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Solving Complex Retrofit Problems using Constraints and Bridge Analysis

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The aim of this paper is to conduct retrofit analysis of large, complex industrial Heat Exchanger Networks using an automated Bridge Analysis. Large, complex networks have many different possible retrofit designs, or Retrofit Bridges, which requires both computational effort and user effort to evaluate. In this paper, constraints relating to the thermodynamic and economic performance of a retrofit design are proposed and applied to significantly reduce Retrofit Bridge options to a smaller, manageable number of design options. These constraints relate to capital costs, payback period, piping, and plant layout. The method is demonstrated with a Kraft pulp mill case study. The Kraft pulp mill currently has 54 heat exchangers and 73 hot and cold streams. Without constraints, the number of possible Retrofit Bridges is 1×10^{20}. After applying the constraints, this number is reduced to 15. The remaining Retrofit Bridges are considered to provide high thermodynamic and economic benefit and can be more easily assessed for the best projects. The use of constraints has allowed the complex case study to be solved quickly, and a single design can be selected for further development. The suggested design reduces the utility consumption by 9.2 MW and has an annual Total Retrofit Profit of NZD 2,140,000, requiring a single new exchanger.

1. Introduction

To reduce the utility consumption of an existing Heat Exchanger Network (HEN) it needs to be retrofitted. Retrofitting a HEN involves modifications such as adding a new heat exchanger to the HEN or adding heat transfer area to existing exchangers. There are many ways of retrofitting a HEN and, therefore, a retrofit design method can be used to help find the retrofit modifications that are likely to provide the greatest benefit. Several different retrofit design methods have been developed in recent years, such as the Temperature Driving Force Curves (Kamel et al., 2017), the STEP method (Lai et al., 2017), and the Energy Transfer Diagram (Bonhivers et al., 2017), which was later modified by Walmsley et al. (2017) into the Modified Energy Transfer Diagram (METD). These are examples of graphical methods that can be used to find retrofit modifications; however, their usefulness can be limited when dealing with large HENs which are not well suited to graphical methods because of the increased complexity. Mathematical programming techniques can be better-suited to these situations, but often can neglect valuable user insight. Walmsley et al. (2017) also introduced the Heat Surplus-Deficit Table (HSDT) as a numerical tool that could be used in lieu of the METD to conduct a type of retrofit analysis known as Bridge Analysis. The benefit of the HSDT over other numerical tools (i.e., mathematical programming techniques) is that the HSDT is a direct numerical representation of the METD and therefore, analysis conducted using the HSDT can be readily related to the METD. However, the HSDT also falls into a problem where it identifies so many possible retrofit design options that it can be difficult to find the best retrofit project.

The aim of this paper is to develop constraints that narrow down the retrofit design options for a large industrial retrofit problem to the designs that offer the greatest thermodynamic and economic benefit. These constraints will be able to be applied to any retrofit design method that has the potential to produce a wide range of results, but have been developed with Bridge Analysis in mind. Constraints developed relate to plant layout and

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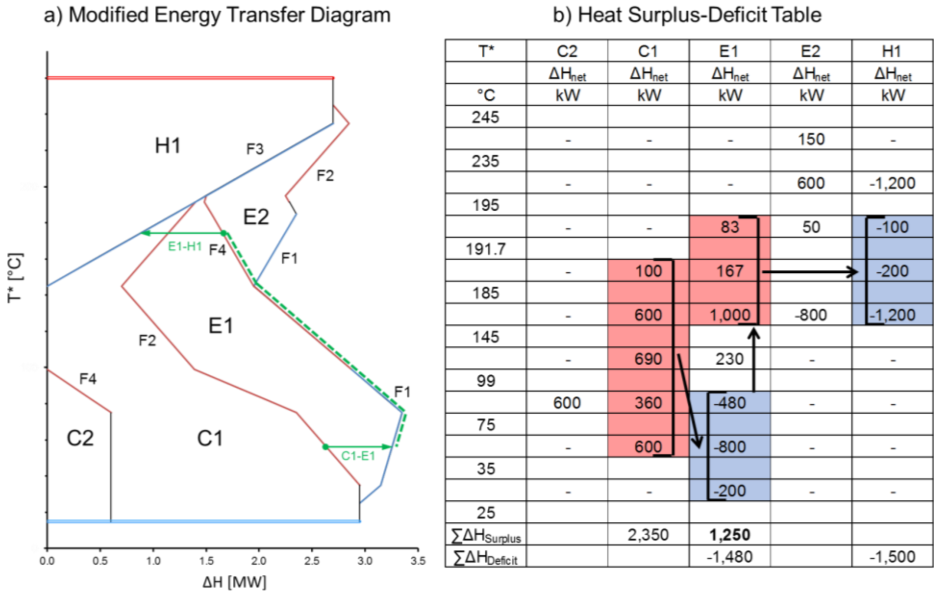
economic performance. The techniques are demonstrated with a Kraft pulp mill case study, using Bridge Analysis to develop retrofit designs. This method of solving the retrofit problem has been shown to greatly reduce the design effort and identify practical, economical modifications that provide the greatest profit.

2. Bridge Analysis

Bridge Analysis involves the identification of pathways, or Retrofit Bridges, that can be used to achieve energy savings. A Retrofit Bridge creates a link between a cooler and a heater with a set of modifications, typically new exchangers or additional heat transfer area. Heat is then shifted from the utilities to the recovery exchangers.

Bridge Analysis was originally introduced by Bonhivers et al. (2017) before being modified by Walmsley et al. (2017) and then further developed by Lal et al. (2018). A graphical tool called the Modified Energy Transfer Diagram (METD) (Figure 1a) was introduced, as well as its numerical counterpart, the Heat Surplus-Deficit Table (HSDT) (Figure 1b). Recent developments by Walmsley et al. (2018) have also introduced use of an Automatic Retrofit Targeting (ART) algorithm for use with the HSDT. This improves the usefulness of the HSDT as all feasible Retrofit Bridges can be identified and quantified with minimal user effort. A detailed explanation of the method is presented in Lal et al. (2018), with ART explained by Walmsley et al. (2018). In brief, the red and blue lines in the METD and the positive and negative enthalpies in the HSDT represent heat surpluses and deficits, respectively. Retrofit Bridges are sets of matches between heat surpluses and heat deficits that link a cooler with a heater. The energy savings potential of a Retrofit Bridge is determined by the minimum enthalpy in the set of matches, as this is a bottleneck for heat recovery. In the example given in Figure 1b, the bridge can only achieve a savings of 1,250 kW as this is the minimum enthalpy. Additionally, each curve in the METD represents a different heat exchanger, allowing the existing HEN to be characterised.

The METD is an effective visualisation tool but struggles to be useful for large, complex problems due to the increased number of curves. The HSDT is more capable of handling these problems, especially with ART, but can return an unmanageable number of possible Retrofit Bridges.



b) Heat Surplus-Deficit Table

T*	C2	C1	E1	E2	H1
	ΔH_{net}	ΔH_{net}	ΔH_{net}	ΔH_{net}	ΔH_{net}
°C	kW	kW	kW	kW	kW
245					
	-	-	-	150	-
235					
	-	-	-	600	-1,200
195					
	-	-	83	50	-100
191.7					
	-	100	167		-200
185					
	-	600	1,000	-800	-1,200
145					
	-	690	230	-	-
99					
	600	360	-480	-	-
75					
	-	600	-800	-	-
35					
	-	-	-200	-	-
25					
$\sum\Delta H_{Surplus}$		2,350	**1,250**		
$\sum\Delta H_{Deficit}$			-1,480		-1,500

Figure 1: a) Modified Energy Transfer Diagram, and b) Heat Surplus-Deficit Table (Lal et al., 2018).

3. Method

The proposed methods begins with the formulation of the HSDT for the given retrofit problem. Using previously-developed Microsoft Excel spreadsheet tools, the Retrofit Bridges can then be computed using the ART algorithm. The proposed method highlights the use of constraints to allow for efficient solving of large, complex retrofit problems. For explanation of other aspects of the method, readers are directed to the previously-mentioned papers.

3.1 Economic analysis

Economic evaluation of the Retrofit Bridges requires the estimation of the Total Retrofit Profit (TRP) and simple payback period (PB). To estimate these profitability indicators of a Retrofit Bridge, the utility savings (US) and total capital cost are also estimated.

US (NZD/y) is calculated using Eq(1), where ΔQ_{HU} is the reduction in hot utility (kW) and P_{HU} is the price of hot utility taken (NZD/kWy). Cold utility savings are negligible.

$$US = \Delta Q_{HU} * P_{HU} \tag{1}$$

The total capital costs consists of the capital cost of the heat exchangers and heat transfer area, as well as the estimated cost of piping. In current literature, plant layout is often not a major consideration in the initial retrofit design stage, despite there being significant cost differences between matching close streams and matching streams on other ends of an industrial site. Estimating the piping costs allows the plant layout to influence the retrofit design, penalising those matches that would require piping across large distances.

To do this, different processing areas, or zones, are identified from the sitemap and a distance matrix is developed, based on the distances between each of the zones with each other. Each exchanger and the corresponding stream segments in the initial HEN are located within one of these zones. Therefore, when a Retrofit Bridge is found, the distance between the matched streams (heat surplus within one exchanger being matched with a heat deficit in another exchanger) can be estimated. These distances are the total distance for piping to go to another zone and then back. The piping cost (PC) have been estimated using Eq(2) as follows:

$$PC = 105.83\, L\, d^{0.55} \tag{2}$$

Where PC is the installed piping cost in NZD/m, d is the pipe diameter (mm), and L is the required piping length (m), or distance between zones (Sinnott, 1999). It is assumed that the fluid with the cheapest PC will be piped to the other fluid for heat exchange and then back again, with exceptions for safety. Pipe diameter has been estimated from flow rate, assuming a velocity of 2 m/s. It is assumed that the pipe material is carbon steel.

The capital cost of the new exchangers and area (EC) is calculated using Eq(3) (Walmsley et al., 2014), where FC is the fixed cost (NZD), N_{HX} is the number of new exchangers, VC is the variable cost (NZD/m^{2n}), A is the total required additional heat transfer area (m^2), n is an exponent that is dependent on the costing function, and LF is the appropriate Lang Factor (excluding piping costs).

$$EC = (FC * N_{HX} + VC * A^n) * LF \tag{3}$$

PB (y) is then calculated using Eq(4) as:

$$PB = \frac{PC + EC}{UC} \tag{4}$$

For determining TRP (NZD/y), the capital costs are annualised with an annualization factor (AF) based on a discount factor of 5% and a lifetime of 10 years. Therefore, TRP is calculated by Eq(5) as:

$$TRP = US - (PC + EC) * AF \tag{5}$$

3.2 Constraints

To reduce the number of possible Retrofit Bridges to a more manageable number, several constraints have been developed and implemented for the method. While these constraints have been developed specifically for Retrofit Bridges, their usage is not solely limited to Bridge Analysis. By applying these constraints, the number of identified Retrofit Bridges will be greatly reduced, narrowing the final analysis down to those bridges that provide the greatest thermodynamic and economic benefit. The following constraints are presented in the order that they should be applied. The first two constraints have been implemented to speed up by the computation process while the third constraint is used to thoroughly evaluate and filter out the potential Retrofit Bridges.

The constraints are implemented into the ART algorithm (Walmsley et al., 2018) using Microsoft Excel^{TM}, based on the following inequalities. The energy savings and capital costs of each Retrofit Bridge are calculated and then the results are compared with the thresholds given.

Constraint 1: Restrict the number of modifications

In this context, a modification refers to the addition of new heat exchangers as well as the addition of heat transfer area to existing exchangers. Based on experience, the maximum number of modifications should be 4 modifications (N_{mod}). Modifications past this threshold will incur greater capital costs and retrofit effort without necessarily achieving enough energy savings to justify the expenditure. Retrofit designs with 4 or less modifications are more likely to be economic. Retrofit designs will be accepted if they follow Eq(6):

$$N_{mod} \leq N_{mod_{threshold}} \tag{6}$$

Constraint 2: Impose a minimum threshold for heat savings per new exchanger

Following on from Constraint 1, as new exchangers greatly increase the capital expenditure, each new exchanger should provide sufficient energy savings, on average, to justify its purchase. The threshold for heat savings (*Q*) per new exchanger is determined and applied using Eq(7), as follows:

$$\left(\frac{Q}{N_{HX}}\right)_{threshold} = \frac{FC*LF}{P_{HU}} \leq \frac{Q}{N_{HX}} \tag{7}$$

Constraint 3: Restrict the payback period

A company will typically have a maximum allowable PB for any retrofit project. This threshold is applied to filter out Retrofit Bridges that are likely to have poor economic benefits. As this constraint involves significant economic analysis, it is applied after the first two constraints to reduce the computational strain. The constraint inequality is given by Eq(8):

$$PB \leq PB_{threshold} \tag{8}$$

4. Case study

The case study considered in this paper is based on a large Kraft pulp mill in New Zealand. There are many processes involved in a large industrial site and as such there is a large, complex HEN. The HEN has 17 coolers, 18 heaters, and 19 heat recovery exchangers, with a total hot utility of 162 MW and a total cold utility of 131 MW. Using conventional Pinch Analysis techniques, the minimum energy targets can be identified: the hot utility target is 115 MW and the cold utility target is 83.5 MW, meaning that there is approximately 47.6 MW to be reduced. A global minimum approach temperature of 5 °C is applied.

Under normal conditions, there are 1 x 10^{20} possible combinations of Retrofit Bridges (not necessarily thermodynamically feasible). Without the use of constraints to simplify the problem and filter out unfavourable retrofit designs, the retrofit analysis can be near impossible. The proposed method will be demonstrated using this case study to show how Retrofit Bridges with good thermodynamic and economic benefit can be found quickly and effortlessly without sacrificing the benefit of engineer input.

4.1 Economic analysis

For the Kraft pulp mill case study, seven zones were identified from the site-map. The resulting distance matrix is presented in Table 1. As an example, Zone 1 refers to the No.5 Evaporators and Zone 3 refers to the No.2 Pulp Mill. Therefore, the estimated piping distance between the No.5 Evaporators and the No.2 Pulp Mill, or Zone 1 and Zone 3, is 410 metres.

Table 1: Distance matrix for the Kraft pulp mill case study.*

Zone	1	2	3	4	5	6	7
1		408	410	256	698	1,638	1,486
2	408		130	248	466	1,230	1,078
3	410	130		154	336	1,228	1,076
4	256	248	154		442	1,382	1,230
5	698	466	336	442		940	788
6	1,638	1,230	1,228	1,382	940		164
7	1,486	1,078	1,076	1,230	788	164	

* All distances are in metres (m).

UC is calculated with Eq(1) based on a hot utility price of NZD 300 /kWy. PC is determined using the distance matrix and Eq(2). EC is calculated using the following equation, Eq(9), as adapted from Eq(3):

$$EC = (30{,}900 * N_{HX} + 3{,}860 * A^{0.83}) * 3.67 \tag{9}$$

An LF of 3.67 has been applied (Bouman et al., 2004). The calculated economic metrics will then be used with Constraint 3, as well as being used for the final analysis of the remaining Retrofit Bridges.

4.2 Applying constraints

Without the use of constraints, the number of possible Retrofit Bridges is 1 x 10^{20}. This number includes thermodynamically infeasible Retrofit Bridges, but it is very difficult and time-consuming to determine the exact number. In any case, this large number gives proof that constraints are required for an effective retrofit analysis. The constraints are applied to the retrofit problem and the automated HSDT according to the following:

- Constraint 1: The maximum number of modifications is 4.
- Constraint 2: The threshold for heat savings per new exchanger is determined to be 491 kW/unit.
- Constraint 3: The maximum PB is 3 years.

The Retrofit Bridge search results are presented in Table 2. After applying Constraint 1, the number of Retrofit Bridges is reduced to 473,964. This takes 3.641 seconds of computation to determine. Similar results are found when applying Constraint 2 alone; however, when Constraint 1 and 2 are applied together (in that order), 45,698 Retrofit Bridges are found in only 0.410 seconds. This is a significant decrease in computation time and shows that these two constraints are successful in reducing the number of Retrofit Bridges and speeding up the automated process. Constraint 3 cannot be applied on its own due to the large computational effort that would be required, but when applied after Constraint 1 and 2, it reduces the number of Retrofit Bridges down to just 15. This is a >99.99 % reduction in Retrofit Bridges. Note that Constraint 3 has been applied post-processing. While this method does not necessarily guarantee a global optimum solution, it can be assumed with confidence that the Retrofit Bridges were less economical than the remaining options, based on what the constraints target.

Table 2: Results for the number of Retrofit Bridges found after applying each constraint in succession.

Constraint	No. of Retrofit Bridges	Computational Time (s)
-*	1 x 10^{20}	-
1	473,964	3.641
2	313,800	4.430
1+2	45,698	0.410
3**	-	-
1+2+3	15	-

* Cannot be solved in reasonable time, instead the number of possible combinations is determined.

** Impractical to solve without first applying the previous constraints due to the large computational effort.

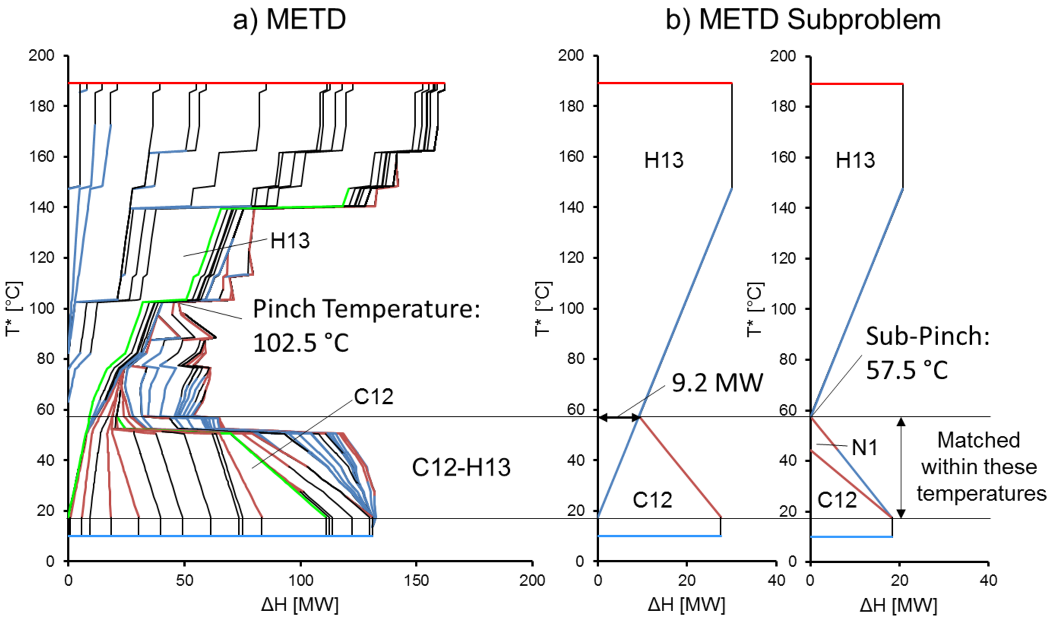


Figure 2: a) The proposed Retrofit Bridge shown on the METD, and b) the METD sub-problem of the involved exchangers before and after the retrofit design has been applied.

The remaining 15 Retrofit Bridges can now be evaluated and compared based on TRP and PB. The design with the greatest TRP is the Retrofit Bridge where cooler C12 is matched directly with heater H13. Therefore, only one new exchanger is required. This design means that, rather than cooling the effluent stream from No.2 Pulp Mill, the heat surplus can be used to heat the deaerator feed water, which is otherwise heated by hot utility at the No.5 Evaporators. The retrofit decreases the utility consumption by 9.2 MW, approximately 19 % of the overall retrofit target. This requires NZD 6,260,000 of capital investment but provides a TRP of NZD 2,140,000 per year. It is estimated that this capital investment would be paid off in 2.21 years, and while this is not the shortest PB, it is still a very reasonable PB considering the large TRP that it would provide. For these reasons, this Retrofit Bridge is selected for further development.

Linking back to the METD, the proposed Retrofit Bridge has been identified on the METD (Figure 2a), as highlighted in green between C12 and H13. Note that using this graphical tool over the HSDT would have been very difficult. In Figure 2b, the relevant curves of the METD have been isolated to demonstrate the effect of the retrofit on the sub-problem. Both utilities are reduced by approximately 9.2 MW and a new match has been created in the temperature interval shown. The sub-problem also has a different Pinch temperature to the overall HEN as there are different retrofit targets for the sub-problems. After applying the Retrofit Bridge between C12 and H13, the sub-problem is now pinched meaning that there are no more savings to be gained between the involved streams. However, H13 is still exchanging heat across the Pinch meaning that there are still savings opportunities involving H13.

5. Conclusions

The proposed method has been demonstrated with a complex case study, showing how retrofit analysis can be conducted using the HSDT, despite the many possible design options. Large HENs can be retrofitted in many ways due to the large number of streams and existing exchanger matches, but using the constraints allows the Retrofit Bridges with low potential for thermodynamic or economic benefit to be filtered and discarded. Application of the constraints reduced the number of possible Retrofit Bridges by >99.9 % leaving 15 options that could be more easily compared and evaluated. Of these remaining options, a single Retrofit Bridge was identified as a candidate for further retrofit design. This retrofit design reduced utility consumption by 9.2 MW, or 19 % of the retrofit target, with a TRP of NZD 2,140,000 /y. With the proposed method, the bridge was found and the large, complex industrial retrofit problem was solved. One limitation of the method is that it does not guarantee a global optimum solution, nor does it handle multi-step retrofit designs. Future work will focus on the latter, where filtering will be an important part of the process due to the significantly larger number of possible Retrofit Bridges that could be found once multi-step retrofit designs are automated.

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