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Systematic thermal energy storage integration in industry using pinch analysis

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Abstract:

Industrial energy use is responsible for a large portion of the total energy consumption in industrialized countries around the world. In Switzerland, for example, the consumption represents approximately 20% of which more than half is used for process heat. To determine how to optimize the use of industrial thermal energy, process integration and pinch analysis methods are used. However, a particular challenge exists in energy optimization of batch and semi-continuous processes commonly found in industry. For such processes direct heat recovery is limited and dependent on the schedule limiting its broad industrial application. Development in recent years in this field has focused on indirect heat recovery using thermal energy storage integration to provide a practical solution to the heat integration of non-continuous processes. A methodology for the conceptual design of a thermal energy storage system and an overview of the calculations based on the indirect sources & sinks profiles are presented.

Keywords:

Indirect Heat Recovery, Batch Process, Pinch Analysis, Thermal Energy Storage, Heat Exchanger Network

1. Introduction

The industrial sector is a major consumer of thermal energy in many countries with energy use as high as 70% in China [1] or as more typically found in other countries of around one quarter [2]. This consumption level is similar in Switzerland where 20% of the total energy use is for industry of which more than half is for process heat. Within this industrial infrastructure, world-wide, time dependent batch processes are estimated to constitute approximately 50% of all industrial processes [3]. The tendency in the future is to remain at this proportion given major market drivers towards small volume high value added product production [4].

As a result, the need for better energy and resource efficiency in batch processes has increased. Research has focussed on two main approaches either mathematical or graphically based pinch analysis. The mathematical approach started in the early 1980's [5] and continues today with more advanced techniques to rigorously handle time as a dependent variable in global optimization studies such as in [4] or simultaneously with the operating policy of the storage media as in [6]. These techniques are effective methods to analyse batch processes for energy saving potential improvements, but are complex to apply in practice. Work to apply a simpler mathematical approach for heat integration in batch processes has been done as for example in [7] and [8] using combinatorial mathematics. Similarly, simpler graphical approaches have also been developed to provide analysis methods that can be applied in the praxis under certain simplifying assumptions such as in [9] or [10]. In addition, further development of a practical methodology based on experimental data to design a thermal energy storage system has also been done in [11].

In this paper, the graphical pinch analysis approach is used in the further development of a methodology and calculation approach for thermal energy storage design. The methodology involves a practical and systematic approach to designing the heat exchanger and thermal energy storage network on a conceptual level allowing quick and rapid design ideas and modifications to be tested and compared. The methodology is presently being implemented in the PinCH software. The software was presented at ECOS 2010 [12] and is being extended to include a third component for indirect heat integration analysis as shown in Fig. 1. The methodology and calculation principles underlying this new development component are reviewed in this paper.

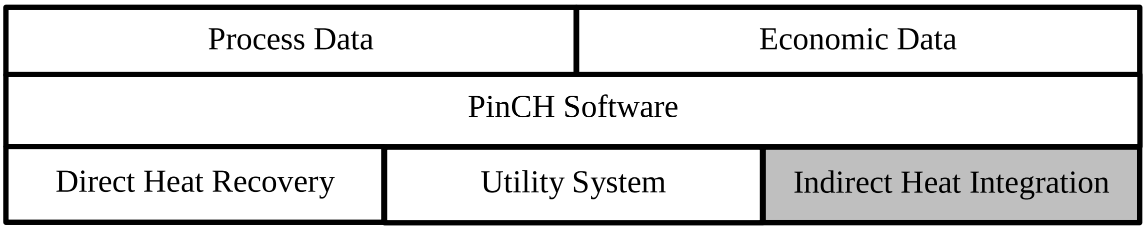

Fig. 1. PinCH software components with new indirect heat integration capabilities as reviewed in this paper.

2. Principles of indirect heat integration using pinch analysis

2.1 General principle

The principle of using pinch analysis for indirect heat recovery is based on the time average model (TAM) [13] as done in a previous study [14] for a single batch. In the present method, the approach of the previous study has been extended in two ways: i. the time frame is not limited to the single batch, but considers the overlapping of consecutive batches of the underlying time slice model (TSM) [15] and ii. the streams themselves are rearranged in priority relative to one another using temperature shifting. As a result, a new form of the TAM is created with a hot and a cold curve called the Indirect Sources & Sinks Profiles (ISSPs).

Fundamentally, the ISSPs do not consider any direct heat recovery. Variability in the existence times of streams leads to the necessity of 100% indirect heat recovery based on the ISSP. However, even though this necessity of indirect heat recovery to overcome the variability is done, it is assumed an average existence time for each stream can be determined to provide the basis for the TSM and hence storage volume calculations as discussed in the next sections. This assumption is most appropriate for the case of single product batch processes, the focus of this study, and less so for multi-purpose batch plants.

As noted previously, this reference TSM model is extended from the single batch schedule to include the streams in subsequent batches. This consideration offers the potential for greater direct heat recovery in comparison to the single batch itself through increased heat recovery available given the presence of more streams from the different batches. In essence a new TSM can be identified encompassing the streams from several batches that repeat over the duration of a base production cycle from start up to shut down. Fig. 2 illustrates the overlap of more than 50% of four single batch processes contained within a single production cycle of one day. The batch cycle duration (BCD) is the time at which the next batch starts and is the duration of the new TSM that forms after the startup period and repeats with the same BCD until the shutdown period.

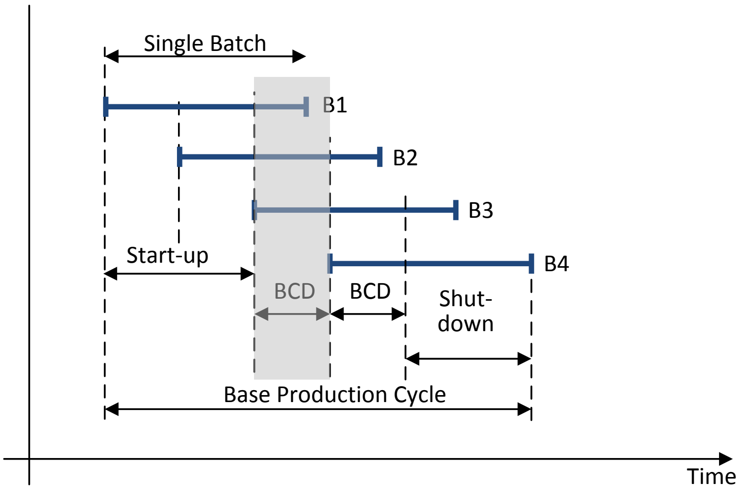

Fig. 2. Time slice model (TSM) shown in grey created from the overlap of more than 50% of consecutive single product batches and defined by the batch cycle duration (BCD).

The ISSPs are built based on the heating and cooling needs of streams defined in the given TSM. Fundamentally, the ISSPs are calculate and displayed in energy, not heat flow, ignoring time information and schedule since all heat recovery is done using the storage system.

As a final step in creating the ISSPs, each stream is then rearranged in priority relative to the other streams to take into account the actual heat exchanger area in the thermal energy storage system. This approach is similar in concept to [10] by focussing on minimizing the heat exchanger area in setting the priority. Therefore, streams that have a long duration or have a large film heat transfer coefficient are prioritized higher in creating the ISSP then those with lower values. To accomplish this prioritization, the supply and target temperatures of the streams are shifted based on a calculated stream specific $\Delta T_{\mathrm{min},s}$ contribution as shown in equation (1).

$$\Delta T_{\mathrm{min},s} = fp\left(\frac{1}{U_s t_s}\right)^y \qquad (1)$$

where the U_s is the overall heat transfer coefficient between the intermediate loop (IL) fluid and the process stream and t_s is the duration of the stream in the TSM. The variable fp is a proportionality constant that is determined beforehand based on a user specified minimum overall temperature difference $\Delta T_{\mathrm{min},ov}$ as shown in equation (2).

$$fp = Max\left\{(U_s t_s)^y\right\}\Delta T_{min,ov} \qquad (2)$$

The y exponent influences the magnitude of the temperature shifting making the range of variation wider or narrower. Hence a large value results in a broader spectrum of $\Delta T_{\mathrm{min},s}$ values and a low value results in a smaller variation. Once each stream's $\Delta T_{\mathrm{min},s}$ is determined, they are either subtracted from the stream supply and target temperatures if a hot stream or added to the supply and target temperature if a cold stream. Using the new shifted stream temperatures the ISSP can then be created in a composite manner.

2.2 Heat storage concept using the ISSP

The ISSP is the basis for systematically assessing thermal energy storage systems in batch processes. It provides engineers the key decision parameters for the conceptual design of such systems using a graphical approach which is easy to understand and use in a rapid manner to test different configurations and ideas. The derived solutions focus on achieving a required level of heat recovery with the minimum number of thermal energy storages.

Indeed, assuming vertical heat transfer from the source profile (hot curve) to the sink profile (cold curve) of the ISSP, and taking into account that stream supply temperatures constrain the heat storage system by bounding the possible storage temperatures, two key characteristics can be determined. They include the minimum number of heat storages (HS) required to achieve the identified heat recovery potential as well as the Temperature-Enthalpy zone (at which the valid heat storage values can be assigned - so called TH-assignment zone) both of which can be graphically determined. The approach in this paper differs from that in [14] as it takes into consideration priority of the streams as discussed previously and extends the TH-assignment to handle special zone types as appears in the case study given in [16] and discussed in section 3.

The following Fig. 3 shows an ISSP built using two streams (the hot stream H1 and the cold stream C1) and illustrates the simple case of a single intermediate loop/heat storage (IL/HS) system required to achieve the desired heat recovery level:

- The IL/HS is represented by a black line in between the ISSPs and is composed of two Volume Storage Units (VSU – representing either a tank volume or a temperature layer of a stratified tank).
- An IL is automatically associated to a HS and represents the circulation of a heat transfer media that transfers the usable heat from the hot stream(s) when loading and transfers it to the cold stream(s) when unloading the HS.
- Since there is one single IL/HS system there is no degree of freedom as regards ΔH , assignment in enthalpy for the placement of the HS and the TH-assignment zones are reduced to two vertical lines at the boundaries of the heat recovery zone.
- The upper point of the black line represents the high temperature VSU and can be moved to any point along the one dimensional TH-assignment zone line on the right.
- The lower point of the black line represents the low temperature VSU and can be moved to any point along the one dimensional TH-assignment zone line on the left.
- The single horizontal red line above and horizontal blue line below the ISSPs represent the range of the sources and sink themselves to allow immediate visualization of the stream supply and target temperatures on the corresponding hot and cold ISSPs.

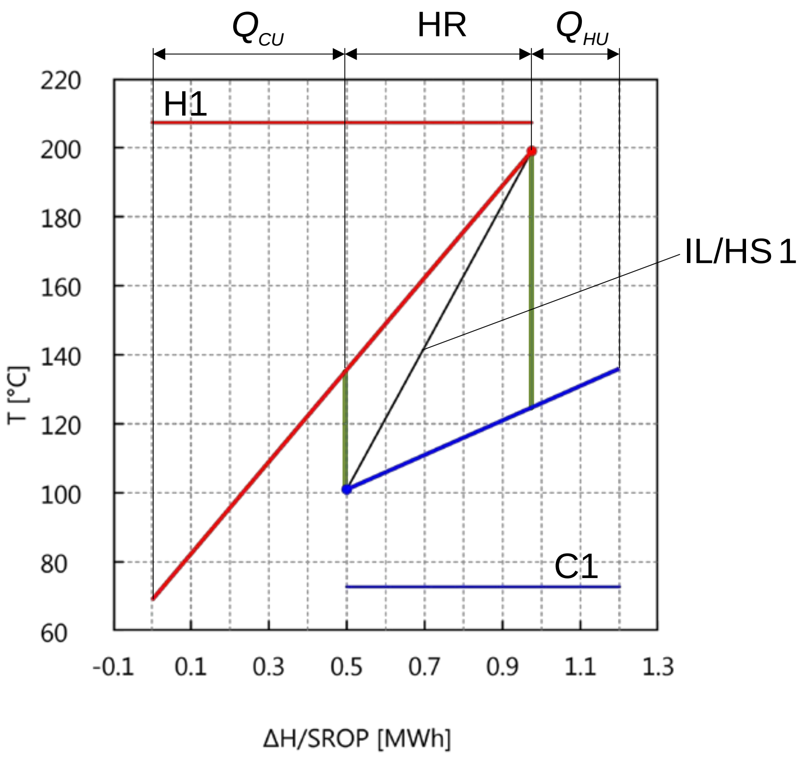

Fig. 3. ISSP chart showing one hot stream and one cold stream with a single IL/HS system. Green lines indicate valid one dimensional TH assignment zones due to their position at the end of the HR region.

It is important to note that the streams and the hot and cold ISSPs are shown in shifted temperature according to their calculated $\Delta T_{\mathrm{min},s}$ yet the IL/HS line is in real temperature. This offers the advantage of being able to read the characteristics of the IL/HS directly from the graph. In addition, the temperature shifting allows the placement of the IL/HS black line directly on the hot or cold ISSPs as the shifted temperature of the underlying streams ensure adequate temperature driving force.

Applying the vertical model, where the contribution from sources and sinks are maintained in a vertical orientation based on pure counter-current heat transfer, for conceptual design has the advantage of easy understanding and a guarantee that the heat balance of an IL/HS system over a cycle is automatically closed. The heat recovery (i.e. heating and cooling savings) as well as the remaining utility requirements can also be read directly on the ISSPs.

In order to physically achieve the indirect heat recovery, two technical solutions are considered as follows:

1. The two VSUs are merged in a single piece of equipment and form a stratified tank.
2. The two VSUs are kept separate and form a fixed temperature variable mass (FTVM) tank system. This solution is less commonly applied in the practice than a stratified tank, but offers the advantage of maintaining temperature better and allowing higher flowrates. Implementations are to be found in processes where hot water consumption (process and/or cleaning) is large enough to serve both process and heat storage, for instance in the beverage industry such as breweries.

In both cases, the IL provides the means to transfer heat indirectly from heat sources to heat sinks of the batch process. The heat exchangers are arranged in parallel and therefore the IL is split into branches to isolate each IL heat exchanger that can transfer heat to or from a process stream. However, on the process stream side, heat can be transferred between multiple IL/HS systems in series. The two types of storages are shown in Fig. 4 for a single IL/HS system with a given T_{low} and T_{high} in each VSU.

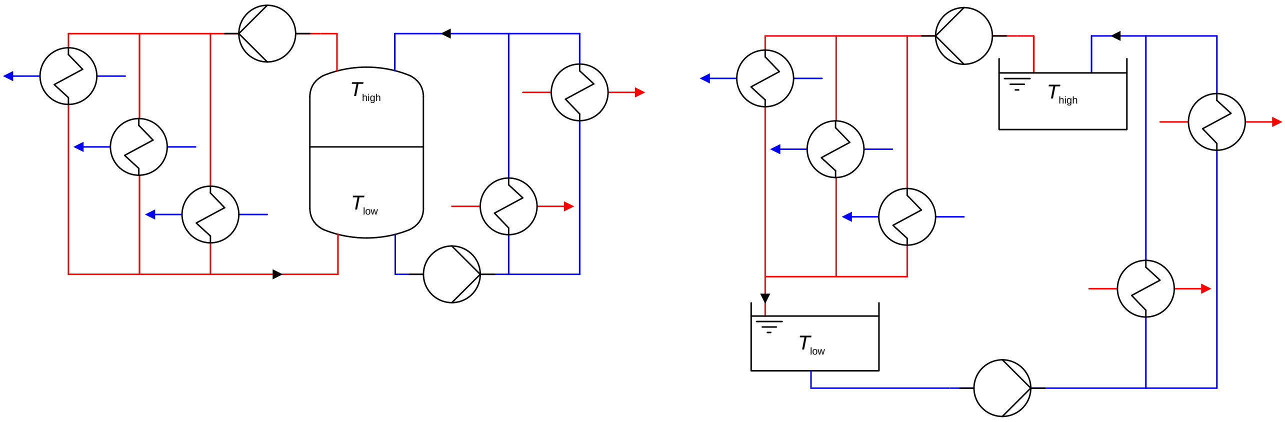

Fig. 4. Stratified Tank solution showing T_{high} and T_{low} layers in the same tank (Left) and FTVM solution with IL T_{high} and T_{low} in separate tanks (Right).

To illustrate the concept of an assignment zone, a second hot stream named H2 is added with a supply temperature lower than the cold stream target temperature. Including this hot stream in the heat recovery zone constrains the TH assignment zone of the upper VSU and creates a storage pinch [14]. In this case the temperature of the hot VSU is bounded between the supply temperature of H2 and the cold curve so that the TH-assignment zone for the upper VSU is reduced to a single point. (Fig. 5.)

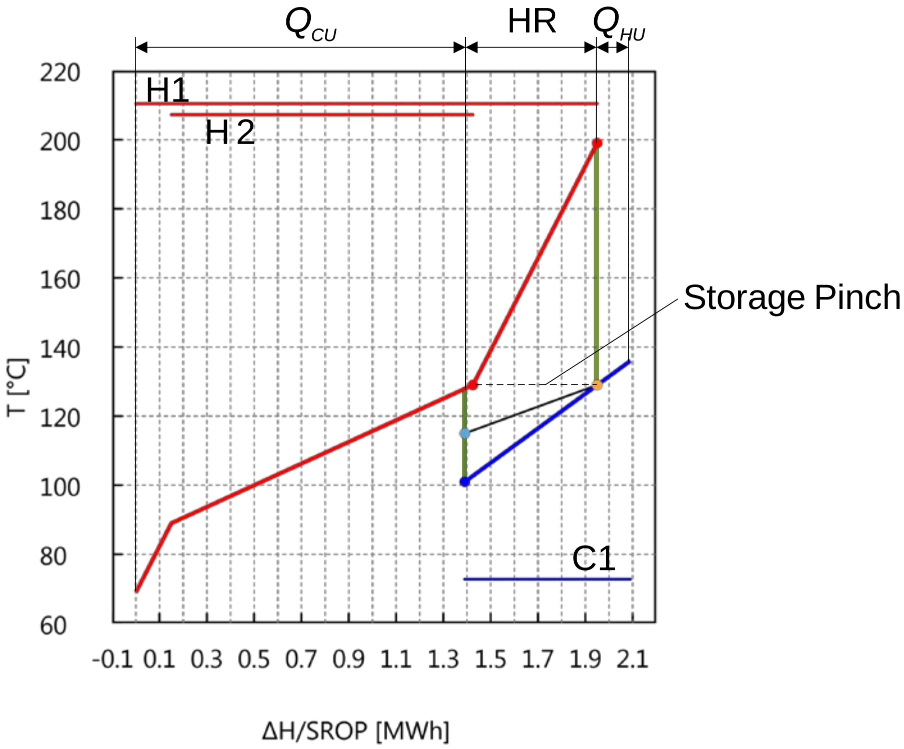

Fig. 5. Storage pinch created by the supply temperature of stream H2 that limits the T_{high} of the IL to a single point for the given amount of heat recovery.

Any further increase of the heat recovery level (i.e. by shifting the cold ISSP towards the hot ISSP further on the left) leads to an increase in the minimum number of IL/HSs to two as shown in Fig. 6. This limitation occurs due to the fact that the supply temperature of stream H2 restricts the VSU T_{high} temperature of the *first* IL/HS [17]. Attempting to set the T_{high} of the first IL/HS above the H2 supply temperature would result in incorrect temperature driving forces. Analogously, selecting a ΔH value lower than that defined at the position of the H2 supply temperature results in the supply temperature of H2 being too low for the T_{high} of the *second* IL/HS. As a result, a zone must be defined for placing the new intermediate VSU that is bounded at a maximum temperature and minimum ΔH value given by the stream H2 supply temperature. Fig. 6 shows the assignment zone defining the TH region in which the intermediate VSU can be placed.

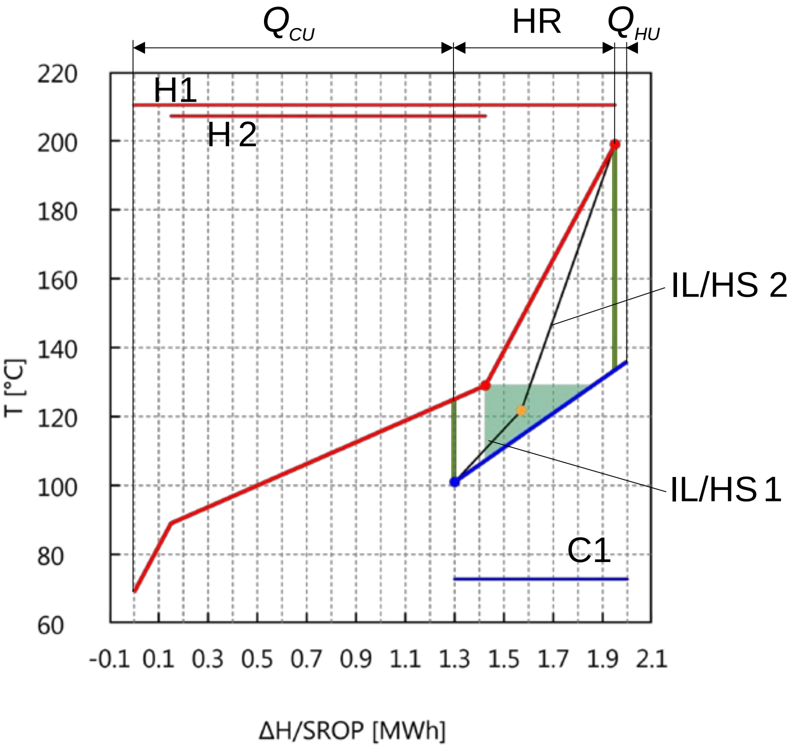

Fig. 6. Three stream example showing TH assignment zone defined for the placement of the intermediate VSU formed due to the supply temperature of H2.

The TH assignment zones that form in the intermediate regions of the ISSP have two technical solutions available to the designer:

1. The two IL/HS systems are hydraulically connected. The intermediate VSU is common to both IL/HS systems and in the ISSPs the black lines are connected and continuously increasing as shown in Fig. 6.
2. The two IL/HS systems are hydraulically disconnected. Each system has its own VSUs at the end temperatures allowing selection of the VSU temperatures to be chosen independently in the TH assignment zone. This effect is shown in the ISSP with the black line as discontinuous (see Fig. 7). However, the ΔH position must be the same (i.e. they must be on the same vertical line) to achieve the same heat recovery and ensure the energy balance is closed.

Although the second option may seem disadvantageous at first sight (the overall number of VSUs is increased by one unit), the hydraulic coupling can be removed and the temperatures can be chosen independently. This allows increasing the temperature difference in the single IL/HS and thus potentially decreasing the overall investment cost for the same amount of heat recovery.

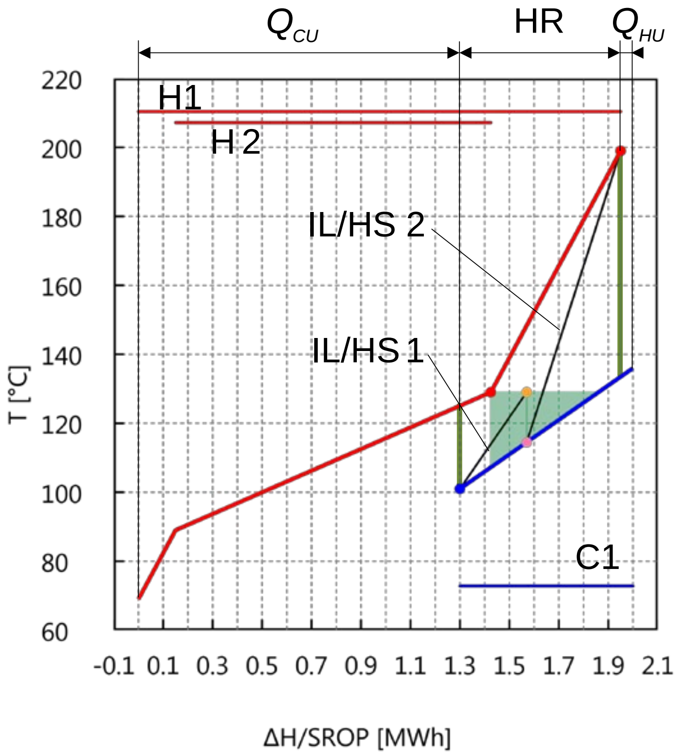

Fig. 7. Three stream example showing hydraulically disconnected IL/HSs represented by the discontinuous jump in the black line of the IL/HS system.

2.3 Assignment zones types

In the previous three streams example, the TH assignment zones are valid independent from the placement of the VSU. These are called restricted TH assignment zones and provide a quick overview on the number of IL/HS systems required to achieve the desired HR level as well as on the key constraining factors in the conceptual design of the indirect heat recovery system (by identifying the constraining supply temperatures).

For a specific placement of the IL/HS boundaries at ΔH or temperature values outside these restricted zones, some streams may be removed from a particular IL/HS system and remain entirely within an adjoining IL/HS. This has the advantage of not constraining the design of the IL/HS under consideration and provides an extension of the restricted zones. By selecting a temperature in the extended zones, a new dynamically updated TH assignment zone is then valid for this IL/HS which is only constrained by the temperatures in the vertical projection of the black line on to the ISSP as limits imposed by other intermediate supply temperatures have been excluded from the IL/HS. In summary three assignment zone types can be identified as follows:

1. Most restricted based on the intersection of possible assignment zones (always feasible, the only restriction being monotonically increasing T).

2. Extended based on the union of possible assignment zones (conditionally feasible, meaning not every assignment is feasible) – used to highlight the “possible solution space” irrespective of the other assignment.

3. Dynamically Updated, i.e. recalculation of the next feasible assignment zone based on user’s decision of current VSU assignment as defined in 1. or 2.

The new degree of freedom of the extended zones can be used in order to decrease the storage volume required for a fixed amount of heat recovery by increasing the temperature difference in the heat storage. This approach takes advantage of lower temperatures available in the extended zones and adhering to the dynamically recalculated zones in higher temperature zones.

In order to illustrate this possibility, a new cold stream (C2) has been added to the previous example with a supply temperature which is lower than the supply temperature of H2 (Fig. 8). These two temperatures bound the TH assignment zone of the intermediate VSU in its most restricted form. Therefore, once the enthalpy position of the intermediate VSU is set in this zone, the left TH assigment zone is bound by the supply temperature of C2 and can only be placed on the line defining the left TH assignment zone between the hot ISSP curve the supply temperature of C2 (identified in Fig. 8 as Restricted Zones).

However, the user is not obliged to select values bounded by the restricted zones. The extended zone of the left TH assignement zone (line shown in orange) can be used for example to set a larger temperature difference in IL/HS 1. As a result, the intermediate assignment zone is dynamically recalculated to exclude the possiblity of having C2 in IL/HS 1 allowing the selected new T_{low} to be used for IL/HS 1.

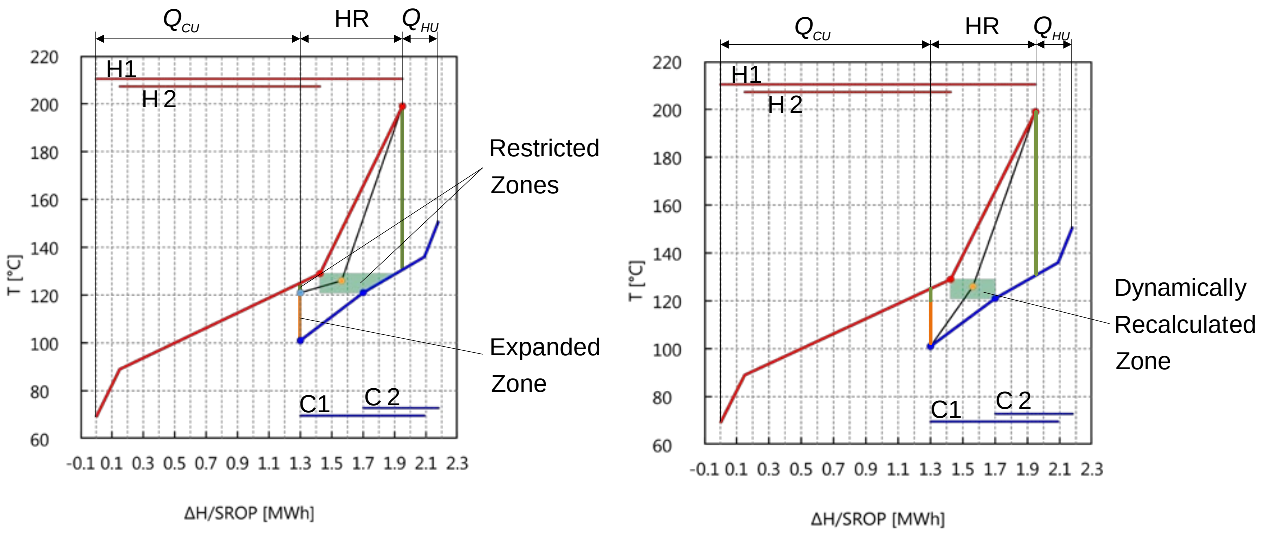

Fig. 8. Four streams example showing the restricted zones when maintaining the T_{low} of IL/HS 1 at a temperature above the C2 supply temperature (Left) as well as the dynamically updated intermediate assignment zone when selecting a T_{low} in the extended zone below the C2 supply temperature shown on the orange line (Right).

3. Methodology

3.1 Goal

The goal of the proposed methodology is to guide the designer in exploring the major degrees of freedom and trade-offs when placing thermal energy storages between the hot and cold ISSPs. The result is the systematic determination of a practical and cost effective heat recovery system from a conceptual design perspective along with the important design characteristics as follows:

- Type, number and temperature levels of storages
- Streams to be integrated and associated heat exchanger areas
- Storage volumes and profiles
- Investment costs and achieved savings of the proposed solution

3.2 User interaction and calculation flow

The approach relies mainly on the TAM in the modified form of the ISSP as described in the previous section. In addition to the ISSP, the sequence of loading and unloading phases is required for the computation of the required storage volumes based on the underlying TSM. The combination of the two models enables a comprehensive methodology for the conceptual design of indirect heat recovery systems while limiting the information level the engineer must consider to the following key decision factors:

- Minimum number of IL/HS systems
- TH-assignment zones (restricted, extended or dynamically updated)
- IL/HS systems characteristics
- Investment costs and utility savings

The user starts the procedure by performing the data extraction and using the process data such as the stream table and the schedule in the analysis. Next, the ISSPs is created using the stream specific shifted temperatures $\Delta T_{\min,s}$ as reviewed in the previous section. When the designer overlaps the hot and cold ISSPs, an indirect heat recovery region is created and the minimum number of IL/HS systems as well as the restricted and extended TH assignment zones can be plotted. Feasible mean value characteristics initialize the IL/HS systems which the user can adapt in order to reduce the complexity or decrease the overall costs based on the following:

- IL/HS systems enthalpy boundaries
- VSU temperature levels
- HS types (stratified tank or FTVM tanks)
- Connection type (i.e. hydraulically connected or disconnected) if more than 2 HS/IL systems

If the user selects a temperature in the extended zone, this triggers the plotting of the dynamically updated TH assignment zones as well as the allocation of streams to individual IL/HS systems. This allocation enables the computation of the required heat exchanger areas for heat recovery as well as the utility savings. It is also combined with the TSM in order to compute the loading and unloading profiles of each IL/HS and the volume computation of each tank or layer. The obtained results allow the estimation of the investment costs and utility savings.

The associated implementation allows the designer to dynamically interact with the ISSP and to control the key aspects of the design procedure through:

- Direct interaction to set the HR level and the IL/HS systems characteristics to assess the effects on the corresponding utility savings and investment costs.
- Scenario management for the assessment of re-scheduling opportunities, stream selection and the trade-off between Heat Exchanger and Storage Network (HESN) complexity and HR level.

This basic methodology from a user interaction and calculation flow perspective is illustrated graphically in Fig. 9.

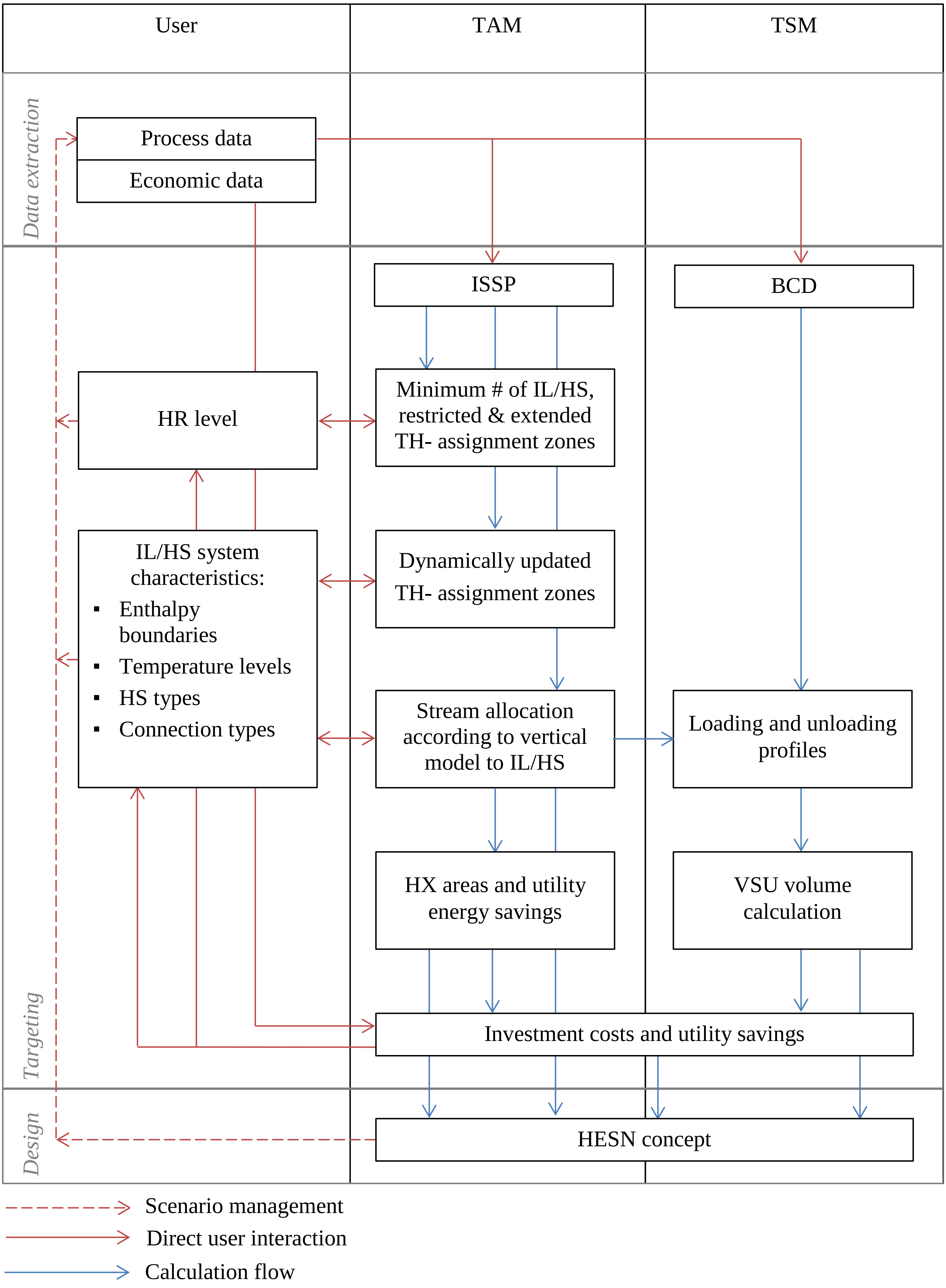

Fig. 9. User interaction and calculation flow diagram underlying the methodology for determining a thermal energy storage design of a batch process.

3.3 Heat Exchanger and Storage Design Result

The proposed methodology leads to several key results necessary for the conceptual design of a thermal energy storage system. As discussed in section 3.2, these results can easily be determined directly from the ISSP given the underlying vertical model assumption which leads to a single solution for the following:

- Minimum number of IL/HS systems
- Temperatures and volumes of the IL/HS systems
- Required Heat Transfer Area
- Investment costs and utility savings

This single solution also leads directly to a heat exchanger storage network (HESN) design displaying the key characteristics. An example of an HESN is shown in Fig. 10. The engineer is able to see all the information and can then proceed to design the process schema and assess how well the storage system concept can be adapted to the existing or planned process flow diagram.

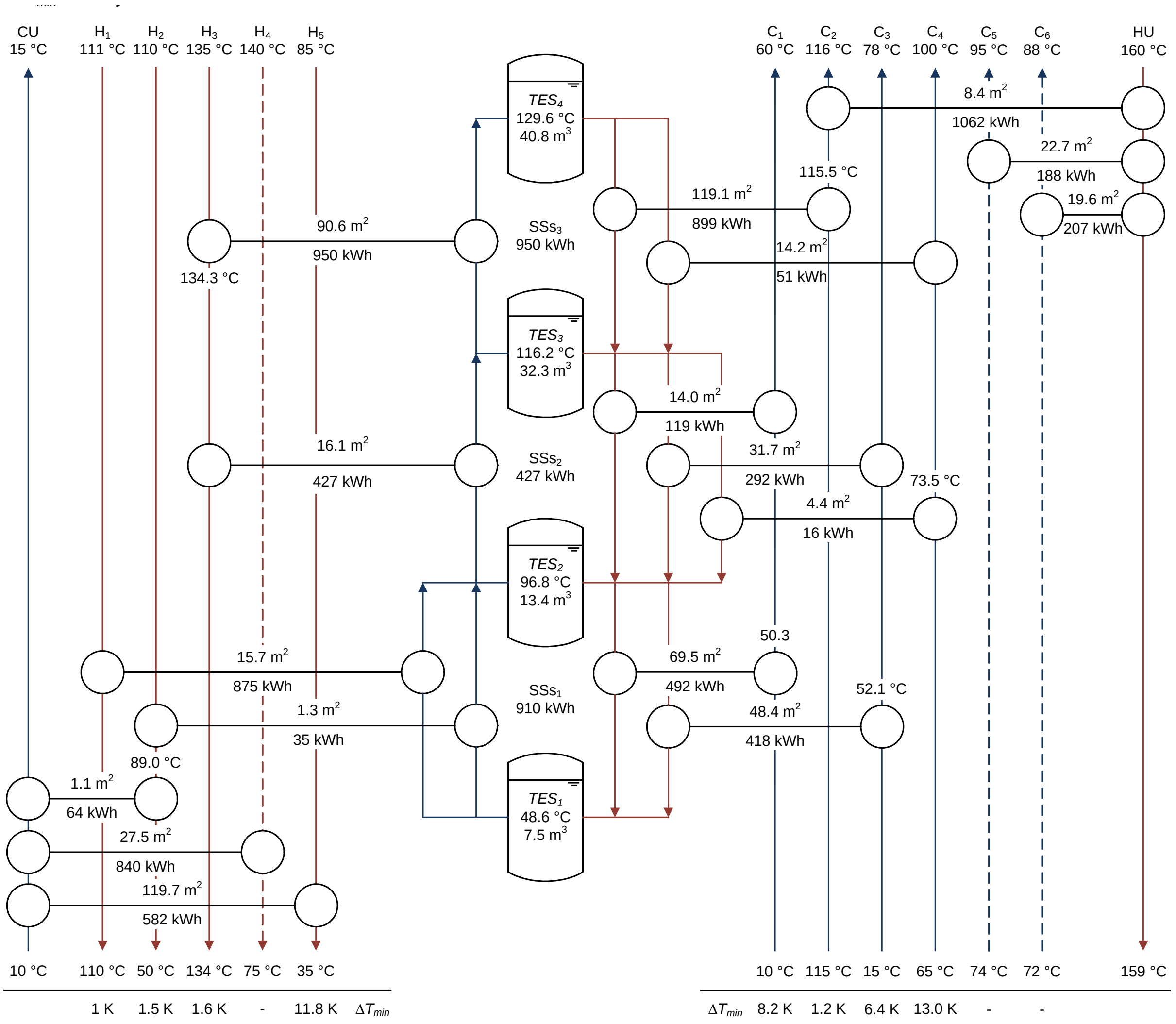

Fig. 10. Example HESN derived directly from the ISSP for a three IL/HS system showing the calculated heat exchanger areas, FTVM tank volumes and heat recovery potential for the given cold and hot streams based on the chemical process given in [16] (TES = VSU; SSs = IL/HS).

4. Conclusion

A methodology that improves upon a previous study [14] has been proposed for the design of thermal energy storages involving batch processes. It involves two main aspects: i. creation of a time average based indirect sources & sinks profiles and ii. calculation and display of assignment zones that are either restricted, extended or dynamically updated. An assumed time slice model of the reference schedule is used to allow the calculation of the tank or temperature layer volumes and hence investment costs. The proposed methodology allows the user to quickly assess various configurations to systematically reduce costs and complexity and determine a practical solution.

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References

[1] Sturm B., Meyers S., Zhang Y., Law R., Siqueiros Valencia E.J., Bao H., Wanga Y., Chen H., Process intensification and integration of solar heat generation in the Chinese condiment sector – A case study of a medium sized Beijing based factory, Energy Conversion and Management 106, 2015, 1295–1308.

[2] Lovins A.B., Reinventing fire. Chelsea Green Publishing Company, USA, 2011.

[3] Szijjarto A., Papadokonstantakis S., Hungerbühler K., Model-Based Identification and Analysis of the Energy Saving Potential in Batch Chemical Processes. Ind. Eng. Chem. Res. 2012, 51, 11170 – 11182.

[4] Majozi T., Batch Chemical Process Integration – Analysis, Synthesis and Optimization. Springer Science+Business Media, USA, 2010.

[5] Vaselenak J.A., Grossmann I.E., Westerberg A.W., Heat integration in batch processing. Ind. Eng. Chem. Process Des. Dev. 1986 25 (2), 357.

[6] Chen C.L., Ciou Y.J., Foo D.C.Y., Indirect Heat Integration of Batch Processes, In Foo D.C.Y, El-Halwagi M.M. editors. Recent Advances in Sustainable Process Design and Optimization. Advances in Process Systems Engineering - Vol. 3, World Scientific Publishing Company, 2012, pp. 485 – 525.

[7] Stoltze S., Mikkelsen J., Lorentzen B., Petersen P.M., Qvale B., Waste-Heat Recovery in Batch Processes Using Heat Storages, Journal of Energy Resources Technology, 1995, Vol. 117; 142-149.

[8] Fluch J., Brunner C., Muster-Slawitsch B., SOCO – Storage Optimisation Concepts in Industries, Commerce and District Heating Businesses, Chem Eng Trans, 2012, 29:493–498.

[9] Krummenacher P., Favrat D., Indirect and mixed direct-indirect heat integration of batch processes based on Pinch analysis. Int. J. Appl. Thermodyn. 2001;4(3):135–43.

[10] Atkins M.J., Walmsley M.R.W., Neale J.R., Methods for improving heat exchanger area distribution and storage temperature selection in heat recovery loops, Energy 55, 2013, 15-22.

[11] Atkins M.J., Walmsley M.R.W., Neale J.R., Process integration between individual plants at a large dairy factory by the application of heat recovery loops and transient stream analysis. Journal of cleaner Production 34, 2012, 21 – 28.

[12] Olsen D., Egli A., Wellig B., PinCH: An Analysis Tool for the Process Industries. 23rd International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS), 2010 June 14-17, Lausanne.

[13] Clayton, R.W., Energy Efficiency Office R&D reports RD/13/15 and RD/14/14, 1986, UK.

[14] Krummenacher P., Contribution to the heat integration of batch processes (with or without heat storage), PhD Thesis Nr 2480 (2001), EPFL, http://infoscience.epfl.ch/record/32956.

[15] Obeng E.D.A., Ashton G.J., On pinch technology based procedures for the design of batch processes, Chem. Eng. Res. Des., 1988, 66: 255-259.

[16] Gremouti I.D., Integration of batch processes for energy savings and debottlenecking, MSc Thesis at Department of Chemical Engineering, University of Manchester Institute of Science and Technology (UMIST), August 1991, UK.

[17] Sadr-Kazemi N., Polley G.T., Design of energy storage systems for batch process plants, Trans IChemE, Vol. 74, Part A, July 1996, pp. 584-596.