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Holistic and Versatile Process Integration Framework for Maximising Resource Efficiency

Zainuddin A. Manan*, Sharifah R. Wan Alwi

Process Systems Engineering Centre (PROSPECT), Faculty of Chemical Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Malaysia
zain@cheme.utm.my

This paper describes a new holistic and versatile process integration framework for maximising resource efficiency, The *minimum resource targets* can be achieved when all options for resource minimisation, including elimination, reduction, reuse/recycling, outsourcing, and regeneration, have been holistically applied using the resource management hierarchy as a guide. A sample of the use of this framework for energy minimisation is demonstrated in this paper together with a versatile tool which allows simultaneous targeting and network design, i.e. the *Streams Temperature vs Enthalpy Plot* (STEP). *Systematic Hierarchical Approach for Resilient Process Screening* (SHARPS) method is used for cost screening the various process changes to ensure a reasonable and practical payback period.

1. Introduction

Process Integration using Pinch Analysis (PA) is a well-established tool for the design of a maximum resource recovery (MRR) network. Even though it has been widely regarded as a very mature technique, ample rooms for enhancement of the PA tools have only been recently identified. Two recent developments have enhanced the versatility and the holistic nature of well-established PA targeting tools such as the graphical Composite Curves (CC) (Hohmann, 1971) and Problem Table Analysis (Linnhoff and Flower, 1978) techniques.

The first development is the holistic framework for resource conservation. The MRR, which is primarily concerned with resource recovery and regeneration only partly addresses the resource minimisation problem. Strictly speaking, PA only leads to MRR targets and not the minimum resource targets. The minimum resource targets can be achieved when all options for resource minimisation, including elimination, reduction, reuse/recycling, outsourcing, and regeneration, have been holistically applied using the resource management hierarchy as a guide (Wan Alwi and Manan, 2006).

The second development is the introduction of Stream Temperature versus Enthalpy Plot (STEP) (Wan Alwi and Manan, 2010) that enhances the versatility of composite curves (CCs) and grid diagrams (GD). Due to its composite nature, the CCs cannot completely map individual hot and cold process streams, as well as process and utility streams, and cannot be used for HEN design. In addition, CCs cannot be conveniently and effectively used to predict minimum network area and the optimum ΔT_{min} that should strictly be based on parameters and properties of individual as opposed to composite streams. Grid diagrams (GD) on the other hand require designers to provide or calculate stream temperatures as well as enthalpies, to conduct heat balances and check temperature feasibility during HEN design, as the diagrams do not follow any temperature or enthalpy scale.

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This paper presents the holistic framework that enhances the Pinch Analysis versatility and holistic nature in providing assistance to designers to produce a minimum resource conservation network. The framework consists of five key steps, i.e. (1) Specify the limiting data, (2) Determine the MRR targets, (3) Screen process changes using resource management hierarchy (RMH), (4) Apply *Systematic Hierarchical Approach for Resilient Process Screening* (SHARPS) strategy, and (5) Network design. The vital stages involving determination of the MRR targets and network design are accomplished using STEP (Stream Temperature vs. Enthalpy Plot) as a new graphical tool for simultaneous targeting and design of a HEN that overcomes the key limitations of CCs and the GD. The combination of holistic framework and STEP technique provides a vital alternative graphical approach for optimal design of resource conservation networks.

2. Methodology

The Resource Management Hierarchy (RMH) shows the levels of minimisation strategies from the most to the least preferred. It includes five levels, namely elimination, reduction, reuse/recycling/outsourcing, regeneration and use of fresh resources. A sample of the application of RMH on water and carbon minimisation can be referred to the work of Manan and Wan Alwi (2006) and Sadiq et al. (2012) respectively. In this work, a RMH for energy will be illustrated to show its usage with STEP.

2.1 Energy Management Hierarchy (EMH)

Figure 1 shows the Energy Management Hierarchy (EMH), which is a special case of the RMH applied for energy minimisation. The hierarchy consists of five levels, namely (1) source elimination, (2) source reduction, (3) energy recovery/outsourcing, (4) energy upgrading, and (5) use of extra utilities. The levels are arranged in order of preference, from the most preferred option at the top of the hierarchy (level 1) to the least preferred at the bottom (level 5). Energy minimization is concerned with the first to the fourth level of the hierarchy.

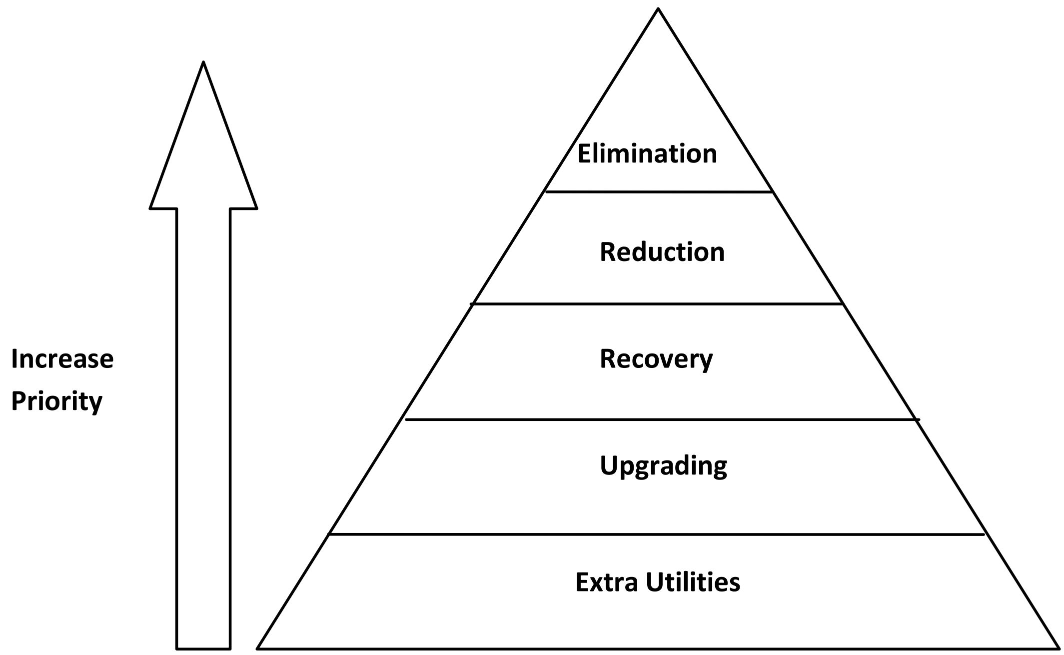

Figure 1: Energy Management Hierarchy

Source elimination (level 1) at the top of the hierarchy is concerned with the complete avoidance of energy utility usage. Sometimes it is possible to eliminate rather than to reduce, reuse or recycle the energy. Even though source elimination is the ultimate goal, often, it is not possible to eliminate energy completely.

If total elimination is not possible, then possible *source reduction* (level 2) should be considered. This can be done by changing equipment, improving processes and implementing good housekeeping. Examples include use of water cooler instead of refrigerator, using double-layer-glasses to reduce heat losses (changing equipment), changing pressure of distillation columns to obtain optimized energy (improving processes) and maintaining optimum combustion in boilers and furnaces (good housekeeping).

When it is not possible to eliminate or reduce utilities at source, direct energy recovery/outsourcing (Level 3) should be considered. Direct energy reuse or outsourcing may involve using thermal energy from within a facility (process heat, waste heat) or using an available external thermal source (e.g. solar heat or geothermal heat). Through direct reuse (level 3), wasted thermal energy or external thermal source can be fully utilised to heat or cool processes. An established method to determine the maximum potential heat recovery is via pinch analysis.

Energy upgrading (Level 4) such as the use of heat pump can be used to upgrade lower quality heat energy to a higher quality, and more useful temperature level by consuming a relatively small amount of high grade energy. This can further improve energy recovery as shown by Bagejewicz and Barbaro (2003). Extra utilities should only be considered when all levels of the hierarchy have been considered.

2.2 A Holistic Framework for Cost Effective Minimum Energy Network (CEMEN) Design

The Cost Effective Minimum Energy Network (CEMEN) design procedure is a holistic framework for energy management that extends the method proposed by Wan Alwi and Manan (2008) for the design of cost-effective minimum water networks. Five key steps are involved in generating the CEMEN, i.e. (1) Specify limiting energy data, (2) Determine the maximum energy recovery (MER) targets, (3) Screen process changes using EMH, (4) Apply SHARPS strategies and (5) Design CEMEN. The step-wise approach is described in detail next.

2.2.1 Step 1: Specify the limiting energy data

The first step is to specify limiting energy data. This involves process line-tracing, establishing process material balances and isolating the appropriate energy sources and energy “demands”. The energy sources and demands were listed in terms of quantity such as flowrate, temperature supply and target and heat capacity for each process stream.

2.2.2 Step 2: Determine the MER targets

Next, it involves setting the maximum energy recovery (MER) targets and getting the pinch temperatures by using STEP (see Figure 2). Readers are referred to Wan Alwi and Manan (2010) for the full description STEP construction. The graphical STEP is crucial to assist process changes in the later stage. Note that, establishing the thermal energy targets at level 3 of the EMH is crucial in order to assess the maximum heat recovery potential for the existing process/waste thermal stream within the plant. The targets provide a basis to assess/analyse further savings through process changes, including thermal energy reduction and elimination. The benefit of using STEP is that it provides clear guidance for performing process changes on individual streams, and insights on redesigning the heat exchanger network (HEN) from a single graphical tool.

2.2.3 Screen process changes using EMH

The third step after targeting is to incorporate possible process changes or modifications based on the energy management hierarchy (Figure 1). The first level process change is considered. The limiting data is modified and new MER target is generated. The consecutive level of the energy management hierarchy is then considered and step 1 to 3 is repeated until there are no more process changes possible. Process changes at each level can be performed using the following heuristics:

Heuristic 1: Select process changes that reduce cold stream flowrate for the above pinch region, or hot stream flowrate for below pinch region, starting from the stream nearest to the pinch. Do not decrease the flowrate until a threshold problem occurs as this will incur energy penalty.

Heuristic 2: Upgrade heat across the pinch region in order to reduce both hot and cold utilities.

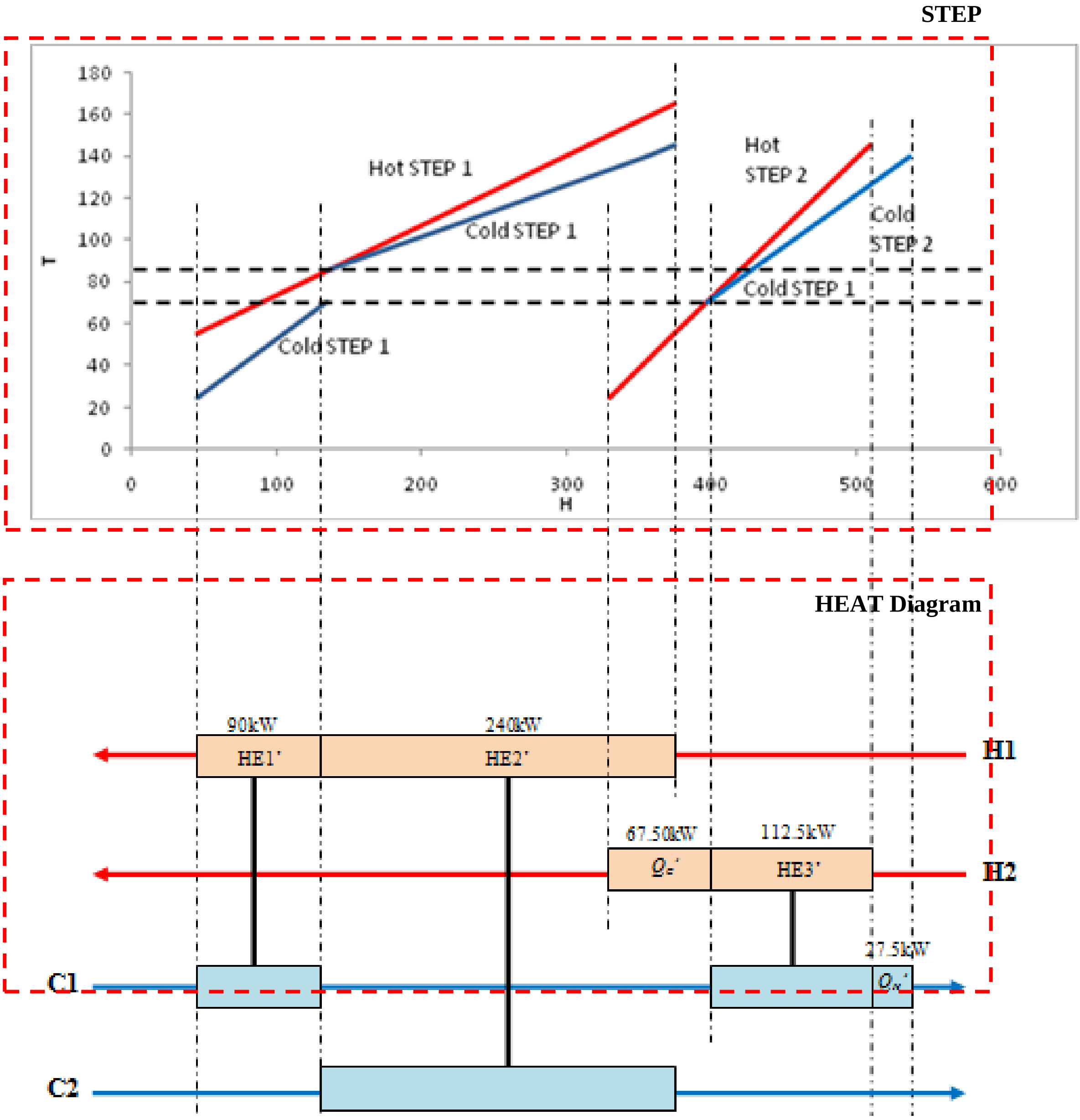

Figure 2. STEP and HEAT Diagram for simultaneous targeting and network design (Wan Alwi and Manan, 2010).

2.2.4 Step 4: Apply SHARPS strategy

This step involves the preliminary economic analysis of the HEN design. The benefit of STEP is that it is based on heat exchange between individual streams instead of composited streams. It allows multiple utilities to be identified and directly mapped with the individual streams. This allows the total minimum network area to be easily calculated in just a single step, i.e., by summing up the individual areas, and hence, the capital and operating costs for all heat exchangers that exist within the STEP enthalpy intervals.

The payback period can be calculated based on the investment and energy saving options that exist at various levels of the EMH. If the payback period exceeds the requirement of the designer, the Systematical Hierarchical Approach for Process Screenings (SHARPS) technique proposed by Wan Alwi and Manan (2008) will be used to screen process changes. SHARPS provides a preliminary cost estimate of the energy management (EM) options prior to detailed design. It includes a profitability measure in terms of payback period; i.e. the duration when a capital investment can be fully recovered. The method involves the development of 'Net Capital Investments vs Net Annual Saving' plot which is constructed based on the cumulative process changes guided by EMH. There are two strategies to ensure a desirable payback period is achieved. The first strategy is 'substitution' which involves replacing the equipment/process that causes the steepest positive gradient in the 'Net Capital Investments vs Net Annual Saving' plot, with an equipment/process that results in a less steep gradient. The second strategy is 'intensification' where the length of the steepest positive gradient is reduced by reducing the size of an equipment/process change.

2.2.5 Step 5: Network design

Once the payback period is achieved, the new cost effective minimum energy network (CEMEN) is designed based on the final STEP by using HEAT (Heat Allocation) diagram as introduced by Wan Alwi and Manan (2010) (see Figure 2).

3. Conclusion

A conceptual holistic framework for minimum energy network design has been developed. The *energy management hierarchy* provides clear qualitative as well as quantitative guidelines on how to approach process changes and ultimately achieve the minimum energy design. By using the *SHARPS technique*, one can screen inferior process changes and design a cost- effective minimum energy network based on a desired payback period.

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