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Non-continuous and Variable Rate Processes: Optimisation for Energy Use

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The need to develop new and improved ways of reducing energy use and increasing energy intensity in industrial processes is currently a major issue in New Zealand. Little attention has been given to optimisation of non-continuous processes in the past, due to their complexity, yet they remain an essential and often energy intensive component of many industrial sites. Novel models based on pinch analysis that aid in minimising utility usage have been constructed here through the adaptation of proven continuous techniques. The knowledge has been integrated into a user friendly software package, and allows the optimisation of processes under variable operating rates and batch conditions. An example problem demonstrates the improvements in energy use that can be gained when using these techniques to analyse non-continuous data. A comparison with results achieved using a pseudo-continuous method show that the method described can provide simultaneous reductions in capital and operating costs.

Keywords: energy optimisation, non-continuous and variable rate processes, heat integration, pinch analysis, OBI software

Introduction

There is a growing uncertainty in New Zealand surrounding the future availability of cost effective energy supply. To reduce reliance on increasingly expensive fuel sources and to diminish the need for further generating capacity, New Zealand needs to become more energy efficient. Unless this concern is dealt with there will continue to be reliance on less secure and more expensive energy supplies, which will impact on the competitiveness of New Zealand industry.

New Zealand used 471 PJ of energy in the year ending March 2002, which on a per capita basis equates to twice the energy use compared with 1960. A third of New Zealand's primary energy consumption is used by the industrial sector. Many of these sites are large-scale, energy intensive and have variable production rates or non-continuous processes. The varying operation is due to the production of multiple grades and products, as well as the impact of external factors such as the electricity spot market. This provides opportunities for industries, for example dairy and pulp and paper, where small increases in efficiency will realise significant net savings.

The development of technological solutions for energy optimisation is a timely issue and crucial to the New Zealand economy. Their implementation will increase industrial efficiency, helping to decouple rising energy demand from economic (GDP) growth. Process heat integration is a successful field of engineering and formal methodologies such as pinch analysis have been developed and used in the past with proven and useful results. However, application to non-continuous and variable rate processes remains as an unexploited and potentially valuable new direction. The increased cost of energy will also make many process improvements viable that were previously nonviable, providing further opportunities to improve the energy efficiency of these sites.

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Pinch Analysis

The formulation of pinch analysis as a process integration tool occurred in the 1970's, and can be attributed to concepts developed by Hohmann[1], Linnhoff and Flower[2,3], and Umeda et. al.[4,5]. It has been successfully applied to an array of industrial operations, and has generated significant energy savings in industrial applications. The majority of present pinch analysis methods still assume that the industrial processes are continuous. Methods concerning how to deal with batch or other non-continuous processes are inadequately developed. While batch plants are generally smaller scale than continuous operations, they can require considerable utilities. This is because their heating and cooling requirements are often met through utilities rather than via heat exchange (see Lee and Reklaitis[6]). Gaining the same reductions in energy from batch processes is intrinsically more difficult due to the time dependent nature of the process streams.

As energy savings obtainable from batch processes are less than those from continuous processes, less effort has been put into investigating rigorous methods for batch heat integration. A greater amount of attention is now being placed on heat recovery in non-continuous processes due to the growing requirement for high value biochemical products that rely on batch operations (see Zhao et. al.[7]). Due to the scarcity of appropriate pinch analysis methods, large percentage savings are possible (see Lee and Reklaitis[6]).

In addition to energy savings, there are opportunities for significant improvements in the operability of non-continuous processes. By taking in to account the variable operating rates at different stages of the process, possible operability and control issues can be eliminated early in the analysis. This can prevent design problems from occurring during constrained time intervals such as start up, shut down and other transition periods.

The very early work on batch processes implemented a "pseudo-continuous" approach where the heat flows were averaged over the entire operating period. This is a simple approach and only a small proportion of the predicted savings were ever achieved in practice (see Kemp and Deakin[8]). The first quantitative study on heat recovery in batch processes was carried out by Vaselanak et. al.[9]. They investigated heat recovery between vessels as heat was added or removed, but did not introduce the time dependence of streams.

Kemp and MacDonald[10] took a different approach by applying the pinch method to a batch process. As well as integrating heat, they proposed time intervals that allowed the construction of time dependent heat cascades, which in turn provided targets for the amount of heat exchange and heat transfer. The following paper (see Kemp and MacDonald[11]) expanded on this work to include the design of heat exchanger networks and the effects that schedule modifications could have on heat recovery in batch processes. Kemp and Deakin[12,13] and Kemp[14] showed in greater detail how cascade analysis could be applied using a case study of a specialty chemical batch plant, as well as a hospital site. Concurrently, Obeng and Ashton[15] used a time-slice model to identify heat exchange opportunities, but their work, containing only direct heat transfer, was limited in comparison to the direct and indirect options highlighted elsewhere.

The most recent work directly related to heat integration for batch processes was published by Zhao et al.[7]. A systematic mathematical formulation was presented for the scheduling of cyclically operated batch processes. It is based on cascade analysis and involves heat integration but no intermediate storage. This led to a mixed integer non-linear programming model that finds the optimal schedule under countercurrent heat exchange, allowing other modes to be introduced after rescheduling. A three-step design procedure for heat exchanger networks for batch processes was also proposed (see Zhao et al.[16]). This involved the initial individual design, a rematching design, and a final overall design that is obtained through optimisation of the whole system.

There is a lack of literature published in the last seven years that is strongly applicable to heat integration of non-continuous processes. Work by Tantimuratha and Kokossiss[17] pointed out that heat exchanger networks are still designed under the assumption of fixed operating conditions, leading to reductions in efficiency when the nominal conditions are not in operation. They propose addressing flexibility during the targeting and network development stages to increase efficiency under different conditions. While this is not batch processing *per se*, it does highlight the importance of investigating non-continuous systems.

Process Description

A test case was created to demonstrate the value of the proposed methodology, similar to the approach used by Kemp and Deakin[12] and Obeng and Ashton[15].

Stream data for the example case are displayed below in Table 1. All streams are available for matching and only direct counter-current heat exchangers with a minimum temperature difference of 10°C are employed. The pinch methods for batch processes as described by Kemp and Deakin[8] were followed to calculate the required information. Heat storage and process rescheduling have not been implemented at this time, but will be included in future analysis.

Table 1. Process data at maximum (100%) operating rate

Name	Type	Inlet Temp °C	Outlet Temp °C	FCp kW/°C	Energy Flow kW
H1	Hot	160	40	165	19800
C1	Cold	30	105	120	9000
H2	Hot	175	65	60	6600
C2	Cold	80	150	250	17500

Operating Conditions

Added complexity is introduced through varying the data set through time. This was achieved by setting four different operating rates, each a linear scaled version of the maximum operating rate.

Table 2. Operating conditions for process streams

Operating Rate (percentage of maximum)	Frequency (percentage of overall time)
100%	10%
90%	60%
50%	20%
0%	10%

This method of simulating a variable operating rate process is notably different to previous published batch examples. In a typical batch process individual streams will be in operation for certain portions of the overall process timeline. While their occurrence will vary, whilst present, they will be at fixed conditions. Instead of "turning-on-and-off" different streams at different times in this manner, the operating rates of all four streams were adjusted across multiple time intervals.

As Table 2 shows, four different operating rates were used at different stages of the overall process. As only direct heat exchange was being considered there was no need to construct a schedule; the frequency of each operating rate was sufficient.

The second modification involved adding a fifth stream to the process as shown in Table 3.

Table 3. Extra stream at maximum (100%) operating rate

Name	Type	Inlet Temp °C	Outlet Temp °C	FCp kW/°C	Energy Flow kW
C3	Cold	20	200	70	12600

Table 4 shows the relationship between the operating rate of the main four stream process and the operating rate of the fifth stream, C3. It can be considered that C3 is required as an export stream to another process. When the four stream process is 100% operational it is completely fulfilled, while at 50% no export is possible.

Table 4. Operating Conditions for extra stream

Process Operating Rate (percentage of maximum)	5th Stream Operating Rate (percentage of maximum)
100%	0%
90%	20%
50%	100%
0%	100%

Without the addition of the fifth stream the process could be averaged out and represented as a continuous system. It would be relatively simple to obtain the optimal network, taking in to account the overall time period, as the configuration of the network would remain the same in each interval.

Results and Discussion

The network created using the process data from Table 1 is displayed in Figure 1. When this four stream example is subjected to the various operating conditions in Table 2, the general structure of the network is not altered. The duty of each heat exchanger is simply scaled in size in direct relationship to the change of operating rate. Addition of the fifth process stream produces a variation in the network structure due to the different combination of operating rates.

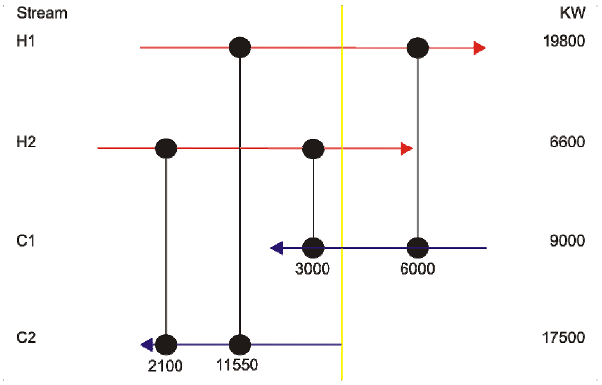


Figure 1. 4 Stream Example

The way in which the stream data were altered is different to the methods used when dealing with a batch process. However, it has a similar effect in altering the properties of the streams in the different time intervals, leading to a need for various network structures.

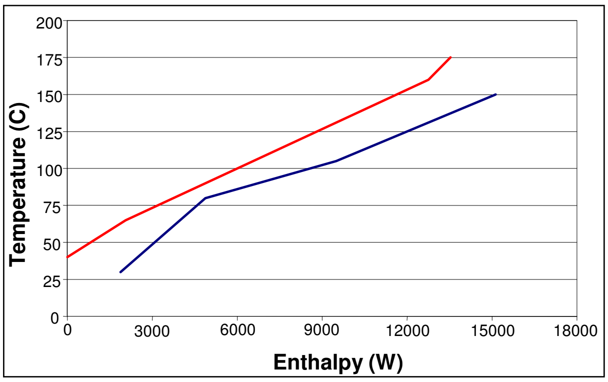


Figure 2. 4 Stream Example - Composite Curves

The expected variation in the network structures is particularly evident when examining the composite curves shown in Figures 2 and 3 below. There has been a shift in the location of the pinch point, which will lead to major changes in the way that the heat exchanger network is configured.

The network in Figure 4 displays the design that was reached when a pseudo-continuous analysis was carried out on the process data. The results obtained are infeasible, as a large amount of the heat integration shown could not be obtained via direct heat exchange. This was because not all the streams existed at the same time to allow heat to flow between them.

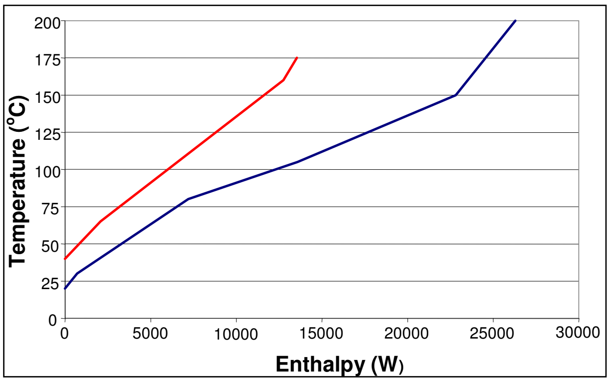


Figure 3. 5 Stream Example - Composite Curves

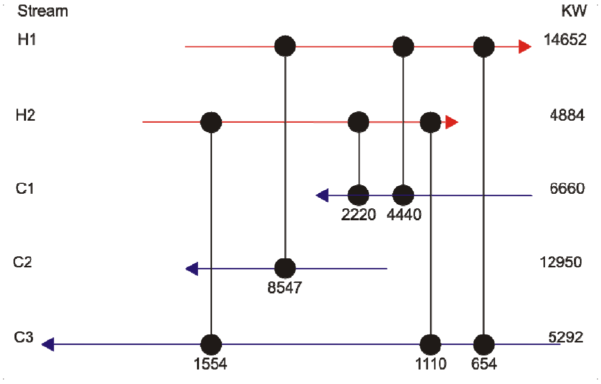


Figure 4. 5 Stream Example – Infeasible Pseudo-continuous Network

By analysing each heat exchanger match individually it is possible to calculate the feasible network that contains only direct heat exchange. It is worth noting that one of the proposed heat exchangers is made completely redundant as identified by its duty being reduced to zero. It can be eliminated as it would not be utilised at all for direct heat exchange. The feasible network is shown in Figure 5, with an amended design displayed in Figure 6.

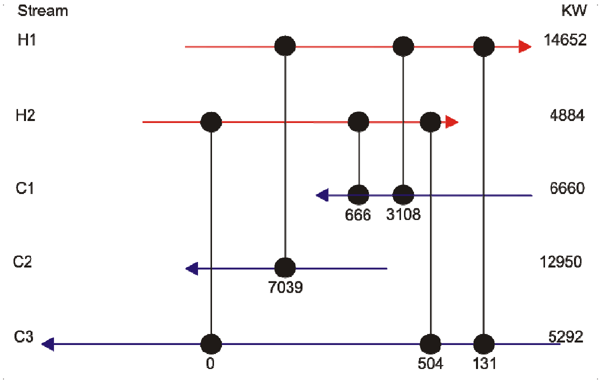


Figure 5. 5 Stream Example – Feasible Pseudo-continuous Network

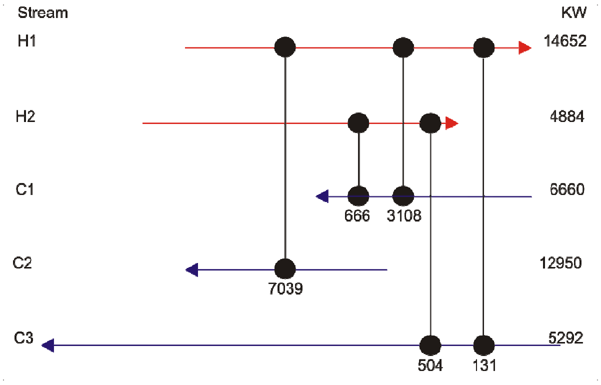


Figure 6. 5 Stream Example – Feasible Pseudo-continuous Network with Exchanger Removed

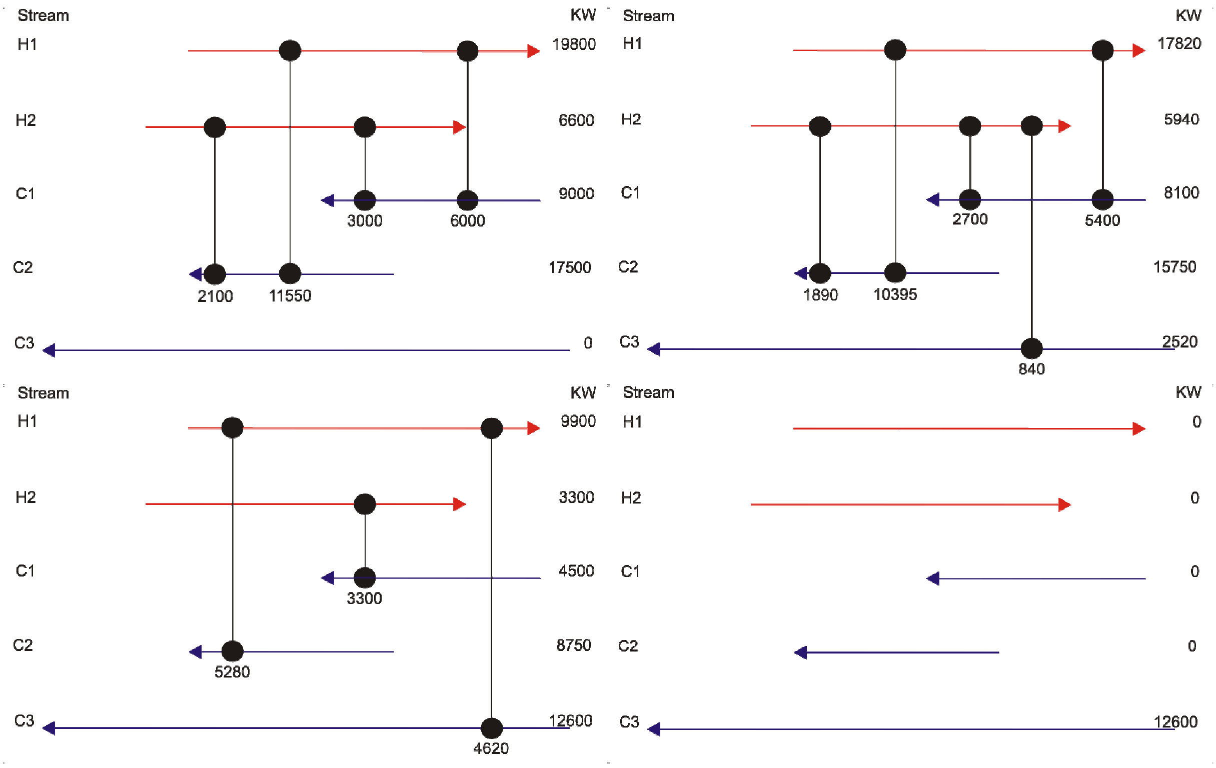


Figure 7. 5 Stream Example – Optimal Network for Each Operating Level

Once a pseudo-continuous target was reached, the improved method was used to generate an optimal non-continuous design. Individual network designs as shown in Figure 7 were generated for each time interval. Each heat exchanger network clearly showed variations from both the pseudo-continuous design and the other individual networks. In addition, some of the proposed heat exchangers transferred heat across the pseudo-continuous pinch point. These potential designs would not be generated using averaging techniques in combination with pinch analysis methods.

By combining all of the individual network designs from each time interval the optimal overall network for the non-continuous process was generated. It contains six heat exchangers and is displayed in Figure 8.

When the optimal network design is compared to the pseudo-continuous network design a number of similarities in the position of heat exchangers are evident. The same five matches between streams are identified, as well as an additional match between streams H2 and C2 that was not included in the pseudo-continuous network design.

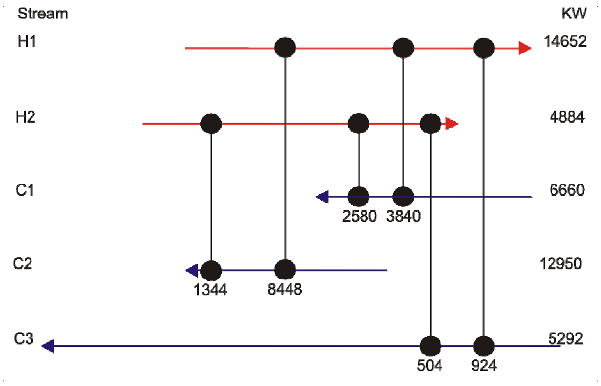


Figure 8. 5 Stream Example – Optimal Overall Network for Operating Conditions

The optimal network design can be adjusted so it also implements only five heat exchangers. Figures 9 and 10 show two possible designs where one heat exchanger has been removed. Both these designs utilize slightly less heat exchange from the network, and require a small amount of additional utility.

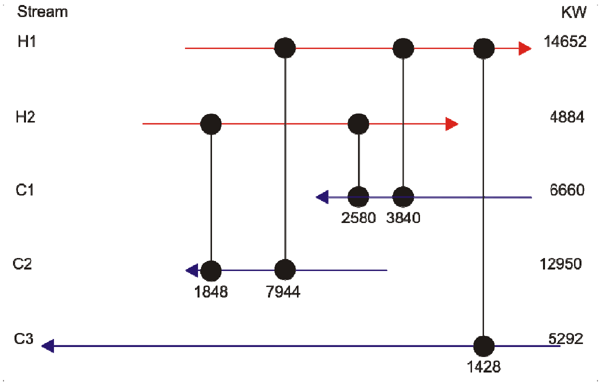


Figure 9. 5 Stream Example – First Alternate Optimal Overall Network with Exchanger Removed

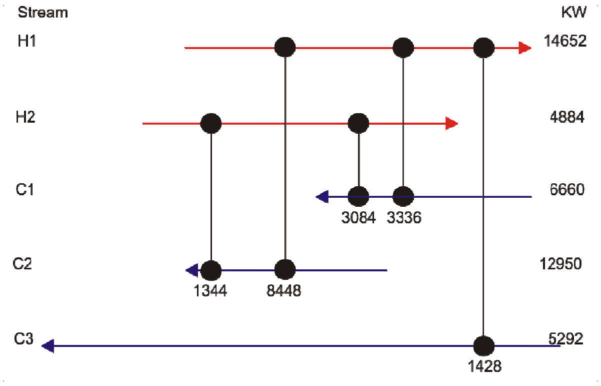


Figure 10. 5 Stream Example – Second Alternate Optimal Network with Exchanger Removed

Comparison of Results

The results from the analysis have been split into two sections. Table 5 displays a comparison between the heat exchange networks, while Table 6 compares the utility requirement for each of the different designs.

The Total HX Duty and the number of HX's together represent the proposed network designs. Due to the non-continuous nature of the processes, only part of this actual heat exchange opportunity is utilised. The results show that the optimal non-continuous designs require less total duty than the pseudo-continuous designs. They also utilise a greater amount of the heat exchange that is available, and the altered design does not require extra heat exchangers.

Table 5. Comparison of networks

	Total HX Duty kW	No. of HX's	Actual HX Utilised kW
Pseudo-continuous method – feasible network	18525	5	11448
Optimal non-continuous method – feasible network	17640	6	14492
Optimal non-continuous method – feasible network with 1 exchanger removed	17640	5	14275

As well as reducing the total heat exchange duty required, the optimal non-continuous designs also show an improvement over the pseudo-continuous design in utility requirement. A reduction of over 18% in total utility usage is possible by implementing the improved design. Once the extra heat exchanger is removed to match the pseudo-continuous design, this value decreases. However it still shows a considerable utility saving of over 15%.

Table 6. Comparison of utilities

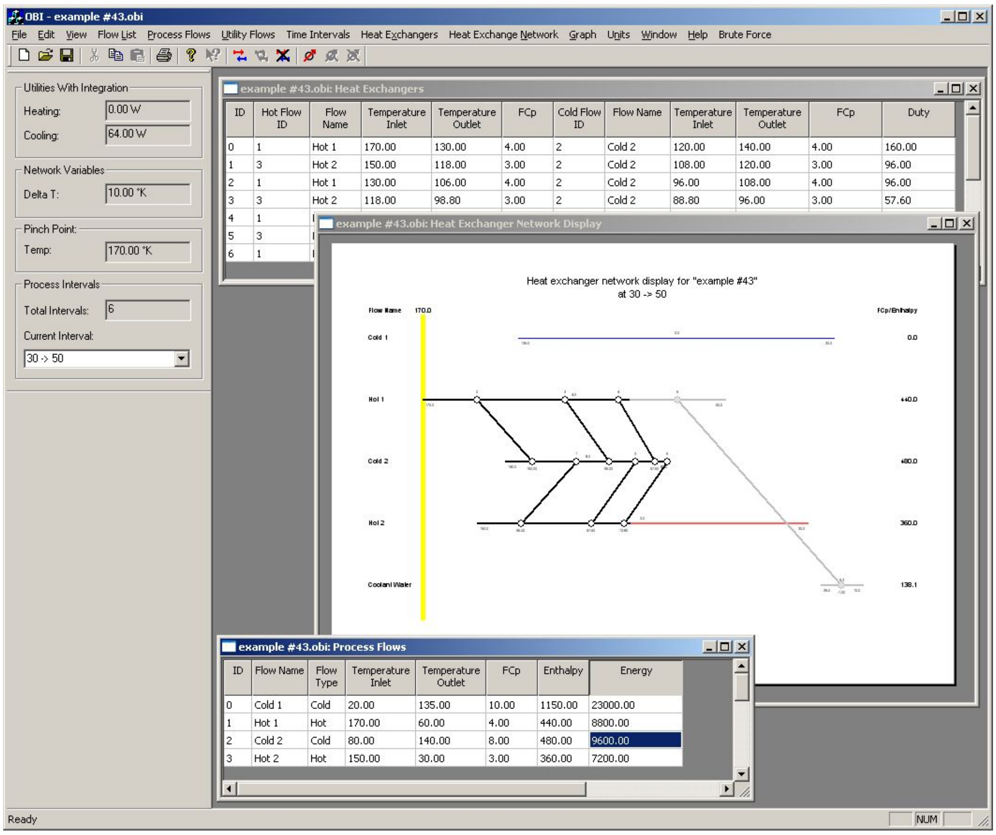
	Total Hot Utility kW	Total Cold Utility kW	Total Utility kW
Pseudo-continuous method – feasible network	12122	6756	18878
Optimal non-continuous method – feasible network	10400	5044	15454
Optimal non-continuous method – feasible network with 1 exchanger removed	10627	5261	15888

OBI Software

The models and methods shown in this paper, as well as additional algorithms, have been merged into a user-friendly software package known as OBI. This is being developed into a powerful tool that is able to receive and manipulate non-continuous and variable rate process data. Pinch analysis calculations can be carried out to reach a range of targets for different variables including hot and cold utility usages and heat exchanger network areas. These results from individual time intervals can then be combined to create the optimal overall design for the given process data. The overall design process is fully automated within the application, enabling any output to be reached with one click of a button.

OBI can also simulate and evaluate the cost of combinations of various operating conditions. While only one operating condition has been completed to the targeting level in this example, the cost of any design can be quickly evaluated. This includes any alterations to operating rates or heat exchanger networks as stipulated by the operator. Further development will extend the capabilities of the software, allowing it to be used on a wide range of practical case studies.

Currently investigations are under way, with the assistance of OBI, to analyse a non-continuous process plant. Actual plant operating data have been extracted under various operating conditions and used to model the optimal design. Once a full set of utility and capital costings are obtained the various opportunities identified by OBI will be further assessed. It is expected that they will highlight scenarios where economically feasible improvements are possible.



Utilities With Integration
Heating: 0.00 W
Cooling: 64.00 W

Network Variables
Delta T: 10.00 °K

Pinch Point:
Temp: 170.00 °K

Process Intervals
Total Intervals: 6
Current Interval: 30 -> 50

ID	Hot Flow ID	Flow Name	Temperature Inlet	Temperature Outlet	FCp	Cold Flow ID	Flow Name	Temperature Inlet	Temperature Outlet	FCp	Duty
0	1	Hot 1	170.00	130.00	4.00	2	Cold 2	120.00	140.00	4.00	160.00
1	3	Hot 2	150.00	118.00	3.00	2	Cold 2	108.00	120.00	3.00	96.00
2	1	Hot 1	130.00	106.00	4.00	2	Cold 2	96.00	108.00	4.00	96.00
3	3	Hot 2	118.00	98.80	3.00	2	Cold 2	88.80	96.00	3.00	57.60
4	1										
5	3										
6	1										

Heat exchanger network display for "example #43"
at 30 -> 50

ID	Flow Name	Flow Type	Temperature Inlet	Temperature Outlet	FCp	Enthalpy	Energy
0	Cold 1	Cold	20.00	135.00	10.00	1150.00	23000.00
1	Hot 1	Hot	170.00	60.00	4.00	440.00	8800.00
2	Cold 2	Cold	80.00	140.00	8.00	480.00	9600.00
3	Hot 2	Hot	150.00	30.00	3.00	360.00	7200.00

Figure 11. Screenshot of OBI software

Conclusions

Heat integration is an essential aspect of virtually all industrial processes due to its ability to reduce the amount of hot and cold utilities consumed, and consequently lower the operating costs of the process. While conventional pinch analysis has been successful in providing solutions for continuous processes, a different method is required to highlight the optimal design for non-continuous and variable rate processes.

The method shown can be used to provide significant improvements, compared to pseudo-continuous techniques, when dealing with non-continuous and variable rate processes. Simultaneous capital and operating reductions can be achieved, at this stage without the need for implementing rescheduling or heat storage capabilities. Further improvements are anticipated through developments such as altering the minimum temperature difference constraint within individual time intervals.

Development of the current OBI software will result in a user friendly tool for designing and analysing non-continuous processes. The dairy and pulp and paper industries represent two key opportunities within New Zealand where considerable energy savings are possible in variable production and/or non-continuous processing plants.

Acknowledgement

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