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Flexibility Analysis of Heat Exchanger Network Retrofit Designs using Monte Carlo Simulation

Nathan S. Lal[a,*], Martin J. Atkins[a], Timothy G. Walmsley[b], Michael R. W. Walmsley[a], James R. Neale[a]

[a]Energy Research Centre, School of Engineering, University of Waikato, Private Bag 3105, Hamilton, New Zealand
[b]Sustainable Process Integration Laboratory – SPIL, NETME Centre, Faculty of Mechanical Engineering, Brno University of Technology - VUT Brno, Technická 2896/2, 616 69 Brno, Czech Republic
nl93@students.waikato.ac.nz

The aim of this paper is to use Monte Carlo Simulation (MCS) to conduct an analysis of the flexibility and controllability of retrofitted Heat Exchanger Network (HEN) designs. Historical plant data is often uncertain and variable but is an important tool for understanding the real-time operation of a HEN. MCS uses these uncertainties to give an analysis of the retrofitted HENs, and it can be used in a more detailed analysis of the controllability and flexibility. Using Monte Carlo Simulation, inflexibility has been defined as the probability of a HEN to fail to meet temperature targets within defined tolerances. Inflexibility can be used as a tool to guide the retrofit analysis of a HEN. A retrofit HEN design should improve the flexibility of the network without compromising on the expected energy savings. The proposed method is demonstrated using a four-stream HEN problem. The inflexibility of the network was shown to be improved with bypass control and optimal allocation of retrofit area and the proposed method succeeds in augmenting the retrofit design method so that cost-effective, flexible retrofit HENs can be identified.

1. Introduction

Flexibility of a Heat Exchanger Network (HEN) is an aspect of its operability and refers to the ability of a network to feasibly operate at steady-state despite variations such as periodical changes or uncertainties in process streams (Swaney and Grossmann, 1985). Consideration of flexibility in the early stages of retrofit design is important as modifications made to an existing network in favour of more obvious returns (economic or energy) can lead to uncontrollable networks (Westphalen et al., 2003). Flexible control of a HEN is often achieved using bypasses (Mathisen et al., 1992); however, there is a trade-off as larger bypass fractions are better at handling variations but can also require larger heat transfer areas (Luyben, 2011). Several key works relating to the flexibility of a HEN include: Swaney and Grossman (1985), who developed a flexibility index which measures the range of parameters that flexible HEN operation can be maintained with appropriate process control; Papalexandri and Pistikopoulos (1994), in which a systematic framework was created with the objective of determining a minimum cost flexible retrofit design; and Varga et al. (1995), where HENs were modelled as time-varying linear systems responding to variations in flow rate. More recently, Gu et al. (2018) optimised the HEN synthesis and bypass fractions simultaneously as a way of accounting for flexibility in the initial design. In many cases, mixed integer non-linear programming (MINLP) (or similar mathematical programming methods) is used to determine the network's flexibility. It is proposed that a simple estimate of flexibility, or inflexibility, could be determined using Monte Carlo Simulation (MCS) to model a HEN's response to uncertainty, based on historical precedents in the HENs operation.

The use of Monte Carlo Simulation (MCS) is still sparse in Heat Exchanger Network (HEN) retrofit literature, despite its proven usefulness in other areas of Process Integration such as water networks (Tan et al., 2007), bioenergy parks (Benjamin et al., 2017), and more recently to verify the reliability of resource allocation networks (Arya and Bandyopadhyay, 2018). Previous work by the authors of this paper used MCS to generate probability histograms for the heat recovery performance of different retrofit HEN designs to graphically and statistically

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guide the selection of the optimal design (Lal et al., 2018a). The current paper is a continuation of this work and further explores how MCS can be used to aid the retrofit design of HENs by quantifying flexibility.
The aim of this paper is to use Monte Carlo Simulation-based techniques to address the flexibility of a HEN during retrofit analysis using historical plant data. This is a simple analysis that will provide insights about the flexibility of a network without the need for complex calculations. The novel method is demonstrated using a four-stream HEN problem as an illustrative example with bridge analysis as the retrofit design method (Lal et al., 2018b). The method shows how the flexibility analysis can be used to improve the flexibility of the retrofitted HEN using optimal use of retrofit area and bypass control, while maintaining the estimated retrofit energy targets. A comparison with concepts such as the flexibility index are outside the scope of this paper, but will be covered in future work. The work in this paper is a shift away from complex mathematical programming methods, such as MINLP, towards a simpler tool with a greater ease of use and accessibility.

2. Method

Monte Carlo Simulation (MCS) uses probability distributions that represent the uncertainty in a measured input variable to determine the probability of the outputs, such as heat exchanger duty or outlet temperature. Therefore, MCS can be used to determine the probability of a HEN failing to meet targets (for a given set of inputs) – representative of poor flexibility or inflexibility. The probability distributions for the input variables are built using historical plant data. Several probability distributions will be fitted to the data and the best fitting distribution (based on the Akaike Information Criterion) will be selected. The proposed method uses the MCS-based flexibility analysis to define a network inflexibility as a simple estimate for evaluating retrofitted HENs. In this paper, only the flexibility of the HEN with respect to uncertainties in the process streams is considered. The inflexibility in the HEN is calculated using the following two equations:

$$\text{Inflexibility} = \frac{1}{n}\sum p_i \tag{1}$$

$$\forall\, i \in n, \qquad \begin{cases} t_{lower,j} \leq v_{j(i)} \leq t_{upper,j} \;\; \forall\, j: \;\; p_i = 0 \\ \qquad\qquad \text{Else:} \;\; p_i = 1 \end{cases} \tag{2}$$

Where i is the iteration number within the simulation, v_j is the controlled variable (with j number of controlled variables), t is the target value (with an upper and lower limit), n is the total number of iterations, and p_i is an integer that represents a pass (0) or fail (1) for the target being met. In other words, if any controlled variables do not meet their target then p_i is equal to one for that iteration. The total number of non-zero values of p_i is divided by the total number of iterations to find the inflexibility. The inflexibility is calculated before and after the retrofit and is used in the decision-making process.
When a bypass is used, the new temperature (T_{mix}) after the mixing of the bypass stream and the main branch of the process stream is given by the following approximation:

$$T_{\text{mix}} \approx \frac{(CP_1T_1 + CP_2T_2)}{CP_2 + CP_2} \tag{3}$$

Where T is temperature (°C), CP is the heat capacity flow rate (the product of mass flow rate and specific heat capacity) (kW/°C), and indices 1 and 2 represent the bypass branch and the main branch of the process stream. The approximation for T_{mix} assumes that the heat capacity flow rates are constant.
The general method for the flexibility analysis of the retrofit designs is as follows:

1. Extract stream data and fit a probability distribution to each input (temperatures, flow rates, etc.).
2. Model the starting HEN and run the Monte Carlo Simulation.
3. Calculate the network inflexibility.
4. Conduct the retrofit analysis and run the Monte Carlo Simulation for the retrofitted HENs.
5. Calculate the new inflexibility.
6. Find the optimal retrofit area for the design and implement control strategies, improving utility consumption and flexibility.
7. Make recommendation for the retrofit design.

The HEN model is developed using energy balances and the ϵ-NTU method. The recovery heat exchangers are assumed to be double pipe counter-flow exchangers and the utility exchangers are considered to be oversized. The MCS is conducted using @Risk, a Microsoft Excel-based software package developed by Palisade (2019). All aspects of the method are conducted using Excel and @Risk, including the generation of input probability distributions, the simulation, and the flexibility analysis. Use of Excel complements the usefulness of the method due to the accessibility of Excel for industry.

3. Heat Exchanger Network retrofit problem

The following Heat Exchanger Network (Figure 1) is a four-stream problem that was previously presented in Lal et al. (2018a), after being adapted from a network in Klemeš et al. (2014), and is used to demonstrate the proposed method. The goal of the retrofit is to improve the flexibility of the network and then integrate a new cold stream (F3) into the network so that the duty of the heater (H1) may be reduced. The heat transfer areas of heat exchangers E1 and E2 are 61.3 m^2 and 24.6 m^2, respectively. Following the heuristic of bypassing the stream whose outlet is being controlled (Mathisen et al., 1992), bypasses are placed on the hot side (F4) of exchanger E1 and on the cold side (F1) of exchanger E2. The historical HEN data has been extracted from over a period of one month. The data necessary for the MCS includes the supply temperatures and mass flow rates for each stream. Each target temperature is controlled and maintained by utility exchangers, except for the target temperature on stream F1. The target temperature is 180 °C with an allowable deviation of ±5 °C. The duties on the utility exchangers and the outlet temperature of stream F1 are the key outputs for MCS. The duties provide information about whether the target temperature can be met (based on a specified tolerance) – a negative duty implies that the target cannot be met.

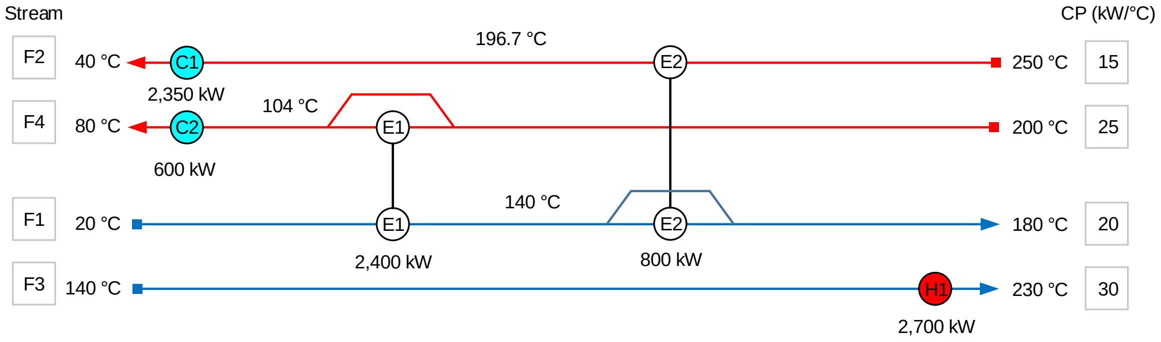

Figure 1: Four-stream Heat Exchanger Network problem

4. Validation of the Monte Carlo Simulation approach to measuring network flexibility

A flexibility analysis of the initial network was conducted using MCS (n = 1,000,000) with and without bypasses to validate the approach. The results show that the network has an inflexibility of 81.1 % without bypass control. There is a 19.3 % probability of cooler C2 not being able to adequately control the target temperature of stream F4 (Figure 2a), and for stream F1 there was a 43.5 % probability of being under target and a 37.3 % probability of being over target (Figure 2b). In the case with the bypass control, the results show that the HEN has a much lower inflexibility of 45.3 %. There is now a 0 % probability of C2 failing to meet the temperature target and the probability of the temperature of F1 exceeding 185 °C is reduced to 1.9 %. There is no change to the probability of the temperature failing to reach the minimum of 175 °C. This comparison validates how the inflexibility can be analysed using MCS, as the inflexibility can be quantified before and after changes are made to the HEN, allowing insights into how retrofit modifications will affect the HEN.

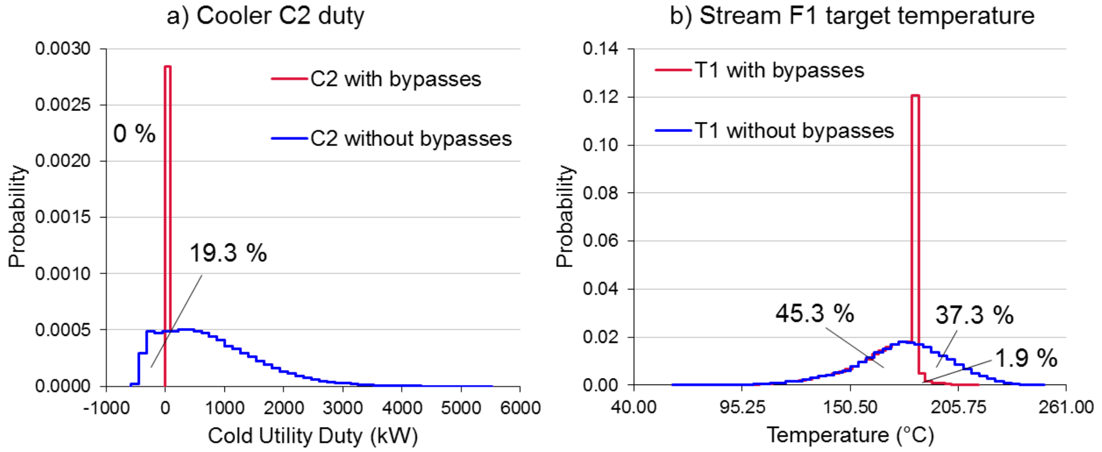

Figure 2: a) Probability of duty for cooler C2 with and without bypass control, and b) probability of outlet temperature for stream F1 with and without bypass control

5. Retrofitting the Heat Exchanger Network

Retrofit analysis of the HEN, specifically bridge analysis, is used to find potential HEN configurations that would improve the heat recovery and reduce utility consumption. Bridge analysis involves creating or using a pathway, or bridge, between a heater and a cooler to shift heat around via the available heat surpluses and deficits. The bridge is described in terms of the exchangers (utility and recovery) that are affected by the retrofit. This bridge relates to a retrofit design because it indicates where new heat exchangers can be implemented in the HEN. The bridge C2-E1-H1 would result in two new potential matches. The first would be between the hot side (surplus) of C2 and the cold side (deficit) of E1; however, this match already exists due to E1 and no new exchanger is added here. The second match would be between the surplus of E1 and the deficit of H1, and because there is no existing match, a new recovery exchanger can be implemented here. For further explanation of bridge analysis, please refer to Bonhivers et al. (2017).

Bridge analysis of the four-stream HEN problem shows that there are seven retrofit configurations that could reduce the duty of H1, as per the retrofit goal. Four of these designs are considered, and new exchangers are sized based on the steady-state values of the HEN and a ΔT_{min} (minimum exchanger approach temperature) of 10 °C. The grid diagrams for the retrofitted HENs are presented in Figure 3. At this stage, the only retrofit modifications made are the additions of new exchangers. Modifications such as bypasses and increased heat transfer area on existing exchangers are not initially considered. Heat exchanger loops are not considered in this paper due to their complexity and the significant controllability issues that they can cause. The effect of these retrofit modifications on the flexibility of the HEN will be examined in the next section.

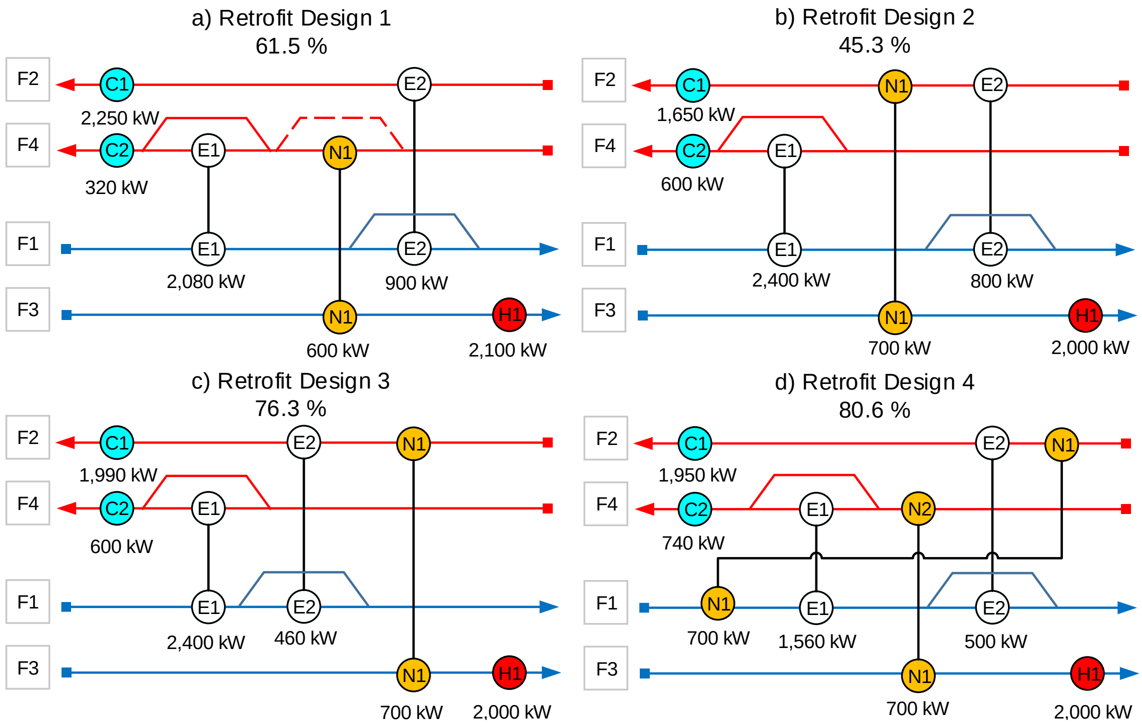

Figure 3: Retrofit designs for the 4-stream HEN: a) retrofit design 1, C2-E1-H1; b) retrofit design 2, C1-H1; c) retrofit design 3, C1-E2-H1; and d) retrofit design 4, C1-E2-E1-H1

6. Flexibility analysis of retrofit designs

The flexibility analysis shows that the inflexibility of the HEN has increased in all but one retrofit design: retrofit design 2 has the same inflexibility as the retrofit modifications had no effect on the 'problematic' temperature targets on streams F4 and F1. The MCS results for the cold utility duty of C2 are presented in Figure 4a and show that the existing bypass control is enough for controlling the target temperature, as there is a 0 % probability of a negative duty in all cases. In Figure 4b, the MCS results show that the capability of the retrofitted HEN to meet the target temperature has worsened in all designs but retrofit design 2. Because the mean temperature tended to drop, the ability of the bypass control to correct for an excessive temperature was improved slightly (although only from 1.9 %). The base case is not shown in Figure 4 to improve clarity, as it is identical to retrofit designs 2 and 3 in Figure 4a and identical to retrofit design 2 in Figure 4b. The results of the flexibility analysis are summarised in Table 1.

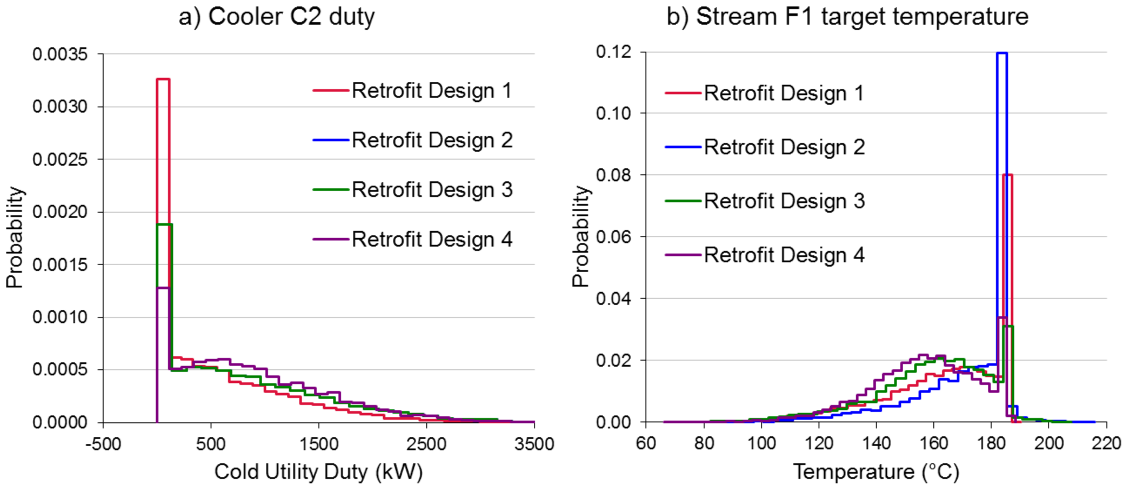

Figure 4: a) Probability of cold utility duty for C2 in each retrofit design, and b) probability of target temperature for stream F1 in each retrofit design

Table 1: Flexibility analysis results for each retrofit design

Design	Bridge	Hot Utility Savings (kW)	Inflexibility (%)	T1 Failure Probability (%)	
				Lower (<175 °C)	Upper (>185 °C)
Base			45.3	43.5	1.9
1	C2-E1-H1	600	61.5	61.5	0
2	C1-H1	700	45.3	43.5	1.9
3	C1-E2-H1	700	76.3	74.6	1.7
4	C1-E2-E1-H1	700	80.6	80.6	0

The next step of the flexibility analysis is to find the optimal use of area and bypass control to improve the flexibility and meet all targets (including the hot utility target) for each design. In this demonstration, only retrofit design 1 will be considered. Any improvements need to focus on controlling the target temperature of F1 and there are three ways that are considered: 1) increase the area on exchanger E2, 2) reduce the area on new exchanger N1, and 3) implement bypass control on the hot side of N1. The results from the first two scenarios are presented in Figure 5. Figure 5a shows that increasing area of E2 will reduce the inflexibility with no change to the hot utility; however, after an inflexibility of ~30 % is achieved there are diminishing returns. Figure 5b shows the opposite; when the area of N1 is reduced, the inflexibility decreases but the hot utility duty also significantly increases away from the target of 2,100 kW.

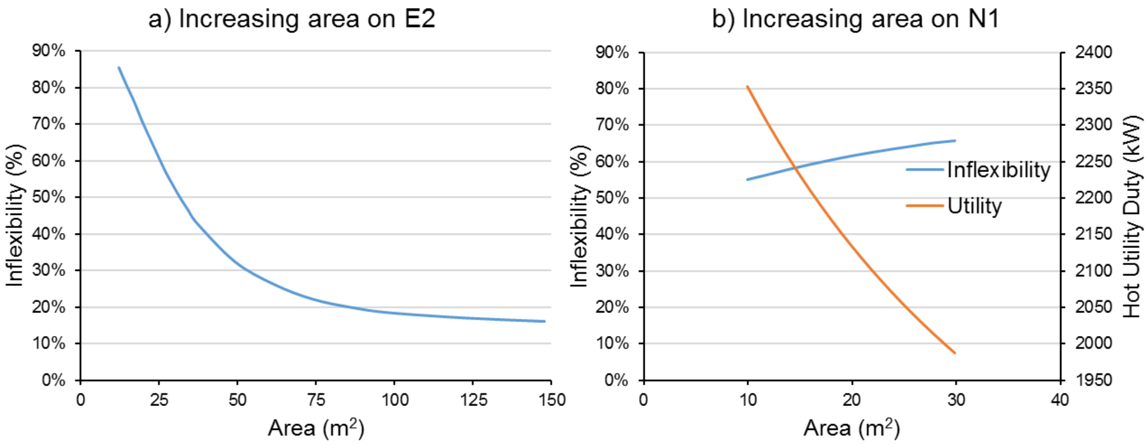

Figure 5: a) Relationship between E2 area and inflexibility, and b) relationship between N1 area and inflexibility and hot utility duty

The third way of improving the flexibility was the use of a bypass on the hot side of N1, as shown in Figure 3a. With the bypass, inflexibility was reduced by a further 3-5 % (in addition to changes due to the retrofit area) but increased the mean hot utility duty by over 300 kW. A combination of increasing the area of E2 by 10 %, decreasing the area of N1 by 10 %, and using bypasses, resulted in an inflexibility of 39 %. This would bring the inflexibility down to below the original HEN's inflexibility.

7. Conclusion

The work in this paper extends a previously-developed method in which Monte Carlo Simulation was used as a comparative tool for retrofit analysis while accounting for historical plant data. The novel method now uses MCS as a simple tool for analysing the flexibility, or inflexibility, of a Heat Exchanger Network based on its historical plant data. It has been shown how the MCS results can be used to 1) improve flexibility and 2) analyse the flexibility of retrofit designs to inform decision-making.

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