CHEMICAL ENGINEERING TRANSACTIONS

VOL. 94, 2022

A publication of AIDIC
The Italian Association
of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Yee Van Fan, Jiří J. Klemeš, Sandro Nižetić

ISBN 978-88-95608-93-8; **ISSN** 2283-9216

DOI: 10.3303/CET2294051

A Segregated Targeting Algorithm for Concurrently Targeting and Designing of Batch Heat Exchanger Network

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Batch heat integration is a critical aspect of process integration. Also, designing heat exchanger networks (HEN) is an important step in heat integration. This article presents a segmented strategy for concurrently targeting and constructing the HEN for the batch process. This method is built on the framework of segregated targeting of utilities in order to design HEN. The main objective is to provide a holistic picture of segregated targeting and build the HEN in a batch process. This method clearly captures the role of individual streams, which may be helpful in exploring reuse and recycling options within the streams. The concept of a segregated time-level grand composite curve was created in order to design a segregated heat distribution network (SeHDN). In a batch process, heat transfer can occur in two ways: direct and indirect. The developed method is capable of incorporating both types of heat transfer, which is further demonstrated through an example. SeHDN depicts the distribution of heat at different time intervals.

1. Introduction

The drive towards high-valued, low-capacity products such as specialty chemicals, fine chemicals, and pharmaceuticals has stimulated the batch process industries to develop new methods to minimize energy requirements and maximize energy recovery. Process Integration (PI) plays an important role in resource minimization. Alwi et al. (2013) developed the SePTA (Segregated Problem Table Algorithm), which is an algebraic tool for simultaneous targeting and designing of heat exchanger networks (HENs) for continuous processes. SePTA may be utilized not just for utility targeting but also for HEN design. The SePTA is a modification of the STEP technique (Alwi and Manan, 2010), which is a graphical tool for simultaneous targeting and designing of HEN. Sudi et al. (2021) introduced a new HEN retrofit technique called the Individual Stream Heat Cascade Analysis and calculated the minimum utility requirements for a HEN retrofit that adheres to the pinch design rules. Using a pseudo-T-H diagram technique, Du et al (2013) developed a method that utilizes heat storages in two ways to facilitate heat recovery for the synthesis of batch HEN. Chaturvedi and Bandyopadhyay (2014) proposed a method for single and cyclic batch operations for indirect thermal integration. In order to address intermediate fluid issues, Chaturvedi (2018) proposed a linear mathematical approach to minimize intermediate fluid requirements while meeting the minimal utility criteria. Research on the role of individual streams in HENs for batch processes is still in its infancy. HENs, which describe the composite functions of process streams, are the subject of most research. Responsibilities or pieces of information complicate the challenge of designing a batch process. This is true due to the fact that batch processes have distinct activities, resource sharing, and flexibility, among other characteristics. These functions need knowledge of the different process streams. Researchers have worked on various important issues of batch process integration, such as Utility targeting, Storage optimization, HEN synthesis, Fixed-flow batch targeting of the water allocation network (WAN), Automated targeting technique for batch process integration, Targeting of semi-continuous/fixed load batch WAN, Batch WAN targeting and synthesis with multiple resources, Batch WAN synthesis, etc. A recent research work based on separated targeting for resource conservation for batch processes was done by Haider and Chaturvedi (2021). Furthermore, Shukla and Chaturvedi (2021) presented a graphical method based on pinch analysis for minimizing compression energy in batch gas allocation networks while maintaining a minimum resource need.

Paper Received: 15 April 2022; Revised: 09 May 2022; Accepted: 12 May 2022
Please cite this article as: Haider M.A., Chaturvedi N.D., 2022, A Segregated Targeting Algorithm for Concurrently Targeting and Designing of Batch Heat Exchanger Network, Chemical Engineering Transactions, 94, 307-312 DOI:10.3303/CET2294051

In this paper, a new method has been developed for designing batch HEN where each individual stream can be identified at any stage of the algorithm. Also, the method can be applied to both cases of heat integration: direct and indirect. This algebraic technique can be used for determining the utility target and designing a HEN concurrently for any fixed-schedule batch process. HEN is developed in segregated form and represented as a heat distribution network (HDN), which is termed here as a segregated heat distribution network (SeHDN). Every segment in a segmented form has a complete piece of information. Within each segment, this data comprises an energy exchange in each time period and at each temperature interval. This type of description helps in exploring opportunities for reuse and recycling of streams. The concept of Segregated Time-Level Grand Composite Curves (SeTGCCs) was created in order to design SeHDN. SeTGCCs are utilized to display individual stream responsibilities. The suggested technique solves the drawbacks of previous methodologies that lacked precise interval segment data. The suggested technique also addresses the constraints of previous methodologies, which get increasingly complicated as design progresses and need meticulous PDM compliance.

2. Problem Statement and Mathematical Formulation

The general problem of minimizing utility consumption and designing a SeHDN for a batch process can be stated as follows:
Internal hot process streams (H_i) with cooling requirements for a specified time interval are given, along with their respective supply (T_s) and target (T_t) temperatures.
A set of internal cold process streams (C_j) with heating requirements for a specified time interval is provided, along with their associated supply and target temperatures.The objective is to concurrently target and design batch HEN in segregated form.All streams can be divided into several time intervals (such as I_1, I_2, and I_3) so that all cold and/or hot streams begin or end at these points in the intervals. It should be noted that no stream will begin or end during any of the time intervals. The total requirement for hot utilities is the sum of the individual requirements for hot utilities. Similarly, the total requirement for cold utilities is the sum of the individual requirements for cold utilities.

$$Q_{HU_{Total}} = \sum Q_{HU_i} \tag{1}$$

$$Q_{CU_{Total}} = \sum Q_{CU_i} \tag{2}$$

The methodologies developed for designing HEN for continuous processes cannot be directly applied to batch HEN design. In continuous processes, all streams are available throughout the process. However, in a batch process, streams are available in a discrete manner. In a batch process, there may be some unutilized heat in any time interval, and that unutilized heat should be carried to upcoming intervals in order to explore its utilisation opportunity.In the case of indirect heat transfer, an intermediate fluid is required for a feasible heat transfer between two different time intervals, resulting in a double minimum approach temperature difference ($2\Delta T_{min}$). As a result, additional stream shifting is required (Chaturvedi and Bandyopadhyay, 2014). A segregated form of PTA is used to show the role of individual streams. Because each stream has its own heat capacity and specified time interval ($MCp\Delta t$), which plays an important role in heat transfer. Each interval uses one pair of the highest $MCp\Delta t$ of hot and cold streams to calculate utility requirements in first segregated form, then uses another pair of the next highest $MCp\Delta t$ of hot and cold streams to calculate utility requirements in second segregated form, and so on until all $MCp\Delta t$ have been exhausted (Alwi et al., 2013). These steps enable us to visualise each segregated form without affecting actual utility requirements.
In order to design batch SeHDN, targeting should be carried out in strictly sequential order of time intervals, starting from the first-time interval to achieve the minimum utility target.

3. Proposed Algorithm

Based on the above analysis, the following procedure for concurrently targeting and designing batch HEN in segregated form has been developed:
Step 1: Divide the entire batch process time horizon into several time intervals (for example, I_1, I_2, I_3), with each time interval containing points at which all cold and/or hot streams must begin, end, or change their heat capacity flow rate.
Step 2: Determine the utility requirements for each time interval separately.

a) Shift all streams by adding or subtracting by $\Delta T_{min/2.}$ All the first stage shifted temperatures are denoted by TS'.
b) Arrange all TS' in decreasing order and put them in a column.
c) Put all the hot streams in the upcoming columns according to their heat capacities ($MCp\Delta t$) (from highest to lowest) in their respective temperature intervals.

d) Repeat Step 2 (c) above for cold streams.
e) Segregate streams by making pairs of hot and cold streams. The highest values of *MCpΔt* for hot and cold streams make one pair in each temperature interval. The next highest values of *MCpΔt* for hot and cold streams make another pair, and so on until all streams are exhausted.
f) Find the difference in *MCpΔt* in each pair in order to calculate the net *MCpΔt* in each temperature interval and put it in the upcoming columns.
g) Calculate the energy, cascaded energy, and revised cascaded energy required in each temperature interval.
h) Repeat Step 2 (g) for all pairs.

Step :3 Create a Segregated Grand Composite Curve (SeGCC). This can be done by plotting *TS'* on one axis of ordinates and $Rcas_i$ on another axis. Generate all SeGCCs.

Step 4: Using the following steps, modify SeGCCs to create Segregated Modified Grand Composite Curves (SeMGCCs) (in the case of indirect heat transfer).
a) All segments of SeGCC with a positive slope should be shifted upward by $\Delta T_{min}/2$.
b) All segments of SeGCC with a negative slope should be shifted downward by $\Delta T_{min}/2$.
c) All second-level shifted temperatures are denoted as *TS"*.
d) Eliminate sections that overlap and/or intersect.
e) Pseudo-hot streams are identified from unutilized heat and sent to the next interval.
f) SeMGCCi can be generated via plotting *TS" on the* axis of ordinates vs. on another axis and generate all SeMGCCs.

Step 5: All *TS"* are now used to generate the SeTGCC (in the case of indirect heat transfer). Pseudo-hot streams from the previous interval are also included. SeTGCC is created in accordance with step 2.

Step 6: $SeTGCC_i$ can be generated by plotting *TS"* on the axis of ordinates vs. $Rcas_i$ on another axis. Generate all SeTGCCs.

Step 7: All *TS "are* compared to all *TS'*. Put *TS*, *TS'*, and *TS"* in the SeTGCC tables (shown in example) to keep track of the actual temperatures in the problem.

Step 8: Create data for the Segregated Heat Allocation Network (SeHAN). Calculate the heat required in each interval for hot and cold streams separately. Transfer the required amount of heat from hot to cold streams.

Step 9: Using the SeHAN data, SeHDN can be created using the following method. Note that HDN is a kind of representation of HEN.
a) Place TS" (marked blue in example) at the top with the highest temperature from the leftmost to the lowest temperature on the rightmost. The corresponding actual temperatures TS (marked green in examples) are placed just below the temperature intervals.
b) Place the hot stream (SH_i) just below the *TS*, running from left to right. Insert energy available from the hot stream into the respective temperature intervals.
c) Similarly, place the cold stream (SC_i) at the bottom, running from right to left. Insert the energy requirement of the cold stream into the respective temperature intervals.
d) Transfer energy available from the hot stream to energy required for the cold stream, starting from the leftmost temperature interval of the hot stream to the first available temperature interval in the cold stream.
e) The transferred amount of energy is mentioned along with the lines that show the transfer direction (in example, both are shown in the same colour in order to clearly identify them).

4. Illustrative example

In this section, the proposed algorithm is used to calculate the segregated utility requirements and design SeHDN for each time interval of a batch process. The proposed algorithm's applicability is demonstrated through an illustrative example of indirect heat integration.

Table 1: Stream data for indirect heat integration

Stream	Supply Temperature T_s(^{0}C)	Target Temperature T_t(^{0}C)	Heat Capacity rate MCp(kW/^{0}C)	Initial Time t_i (h)	Final Time t_f(h)
H1	150	55	0.8	0	2.8
H2	122	82	0.15	0	1.9
H3	135	45	0.7	2.8	3.5
C4	25	110	0.3	1.9	3.5
C5	55	80	0.6	0	1.9
C6	55	140	1	0	2.8

Table 2: Shifted stream data of all time intervals along with heat capacity

I_1(0-1.9h)				I_2(1.9 - 2.8 h)				I_3(2.8 - 3.5 h)			
Stream	Ts' (^{0}C)	Tt' (^{0}C)	MCpΔt (kWh/^{0}C)	Stream	Ts' (^{0}C)	Tt' (^{0}C)	MCpΔt (kWh/^{0}C)	Stream	Ts' (^{0}C)	Tt' (^{0}C)	MCpΔt (kWh/^{0}C)
H1	140	45	1.52	H1	140	45	0.72	H3	125	35	0.49
H2	112	72	0.285	C4	35	120	0.27	C4	35	120	0.21
C5	65	90	1.14	C6	65	150	0.9				
C6	65	150	1.9								

Stream data comprising a total of six streams is shown in Table 1. The minimum allowable temperature for the given stream data is 20^{0}C. As per step 1, the entire process is divided into three-time interval zones (0 – 1.9 h, 1.9 – 2.8 h, and 2.8 – 3.5 h), as shown in Table 2 with shifted temperatures. Step 2 is used to segregate each interval and then determine utility requirements. The first-time interval was segregated into two parts based on step 2. The minimum required hot and cold utilities for the first part are 47.5 and 30.4 kWh. The second part requires a minimum of 17.1 and 0 kWh of hot and cold utilities.

SeGCC for both parts are now being built. SeMGCCs are drawn in accordance with step 4. Due to the fact that this is the first interval, no pseudo streams from previous intervals are available. As a result, SeTGCC for both parts will be the same as SeMGCC. Utilities values are calculated for SeTGCC data. The SeTGCC1 requires a minimum of 55.1 and 30.4 kWh of hot and cold utilities, respectively. SeTGCC2 requires a minimum of 39.9 and 0 kWh of hot and cold utilities. Figure 1 shows SeGCC1 for the first-time interval. Heat allocation for the first and second segregated pairs is shown in Figures 2 (a) and 2 (b).

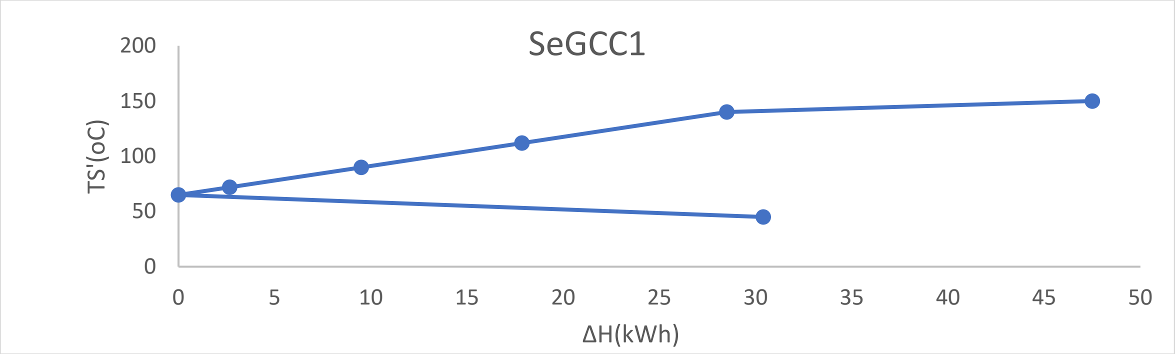
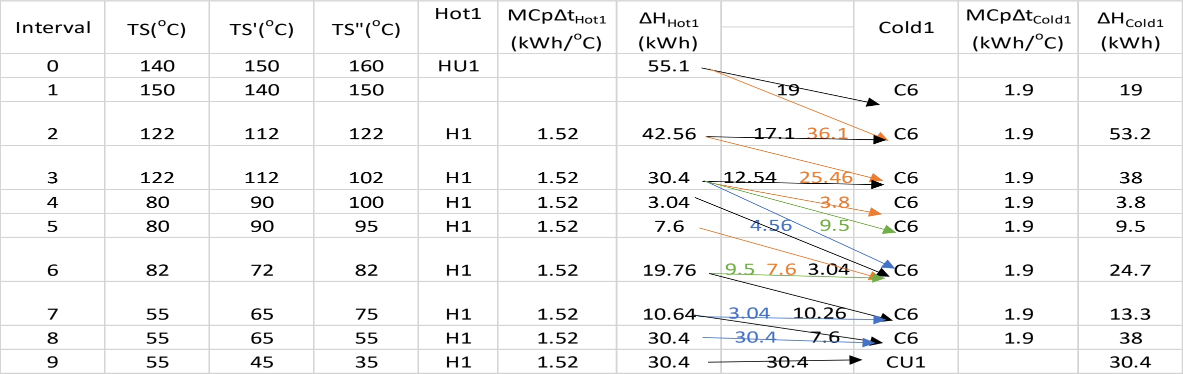


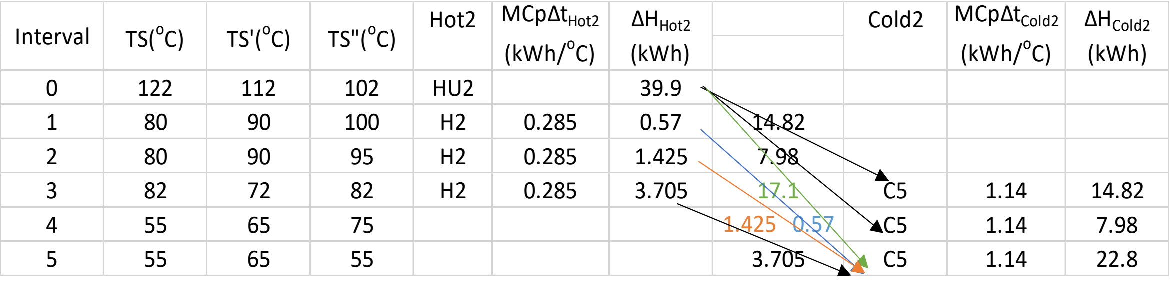
Figure 1: SeGCC1 for 1st interval



Interval	TS(°C)	TS'(°C)	TS"(°C)	Hot1	$MCp\Delta t_{Hot1}$ (kWh/°C)	ΔH_{Hot1} (kWh)		Cold1	$MCp\Delta t_{Cold1}$ (kWh/°C)	ΔH_{Cold1} (kWh)
0	140	150	160	HU1		55.1				
1	150	140	150				19	C6	1.9	19
2	122	112	122	H1	1.52	42.56	17.1 36.1	C6	1.9	53.2
3	122	112	102	H1	1.52	30.4	12.54 25.46	C6	1.9	38
4	80	90	100	H1	1.52	3.04	3.8	C6	1.9	3.8
5	80	90	95	H1	1.52	7.6	4.56 9.5	C6	1.9	9.5
6	82	72	82	H1	1.52	19.76	9.5 7.6 3.04	C6	1.9	24.7
7	55	65	75	H1	1.52	10.64	3.04 10.26	C6	1.9	13.3
8	55	65	55	H1	1.52	30.4	30.4 7.6	C6	1.9	38
9	55	45	35	H1	1.52	30.4	30.4	CU1		30.4

Figure 2(a): Heat allocation of first segregated pair for 1st interval

In Figure 2(a), Transfer of energy from Hot1 to Cold1 is done, shown by color line along with amount of energy (with same color) e.g., 19 kWh energy is transferred from HU1 to C6 of temperature interval of 160 to 150 ^{0}C by black color line and amount of energy is also shown by black color. The remaining amount of energy 36.1 kWh is transferred to next temperature interval 150 to 122 ^{0}C with help of orange arrow line and the amount is also shown by orange color to easy identification. All the upcoming energy transfer have same type of description.



Interval	TS(°C)	TS'(°C)	TS"(°C)	Hot2	MCpΔt$_{Hot2}$ (kWh/°C)	ΔH$_{Hot2}$ (kWh)		Cold2	MCpΔt$_{Cold2}$ (kWh/°C)	ΔH$_{Cold2}$ (kWh)
0	122	112	102	HU2		39.9				
1	80	90	100	H2	0.285	0.57	14.82			
2	80	90	95	H2	0.285	1.425	7.98			
3	82	72	82	H2	0.285	3.705	17.1	C5	1.14	14.82
4	55	65	75				1.425 0.57	C5	1.14	7.98
5	55	65	55				3.705	C5	1.14	22.8

Figure 2(b): Heat allocation of second segregated pair for 1st interval

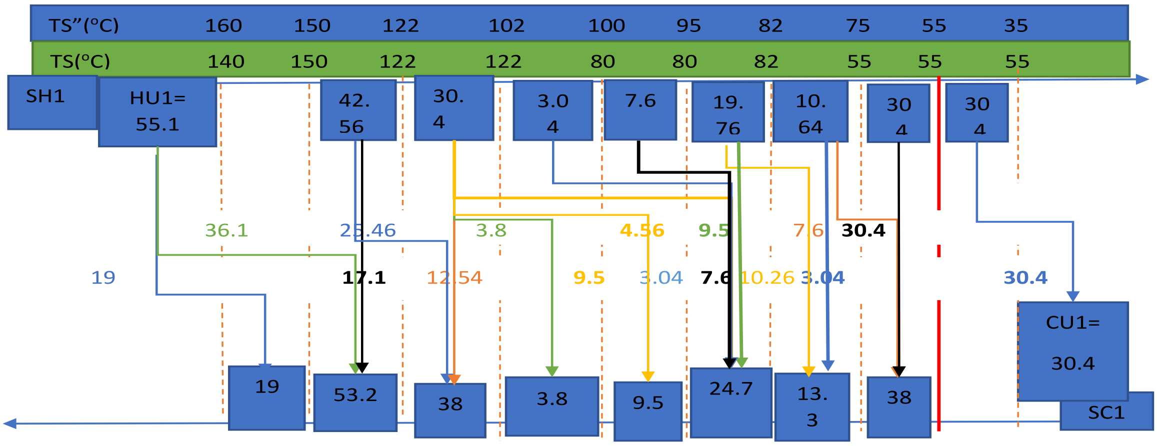


Figure 3(a): SeHDN1 for 1st interval

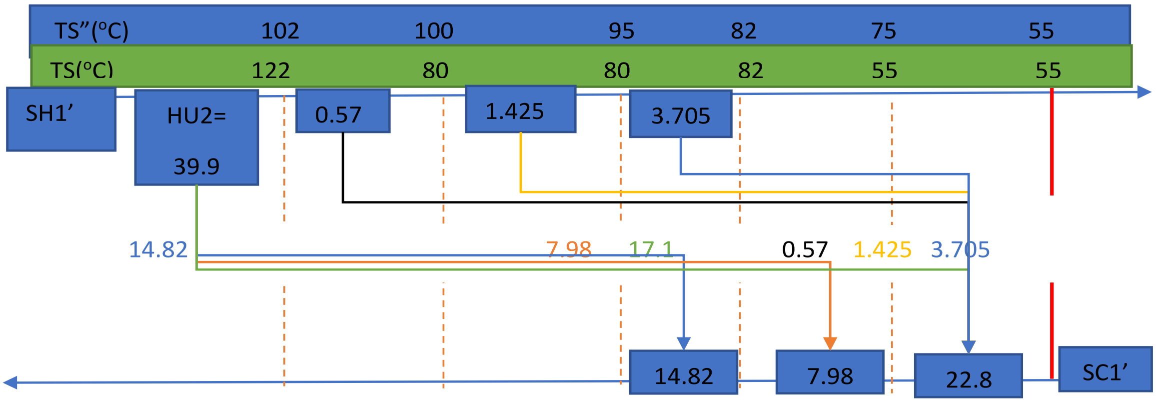


Figure 3(b): SeHDN2 for 1st interval

For the first time interval, the SeHDN of the first and second segregated pairs are shown in Figures 3 (a) and 3 (b). In Figure 3(a), temperature intervals are formed with help of orange broken lines. Transfer of energy from SH1 to SC1 is shown by color line along with amount of energy (with same color) e.g., 19 kWh energy is transferred from HU1 to SC1 of temperature interval of 160 to 150 ^{0}C by blue color line and amount of energy is also shown by blue color. The remaining amount of energy 36.1 kWh is transferred to next temperature interval

150 to 122 ^{0}C with help of green arrow line and the amount is also shown by green color to easy identification. Red Bold line represents Pinch Section. All upcoming SeHDNs have same color description as explained here. The first-time interval's unutilized heat is transferred to the subsequent time interval. The SeTGCC1 plot contains one hot stream below the Pinch Point. This hot stream is sent to the second interval as a pseudo hot stream HS1. HS1 operates at supply and target temperatures of 55 and 35 ^{o}C, and has an MCpΔt of 1.52 kWh/^{o}C.

There is one hot stream (H1) and two cold streams in the second time interval (C4 and C6). The second time interval was also segregated into two parts. For the first part, the hot and cold utility requirements are 22.5 and 6.3 kWh. The second part requires 14.85 and 0 kWh of hot and cold utilities. SeMGCCs are plotted in the manner described in Step 4. Because this is the second interval, there is only one pseudo hot stream in HS1. The HS1 is now in use. SeTGCC1 data is calculated using HS1. SeTGCC1 requires a minimum of 26.1 and 25 kWh of hot and cold utilities. SeTGCC2 requires a minimum of 25.65 and 14.4 kWh of hot and cold utilities. The SeTGCC1 second interval contains pseudo streams named as HS2. HS2 operates at supply and target temperatures of 55 and 35 ^{o}C, and has a heat capacity of 1.25 kWh/^{o}C. SeTGCC2 contains one pseudo stream, named HS3. HS3 operates at supply and target temperatures of 55 and 35 ^{o}C, and has a heat capacity of 0.72 kWh/^{o}C. Due to briefing, not all figures and tables are shown.

There are two streams in the third time interval: H3 and C4. It begins at 2.8 h and ends at 3.5 h. The requirements for hot and cold utilities are 0 and 26.25 kWh. Next, SeGCC and SeMGCC are formed, followed by the calculation of SeTGCCs. SeTGCC1 requires a minimum of 0 and 41.45 kWh of hot and cold utilities. SeTGCC2 requires a minimum of 0 and 14.4 kWh of hot and cold utilities. SeTGCC3 requires a minimum of 0 and 9.8 kWh of hot and cold utilities. SeHDNs for SeTGCC1, SeTGCC2, and SeTGCC3 are plotted.

5. Conclusions

A novel algorithm has been developed to simultaneously target and design a batch HEN. The proposed algorithm is developed on the concept of segregated targeting and SeTGCC plots. The segregated form of PTA and the SeTGCC provide a comprehensive view of the batch process that is not possible with conventional targeting and design. This algorithm is capable of targeting and designing any fixed-schedule batch process concurrently. Additionally, the algorithm supports indirect heat integration problems, implying that it is compatible with the inclusion of heat storage. The proposed algorithm's applicability is demonstrated through an illustrative example that exhibit the benefits of a segregated form of targeting and designing in any fixed-schedule batch process. The insight-nature of the algorithm is helpful in addressing the dynamism associated with batch processing. Additionally, the proposed algorithm is accompanied by actual temperatures, which minimizes the designer's effort during the final design phase. SeHDN indicates which temperature interval of the network exchanges the most energy and which one exchanges the least energy. This data enables designers to quickly and easily improve HENs. In the heat allocation data table, pseudo stream actual temperatures (based on previous intervals) are also shown, which overcomes the limitations of earlier methodologies in which pseudo stream actual temperatures could not be predicted. The representation of HEN in the form of SeHDN enables us to clearly identify each individual stream. This feature of SeHDN can be utilized to explore further reuse and recycle options.

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