is classified as a low temperature system. The reason for choosing this system is the potential of applicability. In fact, due to the important recovery potential and the greatest energy saving feasibility, the combined approaches have been recommended in numerous studies for processes with low operating temperatures. However, this does not preclude the use of such a combined method in high- and medium-temperature processes (not simple and straightforward but achievable). To this purpose, the algorithm can be used to help in improving and understanding the industrial processes through automatic calculation of various energy and exergy quantities, and on which the experts can base themselves to bring more effective solutions. The algorithm versatility in terms of computing lies in the fact that it performs all the calculations imposed by the calculation variables. In our case, the calculation variable is the minimum temperature approach $\delta T_{min,i}$ included in the interval ΔT_{min}[0:10] with a step *s* equal to 2 (δT_{min} = 0, 2, 4, 6, 8 and 10).

Table 4. Process data acquisition

Stream	type	T_{in}(°C)	T_{out}(°C)	*Cp (MW/K)*
S_1	hot	6.85	-123.15	0.185
S_2	hot	-23.15	-158.15	0.35
S_3	cold	-173.15	-43.15	0.325
S_4	cold	-83.15	6.85	0.35

The specification of ΔT_{min} interval for which the calculations are performed is imposed after the process data insertion. The energy scripts begin with the temperature intervals identification and the shifted temperature calculation based on Linnhoff's law. Instructions contained in the energy scripts involve the equations located in the description section of the algorithm to calculate the different energy quantities according to the variable $\delta T_{min,i}$. Table 5 summarizes the main energy results analysis by the algorithm. These results are the standard results of the pinch method (the external utilities needed to fulfill the heating and cooling requirements as well as the process pinch point temperature). The detailed calculation of each script according to the instructions is illustrated in Appendix A- Table 6 for the value of $\delta T_{min,6}$ = 6°C

Table 5. Pinch-energy calculation results

$\delta T_{min,i}$ (°C)	0	2	4	6	8	10
$T_{process,pinch}$ (°C)	-83.15	-82.15	-81.15	-80.15	-79.15	-78.15
U_{Hot} (MW)	6.8500	7.9200	8.9900	10.0600	11.1300	12.2000
U_{Cold} (MW)	4.3999	5.4699	6.5399	7.6099	8.6799	9.7499

Once the pinch main results have been calculated and acquired ($Q_{stage,2}$ *[]* and $T_{interval,2}$ *[]*), the exergy scripts begin with the temperature interpolation for each $\delta T_{min,i}$ value. The scripts identify the pockets in the GCC curve from the header and rearrange them in T_{pocket}*[]* as indicated in table 6. The algorithm creates the exergetic temperature list ($T^*_{interval,2}$[]) based on $T_{interval,2}$ *[]* and T_{pocket} *[]* as well as the imposed reference temperature $T_{ref}=15°C$ in order to generate the final enthalpy cascade $H_{f,2}$ *[]*, identify H_{req} *[]* and H_{pock} *[]* and perform exergy calculation (appendix A- table 8 to table 11). Table 7 represents the total exergy results calculation in which the third and fourth columns designate the total exergy surplus and the total exergy deficit respectively. These two results allow or make it possible to place utilities in an efficient way and avoid the inefficiencies. The fifth and sixth columns designate the minimum exergy rejection and the maximum exergy requirement. These two results give an idea about the advanced utility installation or integration like turbines and compressors; the maximum exergy requirement concerns the turbine expansion and the minimum exergy rejection concerns the compressor The computation of the algorithm indicates a similarity with the results produced by Hamsani et al. (2018), which demonstrates the validity and the computational power of the developed interconnected scripts.

Table 6. Interpolated temperature for each value in ΔT_{min}

ΔT_{min} (°C)	$T_{pocket,1}$	$T_{pocket,2}$	$T_{pocket,3}$	$T_{pocket,4}$
$\delta T_{min,1}=0$	-23.15	-69.7	-103.5	-173.15
$\delta T_{min,2}=2$	-24.15	-65.3	-107.7	-172.15
$\delta T_{min,3}=4$	-25.15	-63.3	-111.7	-171.15
$\delta T_{min,4}=6$	-26.15	-58.1	-116.2	-170.15
$\delta T_{min,5}=8$	-28.15	-54.7	-120.4	-169.15
$\delta T_{min,6}=10$	-29.15	-51.36	-124.58	-168.15

5. Results and discussion

During the evaluation of the heat integration opportunities in the studied plant using the algorithm, we assumed the same starting assumptions. The case study results are tabulated in tables 4 and 6 to compare them with those of Hamsani et al. (2018) and to consider the effect of ΔT_{min} on energy and exergy targets. Regarding pinch-energy analysis results, the algorithm returned the same results for δT_{min}=0, 2 and 10 which proves its computational efficiency. Furthermore, it provides additional results for the extra respective δT_{min} values of 4, 6 and 8°C. For the hot and cold utilities, the first value of δT_{min}=0°C corresponds to an amount of U_{Hot} =6.8500 MW and U_{cold} =4.3999S MW and these values raise up to 12.2000 MW and 9.7499 MW respectively for δT_{min}=10°C. Figure 9 depicts the GCC curves for all δT_{min} values in ΔT_{min} range. It is clear that an increase in the ΔT_{min} value directly affects the high external utility requirement to cover the plant energy needs. In fact, the increase of the minimum temperature approach value creates a large gap between the process streams, which results in a relatively limited amount of energy that can be recovered. For the exergy results, the range of ΔT_{min} values provides a better understanding of its impact on the exergy targets (exergy rejection, exergy requirement and avoidable exergy loss). The decomposition script implemented in the algorithm at the exergy analysis level takes into account the behavior of the pockets; therefore, it defines the avoidable exergy losses based on heat recovery pockets. Figure 10 illustrates the process exergy results for all δT_{min} values in ΔT_{min} range. According to the outcome of the algorithm calculation, unavoidable exergy losses or the total exergy increases with increment of δT_{min}, which means that the energy recovery and avoidable exergy losses below and above the pinch decrease with respect to δT_{min}. For the exergy requirement and rejection targets, they increase with δT_{min} increment indicating the opportunity to design a system to recover work through turbine expansion. The obtained results through the interconnected scripts are similar to those found by Hamsani et al. (2018) study. To this effect, the developed algorithm turns out to be efficient and powerful in terms of analysis and calculation.

Table7. Exergy analysis calculation results

δT_{min}	$T_{process,pinch}$ (°C)	$X_{tot,sur}$ (MW)	$X_{tot,def}$ (MW)	Min X_{req} (MW)	Max X_{rej} (MW)	$X_{loss,below}$ (MW)	$X_{loss,above}$ (MW)
0	-83.15	1.8019	-1.2752	2.6602	1.3231	0.4810	3.9610
2	-82.15	1.8810	0.1434	3.3918	1.4919	0.3773	3.2708
4	-81.15	1.9604	1.5615	4.1536	1.6606	0.2999	2.6207
6	-80.15	2.0403	2.9792	4.9711	1.8077	0.2228	2.0015
8	-79.15	2.1206	4.3970	5.8199	1.9522	0.1629	1.4274
10	-78.15	2.2013	5.8152	6.7111	2.0880	0.1132	0.8958

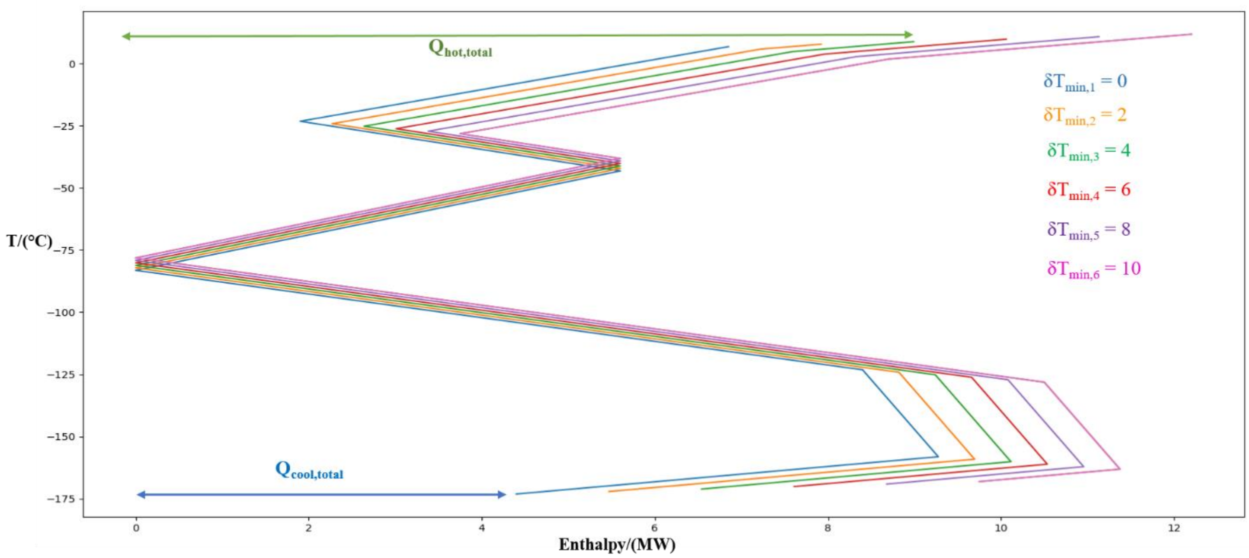

Figure 9. GCCs plot for the imposed ΔT_{min} range

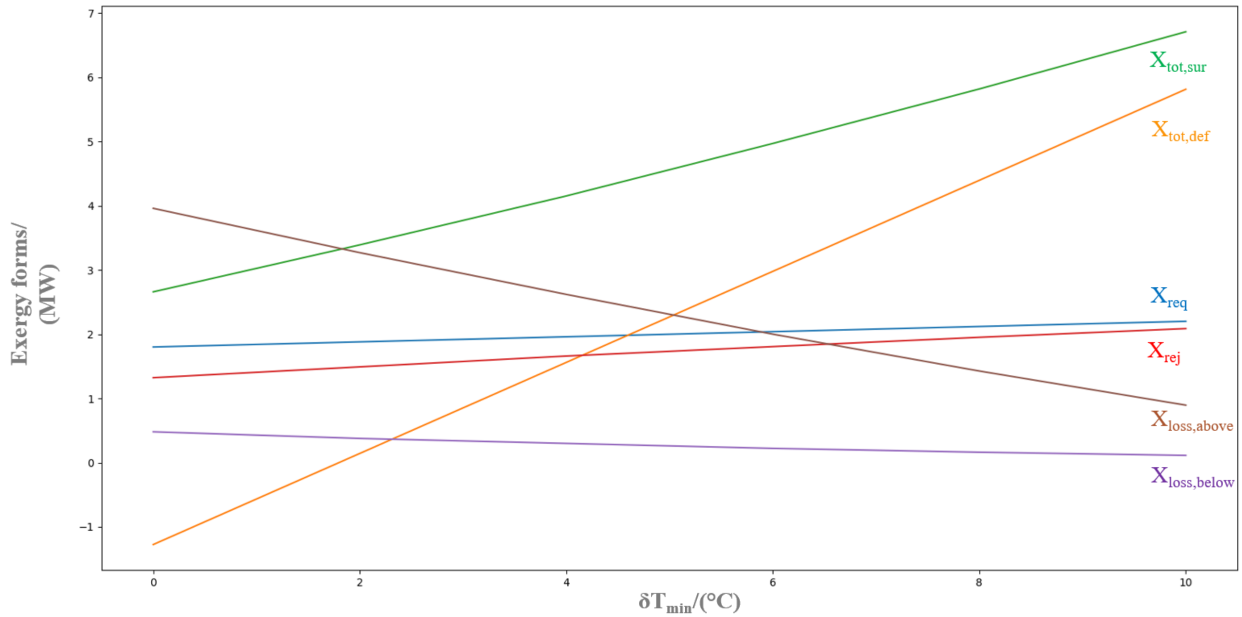

Figure 10. Exergy results plot for the imposed ΔT_{min} range

6. Conclusion

To evaluate energy-efficiency options with minimum exergy losses in an industrial process, a combined pinch and exergy analysis is conducted through interconnected scripts. In this study, a pinch-exergy algorithm was developed using python language to investigate the minimum temperature approach (ΔT_{min}) effect on energy and exergy targets. The body of the algorithm is built using structured scripts that encode energy and exergy concepts. The developed algorithm potential application lies in the fact that it can be used to facilitate and make the combined analysis automatic. In this regard, it provides industrial specialists with an automatic framework to better benefit from the combined analytical power. This work is initiated by providing a comprehensive overview of interconnected scripts, ensuring that each step within the algorithm is clearly defined and integrated. The approach involves meticulously designed scripts that encompass diverse stages such as data gathering and manipulation, energetic analysis, and exergetic analysis.

At first, the algorithm involves pinch-energy scripts to establish the pinch parameters such as the pinch point temperature and external utilities according to each δT_{min} value in range ΔT_{min}. Based on that, an initial heat exchange network can be designed. Second, it invokes exergy scripts with the interest to determine the system irreversibilities. Subsequently, the algorithm is validated by applying it to a previously examined process, thereby affirming its reliability and fluidity in terms of calculation of minimum energy consumption targets as well as exergy analysis targets (including exergy requirement, exergy rejection, and avoidable exergy losses). For ΔT_{min} in range [0,10] and step s =2, the calculations are carried out. On the one hand, energy results demonstrate the traditional direct impact of δT_{min} on external required utilities (the increment of δT_{min} implies the increase of external utilities). On the other hand, the exergy results reveal that the energy recovery and avoidable exergy losses decrease with respect to δT_{min}, which means that unavoidable exergy losses increased with increment of δT_{min}. Finally, exergy requirement and rejection increases slightly with δT_{min} increment and that offers an insight into the opportunities of designing a work recovery system through turbine expansion and compressor equipment.

The present work can be further developed through default algorithm structure improvement. A possible extension may include impact of both ΔT_{min} and the temperature reference T_{ref} on energy and exergy targets. The present paper has the potential for further advancement through default algorithm structure improvement. One potential extension could involve impact of both ΔT_{min} and the temperature reference T_{ref} on energy and exergy targets. The authors intend to utilize the algorithm to enhance the design and integrate reactors, while simultaneously promoting exergy analysis (ExA).

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Appendix A.

Energy and exergy detail calculation for $\delta T_{min}=6°C$.

Table 8. Energy analysis results for $\delta T_{min}=6°C$

$T_{inter,2}(°C)$	$\Delta T_{inter,2}(K)$	$Cp_{net}(W)$	$\Delta Q(W)$	$Q_{stage,2}(W)$
9.85				10.0600
	6	-0.35	-2.1	
3.85				7.9600
	30	-0.1649	-4.95	
-26.15				3.0100
	15	0.1849	2.775	
-40.15				5.6000
	40	-0.14	-5.6	
-80.15				00.00
	46	0.21	9.66	
-126.15				9.6599
	35	0.025	0.875	
-161.15				10.5349
	9	0.325	-2.925	
-170.15				7.6099

Table 9. Enthalpy decomposition for $\delta T_{min}=6°C$

$T_{inter,2}(°C)$	$H_{f,2}(kW)$	$H_{req}(kW)$	$H_{pock}(kW)$
9.85	10.0600	10.0600	00.00
3.85	7.9600	7.9600	00.00
-26.15	3.0100	3.0100	00.00
-40.15	5.6000	3.0100	2.5899
-58.1	3.0100	3.0100	00.00
-80.15	$-8.8817.10^{-16}$	$-8.8817.10^{-16}$	00.00
-116.2	7.6099	7.60999	00.00
-126.15	9.6599	7.60999	2.0500
-161.15	10.5349	7.60999	2.925
-170.15	7.6099	7.60999	00.00

Table 10. Pure heat requirement exergy calculation for δT_{min}=6°C

$T_{inter,2}(°C)$	$H_{req}(kW)$	$T^E(K)$	$\Delta T^E(K)$	$Cp_{net,req}(MW/K)$	$\Delta X_{req}(MW)$	$X_{req,i}(MW)$	$X_{req,f}(MW)$
9.85	10.0600	0.04660				00.00	1.8077
			0.17497	-0.3499	-0.0612		
3.85	7.9600	0.22157				-0.0612	1.7464
			3.03215	-0.1649	-0.5003		
-26.15	3.0100	3.2537				-0.5615	1.2461
			2.8152	00.00	00.00		
-40.15	3.0100	6.0690				-0.5615	1.2461
			5.15383	00.00	00.00		
-58.1	3.0100	11.2228				-0.5615	1.2461
			9.1289	-0.1365	-1.2461		
-80.15	$-8.88178.10^{-16}$	20.3517				-1.8077	$2.22044.10^{-16}$
			23.5491	0.2110	4.9711		
-116.2	7.6099	43.9009				3.16341	4.9711
			8.93112	00.00	00.00		
-126.15	7.6099	52.8320				3.16341	4.9711
			43.4088	00.00	00.00		
-161.15	7.6099	96.2409				3.16341	4.9711
			15.1594	00.00	00.00		
-170.15	7.6099	111.4003				3.16341	4.9711

Table 11. Heat pockets exergy calculation for δT_{min}=6°C

$T_{inter,2}(°C)$	$H_{pock}(kW)$	$\hat{T}^E(K)$	$\Delta\hat{T}^E(K)$	$Cp_{net,pock}(MW/K)$	$\Delta X_{pock}(MW)$	$X_{pock,i}(MW)$	$X_{pock,f}(MW)$
9.85	00.00	0.04660				00.00	0.22281
			0.17497	00.00	00.00		
3.85	00.00	0.22157				00.00	0.2228
			3.03215	00.00	00.00		
-26.15	00.00	3.2537				00.00	0.2228
			2.8152	0.1849	0.5208		
-40.15	2.7749	6.0690				0.52082	0.7436
			5.15383	-0.14428	-0.7436		
-58.1	00.00	11.2228				-0.2228	00.00
			9.1289	00.00	00.00		
-80.15	00.00	20.3517				-0.2228	00.00
			23.5491	00.00	00.00		
-116.2	00.00	43.9009				-0.2228	00.00
			8.93112	0.2060	1.8400		
-126.15	2.3750	52.8320				1.6172	1.8400
			43.4088	0.0249	1.0852		
-161.15	3.25	96.2409				2.7024	2.9253
			15.1594	-0.325	-4.9268		
-170.15	00.00	111.4003				-2.2243	-2.0015

Table 12. Total exergy calculation for $\delta T_{min}=6°C$

$T^{*}(°C)$	$Q_{stage,2}(MW)$	$T^{E}(K)$	$\Delta T^{E}(K)$	$Cp_{net,tot}(MW/K)$	$\Delta X_{tot}(MW)$	$X_{tot,i}(MW)$	$X_{tot,f}(MW)$
9.85	10.0600	0.04660				00.00	2.0403
			0.17497	-0.3499	-0.06124		
3.85	7.9600	0.2215				-0.0612	1.9790
			3.0321	-0.1649	-0.5003		
-26.15	3.0100	3.2537				-0.5615	1.4787
			2.8152	0.18499	0.5208		
-40.15	5.6000	6.0690				-0.0407	1.9995
			14.2827	-0.1400	-1.9995		
-80.15	00.00	20.3517				-2.0403	$-2.2204\ 10^{-16}$
			32.4802	0.20999	6.8208		
-126.15	9.6599	52.8320				4.78055	6.8208
			43.4088	0.02499	1.0852		
-161.15	10.5349	96.2409				5.8657	7.9060
			15.1594	-0.325	-4.9268		
-170.15	7.6099	111.4003				0.9389	2.9792