Investigating operability issues of heat integration for implementation in the oil refining industry

Sofie Marton
Division of Industrial Energy Systems and Technologies
Department of Energy and Environment
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
sofie.marton@chalmers.se

Elin Svensson
Division of Industrial Energy Systems and Technologies
Department of Energy and Environment
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
elin.svensson@chalmers.se

Simon Harvey
Division of Industrial Energy Systems and Technologies
Department of Energy and Environment
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
simon.harvey@chalmers.se

Keywords
pinch analysis, energy efficiency improvements, chemical industry, energy efficiency gap, retrofit, operability, heat exchanger networks

Abstract
Heat integration is important for increasing the energy efficiency of industrial processes. However, the increased interdependencies caused by heat integration can result in process operability issues. Depending on which operability and implementation issues that are considered in retrofit of heat exchanger networks (HENs), the savings potential varies significantly. It is important to know what operability issues to consider in order to estimate reliable heat savings potentials while at the same time maximize the possibilities for implementation of heat recovery through heat integrated HENs. Although operability has been studied previously, the literature is not consistent in categorizations and definitions of the concept. No systematic and complete survey of operability perspectives of heat integration has been presented. This paper aims to map and categorize the relations between heat integration retrofit measures and potential effects on process operability in order to better understand which operability issues that are likely to have a large effect on heat savings potential and/or likeliness of implementation. A literature survey of operability research in process industry is presented to clarify the definition of operability. Previous studies define operability in different ways; in this paper these variations of definitions are compared and evaluated. One definition is proposed for the purpose of heat integration, which combines previous definitions in literature. Following this definition, operability is divided into the subcategories; Flexibility, Controllability, Startup/Shutdown and Reliability/Availability. These subcategories, and other practical implementation issues, are matched with different implications of heat integration measures commonly used for retrofit of HENs in chemical processes. The results are then presented in a schematic view and conclusions are drawn about operability aspects to consider for the retrofit of HENs.

Introduction
Heat integration is one of several options for improving the energy efficiency of industrial plants. Heat is widely used in the chemical and oil refining industry as well as in, for example, the pulp and paper and steel industry. Consequently, an energy and cost efficient use of heat is of great importance. Heat integration is used to recover heat from the process to replace external heating, thereby improving the energy efficiency. Although several case studies have shown large theoretical potentials for energy savings by heat integration in existing industrial plants, the sector-wide implementation potential is not yet well defined and is, furthermore, likely to change over time. One implication of increased process integration is that the number of interdependencies between different parts of the process increases. In previous studies it is recurrently discussed that operability is strongly connected to the number of interdependencies of a process, and that interconnections could cause operability or control problems (Setiawan and Bao, 2009, Setiawan and Bao, 2011, Subramanian and Georgakis, 2005). This implies the importance of not neglecting operability of heat integration. Not the least, it is important to overcome the potential operability problems if use of excess heat for internal heat recovery is going to be able to compete with alternative uses of excess heat such as district heating or low-temperature electricity generation

(Broberg Viklund and Karlsson, 2015), in the cases where this is desirable from an overall systems perspective.

Heat integration analysis can be based on mathematical programming or graphical insights (e.g. pinch analysis) (see e.g. Klemeš (2011)). Normally, practical considerations, and associated costs, are not taken into account in the analysis. These might be especially important when considering integration in large sites or even across company boundaries, which is the case, for example, for costs related to piping and pressure drops (see e.g. Hiete et al., 2012, Polley and Kumana, 2012). Similarly, operability issues are traditionally not considered in the conceptual design phase. Methods have been proposed to account for some of the mentioned practical and operability considerations in network design (see e.g. Escobar et al., 2013, Hackl and Harvey, 2015, Nemet et al., 2015, Reddy et al., 2013). However, the resulting designs and realized energy savings will obviously vary widely depending on the limitations considered.

Heat integration is used in industry to various extents, not the least because of individual variations in the existing process designs. This gives different energy saving potentials and operability constraints for different plants. Nevertheless, a wide variety of case studies have shown a large potential and need for increased energy efficiency and retrofit of HENs at different process industrial sites. There exist a number of different methodologies to identify HEN retrofit designs that reach high energy savings at low cost, each of which has their own benefits and drawbacks (see e.g. Sreepathi and Rangaiah (2014) for a review of HEN retrofit methodologies and applications). Nevertheless, it is common that several HEN designs can be identified that achieve approximately the same energy saving at similar costs. However, the designs can vary significantly regarding network complexity (stream splitting, number of units, characteristics of spaghetti design), where new heat exchangers are placed, the placement of utility heaters and coolers for target temperature control, etc. It is clear that economical factors like investment cost and fuel savings need to be considered together with technical and operational factors, and this has to be done for each process plant and company individually.

Since the conditions for implementing heat saving measures vary between different process plants and there are a number of retrofit possibilities within each plant, there is no standard way of considering operability for heat integration. Although retrofit measures might have operability effects for the process there is a limited amount of research on the subject. Implementation and operability issues of heat integration have been discussed in literature (see e.g. Aguilera and Nasini (1996), Chew et al. (2013) and Escobar et al. (2013)), but no schematic presentation has been made of the connections between different aspects of operability, and the various implications in the plant of implementing heat integration measures.

The contribution of this paper is the systematic overview of a wide variety of potential implications of heat integration projects and their connections to various operability factors and implementation issues. Similarities and discrepancies in definitions from literature are discussed and a categorization of operability proposed that is suited for evaluation of heat integration retrofits. The analysis is based on qualitative assessments of actual suggestions for heat integration retrofits taken from an ongoing case study, and their expected consequences on operability of the process.

The aim of the study is to investigate, discuss and clarify the relations between different operability factors and the implementation of heat integration measures in the oil refining industry. The purpose is to get a better understanding of operability and implementation issues and possibilities connected to heat integration in existing industrial process plants.

Methodology

An overview of the work flow of this paper is shown in Figure 1. The analysis is based on a literature review of operability definitions (1), including both operability connected to process engineering in general and related to heat integration in particular. Different authors' definitions of operability and operability factors are compared and discussed. Operability is then defined and categorized (2), based on the result from the literature review.

To relate heat integration to operability, several implications of heat integration measures, that have connections to operability issues, are listed (3). The selection of implications listed is based on results from an ongoing case study of an oil refinery, where several heat integration retrofit proposals are identified (4). In the case study, there has been a deliberate effort to identify retrofit proposals that affects the process in many different ways. The retrofit proposals in the ongoing case study are designed to be used to investigate operability perspectives of heat integration in an interview survey. The interview study and design of retrofit proposals are not in the scope of this paper, but affect the listed implications used in the paper. The listed implications and their relations to the retrofit proposals from the case study are further explained in 'Implications of heat integration retrofit measures'.

Finally, the operability factors are analysed for the various process implications of heat integration retrofit measures (5). The results are presented in a schematic way in a matrix, where relations between them are clearly shown. The connections between operability and heat integration are then discussed and clarified.

Implications of heat integration retrofit measures

When a heat integration retrofit measure is implemented in an industrial plant, this will affect the process in different ways. Several potential process implications are listed below; the list is based on retrofit proposals developed for an ongoing heat integration study of an oil refinery, and will in this paper be used to evaluate consequences for process operability of heat integration retrofit measures (see Figure 5).

1. De-bottlenecking
2. Stream splitting
3. Network complexity
4. Reduced load on a furnace
5. Reduced load on an air cooler
6. Pressure drop
7. Change in steam balance
8. Shut down of furnace before reactor

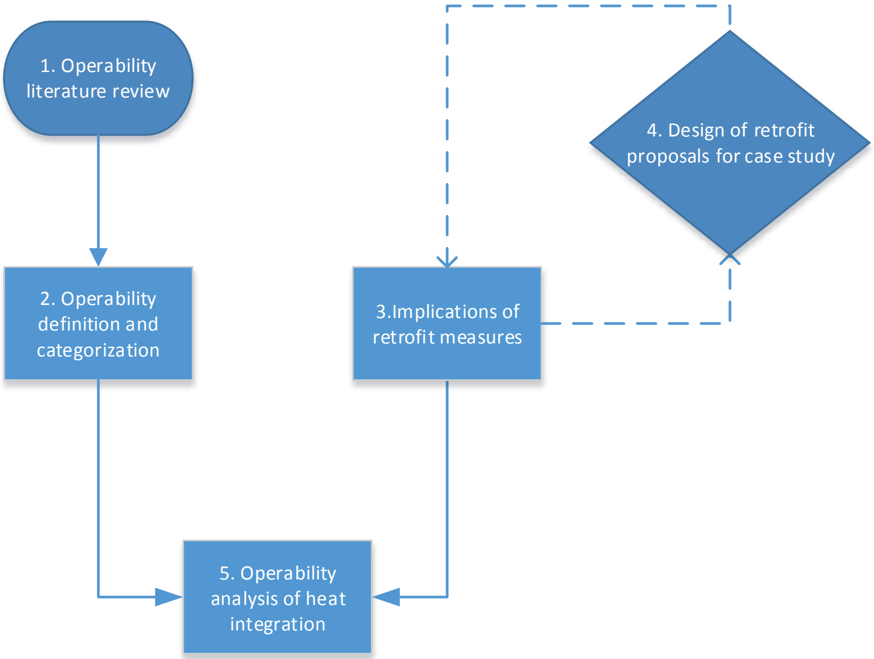

Figure 1. The figure displays the work flow for this paper. Dotted lines show relations to work outside the scope of this paper.

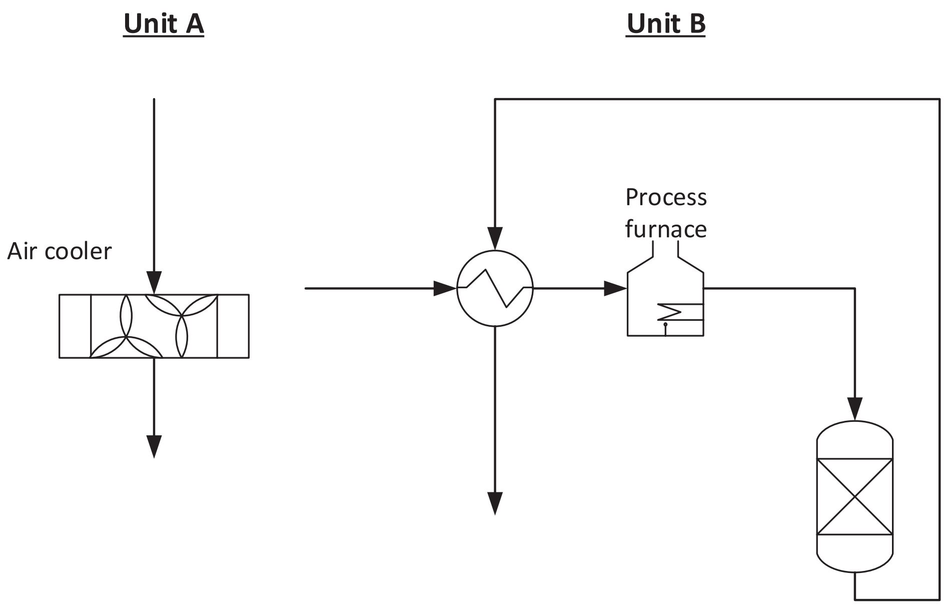

Figure 2. The original process part before the suggested retrofit. From Unit A a hot process stream is cooled by an air cooler. From Unit B a cold stream needs heating before entering a reactor. The stream is heated both with the hot reactor outlet and finally by a process furnace.

9. Heat exchange between process units
10. New equipment installation
11. Rebuilding existing equipment
12. Pressure differences between streams or high pressures

In this section, one example of a retrofit proposal is shown to illustrate how a retrofit heat integration measure could have several implications for the plant. This example includes several of the implications listed above.

The example is shown in Figure 2 and Figure 3, and is a heat exchanger retrofit proposal that includes the addition of a heat exchanger between two process units to reduce the process demand of hot and cold utility. In Figure 2, parts of the original process layout are shown. In unit A, a process stream containing excess heat is cooled by an air cooler. In Unit B, a process stream requires heating before entering a reactor, which is obtained from the outlet stream from the reactor and from a hot utility, a process furnace. The excess heat available from Unit A has a high enough temperature to pre-heat the reactor feed.

Therefore a new heat exchanger between the units is suggested, as shown in Figure 3. Due to the new heat exchanger, the load of the air cooler is also reduced. Since the temperature difference will decrease in the old heat exchanger, the area needs to be extended if the load, and thereby the final temperature of the hot stream in the heat exchanger, is to be kept unaffected. Finally, the temperature of the cold stream entering the process furnace will have an increased temperature, and the process furnace will have a reduced load.

Referring to the numbered list of implications presented above, this retrofit proposal includes the obvious process implications of rebuilding and adding equipment (#10–11), heat exchanging between process units (#9) and reduction of utility load (#4–5), but might also include more implications. For example, due to increased pressure drop in the heat exchangers, either the pressure of the cold stream at the reactor inlet will get lower, or the power demand for pumping will get higher (#6). The network complexity increases (#3), especially when more than one process unit is involved. The proposal might also include de-bottlenecking (#1) if any of the utilities is a bottleneck, or some of the process streams can have high pressures (#12) that needs to be considered.

Other retrofit proposals include different combinations of implications from the list, and all implications are covered from the various retrofit proposals. Although the list of implications is based on results from an oil refinery, similar implications exist for heat integration retrofit measures in other industries.

Literature review

The term operability is defined in different ways by different scientists. In this section, relevant definitions from literature are described and compared. The definition used in this paper is described in the section 'Operability perspectives of heat integration – Proposed definition and categorization', and is a result of the literature discussion below.

OPERABILITY DEFINITIONS

Operability in literature is in some cases related to chemical engineering in general and in others to heat exchanger networks in particular.

Escobar et al. (2013) describes operability connected to heat exchanger network design and defines it as stated:

> The term operability is often referred to the ease with which a process can be operated and controlled. It includes both flexibility and controllability, and is strongly affected by the network design.

In several previous studies, operability is described as different aspects of process control and/or as degrees of freedom of the process, and is strongly connected to the number of interdependencies of a process (Annakou et al., 1996, Setiawan and Bao, 2009, Setiawan and Bao, 2011, Subramanian and Georgakis, 2005). Setiawan and Bao (2009) describes operability as a key to analyzing both design of control system and process design simultaneously, since the process design affects the operability and control of the plant. This is similar to the above definition of Escobar et al. (2013), which also highlights the strong connection with process design and control. However, the term can include more than process control.

Aguilera and Nasini (1996) have discussed different definitions of flexibility and have made a flexibility test for HENs in particular. Their definition of flexibility includes operability, which is equated to feasibility. This differs from other definitions where flexibility is considered a part of operability. Aguilera and Nasini (1996) follow a definition of flexibility first

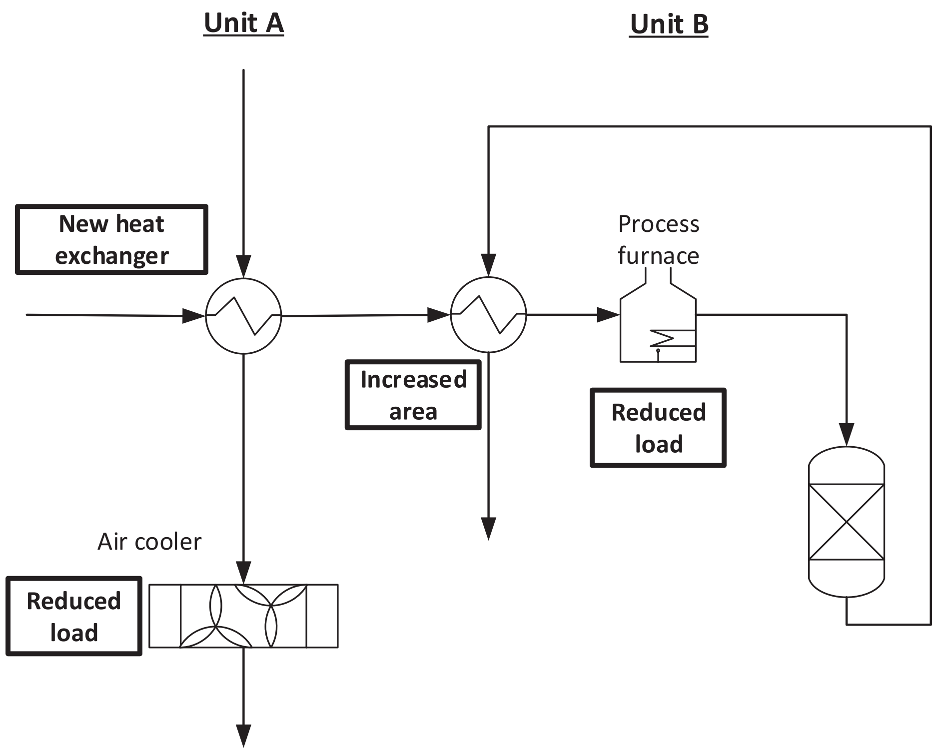

Figure 3. The suggested retrofit proposal.

proposed by Cerda et al. (1990), and formulate the following definition of flexibility:

> … a heat exchanger network (HEN) is structurally flexible for a given range of variation of parameters, if it guarantees operability (feasibility) and maximum energy recovery between process streams.

While Aguilera and Nasini (1996) use the term operability to denote only the aspect of operational feasibility, it is also common to use the term operability as a general concept for the ability to achieve a desirable steady-state and dynamic operation (Escobar et al., 2013, Grossmann et al., 1983, Larsson and Skogestad, 2000, Svensson et al., 2015) For example, Grossmann et al. (1983) states:

> Operability considerations involve flexibility, controllability, reliability, and safety

OPERABILITY CATEGORIES

In line with the more general definitions of operability, other authors divide operability into a number of subcategories, and the choice of these is not obvious. Chew et al. (2013) have divided implementation issues of total site heat integration, related to operability, in the subcategories listed below:

1. Different operating scenarios
2. Startup and shutdown
3. Variation in operating conditions
4. Turndown requirements
5. Controllability
6. Operational hazards.

Reliability, availability and maintenance (RAM) are mentioned as an additional implementation issue as well as economical consideration. Marlin writes about the importance of operability consideration in chemical engineering education. He proposes to divide operability in chemical engineering into other topics than Chew et al. (2013). The suggested topics from Marlin (2010) are listed below:

1. Operating window
2. Flexibility and Controllability
3. Reliability
4. Safety
5. Efficiency
6. Operation during transition
7. Dynamic performance and monitoring
8. Diagnosis.

By studying the description of the sub-categories of operability described by Marlin and Chew, one can see that similar operability aspects are included although their terminologies diverge.

For example, for the first category listed by Chew et al. (2013) "Different operating scenarios" it is described that the heat integration:

> has to be flexible enough to allow for the different operating scenarios, e.g. different feed stock compositions, anticipated

and it is mentioned that this affects the capacity requirements for equipment. The same objective is covered by the first operability issue listed by Marlin (2010) "Operating window", which also concerns the minimum and maximum capacity requirements of process equipment. This in turn partly overlaps with the "Turndown requirements" issue of Chew et al. (2013), which concern the need for process design to cope with reduced flow rates during periods of lower demands. All of these can be considered to be included in a wider (steady-state) flexibility concept, in which also, for example, point 3 on the list of Chew et al. (2013) "Variation in operating conditions" can be included (see also, e.g., Svensson et al. (2015) for a discussion of different flexibility definitions).

Similarly, there are overlaps between the points "Startup and shutdown" suggested by Chew et al. (2013) and "Operation during transition" suggested by Marlin (2010), and between "Controllability" (as described by Chew et al. (2013)), "Flexibility and Controllability" (as described by Marlin (2010)) and "Dynamic performance and monitoring" (as described by Marlin (2010)). All of these can be considered dynamic issues that can be included in a wider concept of controllability, as e.g. defined by Aguilera and Marchetti (1998):

> Controllability is associated with short-term perturbations, stability, and safe transitions from one operating point to another.

Because of the large variations in definitions and categorizations, the terms used to described operability issues of heat integration in this paper have been defined for the purpose of heat integration based on a combination of the suggested definitions found in literature, and are presented in the section 'Operability perspectives of heat integration – Proposed definition and categorization'.

Operability perspectives of heat integration – Proposed definition and categorization

In this paper operability is defined as follows:

> Operability is the ability to operate equipment, process units and total sites at different external conditions and operating conditions, without negatively affecting safety or product quality and quantity. This includes both steady-state and dynamic aspects of operation.

Here, operability is divided into the subcategories: Flexibility, Controllability, Startup/Shutdown, and Reliability/Availability, which are described in the following subsections.

Practical considerations are also included in the analysis. They are a crucial part of implementing heat integration and of rebuilding a chemical process (Sreepathi and Rangaiah, 2014), although they are not a part of the operability definition.

Process safety is not included as a separate category in the analysis. This is because safety aspects relevant for this study are included in the other categories. For example, poor control of the inlet temperature to a reactor could lead to thermal runaway of exothermic reactions. Safety is closely related to controllability and equipment malfunctions. Obviously very

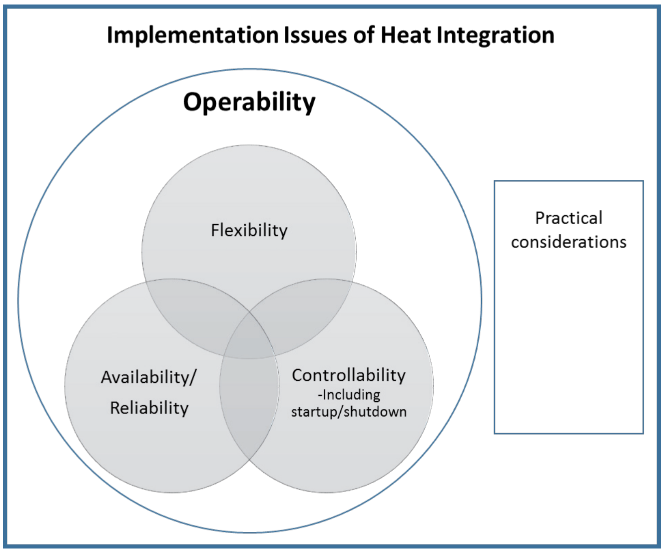

Figure 4. Relations between operability factors, operability and practical considerations.

important for the implementation possibilities of heat integration projects, economic aspects are never forgotten, and furthermore tightly related to most technical issues. They are therefore not included as a separate category in this paper, but briefly discussed in the section 'Some words on the economics of heat integration projects' below.

An overview of possible implementation issues related to operability and practical considerations is shown in Figure 4. Then, the different subcategories are defined.

FLEXIBILITY

A flexible process has the ability to maintain feasible operation for different operating scenarios. For oil refining processes, flexibility includes, for example, being able to handle different crude recipes, product mixes and ambient conditions. Flexibility also includes the ability for the operation to handle long-term variations within the process, such as decreased reactivity in catalyst beds and decreased heat transfer due to fouling.

CONTROLLABILITY

Controllability is defined as the ability to maintain a stable process, while handling disturbances and short-term variations to the process. According to our choice of definition, it also includes being able to maintain a stable process during transition from one operating scenario to another.

FEASIBILITY OF STARTUP/SHUTDOWN TRANSITIONS

Feasibility of startup/shutdown transitions is defined as the ability for the process to be able to startup/shutdown in a controlled and safe procedure. Due to the special characteristics of startup/shutdown transitions, this is important to consider separately, although it is essentially included in the definition of controllability.

RELIABILITY/AVAILABILITY

For this paper, reliability and availability are grouped together. This is because both concepts are connected to equipment or process failure and both have similar operability implications for the process. Reliability is defined as the ability to operate a process without unexpected equipment failure. Availability on the other hand is the expected operating time for equipment during a time period that also includes planned maintenance. (Aguilar et al., 2008).

PRACTICAL CONSIDERATIONS

To be able to implement retrofits of HENs, practical/technical issues other than the operability issues defined above need to be considered (Sreepathi and Rangaiah, 2014). For example, the plant needs to have space for new equipment and for its maintenance. There also needs to be time to do the rebuild of the process, which for most of the measures considered needs to be scheduled during expensive turnaround periods.

SOME WORDS ON THE ECONOMICS OF HEAT INTEGRATION PROJECTS

Economic considerations are included in the traditional pinch design method through the choice of a minimum temperature difference for heat exchange that reflects a trade-off between investment costs for heat exchanger area and operating costs for energy utility. The calculated costs for new heat exchangers and reduced costs for energy utility are straightforward to use for estimating the expected profitability of a heat integration project, for example, by simple payback periods, internal rate of returns or net present values. However, many of the operability issues might affect the expected cash flows of a heat integration project, as discussed in the section 'Operability analysis of HEN retrofit measures'. Typically, operability issues might lead to lower heat savings than expected from the steady-state analysis, thereby leading to lower operational cost savings, or they might lead to additional investments in, for example, over-design capacity, added measurements and/or manipulators for control or back-up systems to overcome potential problems. However, heat integration can potentially also affect quality and/or production rates for the main products in the plant, in which case the economics of the projects will be significantly different compared to a simple heat saving measure, see e.g. Aseeri et al. (2010) for an excellent example of this. Consequently, it is important to consider operability aspects and other practical design constraints in combination with economic evaluations.

It is worth mentioning, that even if an energy efficiency project passes the internal profitability requirement of a large industrial company (for example, to have a payback period less than five years, or even two years), it is not certain that it will be prioritized within the limited investment budget among other potential projects. Most of the budget goes to investments required to fulfill environmental regulations, safety, wastewater treatments and regular maintenance. Only a small share goes to reduction of operating costs, including not only energy cost reductions, but also other operating costs. Consequently, if a heat integration project can be shown to provide additional benefits, its likelihood for implementation increases significantly.

Operability analysis of HEN retrofit measures

Retrofitting of HENs to increase heat integration may have several implications for the process and process equipment that can be related to different operability factors. In Figure 5, twelve possible implications of HENs retrofit measures are related to the operability and implementation factors defined in the previous section. The list of possible process implications is based on the evaluation of several HEN retrofit suggestions from the ongoing oil refinery case study as described in the section 'Implications of heat integration retrofit measures'.

Depending on the complexity and number of modifications suggested in the heat integration retrofit proposal, implementation of one retrofit measure could involve several of the listed implications for the process. These changes in the process would have a direct effect on the operation of the plant if no additional measures would be taken. However, if the effect is significant, this will normally lead to additional design constraints, for example, capacity requirements for off-design operation, demand for improved control systems, or more advanced equipment. By satisfying the additional design constraints, operability, in turn, might be left unaffected. It should be added that design constraints that state a need for extra capacity and/or more advanced equipment obviously will lead to higher investment costs. In the end, there will be an economic trade-off between the operational costs associated with poor operability and the investment costs associated with overcoming the operability problems.

All retrofit measure implications have one or several connections to operability factors. These connections, or relations, can be direct or indirect, weak or strong. Here, the strongest, most direct relations are discussed. The first implication listed (#1), debottlenecking, is related to flexibility. In a bottleneck, the process is operating at an upper limit of an equipment or process unit. If the bottleneck is removed, productivity can be increased, either by allowing for a larger flow to be processed, or by allowing for a

Operability factors and implementation issues / Implications of retrofit measures	Flexibility	Controllability	Startup/ Shutdown	Reliability/Availability	Practical considerations
1. De-bottlenecking	■				
2. Stream splitting		■			
3. Network complexity	■	■			
4. Reduced load on a furnace	■	■			
5. Reduced load on an air cooler	■	■			
6. Pressure drop	■	■			
7. Change in steam balance	■	■			
8. Shut down of furnace before reactor	■	■	■		
9. Heat exchange between process units	■	■	■		
10. New equipment installation				■	■
11. Rebuilding existing equipment				■	■
12. Pressure differences between streams or high pressures				■	■

Figure 5. The matrix gives a schematic view of the connection between implications of retrofit measures at an oil refinery and operability factors. A black box indicates a connection.

better separation of valuable products. The effect on operability of removing a bottleneck is that the upper limit of the operating window of the process is increased, making the process more flexible. For HENs, an example of a bottleneck could be a process furnace operating at maximum load. The second implication from the list, stream splitting (#2), affects mostly controllability. The stream split causes an increase in the number of control variables to consider, but the degrees of freedom increase.

Of the implications of retrofit measures listed in Figure 5, implications #3–7 affect both controllability and flexibility. For example, a complex network (#3), with lots of interconnections, can be hard to control and the dependencies could decrease the flexibility of the process. Some retrofit measures could have implications that affect controllability and flexibility in both a positive and negative way, for example #4, reducing the load on a furnace, or #5, reducing the load on an air cooler. Whether they have a positive or negative effect depends on how the equipment is operated before the suggested retrofit measure. For a furnace or air cooler operated at maximum capacity, a lowering of the load would have a positive effect on both flexibility and controllability. On the other hand, it the equipment is operated close to the minimum load, a load decrease could affect process flexibility and controllability in a negative way. Implication #6, 'Pressure drop', might be an issue due to increased heat exchanger area. If the pressure drop is too high, more pumping power might be needed to transport the flows around the plant. If the pressure drop is not compensated for by increased pumping power (in which case the improvement of the overall system efficiency from the heat integration project will be lower), it will lead to lower pressures that might affect, for example, reactivity in reactors or thermodynamic equilibriums in separation processes.

When making changes to the steam balances (#7) at different pressure levels, flexibility and controllability needs to be taken into account in several ways. If heat that is currently provided by utility steam is replaced by heat from internal heat exchange with process streams, this usually leads to fewer degrees of freedom, making the process harder to control and decreasing process flexibility. The decreased steam consumption can affect the flexibility of the steam network in either a positive or negative way, depending on the steam balance. If a steam header has a lack of steam, a reduction of the steam consumption at that pressure level will lead to an increase in flexibility. On the other hand, if the steam header has a steam surplus, a decreased steam consumption might not affect the flexibility at all or affect flexibility in a negative way. The same reasoning applies for decreased steam production due to increased internal heat exchanging. With a flexible layout of the steam system, for example, with many options to switch the drive of mechanical equipment between steam turbine and electric motor, it is more likely that changes in steam balances can be handled satisfactorily by the steam system.

Besides affecting flexibility and controllability, #8 and #9 ('Shutdown of a furnace before reactor' and 'Heat exchange between process units') also have an effect on startup and shutdown of a process. For example, startup and shutdown conditions are highly important to consider for #9, 'Heat exchange between process units'. Since it is common that not all process units are started up at the same time, heating/cooling that is designed to be supplied from another unit might not be available during startup. This could lead to safety issues or material problems in the heat exchanger, and alternative sources of heating/cooling might be necessary during this operating mode, which therefore needs to be considered in the design phase. In the same way, issues could arise during shutdown. The 'Shutdown of a furnace before reactor' (#8), is mostly affected during startup. If the catalyst needs to be heated, an internal heat exchanger might not be able to do this before the reaction is running. For example, if the hot outlet of the reactor is used to heat the inlet stream to the reactor, it will not be possible to reach the target temperature without external heating. This means that although a process furnace can be shut down during normal operation, it might not be possible to remove it, since it might be needed during startup. The removal of a furnace before a reactor also affects the controllability since the furnace, usually, provides an additional degree of freedom and a direct target temperature control without complex interdependencies with other control variables. It also affects the flexibility, since the use of utility heating provides more flexibility in available heat than other process streams.

The construction and installation of new equipment (or rebuilding of old equipment) and its properties (#10–12), affect mainly the reliability/availability and practical implementation issues. There needs to be space and time for doing the rebuilding of the plant and the installed equipment needs to be maintained. Pressure differences between streams, or high pressures in general, (#12) could affect, for example, the choice of heat exchanger and the need for scheduled maintenance. It also increases the risk of malfunction of the equipment. Any new or rebuilt equipment could potentially affect reliability/availability, for example, through fouling or corrosion that require both scheduled and unscheduled stops of the process.

All these connections between operability issues and implications of retrofit measures show the importance of considering operability in the network design. Figure 5 displays possible connections to operability issues. It is most suitable to be used as a checklist, to ensure that the most important operability factors for a certain retrofit proposal are considered. Especially when choosing between similar heat integration retrofit proposals, this is a guideline of what operability aspects to investigate further, both positive and negative effects, to be able to choose the best retrofit from an operability perspective. It should be added that this study is based on a case study of an oil refinery and might not be representative for other industries, although similar connections could be done for other situations. The connections are based on theoretical assumptions, with roots in literature. In the ongoing case study, these connections will be further investigated and developed as described in 'Future work'.

Conclusions

A diverse range of definitions for process operability and related concepts can be found in literature. In this paper, a definition for operability is proposed for the purpose of heat integration implementation. Based on this, and the literature reviewed, operability issues are divided into the four categories Flexibility, Controllability, Startup/Shutdown, and Reliability/Availability. The paper shows that implementation of heat integration projects can involve many changes and implications for the process operation, sometimes leading to additional design constraints. Examples show that in addition to the intended heat saving, heat integration projects can lead to additional benefits, but also difficulties in achieving a flexible, controllable and reliable process that is feasible to startup and shutdown in a safe manner. It can be concluded that there is a need to consider operability for heat integration projects in order to identify additional design constraints, benefits and costs related to different design proposals. The results from the analysis are displayed in a schematic way in a matrix, mapping relations between operability factors and possible implications of retrofit measures. For a specific heat integration design there are a number of associated process implications that can be identified in the matrix to find out which operability factors will be most important to evaluate further for the suggested design. The matrix can in this way provide guidelines of what operability factors to consider when implementing heat integration projects in oil refining industry.

Future work

Further work needs to be done to verify the relations between operability and heat integration and estimate the relative significance of the various relations. This will be done in connection to the ongoing case study at the oil refinery. Retrofit proposals will be discussed with plant engineers in an interview study to verify the significance of the established connections between implications of heat integration retrofit measures and implementation and operability aspects of the oil refining process, and to identify the need for further development of methods and tools in this area.

References

Aguilar, O., Kim, J. K., Perry, S. & Smith, R. 2008. Availability and reliability considerations in the design and optimisation of flexible utility systems. *Chemical Engineering Science,* 63, 3569–3584.

Aguilera, N. & Marchetti, J. L. 1998. Optimizing and controlling the operation of heat-exchanger networks. *AIChE Journal,* 44, 1090–1104.

Aguilera, N. E. & Nasini, G. 1996. Flexibility test for heat exchanger networks with non-overlapping inlet temperature variations. *Computers & Chemical Engineering,* 20, 1227–1239.

Annakou, O., Meszaros, A., Fonyo, Z. & Mizsey, P. 1996. Operability investigation of energy integrated distillation schemes. *Hungarian Journal of Industrial Chemistry,* 24, 155–160.

Aseeri, A. S., Amin, M. S., Ibrahim, M. S.. 2010. Debottlenecking through heat integration (Case study: Crude distillation unit). *Society of Petroleum Engineers – ADIPEC 2010: 14th Abu Dhabi International Petroleum Exhibition and Conference*, Vol. 1, pp. 111–114.

Broberg Viklund, S. & Karlsson, M. 2015. Industrial excess heat use: Systems analysis and CO_2 emissions reduction. *Applied Energy*, 152, 189–197.

Cerda, J., Galli, M. R., Camussi, N. & Isla, M. A. 1990. Synthesis of flexible heat-exchanger networks .1. convex networks. *Computers & Chemical Engineering,* 14, 197–211.

Chew, K. H., Klemes, J. J., Alwi, S. R. W. & Manan, Z. A. 2013. Industrial implementation issues of Total Site Heat Integration. *Applied Thermal Engineering,* 61, 17–25.

Escobar, M., Trierweiler, J. O. & Grossmann, I. E. 2013. Simultaneous synthesis of heat exchanger networks with operability considerations: Flexibility and controllability. *Computers & Chemical Engineering,* 55, 158–180.

Grossmann, I. E., Halemane, K. P. & Swaney, R. E. 1983. Optimization strategies for flexible chemical processes. *Computers & Chemical Engineering,* 7, 439–462.

Hackl, R., Harvey, S. 2015. From heat integration targets toward implementation – A TSA (total site analysis) –based design approach for heat recovery systems in industrial clusters. *Energy*, 90, 163–172.

Hiete, M., Ludwig, J. & Schultmann, F. 2012. Intercompany energy integration – Adaptation of thermal pinch analysis and allocation of savings. *Journal of Industrial Ecology*, 16, 689–698.

Klemeš, J. 2011. *Sustainability in the process industry: integration and optimization,* New York, McGraw-Hill Professional.

Larsson, T. & Skogestad, S. 2000. Plantwide control – A review and a new design procedure. *Modeling Identification and Control,* 21, 209–240.

Marlin, T. E. 2010. Teaching "operability" in undergraduate chemical engineering design education. *Computers & Chemical Engineering,* 34, 1421–1431.

Nemet, A., Klemes, J. J. & Kravanja, Z. 2015. Designing a Total Site for an entire lifetime under fluctuating utility prices. *Computers & Chemical Engineering*, 72, 159–182.

Polley, G. T. & Kumana, J. D. 2012. Practical process integration retrofit: Part 4. Dealing with large projects. *2012 AIChE Spring Meeting and 8th Global Congress on Process Safety*, Houston, TX, United States.

Reddy, C. C. S., Rangaiah, G. P., Lim, W. L. & Naidu, S. V. 2013. Holistic approach for retrofit design of cooling water networks. *Industrial & Engineering Chemistry Research*, 52, 13059–13078.

Setiawan, R. & Bao, J. 2009. Operability analysis of chemical process network based on dissipativity. *Ascc: 2009 7th Asian Control Conference, Vols 1–3.* Hong Kong, China: IEEE.

Setiawan, R. & Bao, J. 2011. Analysis of interaction effects on plantwide operability. *Industrial & Engineering Chemistry Research,* 50, 8585–8602.

Sreepathi, B. K. & Rangaiah, G. P. 2014. Review of heat exchanger network retrofitting methodologies and their applications. *Industrial & Engineering Chemistry Research,* 53, 11205–11220.

Subramanian, S. & Georgakis, C. 2005. Methodology for the steady-state operability analysis of plantwide systems. *Industrial & Engineering Chemistry Research,* 44, 7770–7786.

Svensson, E., Eriksson, K. & Wik, T. 2015. Reasons to apply operability analysis in the design of integrated biorefineries. *Biofuels Bioproducts & Biorefining-Biofpr,* 9, 147–157.

Acknowledgements

Funding from Preem AB and the Chalmers Energy Initiative is gratefully acknowledged.