Indirect and mixed direct-indirect heat integration of batch processes based on Pinch Analysis

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Abstract

This paper introduces a methodology for the heat integration of industrial batch processes. Based on Pinch Analysis principles, this methodology resorts to intermediate heat storage to prevent adverse effects on the operating flexibility. A systematic procedure, backed with a graphical representation, allows the determination of the minimum number of heat storage units and their range of feasible operation as a function of the amount of heat recovery. Understanding the cause and the bottleneck effect of the so-called storage pinch, heuristics rules are proposed to screen major options corresponding to minimum cost solutions. These rules could be automated to a large extend, making the procedure suitable for targeting purposes. The operating temperature of the heat storage units can be optimized with ease, while other continuous degrees of freedom are more difficult to address using the proposed methodology. Preliminary guidelines are proposed to extend the methodology to mixed direct-indirect heat integration.

Nomenclature

DOF	Degree Of Freedom	LSTP	Limiting Supply Temperatures Profile
EP	Example Process	PA	Pinch Analysis
GRG	Generalized Reduced Gradient	PM	Permutation Method
HEN	Heat Exchanger Network	Sss	Storage Sub-System
HEX	Heat Exchanger	TAC	Total Annual Cost
HR	Heat Recovery	TAM	Time Average Model
HSU	Heat Storage Unit	TDF	Temperature Driving Force
IHRS	Indirect Heat Recovery Scheme		

1 Introduction

The flexibility of operation is generally one of the highly desired features of batch production techniques and operation. Therefore operators of batch plants are

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usually reluctant to envisage direct heat integration approaches (i.e. heat exchanges between process streams which co-exist in time), since this mode of heat recovery (HR) requires stiff scheduling conditions to safeguard product quality and energy efficiency. Stiff schedule conditions are actually seldom found.

Indirect heat recovery (i.e. using intermediate heat storage) is much less schedule-sensitive and therefore alleviates the above-mentioned drawback. Methods to design indirect heat recovery schemes (IHRSs) have already been proposed by several authors, among which Stoltze *et al.* [1] who proposed a combinatorial approach called the Permutation Method (PM). The PM searches, among a set of feasible operating temperatures of heat storage units (HSUs) and a sub-set of process streams to be integrated, the most cost-effective configuration of process streams – HSU matches. To achieve the HSU mass balance[1] at the end of a batch cycle, mixing of storage fluid, followed by utility supply (if needs be), is used. The set of feasible operating temperatures of HSUs is based on the supply and target temperatures of process streams. Within the restricted solution domain resulting from heuristic rules, the search is exhaustive. The PM has been further developed by Mikkelsen [2]; but the proposed post-optimization stage for fine-tuning the continuous variables of IHRSs remains difficult to apply in practice.

In a comparative study with a simplified Pinch Analysis (PA) based approach restricted to indirect heat recovery, Krummenacher & Auguste [3] observed that mixing of storage fluid (to achieve a mass balance at the end of a batch cycle) wastes temperature driving forces, area and possibly capital costs, explaining the slightly higher performances of PA based IHRSs. In addition, being rather a black-box solution method, the PM does not provide the engineer with the necessary insight at the conceptual / targeting stage.

Heat storage issues in a PA oriented approach have been considered by Krummenacher & Favrat [4], and Sadr-Kazemi & Polley [5]. They independently recognized the link between the schedule of the streams and the number of required intermediate HSUs. The former considered the problem in a time slice model context, while the later focused on the supply temperatures of process streams on time average model (TAM) composites (refer to Linnhoff *et al.* [6]). Despite this difference in the context, the resulting guidelines are very similar.

The methodology proposed in this paper results from the application and the further development of these PA oriented contributions.

2 The heat integration methodology

2.1 Assumptions and main issues of an indirect heat integration

Indirect heat integration means that heat from hot process streams is first transferred to a heat storage fluid, which is heated up and stored until heat is finally transferred to cold process streams whenever needed. This indirect mode of heat

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[1] Only "fixed temperature – variable mass" HSUs are considered.

transfer from hot to cold process streams is used regardless of the possible overlap in time, or even simultaneity, of the hot streams with respect to the cold streams.

Designing IHRSs is all about inserting a kind of "storage composite" between the hot and the cold energy composites. What is so difficult in designing such systems, what are the degrees of freedom (DOFs) available to the designer, and what are the major trade-offs ?

A simple process (EP1) is used to highlight the problem and demonstrate the proposed methodology (see [4]). The streams are listed in **Table 1**, which also includes the relevant economic data. The Time Event Model (Gantt Diagram) is depicted in **Figure 1**.

Table 1: Stream data and economic parameters of example process EP1.

Stream Name	T supply [°C]	T target [°C]	MCp [kW/°C]	Heat Rate [kW]	Heat [kWh/bat.]	t start [min]	t stop [min]	h [W/m^2°C]
C1	25	100	1	-75	-127.5	0	102	1000
C2	130	180	3	-150	-180	48	120	1000
C3	80	105	5	-125	-168.75	39	120	1000
H1	135	15	1.1	132	204.6	9	102	1000
H2	100	95	20	100	90	48	102	1000
H3	165	125	3.5	140	21	39	48	1000
H4	165	125	3.5	140	42	102	120	1000
HU	191	190	Hot Utility			0	120	1000
CU	10	11	Cold Utility			0	120	1000
Heat Storage Fluid			Water			-	-	1000

Key Economic Data (for Total Annual Costs model)			
Hot Utility	unit price	[CHF/(kWh•y)]	160
Cold Utility	unit price	[CHF/(kWh•y)]	10
Heat Exchanger Cost Function (annualized costs)			
$C_x=C_{0x}+C_{rx}\bullet A\hat{}m_x$	C_{0x}	[CHF/an]	0
	C_{rx}	[CHF/(m^2•y)]	401
	m_x	[-]	0.71
Heat Storage Unit Cost Function (annualized costs)			
$C_s=C_{0s}+C_{rs}\bullet V\hat{}m_s$	C_{0s}	[CHF/an]	0
	C_{rs}	[CHF/(m^3•y)]	1504
	m_s	[-]	0.71

Figure 2 represents the TAM composites (in energy) for a process $\Delta T_{min}=11.5$°C, and one possible so-called "storage composite". The proposed storage system includes 4 HSUs which are assumed to be of the constant temperature – variable mass (FTVM) type. Unlike the Permutation Method described in references [1, 2] however, the heat storage fluid is always moved (transferred) from one HSU to the next adjoining one, i.e. a storage stream is not allowed to bypass an intermediate HSU by leaving e.g. HSU_k to directly enter in HSU_{k+2}.

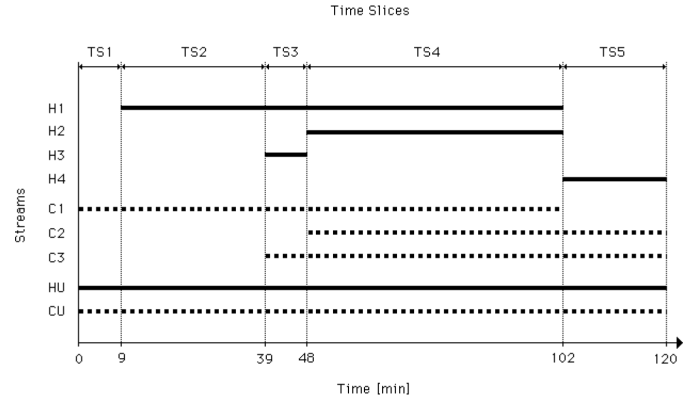

Figure 1: Time Event Model (Gantt Diagram) of example process EP1.

Under this assumption, a storage sub-system (Sss) is made of a couple of adjacent HSUs, which means that the storage system shown on **Figure 2** includes three Sss.

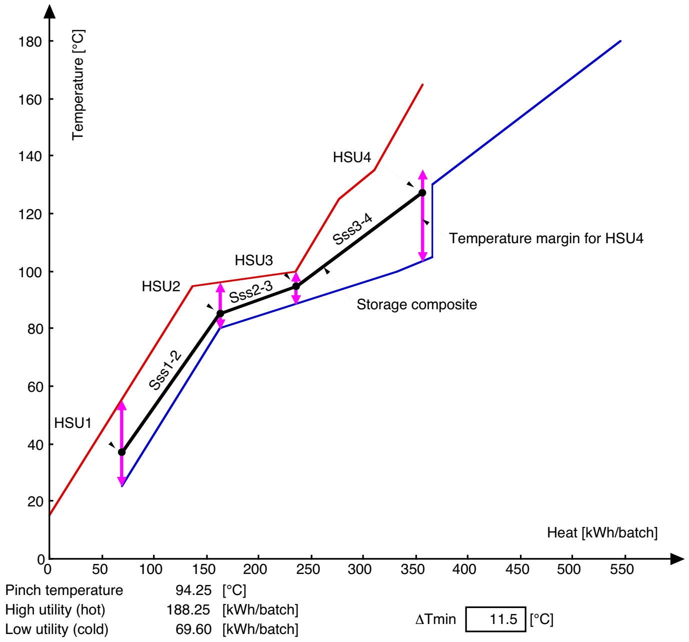

Figure 2: Time Average Model (energy) composites, heat storage units, and storage composite – process EP1.

It is further assumed that each HSU has to be self mass-balanced over a batch cycle without resorting to utility supply or mixing between HSUs. This means that within each Sss, the heat recovered from the connected hot streams is equal to the heat supplied to the connected cold streams.

The temperature margin of each HSU, defined as the feasible range of operating temperature for that HSU, is determined using the rules proposed in reference [5]. Since an additional intermediate HSU has to be introduced whenever the temperature margin of an existing HSU falls to 0°C or below, these rules also allow to target for the minimum number of HSUs, as explained in Section 2.2.

As mentioned above, the global IHRS for the example considered includes three Sss, namely $Sss_{1\text{-}2}$, $Sss_{2\text{-}3}$, $Sss_{3\text{-}4}$. Each sub-system operates in a vertically defined heat recovery region (which ensures individual heat/mass balance of the HSUs). Links between Sss obviously exist since, e.g., HSU_3 is the hot HSU of $Sss_{2\text{-}3}$, and at the same time the cold HSU of $Sss_{3\text{-}4}$.

The simplified nature of the model (TAM composites, vertically defined Sss HR regions, etc.) allows for simple first order solutions to be found. The designer is ultimately interested in identifying the most cost-effective IHRS(s), requiring that major DOFs be explored and optimized to reach minimum total annual costs

(TACs) solutions. The DOFs are (assuming a 100% indirect heat recovery):

- the amount of HR (or a process ΔT_{min}, by analogy to the single DOF of continuous processes at the targeting stage – but the HR is a better choice because of the unicity of the costs versus HR relationship);
- the number of HSUs, which is a fundamental structural dimension of the problem;
- the actual assignment of the HSUs, i.e. which HR region is assigned to (or "covered by") each Sss;
- the operating temperature of each of the HSUs (trade-off between HSU costs and heat exchanger (HEX) costs);
- the "cut-off" temperatures of each stream with respect to the Sss (i.e. the heat contribution of each stream to each Sss), subject to the constraint of heat balance of each Sss. This will account for variations of the heat transfer film coefficient and of the "duty ratio" of streams, but also for the effect of the sequence of sink/source of heat on the HSU capacities and of the constraining supply temperatures;
- the rescheduling of streams (in particular storable process streams) to decrease the capacity of costly HSUs, if rescheduling is acceptable. IHRSs are less sensitive to scheduling variations than direct batch heat exchanger networks (HENs), but still the capacity of HSUs can be influenced;
- the possible re-use of HEXs between streams which exhibit similar thermo-physical properties and which are chemically compatible.

Despite these numerous DOFs, IHRSs are structurally much simpler compared to direct HENs, in that there is no need for splitting process streams since the flow-rate of storage streams can be freely adjusted.

2.2 Targeting for the minimum number of HSUs

The number of HSUs is a key structural decision in the design of IHRSs. Like for continuous processes, for which a target of the minimum number of units can be defined, a target of the minimum number of HSUs can be calculated based on the simplifying assumption of vertically defined HR ranges of Sss and of arbitrary schedule of streams. This last assumption means that, in doing so, the supply temperature of each process stream has to be taken into account. It is reasonable to assume that minimum costs IHRSs shall be found quite close to the HSU target value.

Consider **Figure 2** : to totally recover heat from the vertically defined HR regions, the first and last HSUs have to be assigned at the cold end, respectively at the hot end of the overall HR region. The problem is actually the number and the assignment (operating temperature, HR range) of intermediate HSUs. The rule proposed by Sadr-Kazemi & Polley [5] can be formulated as follows: the operating temperature of any HSU has to be higher than the highest supply[2] temperature of the cold streams included in the Sss on the right of the considered HSU, while it also has to be lower than the lowest supply temperature of the hot streams included in the Sss on the left of the same HSU. Hence the operating temperature of a HSU is constrained upwards by hot streams, while it is constrained downwards by cold streams. The proposed systematic procedure is an application of this formulation.

The above formulation actually contains several cases: an intermediate HSU can be imposed (i.e. the heat recovery range of the Sss be limited) by cold streams only, by hot streams only or by both. To minimize the number of HSUs, the HR range (or region) of a Sss has obviously to be maximized. The starting point can be either the hot end or the cold end of the heat recovery region, providing two boundary cases.

The following graphic based procedure allows for more insight in the constraints introduced from both the supply temperature of streams, and the shape of TAM composite curves. It begins with adjoining the TAM composites with so-called "limiting supply temperatures profiles" (LSTPs), as represented on **Figure 3** by the step curves below the cold composite, respectively above the hot composite. The hot LSTP (cold LSTP, respectively) defines the most constraining hot stream (cold stream, resp.) supply temperature as a function of the vertically corresponding position on the hot composite (cold composite, resp.).

Once the LSTPs have been drawn, the upper boundary position of HSUs can be determined with respect to the cold composite using the following procedure (refer to **Figure 3**):

1) the first heat storage unit (HSU_1) is of course assigned to the cold end of the HR region (point a);
2) from a, move vertically to the hot composite, defining the highest possible supply temperature of cold streams to be included in the storage sub-system (point b). Point b is not constrained by hot streams (actually it is never constrained, since it is the cold end of the heat recovery) and hence represents the absolute maximum operating temperature of HSU_1. Therefore moving horizontally to the vertical segment of the cold LSTP (point c) defines all cold streams (if any) which supply temperature is compatible with Sss_{1-2} and identifies which cold stream requires the introduction of a new heat storage unit (in this case cold stream C3);
3) the cold LSTP segment can be extended to a vertical line, which intersects the cold (point d) and hot (point e) composites. This defines the location of HSU_2 with respect to the supply temperature of the cold streams. Yet it remains to be verified whether the supply temperatures of the hot streams are not more constraining than that of the cold streams (a case that would be encountered e.g.

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[2] According to the definition used in **Table 1**, "supply" temperature means the temperature at the inlet of a stream and "target" temperature means the temperature at the outlet of a stream.

with a process including only one cold stream but several hot streams). This is checked by searching for the intersection of the vertical line passing through point c and the horizontal line passing through the first supply temperature encountered starting from point b (here hot stream H2);

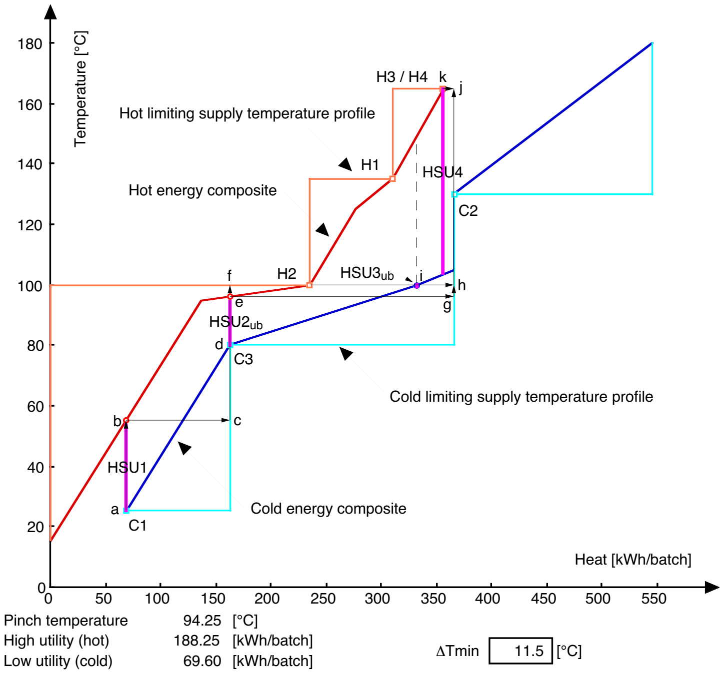

Figure 3: Limiting supply temperature profiles, and the determination of the minimum number of heat storage units with respect to the cold energy composite – process EP1.

4) if the intersection (point f) is above point e (i.e. above the hot composite), hot streams are not constraining at all, i.e. no hot stream starts in the identified storage sub-system Sss_{1-2}. If the intersection is located between point e and d (i.e. in the inter-composite region), the hot streams constrain the operating temperature of HSU_2, but not its location (heat recovery range). If the intersection is located below point d (more generally below the cold composite), the hot streams are more constraining than the cold streams, since they do not only constrain the operating temperature of HSU_2, but also its location, which has to be shifted to the left (see point 7 below for the procedure relevant to this case);
5) point f actually lies above point e, hence HSU_2 can be kept as such. The operating temperature of HSU_2 is not constrained on the hot side and point e represents the maximum operating temperature of HSU_2, and hence moving horizontally to the vertical segment of the cold LSTP (point g) will define the streams which supply temperature is compatible with Sss_{2-3} and identify which cold stream requires the introduction of a new HSU (here cold stream C2);

6) the vertical line passing through point g lies outside the heat recovery range, indicating that HSU_3 could maybe be located at the hot end of the HR range and that the minimum number of HSUs would be 3. But it remains to be verified whether the hot streams are not more constraining than the cold streams;
7) this is checked by searching for the intersection of the vertical line passing through point g and the horizontal line passing through the first (hot) supply temperature encountered starting from point e (here again hot stream H2). The intersection (point h) is located below the cold composite, and the maximum «allowable» location of HSU_3 is actually point i. If HSU_3 is located at point i, its operating temperature is constrained to be lower than or equal to the supply temperature of H2, while at the same time higher than or equal to the temperature of the cold composite at point i, i.e. the operating temperature of HSU_3 is pinched on both sides;
8) moving again horizontally from the highest possible operating temperature of HSU_3 (i.e. temperature of point i) to the cold LSTP defines point h again. But the intersection of the vertical line passing through h and the horizontal passing through the first (hot) supply temperature above (on the right) of HSU_3 (H3/H4) defines point j, which is located outside the HR range. Therefore HSU_4 can be located at the hot end of the HR region, and point j (representing the maximum operating temperature of HSU_4) be translated to point k;
9) finally, starting at the cold end, 4 HSUs are required. The (possibly) constraining supply temperature of cold streams are accounted for by increasing the lower boundary of the temperature margin of storage. Such a case is not found here, since the lower boundary on the operating temperature of all HSUs is defined by the cold composite itself.

The same procedure can be applied starting from the hot end, reversing the role of the hot streams and of the cold streams, which provides the lower boundary position of HSUs. **Figure 4** represents the upper and lower boundary positions of HSUs, defining the feasible assignment ranges. The procedure described above may sound complicated, but it has the advantage of being general and of providing insight in assessing various opportunities for modifications.

To summarize, the above procedure provides with the minimum number of HSUs as well as their feasible assignment range as a function of the amount of HR. Since this number of HSUs is a target value based on simplified assumptions, cases exist which can be integrated with less HSUs, for example in cases when:

- the introduction of an additional HSU may be avoided (up to a certain increase of HR) by removing a constraining small process stream or by resorting to criss-cross[3] heat exchanges (generally for streams with a large thermal capac. (MCp));

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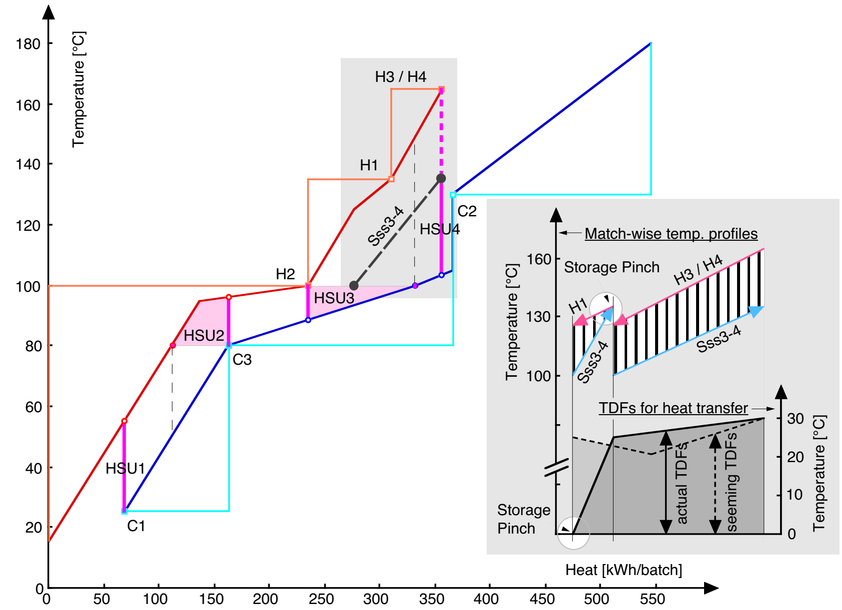
[3] This term refers to heat exchanges which significantly deviate from the case of vertical heat transfer between composites curves, in that some heat exchanges use larger TDFs than the ones available vertically, imposing as a consequence, that other have to cope with proportionally smaller TDFs.



Pinch temperature	94.25	[°C]
High utility (hot)	188.25	[kWh/batch]
Low utility (cold)	69.60	[kWh/batch]

ΔTmin 11.5 [°C]

Figure 4: Heat recovery and operating temperature ranges for the minimum number of heat storage units – process EP1.

- some supply temperatures are actually “wiped-off” (or “covered”) by that of another stream which is simultaneously present. This way of defining the minimum number of HSUs, which considers the start temperature of the hot and the cold composites of each time slice of the batch cycle, is advantageous with respect to the number of HSUs, but is plagued with the drawback of requiring more complicated HEN structures (for which the feasibility has to be systematically checked) and being sensitive to variations of the schedule. This approach shall not be described in detail in this paper but should be kept in mind as a cost improvement opportunity (refer to [7]).

2.3 The proposed heuristic “targeting” search method

The basic principles of the search method are demonstrated on the EP1 process. Consider **Figure 5**, which represents the TACs of IHRSs as a function of the amount of HR; configurations including several numbers of HSUs are calculated, for which the HR ranges of the Sss are defined vertically in every case. The operating temperatures of HSUs are optimized using a Generalized Reduced Gradient (GRG) algorithm, as implemented in the Solver Tool of Microsoft Excel. The discrete nature of HEXs and HSUs is taken into account when calculating their costs, i.e. these costs are practical design costs of simplified configurations rather than “traditional targeting” costs.

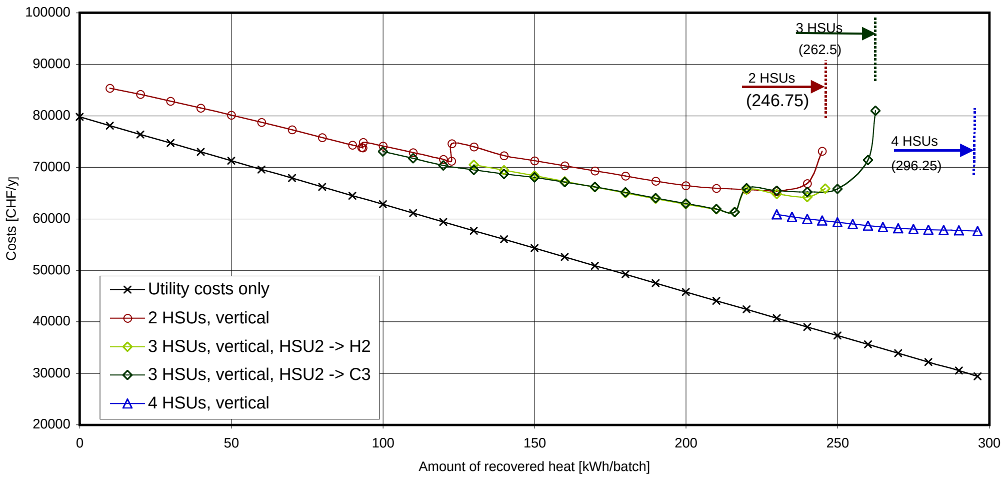


Figure 5: Total annual costs of indirect heat recovery – process EP1 with 2, 3 and 4 heat storage units, assuming a vertical definition of the heat recovery range of storage sub-systems.

Starting with two HSUs and a small heat recovery, the amount of HR is progressively increased. The TACs decrease smoothly as the HR increases, reach a minimum, then increase steeply (if not suddenly). This is due to the introduction, in the HR range of one of the HSUs, of a constraining stream (constraining supply temperature) which suddenly restricts the range of feasible operating temperature (or even makes it infeasible), which results in an increase of HEX and HSU costs. The maximum HR for 2, 3 and 4 HSUs in vertically defined Sss ranges are indicated[4]. The sudden infinite increase of TACs appears for HR>296.25 kWh, since the introduction of stream C2 in the HR range requires a fifth HSU to be introduced.

Analysis of the above observations reveals that the existence of local minimums and of sudden increases of the TACs is due to HSUs which temperature is pinched in a discontinuous manner each time a constraining supply temperature of streams becomes active. This so-called storage pinch effect has similarities as well as differences with the "traditional" process pinch.

A storage pinch is a temperature pinch in heat transfer from (to, resp.) a process stream to (from, resp.) a storage stream. It limits the HR for a given number of HSUs (while the process pinch remains the fundamental limitation to HR, whatever large the number of HSUs). But unlike the process pinch, the storage pinch isn't readily obvious on the TAM including the storage composite. This

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[4] As described in section 2.2, each of the intermediate HSUs has to be defined anywhere within its feasible range (see ranges of feasible assignment of HSU_2 and HSU_3 on **Figure 4**). One way of choosing the position, which is likely the most beneficial strategy and was adopted here, is to assign them to a supply temperature. But cases may be found in which several streams may start in a feasible range (i.e. the feasible range includes several supply temperatures). In such cases, each of the various configurations resulting from assignments to each of these supply temperatures should be systematically evaluated. Such a case is found for EP1 with an IHRS including 3 HSUs: HSU_2 may either be assigned to C3 or to H2 (refer to **Figure 5**).

difficulty is demonstrated by comparing the actual TDFs with the seeming TDFs, as represented in the grey box on the right of **Figure 4**, assuming that HSU_3 is assigned to point a and HSU_4 to point b. The actual TDFs result from the composition of the match-wise temperature profiles (H1 – $Sss_{3\text{-}4}$, H3/H4 – $Sss_{3\text{-}4}$), while the seeming TDFs correspond to the vertical temperature difference between the portion of the hot TAM composite (including H3/H4 and part of H1) and the "storage composite" associated with $Sss_{3\text{-}4}$.

A storage pinch can be identified on the match-wise temperature profiles, while the actual TFDs plot is better suited to assess whether the storage pinch effect is very local (i.e. only a very small amount of HR is pinched, while the large remaining HR benefits from large TDFs – as is the case on **Figure 4**) or affects a large amount of the HR of a Sss. Storage pinch values as low as 1°C found in cost optimal IHRSs are to be explained by this very local pinch effect. In the processes analyzed so far, the storage pinch effect (hence the number of HSUs) are deciding the optimal trade-off between heat recovery and capital costs before any process pinch comes into play.

After approximated TACs "targets" have been obtained using the simplified assumption of vertically defined HR ranges (in short the vertical model), improved solutions may be searched for by systematically removing one bottleneck at a time (most generally constraining supply temperatures of streams). The constraints can be removed by relaxing the assumption of vertical model, which can improve the HR within a limited range.

Opportunities include the removal of constraining streams from the otherwise unconstrained Sss, or criss-cross heat exchanges to avoid (or delay) the action of constraining supply temperatures. Sufficient TDFs should be available for these strategies to be meaningful (see [7] for more details). Improvements over the vertical model are highlighted on **Figure 6**, which also includes, for comparison purposes, the TACs for a direct HEN design (refer to [4]), and for mixed direct-indirect heat integration, described in Section 2.4. The case of 3 HSUs with criss-cross features a significant HR improvement over the vertical model.

For a simple process such as EP1, the scope for a further fine optimization of continuous DOFs is limited, even non-existent. Work is under way to verify that the methodology is equally suitable to more complex, industrially relevant batch processes. The combinatorial dimension and the limited suitability for optimizing continuous DOFs like the cut-off temperatures are two main issues to be verified. A new approach to the design & optimization of IHRSs based on genetic algorithms (GAs), presently in development, shall hopefully provide reference data and allow for the assessment of the quality of the solutions provided by the present heuristic "targeting" methodology.

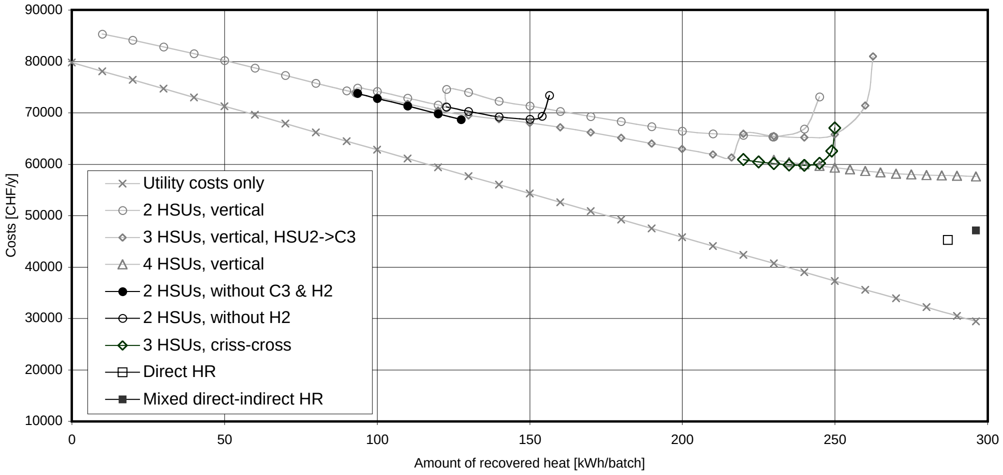

Figure 6: Achievable reduction of total annual costs by relaxing the "vertical model" constraint, compared to direct and mixed direct-indirect heat integration solutions – process EP1.

2.4 Extension to direct-indirect heat integration

The cost-effectiveness of an indirect heat integration can generally be improved by resorting on particular direct heat exchanges which are not sensitive to variations of the process schedule (i.e. the reduction of TACs is not achieved at the expense of decreased operating flexibility). In the context of a Pinch Analysis approach, these opportunities are identified using heuristics rules. Very first trials have resulted in a few guidelines.

Direct matches should decrease the capital costs (both the HEX and HSU costs) without adding significant complexity or operability problems to the HR scheme. Therefore direct matches shall rather be «one-to-one» matches, at any time. The following guidelines for identifying potential direct heat recovery matches can be drawn:

- obvious preliminary conditions are feasible temperature driving forces and overlapping time schedule;
- a significant amount of heat recovery (when compared to the 100% indirect HR) should be possible;
- potential candidates for a beneficial direct heat recovery are streams with significant thermal capacities MCp which are either constraining a HSU (particularly if the specific cost of HSUs is relatively high) or have a relatively low heat transfer film coefficient[5], for which a "suitable" stream of opposite type can be found. A "suitable" stream means that the temperature driving forces of the match are smaller or equal to that on the TAM composites (otherwise the cost-efficiency of the indirect heat recovery is penalized);
- stream matches, for which one of the streams is completely superposed to the

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[5] In direct heat exchange, the temperature driving forces are inherently larger.

other in time (with sufficient margin) and has an adequate temperature range, are good candidates for direct matches.

A more systematic strategy could be to apply a direct heat integration analysis and extract only schedule insensitive, large one-to-one matches as candidate direct HEXs.

The optimization variables are chosen to be the overall HR and the ΔT_{min} of individual direct matches. Note that choosing the match-wise HR instead of match-wise ΔT_{min} is not sensible because of frequent "threshold" matches (similar to so-called threshold processes).

In the case of EP1, direct matches H1-C1 and H2-C3 have been selected, while the remaining parts of the streams, which could still be integrated, were taken into account in the indirect TAM composites. Stream H2 (which features a larger MCp compared to C3) is split into two sub-streams - one for a direct HR match with C3, and one for an indirect HR match with a storage stream. Using a parallel rather than a serial configuration allows to increase the TDFs in indirect HR, which are most critical, at the expense of slightly reducing the TDFs available for direct HR.

The minimum TACs have been searched for with 2, 3 and 4 HSUs, assuming a vertical definition of each storage sub-system. The minimum TACs solution is found to be only 4% more expensive than that of the direct HR (refer to [4]), and 18% cheaper than that of the 100% indirect HR. The cost optimum mixed HR scheme includes 2 HSUs and features $\Delta T_{minH1\text{-}C1}$=12.5°C, $\Delta T_{minH2\text{-}C3}$=2.5°C, and overall HR=296.25 kWh/batch, of which 66% is transferred by the direct matches - refer to **Figure 6**).

The optimization has been performed by trial and error. Unlike the case of 100% indirect HR, the mixed mode is really difficult to optimize. The shapes of TAM composites for indirect HR are changed each time the match-wise ΔT_{min} are adjusted, requiring frequent changes to the assignment of the HSUs to be made. Complex trade-off effects are observed.

This simple trial confirms that the optimization of a mixed direct-indirect heat recovery can only be addressed by automated synthesis methods. Nevertheless it provides with some useful insight, e.g. with respect to the type of simple mixed direct-indirect HEN configurations to be taken into account in an automated synthesis approach.

3 Conclusion

Firmly based on Pinch Analysis principles, the proposed methodology allows for the screening of major decisions regarding the indirect heat integration of batch processes. Unlike the competing (or rather, complementary) Permutation Method (PM), this methodology provides the designer with significant insight in the problem. Graphical tools are proposed for the definition of the minimum number (target) of HSUs to achieve a given heat recovery (HR). A total annual costs

(TACs) versus HR diagram helps in understanding the trade-offs and highlights the key role of constraining supply temperatures and the resulting storage pinches in generating local minimums.

The methodology also differs from the PM in some basic assumptions (e.g. with respect to the way process streams are matched with HSU/Sss and the required mass-balancing strategy). Fine tuning of the operating temperature of HSUs is efficiently achieved using a GRG algorithm. More case studies are needed to verify the quality of the provided IHRSs, and the consequences of the simplifying assumptions.

A stochastic design & optimization approach using genetic algorithms, presently in development, shall hopefully establish a reference database, allowing for the assessment of the quality of the solutions provided by the proposed “targeting” methodology.

A general heat integration would resort to mixed direct-indirect heat recovery schemes. Although simplified guidelines are proposed for the selection of direct matches insensitive to schedule variations, the optimization of such schemes is a major problem and complex trade-off effects are observed.

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