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Original Research

Adapted Time Slice Model of Pinch Analysis for Direct-Indirect Heat Recovery in Buildings

Hossein Akbari [1], Seyed Mojtaba Hosseinnia [1], Mikhail Sorin [1, *], Christopher Reddick [1], Dominic Laperle [2]

1. Department of Mechanical Engineering, Université de Sherbrooke, Québec, Canada; E-Mails: Hossein.Akbari@USherbrooke.ca; Seyed.Mojtaba.Hosseinnia@USherbrooke.ca; Mikhail.V.Sorin@USherbrooke.ca; J.Christopher.Reddick@USherbrooke.ca
2. Intégration Construction Inc., 147, rue Cynthia, Saint-Alphonse-de-Granby, Québec J0E 2A0, Canada; E-Mail: integrations_inc@icloud.com

* **Correspondence:** Mikhail Sorin; E-Mail: Mikhail.V.Sorin@USherbrooke.ca

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Abstract

Heat integration techniques such as pinch analysis can play a significant role in saving energy in the design of buildings. The application of pinch analysis in this sector encounters difficulties due to the highly time-dependent behavior of energy streams such as waste heat and solar thermal collectors, as well as the possible need for heat storage units (HSUs). The existing pinch models in the literature either bear little relation to reality because they ignore the time dependency of the streams, or they do not respect the pinch analysis minimum temperature difference of the system, which leads to temperature penalties. This study introduces a novel and straightforward adapted time slice model of pinch analysis, beneficial for energy targeting in buildings. First, an algorithm for the selection of the appropriate time slice duration is proposed. Then, additional steps are embedded in the conventional problem table algorithm to account for both direct heat transfer (co-existing streams) and indirect heat transfer (time mismatched streams requiring thermal energy storage). i.e., the modified table includes both external and internal streams, respectively. The detailed application of the proposed model is demonstrated through the analysis of a direct-indirect heat recovery system for a residential test building equipped with waste heat and solar energy, considering a summer's day. This case study, or sample calculation, determines the HSU specifications, including their design temperatures and volumes. A heat exchanger evaluation quantifies both their number and their thermal conductances, which are an economic indicator of the system capital cost.

Keywords
Energy targeting; pinch analysis; heat storage unit; buildings; time-dependent stream

1. Introduction

Saving energy is one of the essential strategies for sustainable development, and the residential sector plays a prominent role in promoting energy conservation [1]. The residential sector accounts for nearly 15% of global final energy consumption, which results in nearly 27% of global CO_2 emissions [2]. Therefore, the reduction of energy consumption as well as the utilization of renewable energies within residential buildings can make an important contribution to addressing energy resource shortages and environmental issues.

Since the mid-1970s, heat integration techniques have received much research attention because of their ability to reduce the total energy requirement of the system [3]. These techniques continue to evolve from well-established methods that are highly valuable in dealing with steady-state processes in large industries such as crude oil refineries [4] and power plants [5], to include non-steady or batch processes in intermittently available streams in multipurpose batch plants [6] and, more recently, in residential buildings [7, 8]. Among all heat integration techniques, the pinch methodology is the most practical and wide widespread analysis strategy, which guarantees maximum heat recovery within thermal systems by using several systematic thermodynamics-based steps [9, 10]. Recently, it was shown that the application of pinch analysis to a residential building can lead to up to a 50% reduction in primary energy consumption [7]. Pinch analysis is relatively straightforward for steady-state processes, where the temperature is the only constraint in the procedure of determining the theoretical minimal energy requirements of a system, called "energy targeting" [11]. The application of pinch analysis for a system like a residential building is difficult due to the time-dependent behavior of the thermal streams, such as waste heat and solar thermal energy. In this case, time is another constraint, and there is a need for heat storage units (HSUs) to accumulate available energy from available hot streams, hold the energy effectively, and release it at another time to cold streams. Thus, an effective pinch analysis must be able to consider the dynamic behavior of the streams and identify the optimal specifications of HSUs, including their number, volumes, and temperatures.

Systematic pinch approaches have been developed for calculating the energy targets, HSUs characteristics, and heat exchangers conductance in batch processes through several models, namely: the time average model (TAM) [12, 13], the time slice model (TSM) [14, 15], and time pinch analysis (TPA) [16]. Each approach provides a systematic methodology in batch-process heat integration. However, it should be emphasized that in almost all examples regarding batch processes in the open literature, during the presence of the streams for the batch period, the operating specifications of hot/cold streams are assumed constant: supply and target temperatures, mass flow rates, and specific heat capacities.

The TAM is the simplest approach and the backbone of a large portion of the studies conducted for energy targeting in batch processes and renewable energy integration [17, 18]. Each variable stream load is converted into an average value by dividing the cumulative stream load by the batch period. Therefore, the time constraint is neglected, and the problem is approximated as a steady-state process, where the original pinch analysis, i.e. cascade analysis, can be applied to set the energy targets as well as determine the HSUs characteristics and the heat exchangers conductances. The application of this model to highly dynamic streams such as solar thermal energy and waste heat integration in buildings [7] leads to an imprecise prediction of the energy targets and HSU volumes. The intermittency and time-dependency characteristics of solar irradiation are fundamental aspects of solar thermal energy [19]. Thus, although the expected load from solar thermal collectors (STCs) is highly time-dependent, the TAM converts it to a constant value. The TAM defines an upper bound of heat recovery that a system can achieve by ignoring the time constraint [11].

The TAM has been improved to integrate HSUs into batch processes. Olsen et al. [18] presented a systematic TAM pinch approach for HSU integration in an energy system for full indirect heat recovery. In order to set the priorities among different streams, they introduced the concept of the indirect source/sink profile (ISSP), which defines the temperature shifting based on each stream's heat transfer coefficient and duration. The maximum and minimum temperatures for a pair of fixed-temperature variable-mass HSUs or a stratified HSU can be defined by an ISSP line and some degrees of freedom, and by some heuristic and engineering considerations. Recently, Abdelouadoud et al. [12] proposed the same systematic graphical approach based on the TAM for HSU integration, which was earlier presented in [18, 20], with some modifications. In their graphical model, they defined the aforementioned ISSP curve and added steps for defining restricted zones, extended zones, and a degree of freedom in selecting the temperature range for the assigned heat recovery amount. Additionally, the volume of HSUs and their types can be selected in this graphical approach. However, this model still has the oversimplification inherited from the TAM that makes it unsuitable for energy targeting for a system working with dynamic streams, such as heating loads in buildings or heat transfer fluids for solar energy applications.

The TPA proposed by Wang and Smith [16] is another approach to pinch analysis in HSU-integrated systems. In TPA, energy and time can be seen on the vertical and horizontal axis respectively, instead of temperature and enthalpy in the TSM. In other words, the hot/cold and grand composite curves show the time and energy at each temperature interval. This method can be very complex if several hot or cold streams exist in more than one temperature interval. In this particular case, the number of HSUs can be as high as the number of temperature intervals, which may not be equivalent to the minimum number of HSUs. Furthermore, since the heat transfer between external hot streams and the intermediate medium (the working fluid that stores thermal energy in the HSUs) and the heat transfer between intermediate medium and external cold streams occur within the same temperature interval, double the minimum temperature difference between hot and cold streams must imposed, otherwise temperature difference penalties must be paid by using hot or cold utility. In this context, a "temperature penalty" means that the intended temperature difference will not be achieved, and the actual system performance will suffer. The

TPA does not consider the resultant temperature difference penalties that will occur, due to the neglection of doubling the minimum temperature difference.

The TSM proposed by Kemp [21] was originally developed for batch processes. In this model, the conventional pinch analysis is applied to several specified time slices (TSs) defined base on the start and stop times of each stream (stream schedule or Gantt chart). In contrast to the TAM, the TSM has the advantage of including dynamic loads, such as hot water and heating in a residential building as well as the time-dependent use of solar energy [14]. However, finding the appropriate temperature for the HSUs can be highly complex based on this model [11]. Another shortcoming of this model is that it neglects the fact that storing energy from hot streams into an intermediate storage medium and extracting it by cold streams within the same temperature interval not feasible, due to the minimum temperature difference constraints for charging and discharging processes. Another problem with the TSM presented in [21] is that it is not clear how to find an appropriate time slice duration for a system with highly dynamic loads, such as solar thermal collector duty [22]. The slice duration in the TSM must be selected in an appropriate way for a dynamic load, such that the heat recovery system is able to efficiently benefit from the short-terms minimum and maximum values of the changing steam loads (i.e. capture the extreme values, max. or min.) during a batch period.

Another important design consideration in batch process heat integration is the selection of the heat transfer configuration: direct heat exchange between time co-existing streams [23], indirect heat exchange by means of a HSU [24], or a mixed approach [25]. In this choice, the economic profitability of each configuration option, among direct/indirect/mixed heat recovery, plays an important role. For instance, it was shown that the total annual cost for an industrial case study [20] with a mixed direct/indirect heat recovery was only 4% higher than that of purely direct heat exchange, and 18% lower in comparison to the purely indirect heat exchange. Moreover, the heat recovery configuration strongly influences the required volume of the HSUs.

In summary, there is a need for a systematic model that can fill the gaps in the current pinch models. This model should guarantee the maximum heat recovery through direct/indirect/mixed heat transfer

- be accurate enough to include all extrema of dynamic energy loads for all hot and cold streams within a building's energy system
- determine the design temperature to achieve the heat recovery target for each heat storage unit
- respect the minimum temperature difference for the charging and discharging processes of indirect heat transfer

In this study, the adapted time slice model (ASTM), based on a modified version of the problem table algorithm, is proposed that can fulfill the mentioned objectives. First, this model finds the best time slice duration for time-dependent loads, such as waste heat in a building or/and solar heating. To the authors' best knowledge, this is the first such published procedure for choosing the TS. In the subsequent steps, the conventional problem table algorithm is incrementally adapted to ultimately allow setting energy targets as well as computing the required number of HSUs with their appropriate specifications: temperatures (°C), maximum heat capacities (kWh), and volumes (L). The novelty of these steps is the fact that the adapted problem table algorithm not only accounts for the conventional external hot and cold streams, but also includes on an equal footing the internal streams associated with charging and discharging the HSUs (i.e. the intermediate loop streams). The resulting model, accounting for both direct heat transfer and indirect heat transfer, guarantees maximum heat recovery. To demonstrate each step of the model procedure, a sample calculation will be discussed, where a residential test building equipped with both a waste heat system and solar thermal collectors will be used as the case study. Considering a particular summer's day, a heat exchanger study is presented as a preliminary part of the application of the ATSM to direct/indirect heat recovery in a building. A future article will extend the calculation for a whole year and complete the design of the thermal energy system.

2. Problem Description

Generally, a process can be identified as either continuous or batch. A continuous process exists at all time periods with fixed supply and target temperatures, as well as a fixed heat capacity flow rate (or simply the heat capacity rate), $CP = \dot{m}C_P$. A batch process does not exhibit one or more of the mentioned behaviors of the continuous process. The aforementioned time constraint must be respected in all non-continuous batch processes and requires particular attention when HSUs are present. The common approach to perform pinch analysis on a batch process is to divide the batch period into several time slices, i.e. TSM. A snapshot of each TS is considered, and the average heat load (time average model) over the slice duration will pave the way for treating the streams as continuous [15]. A batch process may be characterized by several hot/cold streams having fixed heat loads with fixed supply and target temperatures of the medium for a certain period of time, or may have heat loads and/or temperatures that vary continuously over time. In the former case, the slice duration can be simply defined as the start/stop boundaries where streams begin or end [11]. In the latter case, slice duration must be defined in a way that can identify all variations in time-dependent behaviors of the streams. In this paper, a pinch analysis model for the latter case will be introduced.

The proposed model will be illustrated and explained for a particular summer's day. The chosen day is part of a study that evaluated the application of waste heat and solar energy integration in a building [7, 14]. The system is composed of three streams including two hot streams, i.e. solar thermal collector (STC) and warm gray water (WGW), and one cold stream, i.e. domestic hot water (DHW). Table 1 shows the supply and target temperatures as well as the periods of the three streams for the summer's day.

Table 1 Stream data for the summer's day.

Stream	Supply temperature (°C)	Target temperature (°C)	Period H:MM
STC	65	40	from 4:40 to 19:05
WGW	30	5	24 h
DHW	5	55	24 h

The method for calculating the time-varying heat capacity rate (in this case, the flow rate $\dot{m}$ varies) of each stream was explained in detail by Hosseinnia and Sorin [14]. Figure 1 shows the heat capacity rates of the streams for the day under investigation. According to their STC model, the STC heat capacity rate depends on daily conditions, including solar irradiance and ambient temperature. As a result, the STC heat capacity rate varies continuously. The heat capacity rates of WGW and DHW vary throughout the day, but they are similar for different days of the year. Here we assume that one repeatable analysis period (batch period) is 24 h for the test building, due to the nature of the STC.

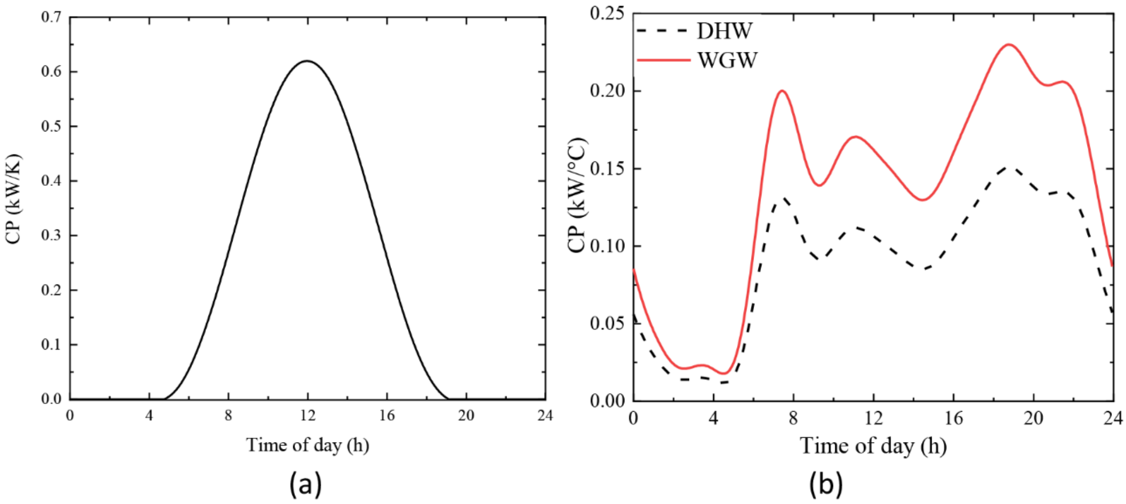

Figure 1 The heat capacity rates of the streams for the day under investigation: (a) STC and (b) DHW and WGW streams.

3. Methodology

3.1 Selection of an Appropriate Slice Duration

The first step to calculate energy targets for the batch process involving streams with continuous but time-dependent CPs is to define an appropriate duration of each time slice. Hosseinnia and Sorin [14] arbitrarily chose 36 s (a very small value) for each time slice, diving the 24-hour batch period into 2400 portions. Although today's computer power reduces the running time of pinch analysis of a system with 2400 TSs, this short time may result in significant computational time when the analysis must be performed for different scenarios with a greater number of streams. In order to overcome this shortcoming, an algorithm to define the most appropriate slice duration with a relative error of ε is presented in Figure 2. The main idea of the algorithm is that the duration of time slice should be sufficient to recognize the CPs' extreme values. The algorithm enables users to define the accuracy of the calculation and the initial slice duration.

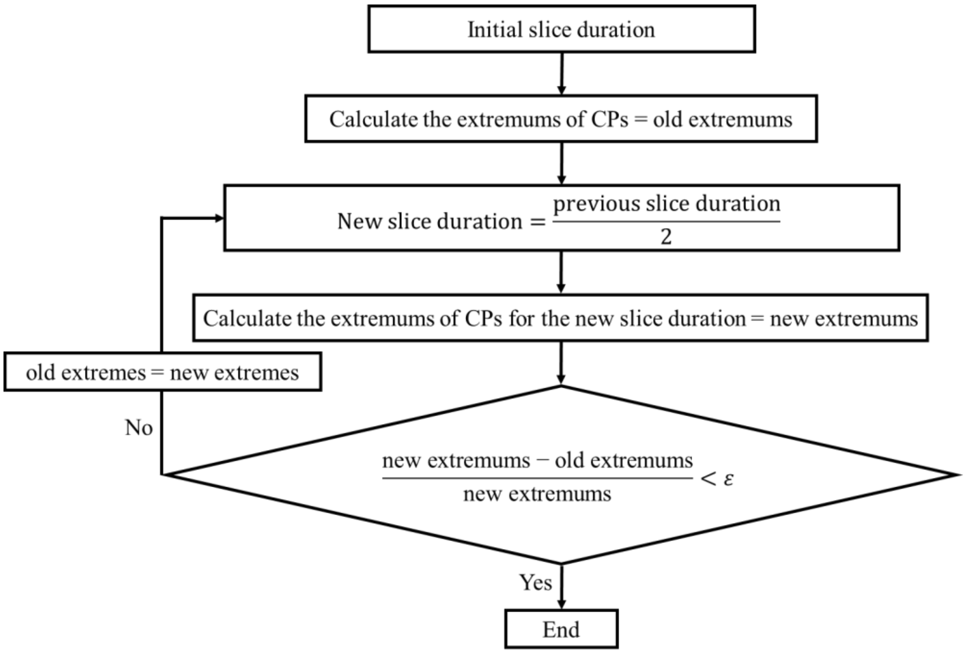

Figure 2 Algorithm for the selection of appropriate slice duration(sec).

The iterative procedure for the selection of the appropriate slice duration with an accuracy of 0.001 converged in 450 seconds (192 TSs) for the case study. It should be mentioned that the algorithm must be carried out for all the time-dependent streams of the system. For instance, the maximum CPs of STC for different slice durations are shown in Figure 3. It can be seen that the time slices smaller than 450 seconds resulted in the maximum CPs, with a relative error of less than 0.1% compared to the slice duration of 450 seconds. Thus, the slice duration shorter than 450 seconds caused higher computation costs, without any advantage.

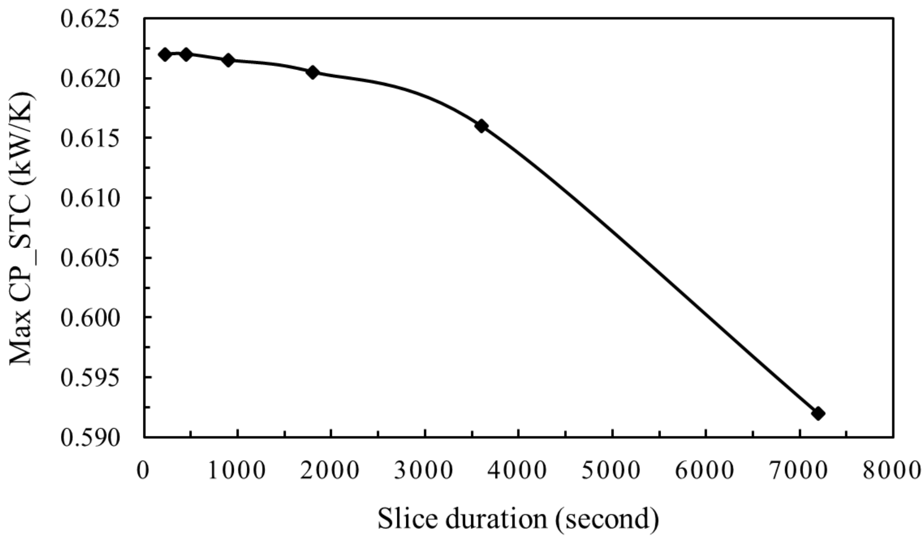

Figure 3 Maximum CP of STC vs. slice duration.

The model introduced in this paper is based on a modified problem table algorithm model that will be explained in the following subsections. Since the solution of the above problem requires 192 TSs, in order to simplify the model's explanation and make the procedure easy for understanding, the slice duration will be assumed to be 2 hours, and consequently the batch period (24 hours) will be split into 12 TSs. Then, in subsection 3-9, the effect of the selection of narrower slice durations on energy targeting will be discussed.

Pinch analysis predicts the minimum energy consumption a system, the part of the analysis known as energy targeting, by using what is known as the problem table algorithm. The results of the problem table algorithm can be show graphically in the form of “composite curves”. This section presents how the modified problem table will be constructed and will be used to determine the potential of integrating HSUs into a heat recovery system.

3.2 Construction of Problem Table with the External Streams

Temperature and Time are subject to constraints in a pinch analysis on a system with time-dependent streams [16]. The temperature constraint states that heat exchange from a hot stream to a cold stream cannot occur where the temperature of the cold stream is greater than that of the hot one. The time constraint states that heat exchange between hot and cold streams cannot occur when each stream exists at different time slices, unless a heat storage unit is introduced into the heat exchanger network (indirect heat recovery). One comprehensible way to demonstrate the heat balance between hot and cold streams of the system throughout the batch period, while both temperature and time constraints are considered, is by placing each TS placed side by side in the problem table algorithm (Table 2). The columns of the table refer to data on each TS and the rows of the table indicate the heat balance between hot and cold streams existing in each temperature interval. To ensure that the temperature constraint is placed within any interval, shifted temperatures are used. The shifted temperatures are here defined by subtracting half of the minimum temperature difference allowed in the system between hot and cold streams ($\Delta T_{min}/2$) from the supply and target temperatures of hot streams and by adding $\Delta T_{min}/2$ to the temperatures of cold streams [11]. These shifted temperatures in descending order define the temperature intervals. Shifting temperatures in this way guarantees that heat transfer between hot and cold streams within any TI is feasible. In each temperature interval, a simple energy balance is calculated. If the hot streams dominate the coexisting cold streams in the same temperature interval, the energy balance will be positive, and the interval is in heat surplus. If the cold streams dominate the coexisting hot streams in the temperature interval, the energy balance will be negative, and the interval is in heat deficit. Since the heat balance is calculated for each TS, the time constraint is automatically respected in the calculation.

Table 2 First step of the proposed model: temperature intervals and enthalpy balance in kWh for the external streams.

	TS: 0-2	TS: 2-4	TS: 4-6	TS: 6-8	TS: 8-10	TS: 10-12	TS: 12-14	TS: 14-16	TS: 16-18	TS: 18-20	TS: 20-22	TS: 22-24
TI 1 62.5 °C-57.5 °C	0	0	0.21	1.52	3.97	5.85	5.82	3.89	1.45	0.19	0	0
TI 2 57.5 °C-37.5 °C	-1.29	-0.58	-0.10	1.61	11.88	19.06	19.39	11.92	0.83	-5.11	-5.39	-3.88
TI 3 37.5 °C-27.5 °C	-0.65	-0.29	-0.47	-2.24	-2.00	-2.17	-1.94	-1.81	-2.49	-2.94	-2.69	-1.94
TI 4 27.5 °C-7.5 °C	0.68	0.31	0.49	2.34	2.10	2.27	2.03	1.90	2.61	3.08	2.82	2.03
TI 5 7.5 °C-2.5 °C	0.49	0.22	0.36	1.70	1.52	1.65	1.48	1.38	1.89	2.24	2.05	1.48

The first step of the proposed model is to construct the problem table algorithm based on the external hot and cold streams. In this article, streams not that do not necessarily require heat storage (e.g. STC, WGW, DHW) are referred to as “external”, whereas streams that arise from the charging/discharging of the HSUs are considered “internal”. Temperature intervals and heat loads for the external streams are shown in Table 2, where we assume the allowed ΔT_{min} of the system equals 5 °C. Each cell of the tables shows the enthalpy balance (in kWh) of the existing streams in the corresponding TI and TS.

So far the original problem TSM table algorithm proposed in [11] has been followed. In the next subsection, some steps will be introduced to integrate HSUs into the problem table algorithm.

3.3 Integration of Heat Storage

The introduction of shifted temperatures and resultant temperature intervals addresses the concern over the temperature constraint. To transfer heat from one TS to another, and to place the time constraint on the analysis, HSUs and the corresponding intermediate heat recovery loops (IHRLs) [26] are used (the second step of the proposed model). The proposed model will be explained for a system equipped with Fixed Temperature Variable Mass (FTVM) heat storage units. However, the model can be extended to other sorts of heat storage, for example, stratified storage tanks [27]. A FTVM system is composed of two storage tanks containing heat storage medium at two different fixed temperatures and internal hot and cold streams that facilitate the heat transfer between the external streams and the storage tanks (Figure 4). The cold internal stream, which comes from the lower-temperature tank, absorbs heat from hot external stream(s), i.e. the left side of Figure 4, while the hot internal stream, which comes from the higher-temperature tank, releases heat to cold external stream(s). It is worth mentioning that the circuit shown in Figure 4 is known as intermediate heat recovery loop (IHRL).

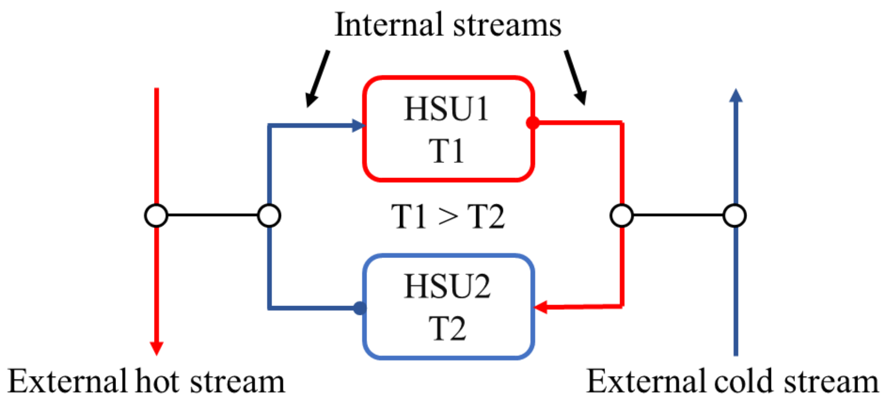

Figure 4 Schematic of Fixed Temperature Variable Mass (FTVM) HSUs and their Intermediate Heat Recovery Loop (IHRL).

The proposed model is based on the surplus and deficit heat loads in Table 2 (the first step of the proposed model), uniquely due to the external streams (direct heat recovery), without consideration of possible HSUs. The algorithm of integrating HSUs into the problem table algorithm is shown in Appendix (Figure A1). The proposed algorithm makes the following assumptions and will be applied to all TIs (started from the first TI to the last one).

1. Two HSUs must be placed between charging and discharging TIs, and each HSU is responsible for only one TI. This means that the charging and discharging processes cannot occur in the same TI in order to guarantee the minimum temperature difference of the system. Some models in the literature considered the charging and discharging processes in the same TI [11, 16], which violates the fixed ΔT_{min} value. The temperature determination of each HSU will be explained in section 3-4.
2. To prevent the oversizing of an HSU, the stored cumulative heat load should not exceed the cumulative deficit heat load in the in the discharging TI.
3. The TS adjoining the last charging TS in the batch period is chosen as the discharge TS. By this assumption, the heat loss to the surrounding space from the heat storage unit will be minimized. It should be mentioned that the discharge time slice of stored heat can be defined by the user. For instance, one may define the discharge time slice according to the off-peak and on-peak hours where the required hot utility is provided by electricity.
4. To guarantee the maximum heat recovery, if any deficit energy remains in a lower temperature interval while there is surplus energy that is not stored in the upper-temperature intervals (the second and higher upper-temperature intervals), then a pair of HSUs will be placed between the charging TI containing surplus energy and the discharging TI containing deficit energy.

It should be mentioned that the direct/indirect heat recovery steps explained above guarantee that the stored energy will be at the highest possible temperature while resulting in maximum heat recovery. The procedure for the implementation of heat storage units for the case study is shown in Figure 5. The cumulative heat loads over the batch period in the first temperature interval, TI1, equals 22.9 kWh (0 + 0 + 0.21 + 1.52 + …0). However, there are 16.35 kWh (-1.29 -0.58 -0.10 -5.11 -5.39 -3.88) of cumulative deficit heat load in the second temperature interval, TI2. Thus, based on the second principle explained above, only the required heat load, i.e. 16.35 kWh, is stored, as shown by the little vertical blue arrows in Figure 5. The same condition is seen for storing surplus heat loads of the second temperature interval, TI2. There are 64.69 kWh surplus heat loads, while there are only 21.63 kWh deficit heat loads in the third temperature interval, TI3. Thus, the total surplus energy at the TSs of 6-8 and 8-10 and partial surplus energy at the TS of 10-12 (the little vertical blue arrows in Figure 5) is stored in HSU3. The energy stored in HSU3 is enough to supply all the deficit energy in the third temperature interval (the little vertical red arrows in Figure 5). It should be noted that the discharge time of the second pair of HSUs (IHRL between HSU3 and HSU4) begins at the TS of 12-14 and ends at the TS of 10-12 of the next batch. Here we assume that the batch process is repeated, as a result, heat can be recovered into the next batch.

		TS: 0 -2	TS: 2 -4	TS: 4 - 6	TS: 6 -8	TS: 8 -10	TS: 10-12	TS: 12-14	TS: 14-16	TS: 16-18	TS: 18-20	TS: 20-22	TS: 22-24	
TI1 62.5℃ – 57.5℃		0	0	0.21	1.52	3.97	5.85	5.82	3.89	1.45	0.19	0	0	HSU1 16.35
TI2 57.5℃ – 37.5℃	HSU2 16.35	-1.29	-0.58	-0.10	1.61	11.88	19.06	19.39	11.92	0.83	-5.11	-5.39	-3.88	HSU3 21.63
TI3 37.5℃ – 27.5℃	HSU4 21.63	-0.65	-0.29	-0.47	-2.24	-2.00	-2.17	-1.94	-1.81	-2.49	-2.94	-2.69	-1.94	
TI4 27.5℃ – 7.5℃		0.68	0.31	0.49	2.34	2.10	2.27	2.03	1.90	2.61	3.08	2.82	2.03	
TI5 7.5℃ – 2.5℃		0.49	0.22	0.36	1.70	1.52	1.65	1.48	1.38	1.89	2.24	2.05	1.48	

Figure 5 Schematic of the integration of heat storages into Table 2.

It is worth noting that the first and second steps of the model show that between direct and indirect heat exchange, the priority was given to the direct heat exchange within the same TI and TS. Then the surplus heat loads can be stored for upcoming time periods as the indirect heat exchange.

3.4 Specification of the Heat Storage Units

One of the issues related to the pinch analysis models in the literature is the determination of the IHRL temperatures. In the following, a straightforward strategy for the determination of IHRL temperatures will be introduced.

The surplus heat load in a TI at a TS that meets the four assumptions explained in subsection 3-3 is stored in a heat storage unit via an IHRL. The IHRL in this situation acts as a cold stream that absorbs heat from hot streams. The target temperature of this cold stream (IHRL) cannot be greater than the upper temperature bound of the corresponding shifted TI minus the $\Delta T_{min}/2$ of the system. Thus, the target temperature of the cold stream of the IHRL, which is the inlet temperature of the HSU, equals the upper temperature of the corresponding shifted TI minus $\Delta T_{min}/2$. The stored energy in the HSU is released to cold streams existing in a lower TI by an IHRL that acts as a hot stream (the right side of Figure 4). Thus, to guarantee to respect the ΔT_{min} of the system, the target temperature of this hot stream is defined as the lower temperature bound of the corresponding shifted TI plus the $\Delta T_{min}/2$. Therefore, the temperatures of the HSUs pair can be defined.

Another important specification of HSUs that must be defined is their volumes. The volume of HSU can be calculated by Eq. (1).

$$V_{HSU} = \frac{heat\ capacity}{\rho C_P \Delta T} \tag{1}$$

The volumes of HSUs depend on the amount of heat load that will be stored (its heat capacity) and the thermophysical properties of the selected heat transfer fluid. According to Figure 5, for the case study under investigation, two HSU pairs are needed. The specifications of the HSUs are shown in Table 3, including their fixed temperatures, maximum heat capacity, and volumes. Water is considered as the intermediate heat-transfer medium.

Table 3 Specifications of HSUs.

HSU number	Temperature (°C)	Maximum heat capacity (kWh)	Volume (L)
1	60	16.35	704
2	40	16.35	704
3	55	21.63	745
4	30	21.63	745

In the second step of the proposed model, the specifications of HSUs and the heat capacity rates of IHRLs are determined.

3.5 Intermediate Heat Recovery Loops and Temperature Intervals

The storage of surplus energy in HSUs and the discharge of stored energy to external cold streams existing in the lower TI is possible via IHRLs. These loops consist of hot (shown in red) and cold (shown in blue) streams that exchange heat with external streams of the system. The IHRL between the first HSU pair is shown in Figure 6, and corresponds to the HSU 1 and HSU 2 in Figure 5.

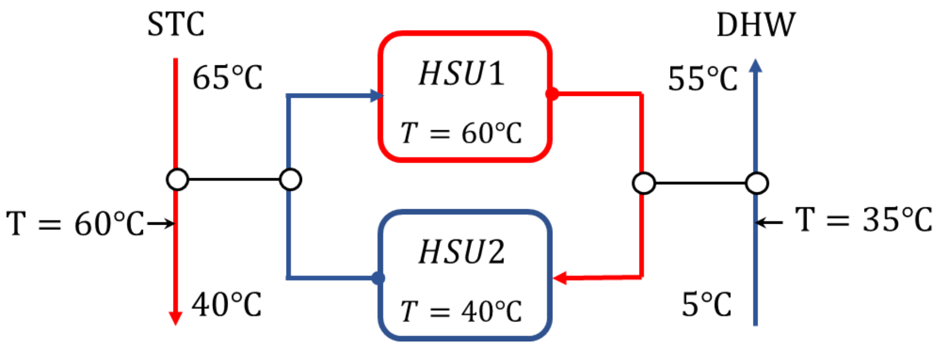

Figure 6 Intermediate loop of the first pair of HSUs.

The implementation of HSUs results in additional internal hot and cold streams for the system. The number of additional hot and cold streams equals the number of HSU pairs. For the case study herein, two hot streams and two cold streams were added to the system. As a result, the number of hot and cold streams increased to four and three, respectively. These additional streams may alter the temperature intervals. For instance, the shifted supply temperature of the cold stream between HSU1 and HSU2 (Figure 6) equals 42.5 °C. However, this temperature is not among the upper or lower bounds of temperature intervals shown in Table 2. Thus, in the third step of the proposed model, the problem table must be reconstructed to include the additional streams led by the implementation of HSUs. The reconstructed table is shown in Table 4. The modified table shows the new heat balances for each TI and TS, due to the new population of streams, including the main (or external) streams and the IHRL (or internal) streams. It should be noted that Table 2 was constructed by main streams without the integration of HSUs and was used to determine the potential of the HSU integration into the system based on surplus/deficit energy loads. The comparison of Table 2 and Table 4 reveals that the inclusion of internal streams led by IHRLs results in three new TIs.

Table 4 Temperature intervals and enthalpy balance in kWh for the external and internal streams.

	TS: 0-2	TS: 2-4	TS: 4-6	TS: 6-8	TS: 8-10	TS: 10-12	TS: 12-14	TS: 14-16	TS: 16-18	TS: 18-20	TS: 20-22	TS: 22-24
TI1 62.5 °C-57.5 °C	0	0	0.16	1.14	2.98	4.39	4.36	3.89	1.45	0.19	0	0
TI2 57.5 °C-52.5 °C	0	0	-0.05	-0.30	-0.40	-0.51	3.39	2.98	0.21	0.00	0	0
TI3 52.5 °C-42.5 °C	0.25	0.12	0.08	0.30	0	-0.15	7.56	6.69	1.41	1.18	1.08	0.78
TI4 42.5 °C-37.5 °C	0.13	0.06	0.09	0.52	1	1.38	5.23	3.34	0.70	0.59	0.54	0.38
TI5 37.5 °C-32.5 °C	-0.19	-0.09	-0.14	-0.99	-2.98	-4.46	-0.58	-0.54	-0.75	-0.88	-0.81	-0.58
TI6 32.5 °C-27.5 °C	-0.19	-0.09	-0.14	-0.67	-0.60	-0.65	-0.58	-0.54	-0.75	-0.88	-0.81	-0.58
TI7 27.5 °C-7.5 °C	0.68	0.31	0.49	2.34	2.10	2.27	2.03	1.90	2.61	3.08	2.82	2.03
TI8 7.5 °C-2.5 °C	0.49	0.22	0.36	1.70	1.52	1.65	1.48	1.38	1.89	2.24	2.05	1.48

The effect of the inclusion of the IHRL streams within the problem table algorithm, part of the proposed model introduced in this paper, will be examined further in Section 3-7. In particular, pinch point effects will be discussed.

3.6 Time Event (Gantt) Chart

One of the valuable tools for a time-dependent system that gives an analyst real insight into the system is the time event (Gantt) chart. This chart does not represent the temperature ranges or heat loads of the streams, but it clearly highlights the periods of time (x-axis) when streams (y-axis), including the main streams and the IHRL streams, coexist. Furthermore, consulting the Gantt chart reveals the occupancy times of the system's components, such as HSUs and heat exchangers. The Gantt chart for the case study is shown in Figure 7. For instance, HSU1 to HSU2 represents the hot stream that connects HSU1 to HSU2 with a supply temperature of 60 °C (Figure 6). Hot streams are shown as red lines and cold streams as blue lines. Three streams exist for the whole the day, while the other streams are intermittent.

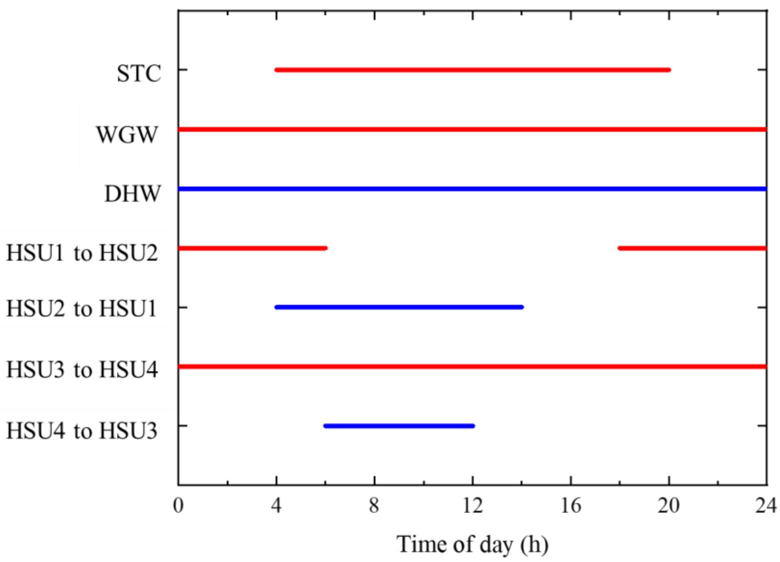

Figure 7 Gantt chart for the external and internal streams, both hot (red) and cold (blue).

3.7 Utility and Pinch Temperature Calculations

As explained in Section 3-2, each column (TS) of the problem table will be treated as a conventional pinch analysis, with heat cascading from the upper temperature intervals to the lower intervals. The novelty of the proposed model is to incorporate the IHRLs in the construction of the modified problem table and to determine the specifications of HSUs (Sections 3-3 to 3-5) without the complexities accompanying graphical models. Thus, in the fourth step of the proposed model, by the incorporation of IHRLs into the system and the calculation of the new energy balance in each temperature interval and each time slice, any remaining surplus energy will be cascaded down from the higher TI to the next lower TI in Table 4 and the remaining deficit energy will be accumulated by going downward in a TS. The largest resultant negative heat load in each TS equals the minimum required hot utility at the corresponding TS. By adding the amount of hot utility to the first TI and cascading right through the TS, the minimum required cold utility that equals the final cascaded energy (i.e. the lowest TI) for the corresponding TSs will be determined. In addition to the hot and cold utility targets, the cascading energy analysis leads to the determination of the pinch temperature for each TS. The pinch temperature equals the lower bound of the TI where the cascaded heat load goes to zero. Table 5 shows the final heat balance in each TI and TS resulted from the cascading procedure in the problem table including the external and internal streams by using enthalpy balances in Table 4. As expected through Figure 5, the implementation of HSUs leads to a system with zero hot utility over the summer's day, because all the deficit heat balances in Figure 5 were supplied by the energy stored in the HSUs. The bottom row of Table 5 shows the minimum required cold utility for each TS. Moreover, the pinch points of the problem table (the cells of the table with a heat balance of zero) are shown. In four TSs from 12-14 to 18-20, Table 5 reveals that there is no TI with a heat balance of zero, which means that the pinch temperature occurs at the first temperature interval, TI1. This type of problem is known as the threshold problem [11].

Table 5 The final heat balances and utilities calculated by the proposed problem table algorithm from the proposed model by using the external and internal streams.

	TS: 0-2	TS: 2-4	TS: 4-6	TS: 6-8	TS: 8-10	TS: 10-12	TS: 12-14	TS: 14-16	TS: 16-18	TS: 18-20	TS: 20-22	TS: 22-24
Hot Utility	0	0	0	0	0	0	0	0	0	0	0	0
TI1 62.5 °C-57.5 °C	0	0	0.16	1.14	2.98	4.39	4.36	3.89	1.45	0.19	0	0
TI2 57.5 °C-52.5 °C	0	0	0.11	0.84	2.58	3.88	7.75	6.87	1.66	0.19	0	0
TI3 52.5 °C-42.5 °C	0.25	0.12	0.19	1.14	2.58	3.73	15.31	13.56	3.07	1.37	1.08	0.78
TI4 42.5 °C-37.5 °C	0.38	0.18	0.28	1.66	3.58	5.11	20.54	16.9	3.77	1.96	1.62	1.16
TI5 37.5 °C-32.5 °C	0.19	0.09	0.14	0.67	0.6	0.65	19.96	16.36	3.02	1.08	0.81	0.58
TI6 32.5 °C-27.5 °C	0	0	0	0	0	0	19.38	15.82	2.27	0.2	0	0
TI7 27.5 °C-7.5 °C	0.68	0.31	0.49	2.34	2.1	2.27	21.41	17.72	4.88	3.28	2.82	2.03
TI8 7.5 °C-2.5 °C	1.17	0.53	0.85	4.04	3.62	3.92	22.89	19.1	6.77	5.52	4.87	3.51
Cold Utility	1.17	0.53	0.85	4.04	3.62	3.92	22.89	19.1	6.77	5.52	4.87	3.51

Figure 8 shows the hot and cold utilities needed for the systems with and without HSUs, calculated by using Table 4 and Table 2, respectively. The system without HSUs needs 25.13 kWh energy as hot utility throughout the day. Figure 8 shows that the implementation of HSUs eliminated the need for the hot utility, but also reduced the amount of cold utility over the day from 108.23 kWh to 71.14 kWh (a 34.3% reduction). In other words, the HSUs played a role similar to a heat pumping system that absorbs heat from below the pinch in some TSs (reduction in cold utility) and releases heat to above the pinch in other TSs (reduction in hot utility). As can be seen in Figure 8, for the system without HSUs, between TSs of 6-8 and 14-16, there are threshold problems where the pinch occurs at the first TI and the system does not need hot utility. Thus, the storage of surplus energy into the HSUs at any TS leads to a decrease in the required cold utility at the same TS.

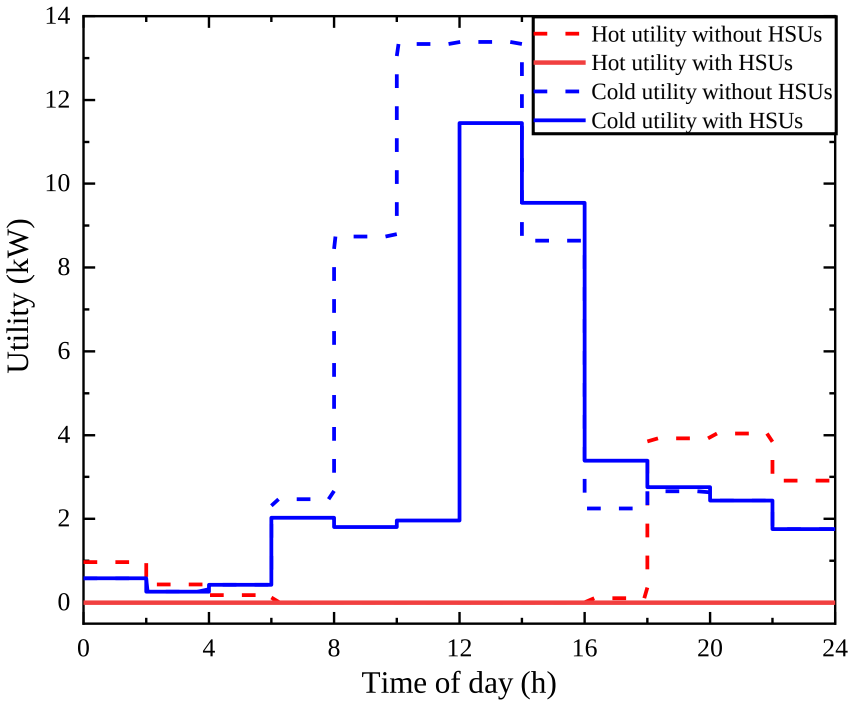

Figure 8 Utility-time graph for the systems with and without HSUs integration.

The implementation of HSUs has an important effect on system heat cascade in terms of pinch temperatures, and actually resulted in double pinch points for eight of the TSs. The pinch temperatures of the system over the batch period are illustrated in Figure 9. Figure 9 (a) shows the pinch temperatures for the system without HSUs (Table 2), while Figure 9 (b) presents the pinch temperatures for the HSUs-integrated system (Table 5). It should be mentioned that the pinch temperature in each time slice depends on the heat capacity of the hot and cold streams. The implementation of HSUs for the TSs 6-8, 8-10, and 10-12 led to new pinch temperatures as process pinch temperatures, and for the TSs between 20-22 and 4-6 led to new pinch temperatures as utility pinch temperatures. Moreover, Table 5 and Figure 9 (b) show that one of the pinch temperatures is located at an additional temperature (52.5 °C) that resulted from the incorporation of the IHRL streams in the problem table. Thus, Figure 9 (b) emphasizes the importance of the inclusion of IHRL streams in the problem table (Section 3-5), which has not been considered through the other models in the literature. Furthermore, the pinch temperature is highly important in the integration of a heat pump system because heat pumps have to work across the pinch temperature, otherwise, the utility (energy) penalty will be doubled [28]. A heat pump must be placed across the pinch temperature to transfer energy from below the pinch temperature where there is an excess of heat to above pinch temperature where there is a deficit.

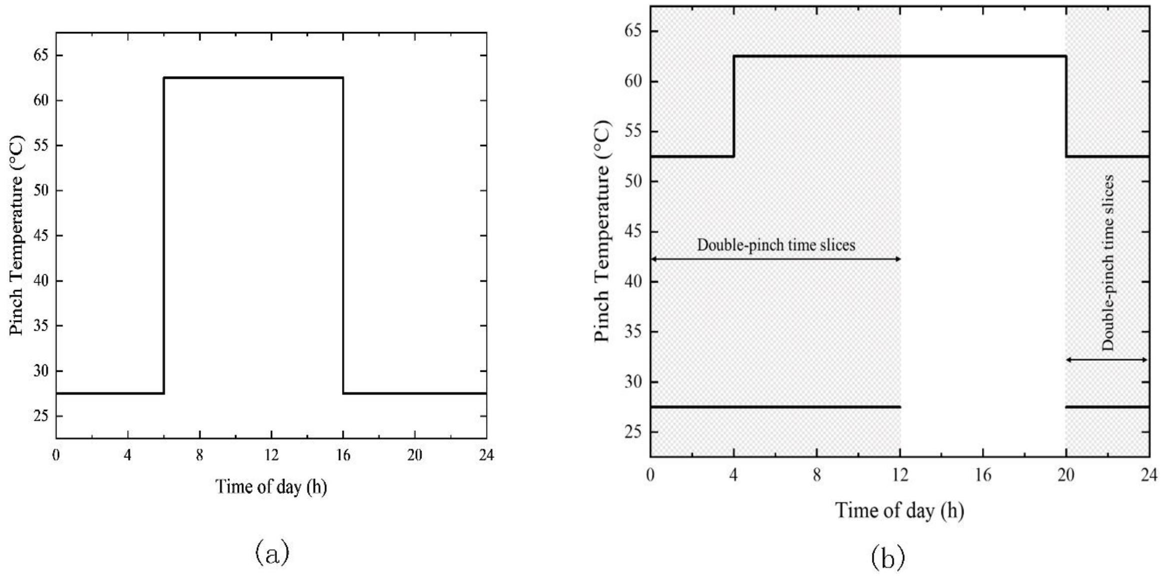

Figure 9 System pinch temperatures vs. time of day, (a) without HSUs and (b) with HSUs.

3.8 Graphical Representation of the Model

The numerical calculation performed with the modified problem table (Table 5) provides key information about the energy targets. Graphical representations of the model through composite curves can shed light on the effect of HSU integration into the system. Composite curves, like the problem table algorithm, can provide information about the minimum required hot and cold utility as well as pinch temperature for each TS. Furthermore, the composite curve provides a unique insight into the selection of ΔT_{min} of the system and its role in a balance between investment costs and utility costs [29].

Figure 10 depicts the composite curves and their stream populations at randomly chosen TS 8-10 for the system without HSUs corresponding to Table 2 and the system with HSUs corresponding to Table 5. The method of drawing the composite curves was already explained in the literature [28]. Without the HSUs, the system is composed of one cold stream and two hot streams. In this TS, the system does not need any hot utility (threshold problem). It is worth noting that the vertical distance between the hot and cold composite curves at the non-utility end is called threshold temperature difference, $\Delta T_{threshold}$ [11]. For a system where $\Delta T_{threshold}$ is greater than the proposed ΔT_{min} of the system, the energy targets do not change as ΔT_{min} changes. The addition of three streams due to the implementation of HSUs resulted in completely different composite curves. Figure 10 (b) shows how the IHRLs changed both composite curves, mainly the cold composite curve, and also resulted in a new process pinch in addition to the existing utility pinch for the system at the TS 8-10. This pinch temperature (27.5 °C) can be also deduced from Table 5 (TI6: 32.5 °C -27.5 °C/TS: 8-10).

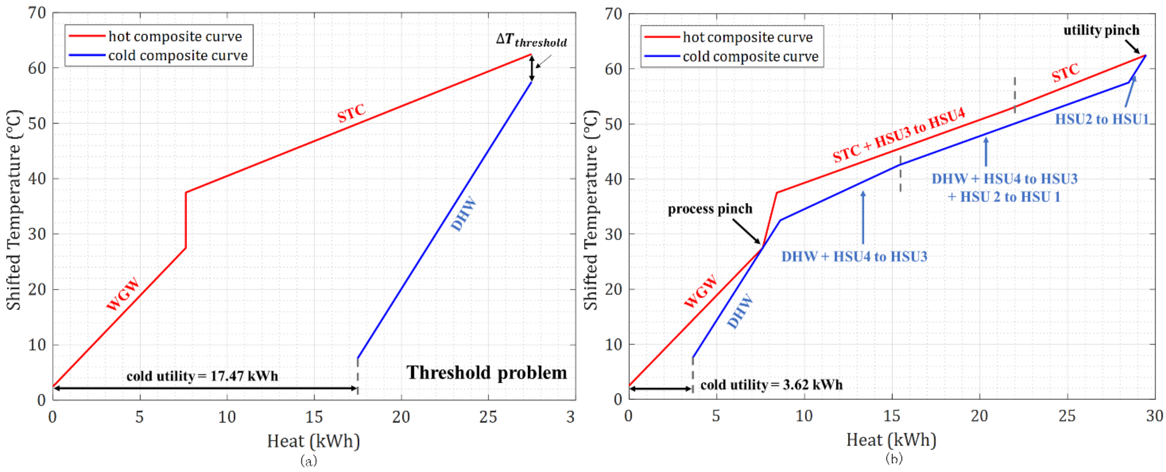

Figure 10 Composite curves at TS 8-10: (a) the system without HSUs and (b) the system with HSUs.

3.9 The Effect of the Selection of the Appropriate Slice Duration

So far, to simply explain the model, the batch period has been evenly divided into twelve TSs. In Section 3, the appropriate slice duration was determined. An appropriate slice duration results in more accurate energy targeting for the system as well as precise HSU volume determination. s which shows the hot and cold utility needed for the system with and without HSUs, and the HSU volumes for different numbers of TSs over the batch period. Table 6 shows that the division of the batch period into 192 TSs resulted in 11% higher overall hot utility (27.87 kWh) for the system without the HSUs, compared to energy targeting calculation with 12 TSs (25.13 kWh). Moreover, the cold utility determined by using 192 TSs is about 1.7% and 13.3% greater for the system without and with HSUs, respectively, compared to the calculation based on 12 TSs. The number of TSs also affects the calculation of HSUs' sizes and capacities. Table 6 shows that the system needs 9.5% and 4.3% bigger HSU1 &2 and HSU3 &4, respectively, where the slice duration decreases from two hours (Figure 5) to 450 seconds because the selection of smaller slice duration leads to the recognition of the extremums of CPs. Hence, this important example reveals how an oversimplified pinch analysis such as TAM may ill-predict the heat recovery amount and consequently, the volume of an HSU. It should be noted that the comparison between the results of 96 TSs and 192 TSs (the two last rows) reveals an error of less than 0.1%, which is in agreement with Figure 3.

Table 6 Effect of the number of TSs on energy targeting and the HSU volumes.

Number of TSs	System without HSUs		System with HSUs			
	Hot utility (kW)	Cold utility (kW)	Hot utility (kW)	Cold utility (kW)	HSU1 & 2 volume (L)	HSU3 & 4 volume (L)
12	25.13	113.89	0	76.81	704.00	745.00
24	27.79	115.83	0	85.36	720.60	752.55
48	27.84	115.83	0	86.41	750.50	765.86

96	27.86	115.84	0	86.99	771.09	777.91
192	27.87	115.84	0	87.01	771.09	777.91

4. Heat Exchanger Network

The principal goal of a pinch analysis is to determine the energy targets for the particular system chosen for study. This objective is not achievable without an accurate heat exchanger network. The heat exchangers are responsible for providing the maximum heat recovery between streams to reach the minimum hot and cold utilities, as determined by the energy target procedure [30]. Furthermore, the thermal conductance (UA) of the heat exchanger, i.e. the product of the overall heat transfer coefficient (U) and the surface area (A), plays a key role in the capital cost of the system [31]. The thermal conductance of a heat exchanger can be calculated by using Eq. (2) [28].

$$UA = \frac{Q}{\Delta T_{LMTD}} \tag{2}$$

Q and ΔT_{LMTD} represent the heat transfer and the logarithmic mean temperature difference between hot and cold streams.

The heat exchanger network will be designed by using the vertical heat transfer model [32], which is defined as counter-current heat exchangers placed between hot and cold streams within enthalpy intervals in the temperature-enthalpy diagram, such as Figure 11. The network design must also observe three golden rules: the heat transfer cannot occur across the pinch; cold utilities cannot be used above the pinch, and hot utilities cannot be used below the pinch [11].

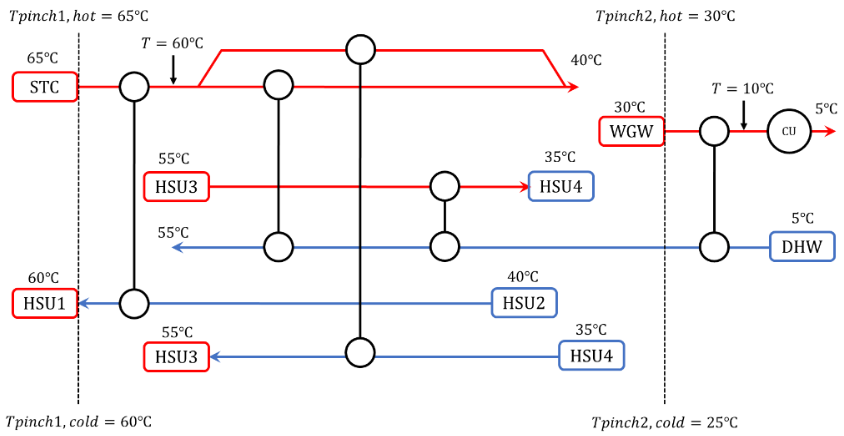

Figure 11 Grid diagram at 8:00 am.

4.1 Heat Exchanger Network with Intermediate Heat Recovery Loops

HSU integration into the system leads to additional hot and cold streams (IHRL). Thus, to design a heat exchanger network for the system with HSUs, some points must be respected:

- The population of streams in each TS can be identified by using the Gantt chart.
- The golden rules and the vertical heat transfer model for heat exchanger network design must be followed.

- A heat exchanger cannot be placed between hot and cold streams of IHRLs.
- The utilities cannot be placed on the IHRL streams.
- The procedure must be applied to each TS.

The gird diagram at 8:00 am is demonstrated in Figure 11. In this TS, the system has two pinch points, i.e. 62.5 °C and 27.5 °C (see Figure 10 (b)). Furthermore, to respect the proposed minimum temperature difference of the system, STC must be split between temperatures of 60 °C and 40 °C to provide the required energy to heat the DHW and the cold stream between HSU4 and HSU3. It should be noted that Figure 11 represents the grid diagram by using the vertical heat transfer model at the TS that includes 8:00 am and is not the superstructure of the system. It must be mentioned that Figure 11 shows the actual temperatures of the streams, not shifted ones. As a result, we have "Tpinch,hot" and "Tpinch,cold" which are equal to pinch temperature determined in section 3-7 plus and minus the proposed $\Delta T_{min}/2$, respectively. Once the heat exchangers are placed between appropriate streams, the thermal conductance related to each heat exchanger can be calculated by using Eq. (2).

In order to meet the energy targets for the hot and the cold utilities determined by the problem table algorithm, the final design of the heat exchangers must be able to provide the required heat recovery between their corresponding hot and cold streams throughout the batch process (24 h and 192 TSs in this case study). The possible heat exchanger network, including heat exchangers, HSUs, and their corresponding streams, which provide the heat recovery throughout the batch period, is illustrated by the superstructure in Figure 12. For instance, four heat exchangers must be placed between the DHW stream and four hot streams, including two external hot streams and two internal heat streams. At some time slices such as at 8:00 am, three heat exchangers are used because according to Figure 7 the internal hot stream between HSU1 and HSU2 does not exist at this time. However, the heat exchanger between DHW and HSU1 and HSU2 is needed to provide the heat recovery at the TSs where both streams co-exist, such as at 4:00 am.

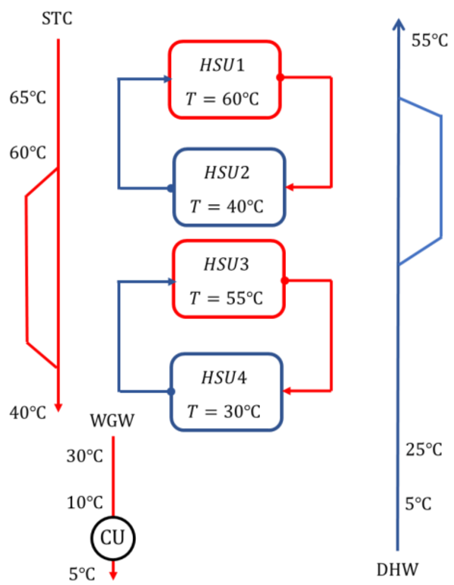

Figure 12 Superstructure of the test building.

The final size of a heat exchanger must be big enough to be able to provide heat recovery between the two streams during the batch period. Thus, the appropriate thermal conductance for each heat exchanger equals the maximum thermal conductance of the heat exchanger throughout the batch process. For instance, by applying the procedure explained above for the heat exchanger network design and repeating the procedure for 192 TSs, there will be 192 different values for the thermal conductance of the heat exchanger between the WGW and DHW streams. Among these 192 heat exchangers, only the biggest one can guarantee to provide all the heat recovery between the corresponding hot and cold streams throughout the day. The maximum thermal conductances of the heat exchangers for the entire day are shown in Table 7.

Table 7 Maximum thermal conductances of the heat exchangers through the day (kW/K).

Hot stream / Cold stream	STC	WGW	HSU1 to HSU2	HSU3 to HSU4
DHW	0.525	0.311	0.596	0.188
HSU2 to HSU1	0.286	0	0	0
HSU4 to HSU3	1.327	0	0	0

Since the pinch model discussed herein is based on the problem table algorithm can be simply applied to other case studies with higher numbers of streams. The objective of this paper is to present the model. Although the model was applied to a simple case study with three streams, the model is capable of analyzing a system with complex components such as heat pumping and air condition systems in a building.

5. Conclusion

In this study, an adapted TSM was introduced to address the two main issues that have arisen through the application of pinch analysis in residential buildings. These issues are the highly dynamic behavior of the streams existing in the system, such as waste heat and renewable energy, and the need for sizing the HSUs. First, an algorithm for the selection of the appropriate slice duration (i.e. the assumed constant stream property time duration) which is capable of exhibiting all variations of the streams, was introduced. Then, the temperature intervals were arranged, and the heat balance within each temperature interval and time slice was calculated. Unlike the available pinch analysis models presented in the literature, where the potential of HSU incorporation has been investigated after the full execution of the problem table algorithm, here, before cascading heat from upper-temperature intervals to lower-temperature intervals in each time slice, the potential of HSUs was evaluated. In this way, the possibility of storing energy at high temperatures has been evaluated. The surplus energy in upper-temperature intervals was stored and then was discharged into the lower temperature intervals through IHRLs at later time intervals. Two principles are laid down to determine the volumes of the possible HSUs. The temperatures of the IHRLs are defined, according to the shifted temperatures of the main streams. The problem table algorithm is then reconstructed with the inclusion of the IHRL streams in the system. Thus, the minimum required hot and cold utilities, as well as the pinch temperature of the system, are calculated. Furthermore, the effects of slice duration selection on the energy targets and the HSUs' temperatures and volumes were discussed. It was observed that the appropriate slice duration selected by the algorithm introduced in this paper for a chosen reference day (192 time slices) resulted in 11% greater overall hot utility demand compared to the overall hot utility obtained with 12 time slices. This example reveals the importance of the selection of a slice duration and how an oversimplified pinch analysis such as the TAM may result in an imprecise heat recovery determination, and consequently, inappropriately sized HSUs. Given that the internal streams of HSUs are included on a par with external cold and hot streams of a building's energy system, the complex problem of the conceptual design of direct and indirect heat recovery system is reduced to heat exchanger network design only. Thus, in the final step, the heat exchangers network is conceptually designed to satisfy the targets set by the modified problem table algorithm. The proposed model is applied to the conceptual design of a direct/indirect heat recovery system for a test building equipped with waste heat and solar thermal collectors.

The implementation of the streams corresponding to the HSUs internal loops into the modified problem table algorithm led to new temperature intervals and even new pinch temperatures for the system. The results obtained through the chosen day illustrated that for the day where the hot stream was enough to supply all the heat demand of the system (threshold problem), the utilization of HSUs not only resulted in a zero hot utility system throughout the day but also led to a 34.3% reduction in cold utility over the day. In other words, in such cases, the HSUs play a role like that of a heat pumping system that absorbed heat from below the pinch in threshold problem (reduction in cold utility) and released heat to above the pinch in other time slices (reduction in hot utility).

A future study will evaluate the energy targeting over a whole year and complete the heat exchanger network conceptual design and appropriate HSU sizing that satisfy the energy targets.

Abbreviation

Nomenclature

c_p	specific heat capacity (kJ/kg-K)
CP	heat capacity flow rate (kJ/K-s)
$\dot{m}$	mass flow rate (kg/s)
ΔT	minimum temperature difference (K)
UA	thermal conductance (kW/K)

Greek letters

ρ	density (kg/m^3)

Acronyms

CU	cold utility
DHW	domestic hot water
FTVM	fixed temperature variable mass
HSU	heat storage unit
IHRL	intermediate heat recovery loop
STC	solar thermal collector
TAM	time average model
TI	temperature interval

TPA	time pinch analysis
TS	time slice
TSM	time slice model
WGW	warm gray water

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Author Contributions

Hossein Akbari: Validation, Methodology, Software, Visualization, Writing - original draft. **Seyed Mojtaba Hosseinnia:** Writing - review & editing. **Mikhail Sorin:** Conceptualization, Supervision, Writing - review & editing. **Christopher Reddick**: Investigation, Writing - review & editing. **Dominic Laperle:** Resources, Funding acquisition.

Competing Interests

The authors have declared that no competing interests exist.

Appendix

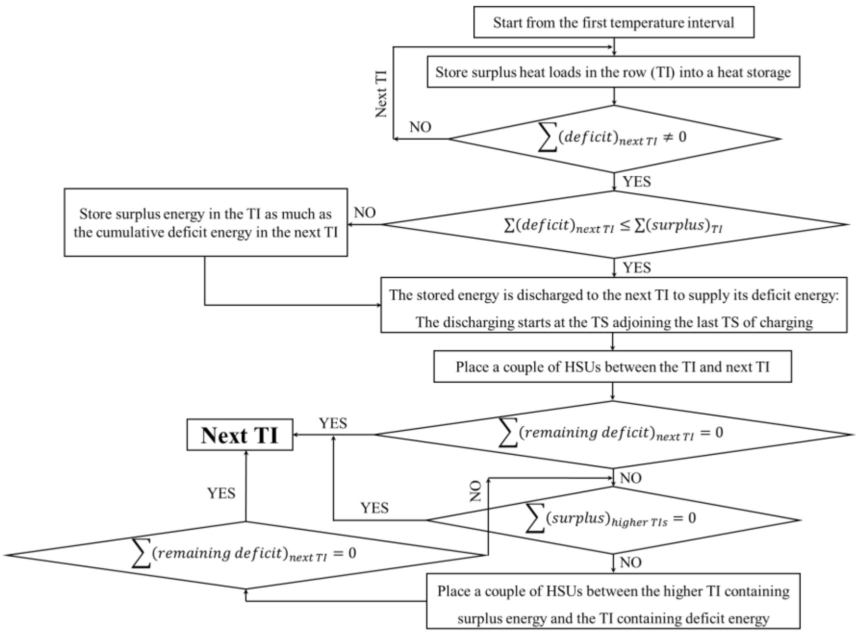

Figure A1 Proposed algorithm for the integration of HSUs into the problem table algorithm.

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