Approaches for Retrofitting Heat Exchanger Networks within Processes and Total Sites

Lidija Čuček[a,*], Stanislav Boldyryev[b], Jiří Jaromír Klemeš[c], Zdravko Kravanja[a], Goran Krajačić[d], Petar Sabev Varbanov[c], Neven Duić[d]

[a]Faculty of Chemistry and Chemical Engineering, University of Maribor, Maribor, Slovenia
[b]Centre for Integrated, Energy Saving, Environmentally Friendly Processes, ITMO University, Saint-Petersburg, Russian Federation
[c]Sustainable Process Integration Laboratory - SPIL, NETME Centre, Faculty of Mechanical Engineering, Brno University of Technology – VUT Brno, Brno, Czech Republic
[d]Department of Energy, Power Engineering and Environment, Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Zagreb, Croatia

Abstract

This study presents developed approaches that could be used for retrofitting of existing heat exchanger networks (HENs) within individual processes and industrial sites to achieve lower energy consumption, cost savings and emission reduction. Successful industrial applications are further presented, and future challenges are identified. Approaches used for retrofitting of existing HENs are based on heuristics, on thermodynamic analysis and insights – Pinch Analysis and recently developed Bridge Analysis, on numerical optimisation - Mathematical Programming, and on hybrid or combined approaches which are based on a combination of heuristics, physical insights and/or numerical optimisation. Optimisation-based approaches could be further divided into deterministic and stochastic (probabilistic) methods. Those systematic approaches (all approaches except pure heuristics) use either sequential (divided into sub-problems) or simultaneous synthesis methods.

Keywords: Energy efficiency; Process and Total Site Integration; Heat Exchanger Network; Retrofit; Approaches for retrofit

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[*] Corresponding author, phone: +386 222 94 454, email: lidija.cucek@um.si (Lidija Čuček)

1. Introduction

The industry currently consumes the biggest amount of primary energy sources of all sectors. It consumes more than 50 % of the total energy produced in the world (US Department of Energy, 2016). There is a high potential of energy consumption reduction in industry (Manan et al., 2017). The role of energy in industries is of increasing importance due to environmental and economic issues (Ben-Guang et al., 2000) and security of supply (Harjunkoski and Hadera, 2016). There are several options how to increase energy efficiency in industries, such as installing more energy-efficient equipment (Bart and Scholl, 2018), better insulation, early detection of leakages, reduction of process waste (Harjunkoski and Hadera, 2016), changes in the use of utilities (Walmsley et al., 2018b), topological modifications (Yong et al., 2015), additional heat transfer area installation, re-piping of process equipment (Walmsley et al., 2018a), heat transfer enhancement and matches modification (Wang et al., 2012). Retrofitting existing Heat Exchanger Networks (HENs) is an important way to achieve energy and cost savings in process industries and entire sites (Wang et al., 2012). It can also bring significant savings of emissions as ‘the cleanest energy is the one that is not used’ (Gundersen, 2013a).

Most industrial plants and sites have considerable potential for energy savings. They are still using significantly higher amounts of energy than is required, as stated in Alfa Laval (2011). Typically identified savings in energy consumption in industrial sectors excluding conventional methods and projects are between 10 and 35 % (Klemeš, 2013a). Additional energy savings obtained from conventional methods and projects, e.g. good housekeeping, monitoring, process modifications, and others are in the range of 5 to 15 % (Klemeš and Varbanov, 2018). By applying e.g. plus minus principle significant savings can also be identified (Kravanja et al., 2013). Heat recovery may be increased by process modifications applying plus-minus principles (Gundersen and Naess, 1988). At Total Site level, there is additional potential for energy savings between 20 and 25 % (Chew et al., 2015b).

During the last three decades, several systematic approaches and strategies have been developed for the retrofit of HENs within individual processes and Total Sites (Klemeš and Kravanja, 2013). In general, those systematic approaches are divided into Pinch Technology or Pinch Analysis (Klemeš, 2013a), Bridge Analysis (Bonhivers et al., 2017), Mathematical Programming (Klemeš et al., 2013a), and hybrid approaches combining the advantages of heuristics, physical insights and/or numerical optimisation. Developed strategies to solve HEN synthesis problems can be in general divided into sequential and simultaneous synthesis methods (Furman and Sahinidis, 2002). Sequential methods divide the HEN synthesis problem into a range of tasks that could be solved more easily. An example of sequential strategy is to solve the problem firstly by

1) Minimising utility both usage and cost, then

2) Minimising the number of units, e.g. heat exchangers, condensers, coolers, heaters and others, and finally

3) Minimising Network capital cost or/and heat transfer area (Biegler et al., 1997).

Approaches using simultaneous strategy, on the other hand, optimize operating and capital costs in one step.

All the approaches have certain advantages and drawbacks. Furthermore, theoretical developments should be supported by solid methodology and proper applications on the case studies to illustrate and stimulate achieving real savings in industrial clusters.

The current study analyses the developed approaches for the retrofit of existing individual processes and Total Sites due to several reasons:

i) Time consumptions on existing plant improvements are much higher than on designing new plants (Gundersen, 2013b). It has been estimated that in the 1980s between 70 and 80 % of all process design projects have dealt with retrofits (Grossmann et al., 1987). It is also estimated that currently, retrofits play even more important role due to market competition and more stringent environmental regulations;

ii) Methods for the design of new energy systems are far more developed than methods for the retrofits of energy systems (Smith, 2013);

iii) Fewer sources are accessible relating to the retrofits of existing processes and Total Sites while the vast amount of literature is available regarding designing new processes and Total Sites– grassroots designs.

This study describes developed approaches for increased heat recovery (HEN retrofit) within existing processes and Total Sites. The methods and approaches which could only be used for grassroots designs, and methods for power generation (Rozali et al., 2017), mass and property integration and operational optimisation (Smith, 2013) are beyond the scope of this contribution. This study complements the studies regarding approaches for retrofit of existing HENs (Sreepathi and Rangaiah, 2014) and various methods for HEN retrofit (Akpomiemie, 2016), and additionally presents industrial applications and future challenges / possible directions for research within this field. The most recent review dealing with new directions in the implementation of Pinch Methodology (PM) has been presented by Klemeš et al. (2018a).

2. Retrofitting of Processes and Total Sites

Retrofitting (also revamping, and debottlenecking in narrower context) refers to making changes and/or additions to existing plants (Rangaiah, 2016) with the main objective to increase energy efficiency (Gundersen, 2013c). There are several reasons for retrofit of existing processes and Total Sites, among them probably the main are cost savings (Boldyryev et al., 2016a), increasing production capacity (debottlenecking) for increased throughput, more efficient production, utilizing different feedstocks, utilizing different processing technology, improving safety and reliability and reducing the environmental impact (Varbanov et al., 2018), such as e.g. to reduce flue gas emissions (Smith, 2005). Often, main savings may be achieved by simple changes, those changes that give significant benefits (the ‘big apples', (Gundersen, 2013c)). Usually, the retrofit with a small number of modifications is more feasible (Smith, 2005). Typically, the most expensive part of retrofit is the cost of piping modifications and civil engineering, and thus one of the interesting options is also the use of heat transfer enhancement for existing heat exchangers (Droegemueller and Gough, 2017).

Heat integration at the process levels deals first with analysing opportunities for the integration; further with identification and quantification of energy consumption reduction and finally by proposing changes of the existing HEN to achieve the reduction in energy consumption. To account for flexibility, multiple operational scenarios could be considered, and the proposed changes are such that can fulfil all the scenarios. In any process, there are typically variations in temperatures, flowrates, and other operating variations due to variable feed/product flows, qualities of feedstocks, ambient temperature variations, processes operate at various capacity levels and other factors (Beninca et al., 2011).

Heat recovery among multiple processes is termed Total Site Heat Integration or sometimes also side-wide integration. The wider Total Site concept assumes an integration of industrial sector with other ones, such as residential, commercial, utility, agricultural and/or other sectors (in the text they are referred to as »processes«), named as Locally Integrated Energy Sectors (LIES) (Bulatov, 2013). Total Site could incorporate both non-renewable and renewable energy sources (Varbanov and Klemeš 2011) and could be extended to a regional level, e.g. by accounting for district heating and cooling (Gundersen, 2013b), see Figure 1.

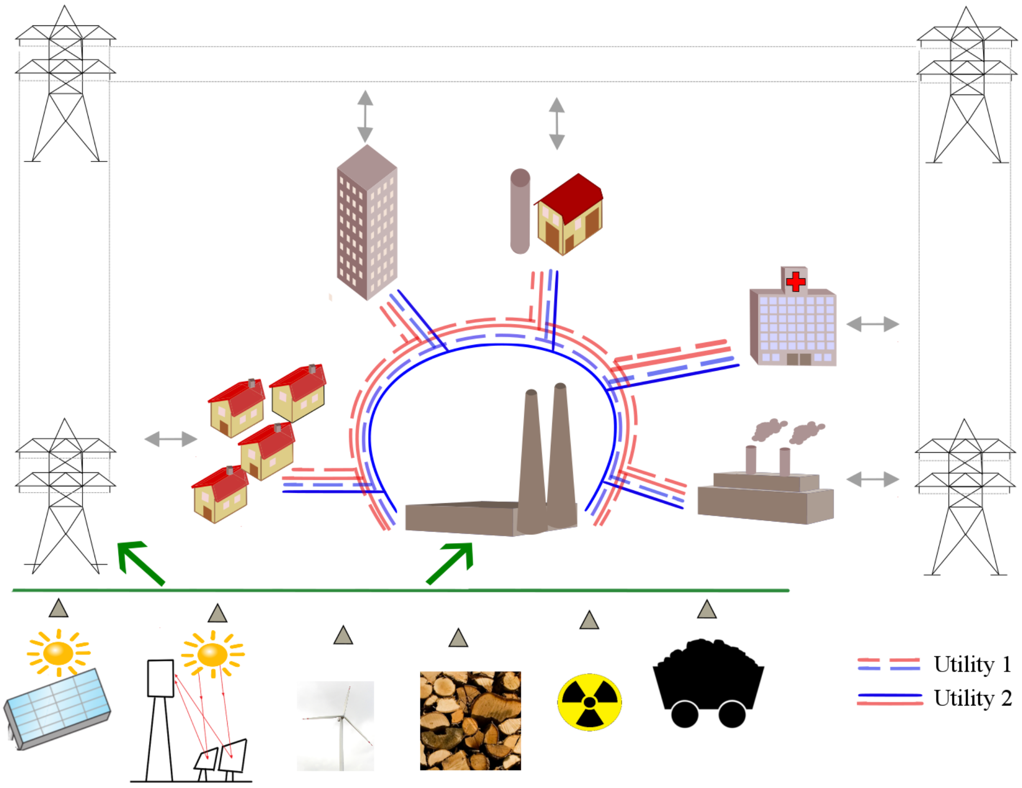

Figure 1. Total Site incorporating different sectors and energy sources - developed after Čuček and Kravanja (2016)

The main advantages of retrofits at Total Site level are to achieve additional energy, cost and emission savings. Potential additional energy savings are between 20 and 25 % (Chew et al., 2015b), as it was stated previously. However, there are also various potential issues connected to Total Site Integration specifically. Probably the main issues are related to possible non-simultaneous operation of processes, possible changes in process design, limitations on utility levels and high piping costs and related layout issues.

Total Site Integration is performed in a similar way as heat integration inside each process but there are some differences:

- Process plants and other integrated sectors (processes) have specific energy consumption/ production patterns and in several cases different ownerships (Laukkanen et al., 2012);
- Heat Integration could be performed either first inside each process and after between the processes and only surplus heat from each process could be transferred to other processes (Walmsley et al., 2018c) or Heat Integration could be performed simultaneously inside and between the processes (Tarighaleslami et al., 2018);
- Heat transfer between processes occurs either via intermediate utilities, also called “indirect heat transfer” (Boldyryev et al., 2014) or via process streams by transferring either hot or cold stream between processes, also called “direct heat transfer” (Laukkanen et al., 2012). Transfer by utility streams is preferred in several cases due to operational concerns, safety and flexibility reasons (Nemet et al., 2017). On the other hand, integration by process streams might be preferred in cases of short distances, smaller number of heat exchange loops and simultaneous operation of such processes among which the integration occurs (Tarighaleslami et al., 2017).

There are several options for performing HEN retrofitting analysis within processes and Total Sites, such as (Kemp, 2007): 1) Developing a Minimum Energy Requirement (MER) design of new plant while retaining the existing Network matches, 2) Initiate with a present Network and proceed towards a MER design, and 3) Begin from a present Network and determine the crucial modifications that could provide most possible savings. An upgrading option (Čuček and Kravanja, 2015b) is to identify for a given number of changes the most profitable modifications. However, besides this, a real-life solution has to deal with a number of other issues (Chew et al., 2013). From them to highlight at last a few, such as pressure drops (Chew et al., 2015a) and process modifications driven to improve the retrofitted process (Chew et al., 2015b). Several other issues identified are presented in the following in Sections Industrial Retrofitting Applications and Conclusions and Future Challenges.

3. Approaches for Retrofit of Processes and Total Sites

There are several approaches for determining energy gaps and thus identifying the possibilities for conserving energy and reducing emissions within Total Sites and individual processes (Nemet et al., 2018b). Generally, these methods may be split up into the technique based on heuristics, insights-based (Pinch Analysis and Bridge Analysis), optimisation-based (deterministic and stochastic methods) and combined or hybrid approaches. Approaches are summarised in Figure 2 and presented in more details in the following. Only the major approaches are presented while the several extensions of those presented approaches are omitted.

The methods that presented major breakthroughs in the Heat Integration and Total Site Analysis were mostly devised in last decades of the last century (Gundersen, 2013c). Latest developments regarding the HEN design and retrofit are focused mainly on creation of methods and approaches for finding grassroots and retrofitting solutions to larger-scale HENs, developments of methods and approaches for global optimisation, detailed design of heat exchange units and whole HEN, improving a Network flexibility, multi-objective optimisation (Klemeš, 2013b), and improving existing approaches and solutions (Gundersen, 2013c).

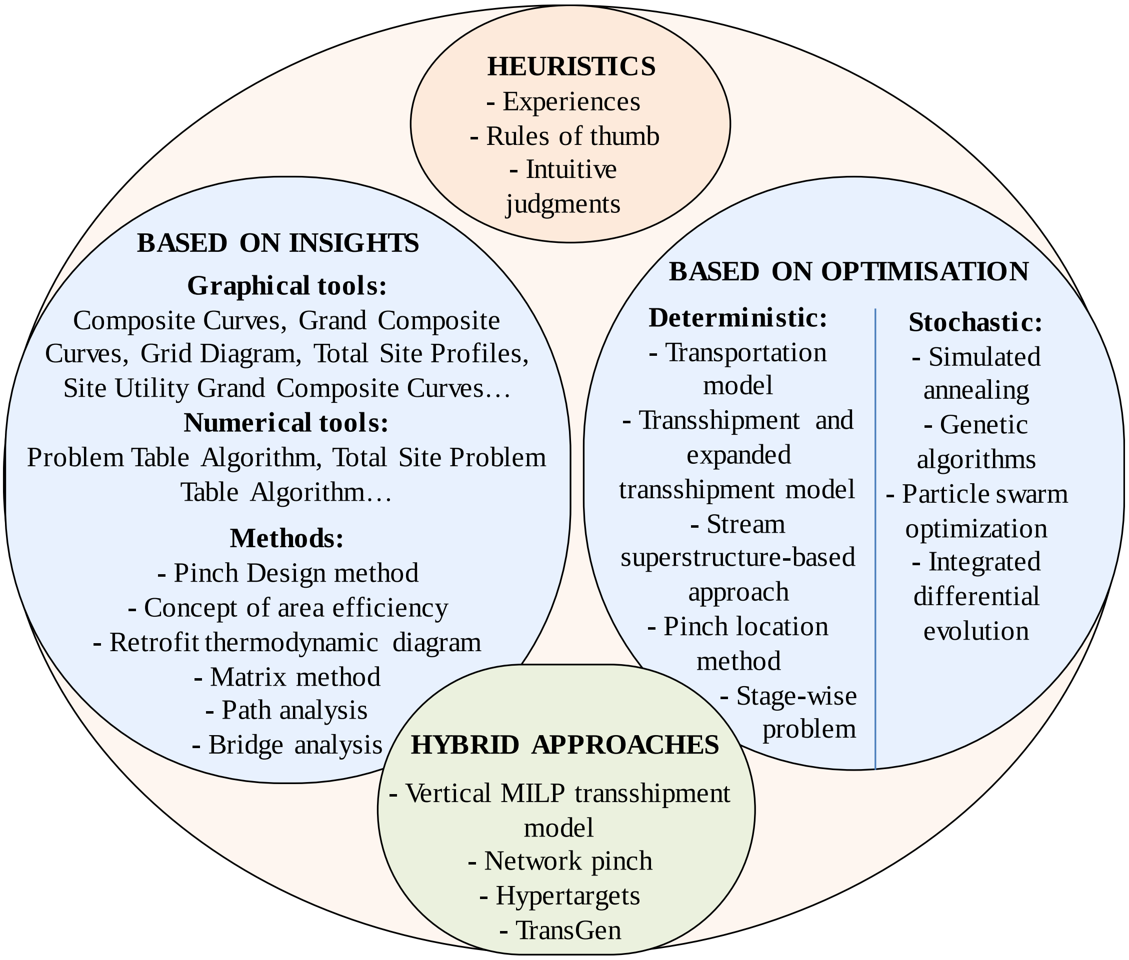

Figure 2. Approaches for retrofitting existing processes and Total Sites

3.1 Heuristics

HEN design methods relied mostly on heuristics for many years (Klemeš et al., 2014). The first methodologies for Process Integration were based on heuristic methods (Navarro-Amorós et al., 2013). Heuristics is the application of knowledge derived from experiences of engineers and designers, using rules of thumb and intuitive judgments for a specific problem (Klemeš and Kravanja, 2013). Together with process knowledge and simulations, it can be used to speed up finding a satisfactory solution and for fast screening in the early stages to avoid infeasible retrofitting modifications (Niu and Rangaiah 2016). Heuristics could be useful for data extraction (CETC-Varennes, 2003), in developing reasonable designs (Douglas, 1985), however, depending on the guesses of process alternatives and variables, the design may be far from the optimal one (Douglas, 1985). The disadvantage of heuristic approaches is the difficulty in judging how good a solution really is. Heuristics e.g. could be used to identify improvements that meet the immediate needs (CETC-Varennes, 2003). It can be applied to reject unfeasible matches (Aly, 1997) or matches that are difficult to be implemented. Heuristics could be applied as well for Network design for approaching to energy targets (Bonhivers et al., 2014b). However, in general, methods relying on heuristics are becoming redundant (Klemeš and Kravanja, 2013), especially for large and complex industrial processes and Total Sites.

3.2 Insights-based Approaches

Pinch Analysis is currently the widely-spread Process Integration approach in the industry (Navarro-Amorós et al., 2013). Simplicity of its concepts, the graphical representations, and the step-by-step user control of the process design make possible to find feasible solutions and facilitate practical realisation (Bonhivers et al., 2016). Pinch Analysis has helped to obtain impressive results in numerous projects worldwide (CETC-Varennes, 2003). Besides Pinch Analysis, recently Bridge Analysis was developed which could identify supplementary solutions to Pinch Analysis.

Pinch Analysis approach consists of graphical and numerical tools for setting energy targets and for performing HEN design. Most common graphical tools are in the form of Composite Curves (CCs) and Grand Composite Curves (GCCs) (Linnhoff et al., 1982). They have been complemented by various developments in Grid Diagram (Linnhoff and Flower 1978) at the level of processes, and Total Site Profiles (TSPs) (Klemeš et al., 1997) or Site Source – Sink Profiles (SSSPs) (Dhole and Linnhoff 1993) and Site Utility Grand Composite Curves (SUGCCs) (Klemeš et al., 1997) at the level of Total Sites. The most well-known numerical tool is Problem Table Algorithm (PTA) (Linnhoff and Flower 1978) which is applied at process level.

More recent developments regarding graphical tools include Stream Temperature versus Enthalpy Plot (STEP) (Wan Alwi et al. 2010), Retrofit Thermodynamic Diagram (Lakshmanan and Bañares-Alcántara, 1996), Composite and Grand Composite Curves for target, existing and modified design under several operational scenarios (Čuček et al., 2014), Retrofit Tracing Grid Diagram (Nemet et al., 2015), Extended Grid Diagram and Heat Path Development (Yong et al., 2015a), Diagram Hot vs Cold Temperature (Gadalla, 2015), Matrix representation of the Grid Diagram (Yong et al., 2015b), Energy Transfer Diagram (ETD), Heat Exchanger Load Diagram (HELD), and other. Recently developed numerical tools include Total Site Problem Table Algorithm (TS-PTA) (Liew et al., 2012), Segregated Problem Table Algorithm (SePTA) (Wan Alwi et al., 2013), Total Site Sensitivity Table (TSST) (Liew et al., 2012), Total Site Utility Distribution (Liew et al., 2012), Time Super Targeting (Boldyryev et al., 2017b) and others.

Pinch Analysis applies well to the design of new systems, while it is less suited for retrofits and for operational optimisation. It has difficulties with large problems and incorporation of constraints (Smith, 2013).

Pinch Analysis based methods are sequential design methods decomposed into several steps: 1) a definition of targets for energy recovery and number of units; 2) process design with changes to existing units; 3) estimation of project economics (Bakhtiari et al., 2013).

There were several methods and their extensions developed based on thermodynamic analysis and insights:

- Pinch Design method (Linnhoff and Hindmarsh, 1983) – method for a design of HENs. It has been later applied by a number of enterprises worldwide (Gundersen, 2013c).
- The concept of area efficiency (Tjoe and Linnhoff, 1986) - first Pinch concept for retrofitting HEN. It is based on a concept: Start with the existing Network and work towards a MER design (Kemp, 2007). The main idea of this method is to eliminate heat transfer across the Pinch with the aim of minimising investment costs for retrofitting modification (Bonhivers et al., 2014b). Disadvantages are that the Network design is obtained manually, which might be time-consuming procedure and difficult in large Networks, and depends also on the designer experiences;
- Incidence Matrix approach (Pethe et al., 1989) for the identification of loops in HEN. The approach helps to visually identify loops;
- Matrix methods such as Area Matrix (Shokoya, 1992) and Cost Matrix (Carlsson et al., 1993) - methods aiming at eliminating Pinch violations. Area Matrix uses optimization approach to find optimal vertical area contributions. Cost Matrix accounts for the cost calculations (heat exchanger area, piping, pumping and maintenance) based on experiences from retrofit projects (Gundersen, 2000);
- Path analysis (Van Reisen et al., 1995) and complemented by Varbanov and Klemeš (2000) - it identifies subnetworks with good economic potential. Subnetworks must contain at least one heater and one cooler. Heat load is shifted along paths between heaters and coolers;
- Retrofit Thermodynamic Diagram (RTD) (Lakshmanan and Bañares-Alcántara, 1996) - a modification of the Conventional Grid Diagram. RTD is a visualisation tool that helps to address retrofit problems by engineering intuition;

- Bridge analysis (Bonhivers et al., 2014a) is a complementary approach to Pinch Analysis. Bridge variations match to consecutions of arrows between heater and cooler. Bridge formulation and insights such as Energy Transfer Diagram (ETD) and Heat Exchanger Load Diagram (HELD) are proposed (Bonhivers et al., 2016).

3.3 Optimisation-based Approaches

Mathematical programming (mathematical optimisation) methods enable automating the search among many design alternatives and explicitly account for both capital and operating costs (CAPEX and OPEX) (Grossmann, 1992). Mathematical programming problems are generally formulated as Mixed Integer Nonlinear Programming (MINLP) problems. To avoid local optimums and long computation times, in many cases the problem may be simplified to reformulate MINLP into Linear Programming (LP) problem, Nonlinear Programming (NLP) problem or Mixed Integer Linear Programming (MILP) (Liu et al., 2014). The most efficient approaches have been presented in the past as MILP-NLP or MILP-MINLP approaches (Tantimuratha et al., 2000).

Methods based on mathematical programming might be preferable for solving larger-scale problems due to some advantages (Smith et al., 2010). Using mathematical programming methods several cases might be easily and more properly handled especially if there are matches that are constrained, e.g. forbidden, restricted and required connections due to possible contaminations and predetermined purity of process streams, operability issues such as control, pipe length and distances between units, scheduling of start-up and shut-down and safety restrictions. Additionally, during the retrofitting most of the existing Network matches remain unchanged. Besides, trade-offs between CAPEX and OPEX can be handled under flexible operation modes and fixed or steady-state operating modes (Čuček and Kravanja, 2016).

However, optimisation-based approaches might be highly complex, and estimation of the result feasibility and quality may not be possible due to uncertainties and obtained local optima (Bonhivers et al., 2014b). Especially simultaneous design methods have the difficulty to get practical solutions reliably for large complex problems (Smith, 2013). Mathematical programming also has limited exploitation in commercial software and provides little scope for user interaction (Akpomiemie and Smith, 2016). Most users still demand the insights that purely mathematical programming techniques do not provide (Smith, 2013). Mathematical programming methods may be separated into stochastic (probabilistic) and deterministic approaches.

3.3.1 Deterministic Methods

Deterministic models are optimisation models when all model parameters are known and are constant. These methods could be based on insights from Pinch Analysis and represent simultaneous or sequential approaches to the design problems. Deterministic methods check several possible variations of optimum solutions by listing different combinations of variables and finally get the best ones. However, these methods have some limitations and challenges that relate to computational complexity (combinatorial explosion) and numerical problems (local optima, “good” initialisation). Simultaneous MINLP formulations are limited to the problems that involve only smaller number of process streams (Nemet et al., 2018a).

There were several methods and their extensions developed based on Mathematical Programming that could address retrofits of existing HENs. Some of more-known approaches are:

- Transportation model (Cerda et al., 1983). It was one of the first problem formulations of Mathematical Programming that allowed the consideration of required, restricted and/or forbidden matches and multiple utilities (Grossmann, 1992). This model makes possible to define a minimum utility consumption when designing HENs (Cerda et al., 1983);
- Transhipment and expanded transhipment model (Papoulias and Grossmann, 1983) that are alternatives to transportation model. Transhipment models could calculate minimum energy consumptions considering constrained matches or minimum number of units by connecting sources (hot streams), warehouses (intervals in Heat Cascade) and sinks (cold streams) (Gundersen, 2013b);
- Stream superstructure-based approach (Floudas et al., 1986) which enables automatic HEN generation. It is solved in three steps; Step 1: minimising utility cost by LP transportation or transhipment model, Step 2: minimising the number of units by MILP transhipment model, Step 3: minimising investment cost by NLP problem;
- An approach based on a Pinch Point Location (Duran and Grossmann, 1986) which provides carrying out process flowsheet optimisation and Heat Integration simultaneously. Heat Integration may be performed by varying temperatures and flow rates, and at the same time, multiple utilities could be applied. Optimised process flowsheet provides energy targets and minimum utility consumption;
- A stage-wise problem (Yee and Grossmann, 1990) enables designing HEN. The model is based on a superstructure comprising all potential matches between hot and cold streams where inlet and outlet temperatures could be fixed or variable. It enables performing simultaneous optimization of CAPEX and OPEX, and also simultaneous optimisation of a process/site with HEN synthesis (Yee et al., 1990). Various extensions of a stage-wise problem have been proposed, such as for the retrofit of HEN (Yee and Grossmann, 1991), by comprising different exchanger types (Soršak and Kravanja, 2004), including possibility of utility selection at each stage and global optimization (Bogataj and Kravanja, 2012) and several others.

3.3.2 Stochastic Methods

Stochastic methods are optimization methods where parameters are specified by uncertain quantities, and at the same time, the probability distributions characterise parameters. The Genetic Algorithms and

Genetic Algorithms coupled with Simulated Annealing are the most widely used algorithms in the HENs synthesis (Toimil and Gómez, 2017).

Stochastic optimisation approaches cover the numerical problems related to nonlinearities, non-convexities, and discontinuities. They have the advantages of finding global optimum for NLP and MINLP problems through the random natures of these types of optimisation methods (Liu et al., 2014), and they don't require good initialisation (Smith, 2013). However, the drawbacks of stochastic approaches are early convergence, they are slower than deterministic methods (Smith, 2013) and they do not employ insights from Pinch Analysis. There is no guarantee of finding global optimum (Gundersen, 2013b) and poor solution quality is obtained in some cases (Yu et al., 2000). There is no information how far the obtained solution is from the optimal solution (Toimil and Gómez, 2017). The solution quality when applying stochastic methods relies on the time consumed for calculation (Anantharaman, 2011).

The structures of the algorithms are typically classified as one-level or two-level structures (Toimil and Gómez, 2017). In the two-level approach the structure is optimised in the first level (outer level), and in the second level (inner level) parameters are optimised (Toimil and Gómez, 2017). At both levels stochastic methods could be used, however more popular is that at one level (usually outer) stochastic and at one (usually inner level) either deterministic or hybrid methods are applied. Several structures to represent HEN are considered such as stage-wise superstructure proposed by (Yee and Grossmann, 1990), incidence matrix proposed by (Pethe et al., 1989), node-based structure (Bochenek and Jeżowski, 2006), graph-based representation (Toffolo, 2009) and other. Some notable developments:

- First use of stochastic methods in HENs (Dolan et al., 1989) through optimisation by simulated annealing and employment to HEN design;
- First use of stochastic methods for HEN retrofit (Athier et al., 1998). Simulated annealing was coupled with an NLP method;
- First use of hybrid optimisation by combining two different methods, genetic algorithm and simulated annealing (Yu et al., 2000);
- Proposed node representation of the superstructure (Bochenek and Jeżowski, 2006). Developed approach is based on genetic algorithm and the Network Pinch concept;
- Proposed graph representations for HEN and used by evolutionary and NLP algorithms (Toffolo, 2009);
- Proposed string rewriting grammar (Fraga, 2009) for the evolution of HEN structure with stream splitting. Procedure consists of two levels, first, the algorithm evolves structures, and further, it optimises specific structures;
- Applications of stochastic (metaheuristic) approaches in HEN design: Random algorithm (Chakraborty and Ghosh, 1999), Evolution strategies (Groß et al., 1996), Genetic algorithm (Lewin et al., 1998), Tabu search (Lin and Miller, 2004), Differential evolution (Yerramsetty and Murty,

2008), Particle swarm optimisation (Silva et al., 2009), Harmony search algorithm (Khorasany and Fesanghary, 2009), and others.

3.4 Hybrid Approaches

Hybrid approaches are the combination of different methods (physical insights, heuristics, optimisation) to get synergistic benefits of the advantages of the separate methods (Fraser, 2013). For solving industrial problems, advantages of all three approaches should be considered (Gundersen and Naess, 1988).

Graphical approaches are powerful tools for demonstrating the results of the optimisation and for applying energy efficiency measures (Maréchal and Kalitventzeff, 1998). Mathematical Programming is a time-consuming approach, and it typically does not give any insight into the problem. Besides, Mathematical Programming methods provide automated HEN design.

There are several possible opportunities for employing hybrid approaches (Klemeš and Kravanja, 2013). When combining Mathematical Programming and Pinch Analysis, searching space of Mathematical Programming is conveniently narrowed. Pinch Analysis is also very beneficial at data extraction stage, and for verification and guiding Mathematical Programming close to global optima (Klemeš and Kravanja, 2013). It was suggested that Pinch Analysis is helpful in the initial steps followed by Mathematical Programming for detailed optimisation (Ahmetović et al., 2018).

There were several methods and their extensions developed that somewhat apply hybrid methods. Some examples of hybrid approaches are:

- Vertical MILP transhipment model (Gundersen and Grossmann, 1990). Probably the first approach which combines the thermodynamics (physical insights) and Mathematical Programming approach.
- Network Pinch (Asante and Zhu, 1997) is a computational approach for HEN retrofit applying minimal topology modifications. It has been successfully applied in industry (Hallale, 2001) and has proved to be beneficial in retrofitting existing HENs (Yong et al., 2015a). It employs a two-stage approach: i) diagnosis stage: identification of promising HEN topology modifications (Pinching matches – bottlenecks of an existing recovery HEN) and ii) optimisation stage: minimisation of capital costs to overcome the Network Pinch. The retrofit design of existing HEN is changed one modification at a time (Hallale, 2001). Modified Network Pinch approach combines two stages into a single step (Smith et al., 2010).
- Hypertargets (Briones and Kokossis, 1999) - systematic approach for retrofitting industrial HENs. It includes targeting and optimisation stages and simultaneously use thermodynamic principles and Mathematical Programming.
- Heat transfer enhancement (Pan et al., 2011) – retrofit without the need for topology modifications and additional heat transfer area. Different approaches have been proposed based on optimisation and heuristics (Wang et al., 2012).

- Transhipment-based code TransGen (Čuček and Kravanja, 2014), and an improved version (Čuček and Kravanja, 2015b) includes insights from Pinch Analysis. TransGen identifies under both fixed and varying operating conditions for a given number of changes, specified payback time or available money for investment the most profitable modifications. TransGen includes physical insights such as insights for target, existing and modified design under one or several operational scenarios (Čuček et al., 2014) and insights from Plus-Minus principles (Čuček and Kravanja, 2015a).

3.5 Comparison of Approaches

Methods based on heuristics use rules of thumb and intuitive judgment of engineers. For many years, methods were mostly relied on heuristics. However, to obtain feasible HEN design, many "trials" and permutations are required (Klemeš et al., 2018b). The main strength of heuristics is in the use of engineering experience and in successive generation/refinement of retrofitting modifications, while the weaknesses are its lack of a systematic approach, its inability to perform simultaneous optimization, and that the obtained solutions may not always be valid (Grossmann and Daichendt, 1996). Thus, retrofit studies are recently performed mainly by using Pinch Analysis methods, Mathematical Programming methods or a combination of these two methods with the help of heuristics (Akpomiemie and Smith, 2015).

Insights-based methods (Pinch and Bridge Analysis methods) are methods based on thermodynamic principles and are used for grassroots design, heat recovery targeting and reducing and/or eliminating heat transfer across the pinch (Akpomiemie, 2016). For retrofit projects, insights-based methods incorporate several heuristics (Lai et al., 2017). The main strengths of insight-based methods are that they set target performance of existing process and provide various graphical and numerical tools. They have high industrial acceptance, proven energy savings (Pinch Technology), are widely used in academia and industry, are widely included in chemical engineering education curricula (Klemeš et al., 2013b) and are mature technologies (Kemp, 2007). There are various software tools available for heat integration (Bulatov, 2013) which are mainly based on physical insights, while also enable simulation or optimisation (Lam et al., 2011). Limitations of such methods are time requirement to generate retrofit designs, especially for large-scale problems (Bagajewicz et al., 2013). Retrofit results are often complex and uneconomic (Akpomiemie, 2016) and are based on sequential approach. Larger-scale retrofit problems offer combinatorial challenge (Čuček et al., 2016) and many modifications are typically required to the existing network (Akpomiemie, 2016). They typically also ignore the constraints related to existing plant layout and require experience and expertise for their application. It is challenging to perform retrofit projects under varying operational conditions, especially at Total Site level, and to consider multiple criteria (Čuček et al., 2016).

Mathematical Programming methods use mathematical models (usually based on optimisation) to assist in taking decisions, and the best solution is obtained by using specified optimisation algorithm. They have several strengths, with the main one that it enables optimality, feasibility and integrity of solutions (Kravanja, 2010). They enable automating the search among many design alternatives by handling several optimization variables. They could explicitly account for any objective (total annual cost, energy consumption, incremental profit and other) or multiple objectives and could explicitly consider certain number of most optimal retrofitting modifications. They could handle and optimally solve retrofitting problems under dynamic operating conditions, constrained matches and multiple utilities. Certain methods also enable synthesizing HEN including positions of heat exchange units including all the temperatures in HEN, and certain methods enable performing simultaneous process optimization and integration (Čuček et al., 2016). However, strengths of Mathematical Programming methods depend on the efficiency of problem representation and optimisation algorithms. They require significant experience and expertise in problem formulation, in building the model, analysing the solution and interpreting the results. Limitations are also the size and complexity of the retrofit problem (Akpomiemie, 2016). In case of nonlinear problems, solutions are only locally optimal and are highly dependent on the initial values of variables. For larger-scale problems, models are typically either rigorous and not solvable, or deficient and solvable (Björk and Nordman, 2005). They provide only numerical results which could be difficult to interpret. In cases when the model is not well-built, the results could be questioned if they represent the real-world solution and some options could be missed. Retrofitting larger-scale HENs with Mathematical Programming has mainly been performed using simplifications and heuristics (Anantharaman, 2011). There is also a lack of available software tools for retrofitting based on Mathematical Programming.

Due to several strengths and limitations of each approach, the most beneficial for solving industrial problems would be to combine all three approaches (Gundersen and Naess, 1988) and to use so-called combined or hybrid approaches. In this way synergistic benefits of the separate methods could be obtained (Fraser, 2013). However, among significant challenges is how to combine all three approaches so that retrofitting problem will be conceptually consistent and rigorous while exploiting the strengths of each approach (Grossmann and Daichendt, 1996). Among recent examples of successful combinations of approaches are e.g. thermodynamic background with advanced graphical approach supporting the designer interactions, such as Retrofit Tracing Grid Diagram (Nemet et al., 2015) and Heat Path Development (Varbanov and Klemeš, 2000) extended by Yong et al. (2015a). A recently developed hybrid approach based on physical insights and mathematical programming for retrofit of large-scale networks within flexible big industrial sites (Čuček and Kravanja, 2016) has been proven to be a valuable methodology that may contribute significantly to global resource saving, such as energy and environmental impact (Varbanov et al., 2018).

4. Industrial Retrofitting Applications

Process Integration methodology for efficient energy use has widespread applications worldwide. Most of the industrial activities are related to retrofit of existing processes for reduced energy demand and increased throughput (Smith, 2013). Nowadays, there have been a lot of successful projects in different industries, such as oil and gas, petrochemical, fine chemical, steel manufacture, chemical, pulp and paper, food and drink and other industries (Smith, 2000). Energy cost savings of 20 % or more were achieved only with few key ideas (Linnhoff, 2013). World leading companies, such as BP-Amoco, Exxon, Shell, Neste Oy, Mitsubishi and several others have demonstrated a primary energy savings of up to 25 % and similar emissions reductions, saving of millions of dollars annually (Hallale, 2001).

Retrofit studies at Total Site level involved big petrochemical sites, such as BP US, BP UK and MOL Hungary (Chew et al., 2013), oil refinery including all the units (Fraser and Gillespie, 1992), large Industrial Site in Japan (Matsuda et al., 2009), Swedish chemical site accounting 360 process streams (Hackl et al., 2011), large-scale steel plant (Matsuda et al., 2012), natural gas industrial parks (Zhang et al., 2018) and other sites. Several studies have also been performed for medium- or small-sized sites. Such examples of retrofit analyses are hospital site including hospital, a sports centre, laundry centre, and minor buildings (Herrera et al., 2003), medium-size refinery using Pinch Analysis (Nemet et al., 2015) and the hybrid approach using TransGen code considering more than 100 heat exchange units under flexible design conditions (Čuček et al., 2015), local community integrating an industry, residential area and business sector (Kostevšek et al., 2015), food producing company (Vujanović et al., 2015), cement factory (Boldyryev et al., 2016b) and several other medium- and smaller-scale sites.

Besides retrofit studies at site levels, there were several retrofit analyses performed at process level such as Heat Integration of sodium hypophosphite production (Tovazhnyansky et al., 2010), refinery (Tovazhnyanskii et al., 2009), bromine production (Boldyryev and Varbanov, 2015), cement production (Boldyryev et al, 2016c), milk powder production (Walmsley et al., 2013), cheese production (Kapustenko et al., 2008), crude oil distillation unit (Ochoa-Estopier et al., 2013), tobacco drying (Arsenyeva et al., 2016), coke-to-chemicals (Ulyev et al., 2013), biofuel production (Nagy et al., 2015), utility retrofit considering solar thermal and periodic heat storage (Abikoye et al., 2018) and other processes. An attempt has been also made to develop methodology for cost-effective integration of geothermal energy within industrial systems with use of Pinch Analysis (Barkaoui et al., 2016).

Despite of many successful industrial retrofitting applications there remained some very important issues that are yet mainly unsolved and are very important to the industry such as detailed plant design (plant layout, pressure drop), fouling (Vasilyev and Boldyryev, 2018), operation (start-up, shutdown, flexibility), reliability, availability and maintenance (RAM), regulation and policy and economic issues (Chew et al., 2013).

Additionally, it is important to consider flexibility of retrofitted HEN, because process plants and especially Total Sites operate under somewhat varying operating conditions. Obtained flexible HEN should be feasible for all operating conditions, and ensuring safe production (Čuček et al., 2016). For Total Site Integration it is important to consider also operation times of each process and possible non-simultaneous operation of processes (Nemet et al., 2014).

Applied retrofitting methods should be such to enable efficient (re)use of existing equipment as much as possible, to consider limitations on investment capital for retrofits and to account for cost due to civil engineering and pipework required and potential economic losses during application of retrofitting modifications (Akpomiemie and Smith, 2015). Besides, many identified retrofitting modifications may be found infeasible (Van Reisen, 2008) or difficult to be implemented due to safety reasons, non-continuous operation, space constraints, possible contamination, undesired phase change and other reasons (Chew et al., 2013).

5. Conclusions and Future Challenges

This contribution has presented different approaches developed that could be applied for retrofit of processes and entire sites, from small industrial processes up to larger-scale industrial and regional sites to improve energy efficiency and consequently to reduce emissions. Approaches are divided into pure heuristic-based, insights-based, optimisation-based and hybrid approaches combining heuristics, thermodynamics and/or optimisation. Among the approaches, Pinch Analysis is currently the most widely used Process Integration approach in the industry (Navarro-Amorós et al., 2013). As it has certain limitations as also all other approaches, it has been beneficial to combine various approaches in a way to take the best from each of them. After analysing the methods presented in the literature, it is not easy to declare which method provides the best results (Toimil and Gómez, 2016) and is the most suitable for industrial practice. Among the reasons are that the conditions, including the economy, processing and power plants, Total Sites and exploitation of renewables can significantly vary. Despite certain limitations of approaches, there have been several thousands of successful industrial examples of retrofitting applications yet, some of them were presented in the previous part of this paper.

Several future challenges have been identified from the review of existing approaches and methods for retrofitting existing process and Total Sites. Among the challenges are:

- To further develop methods that could be applied to larger-scale HENs (Toimil and Gómez, 2017). Several authors claimed good potential for solving important industrial HEN synthesis problems by applying specific methods, such as e.g. insights-based (Nemet et al., 2015), stochastic (Khorasany and Fesanghary, 2009), hybrid (Čuček and Kravanja, 2015b), and other. However, in many cases an objective comparison of all the approaches has been difficult (Toimil and Gómez, 2017);
- Development of appropriate case studies to illustrate and stimulate the decision makers in industry to use the potential of operating expenses (OPEX) reduction and get real savings. Different methods (based on insights, deterministic and stochastic optimisation) should preferably be applied for

solving the same case studies to find strengths, weaknesses and synergies of specific approaches. This is going to be beneficial for identifying the best specifics of each method (Ulyev et al., 2018). Consequently, such hybrid method could be developed that could help industry in achieving savings, and in reducing negative impacts on environment;

- A development of software tools (Gundersen, 2013a), which is of particular importance in retrofit situations where the current configuration needs to be taken into account (Boldyryev et al., 2017a);
- Efficient combination of process modifications coupled with HEN changes (Smith, 2013). To get the most profitable solutions, a process simulation and HEN models have to be considered together (Smith, 2013);
- Adequately addressing design (plant layout, pressure drop), fouling management, operation (start-up, shut-down, flexibility), reliability, availability and maintenance (RAM), regulation, policy (Chew et al., 2013), safety and process control (Smith, 2000);
- Efficient application of Process Integration methodology (Jamaluddin et al., 2018) across all material and energy streams for resources saving (Foo et al., 2012);
- Problem size and non-convexities are still problems that wait for improved solutions (Grossmann, 1992), although the available computer power has been continuously growing. Larger-scale HENs should be solved in a feasible amount of time (Toimil and Gómez, 2017);
- Real-time optimisation of the processes coupled with process control;
- Optimisation of processes and Total Sites from the whole supply chains/supply networks;
- Coverage of the Total Site demands is the most promising means of further improvement via waste heat utilisation, co-generation, efficient retrofit, and energy planning strategies. Nevertheless, the technical side should be developed further for proper technical realisation;
- Updating existing and bringing a new knowledge that has a multidisciplinary impact and further potential developments of clean technologies. The improved heat integration and conceptual design of a heat exchanger network may be a basis of the design of efficient and environmental-friendly production plants. It provides a reduction of the fossil fuel consumption, and as a result, CO_2 mitigation.

Summarising this paper content, the identified challenges could very likely be overcome greatly by developing hybrid approaches which include the best characteristics of developed approaches combined with the development of suitable software tools.

Nomenclature

CAPEX	Capital expenditures
CC	Composite Curve
ETD	Energy Transfer Diagram

GCC	Grand Composite Curve
HELD	Heat Exchanger Load Diagram
HEN	Heat Exchanger Network
LIES	Locally Integrated Energy Sectors
LP	Linear Programming
MER	Minimum Energy Requirement or Maximum Energy Recuperation
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Non-Linear Programming
MP	Mathematical Programming
NLP	Non-Linear Programming
OPEX	Operating expenses
PTA	Problem Table Algorithm
RAM	Reliability, Availability and Maintenance
RTD	Retrofit Thermodynamic Diagram
SePTA	Segregated Problem Table Algorithm
SSSP	Site Source - Sink Profile
STEP	Stream Temperature vs. Enthalpy Plot
SUGCC	Site Utility Grand Composite Curve
TSP	Total Site Profile
TS-PTA	Total Site Problem Table Algorithm
TSST	Total Site Sensitivity Table

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