PROJECT REPORT

2018-08-28

Design of heat exchanger networks with good controllability

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Design of heat exchanger networks with good controllability

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SUMMARY

One important way to improve the energy efficiency of chemical process plants is to improve the heat integration within and between industrial processes. This is accomplished by recovering excess process heat at high temperatures and using it to replace primary heating at lower temperatures through a heat exchanger network. However, as a process becomes more heat integrated, process control may become more difficult. Poor control performance can, in turn, easily lead to increased costs that outweigh the predicted energy cost savings. It is therefore essential to model and analyze the effect of the process changes and address the identified potential control challenges. However, the majority of existing methods for controllability assessment of heat exchanger networks only consider steady-state properties, and not the dynamic aspects, which in reality can seriously affect process control characteristics. With better methods for controllability analysis alternative design options could be evaluated and compared more reliably at an earlier design stage.

This report proposes the basic structure of a step-wise approach for integrating dynamic considerations into the design process for heat recovery improvements in process industry, and suggests suitable methods and tools to be used for the different steps of the proposed framework. As part of this, recent work that has been performed to evaluate and improve the methods used in controllability assessment is outlined. Additionally, a number of areas are identified in which significant further efforts are required before a complete controllability assessment framework can be specified and a toolbox for integrated design and controllability analysis can be developed.

One central area requiring continued research and development is to define an adequate controllability index for use in heat exchanger network design. For example, it is relatively easy to argue that some of the commonly applied controllability measures are insufficient since they are based on steady-state system interactions only. However, as illustrated in the report, alternative measures of system interactions that take dynamics into account suffer from other drawbacks, of which one is scaling dependency. Nevertheless, these are interesting for further development of a new controllability assessment method, since the issues with scaling can possibly be dealt with using an approach evaluated in this project. Another area where further work is needed is to develop tools with some level of built-in support for formulation of dynamic models of heat exchanger networks. Model simplifications, or other means of handling the large model sizes typically resulting from dynamic modelling of heat exchanger networks may also be needed in order to overcome difficulties in model simulation and analysis. In addition to the development needs related to individual assessment steps, there is an apparent need for appropriate protocols for information transfer and conversion of models between different tools.

This report gives an overview of insights revealed in recent research with respect to the controllability of heat exchanger networks. Through this research, the knowledge for continuing the effort to define a better controllability index for heat exchanger networks has been improved.

Contents

1 BACKGROUND

Industry accounts for approximately one third of the global and about two fifths of the Swedish energy end use. Industrial firms are driven by strengthened climate and environmental policy goals and global competition to improve the efficiency of their energy use. One important way to improve the energy efficiency of chemical process plants is to improve the heat integration within and between industrial processes. This is accomplished by recovering excess process heat at high temperatures and using it to replace primary heating at lower temperatures in other parts of the process. This way, the use of primary energy utilities, such as steam and cooling fans, are reduced. The reduced demand for fuel and other utilities implies that heat integration can save money. The more energy prices rise, the more cost-effective are the investments in heat integration. In energy-intensive process industries, the close relationship between energy use and production processes also provides incentives to improve energy efficiency, and thereby also production efficiencies. Another means of reducing CO_2 emissions is to replace fossil raw materials by renewable bio-based feedstock. To accomplish this, new processes that can be efficiently and safely integrated with existing process units are needed.

However, implementation of heat integration projects can result in complex control problems. The purpose of any control system is to move the effect of a disturbance from where it is undesired to where it is unimportant. Utility systems, such as steam networks and cooling water circuits, provide a straightforward and often inexpensive method of absorbing disturbances. As a process becomes more heat-integrated, the utilities available to absorb control disturbances are reduced and control becomes more difficult. Poor control performance can easily lead to increased costs that outweigh the predicted energy cost savings, see e.g. (Slolely, 2006; 2009; 2010). Heat integration projects in different sites pose their own specific challenges. Nevertheless, as the use of utilities is reduced, control issues will generally appear. Consequently, it is essential to model and analyze the effect of the process changes and address the identified potential control challenges.

In the project "Identification of operability challenges of strategic process integration measures", existing methods for operability analysis of process integrated designs were surveyed and critically analyzed. The survey revealed that there are several reasons to increase the use of methods for flexibility and controllability analysis when evaluating strategic energy efficiency measures, not the least when evaluating the integration of processes based on new technology concepts such as different biorefinery processes (Svensson, et al., 2015). The project identified a variety of methods for flexibility and controllability analysis of heat exchanger networks, but it was also concluded that the majority of these had only been demonstrated for theoretical model examples, and only to a very small extent been applied in real industrial case studies. Moreover, the methods generally only considered steady-state properties, and not the dynamic aspects, which in reality can seriously affect process control characteristics. It is also important to consider that retrofit design of existing processes implies further complications compared to design of new processes (greenfield design) because the degrees of freedom that can be used for improving control performance are drastically reduced due to the limitations set by existing unit processes.

There are certain characteristics of process integration designs that are likely to affect the operability of the process. Process integration is accomplished by recycles, which cause interactions in the process, which can lead to amplification of disturbances. Moreover, heat recovery can be increased by allowing smaller temperature differences for heat exchange. This will be at the expense of higher capital investment costs, but at high operating costs for energy it might be motivated. However, it is likely that controllability becomes negatively affected if the temperature difference in a heat exchanger becomes too small. Some process integration designs involve splitting of streams, that is, to split a flow in two or several branches, with heat exchange in parallel lines. The stream splitting is sometimes a prerequisite for enabling effective utilization of the heat in these streams, but since it adds complexity and flexibility to the network, it is often assumed to require more of the control system, see e.g. (Kemp, 2006). With higher energy costs, the trade-off between operating costs for energy and capital costs for heat exchanger area will be steered towards lower temperature differences for heat exchange and more stream splits. It will then be motivated to consider operability aspects such as controllability in the choice between alternative process integration design solutions. With better methods for controllability analysis it would be possible to evaluate and compare the controllability of different design options.

1.1 About MoveDynE

This document is a result of work performed in the project MoveDynE. MoveDynE is carried out within the strategic innovation programme Process Industrial IT and Automation (PIIA), which is a joint initiative by Vinnova, Formas and the Swedish Energy Agency. The project is also supported by financing and active participation from Preem.

The MoveDynE project aims at developing methods for dynamic assessments of heat integration design solutions. The methods are intended to be incorporated into tool packages for industrial heat recovery analysis and design that can thereby be used for industrial energy analysis considering both steady-state and dynamic aspects. A central part of the project is the study of controllability performance indicators. The vast majority of currently available methods for evaluation of controllability and sensor-actuator pairing for heat exchanger networks are based on steady-state descriptions of the processes. It is relatively easy to show that the dynamics can make the use of these indicators unreliable and sometimes misleading. Not the least for systems with dead times it is important to consider the dynamics, and dead times are unavoidable in systems with material and heat transport in flows.

MoveDynE is founded on a process industry need for combining existing methods for design of energy efficient heat recovery systems with new methods for analyzing their controllability and designing their control systems.

1.2 Aim of the report

The aim of this report is to propose the basic structure of a step-wise approach for integrating dynamic considerations into the design process for heat recovery improvements in the process industry, and to suggest suitable methods and tools to be used for the different steps of the proposed framework. The report will also highlight some difficulties in the procedure, and discuss further development needs.

2 THEORY AND DEFINITIONS

2.1 THE INTEGRATION OF PROCESS DESIGN AND CONTROL

A wide yet comprehensive discussion on the challenges involved when considering process design and process control is given in the book "*The Integration of Process Design and Control*" (Seferlis & Georgiadis, 2004). The different papers of the book provide literature reviews, theoretical definitions, descriptions of methods and frameworks as well as discussions on practical considerations together with relevant industrial examples. In the preface, the editors express their aim of bringing together the developments in a variety of topics related to the integrated design and control.

Some of the statements from the textbook are central motivating drivers for the MoveDynE project, and captures well our views on why control system design and controllability assessment should be considered at an early stage of heat integration retrofit design.

"It is quite obvious that the main research trends will be towards a higher degree of integration dictated by the need for increased competitiveness in a fast changing business environment.

"Opportunities for further process integration and intensification in existing plants will be persistently sought. Greater interaction with planning and scheduling levels in the company is also expected [...]."

"The integration of process design and control aims at identifying design decisions that would potentially generate and inherit possible trouble to the dynamic performance of the control system. Furthermore, it aims at exploiting the synergistic powers of a simultaneous approach to ensure the economical and smooth operation of the plant despite the influence of disturbances and the existence of uncertainty."

(Seferlis & Georgiadis, 2004)

"In general, the success of an integrated design is measured based on the agreement with its ability to be controlled and operated safely and profitably. Therefore, a systematic procedure is required to evaluate the controllability issues of the integrated designed processes."

(Alhammadi & Romagnoli, 2004)

"[...] controllability and control strategy design should not be simply an afterthought of the process design."

(Luyben, 2004)

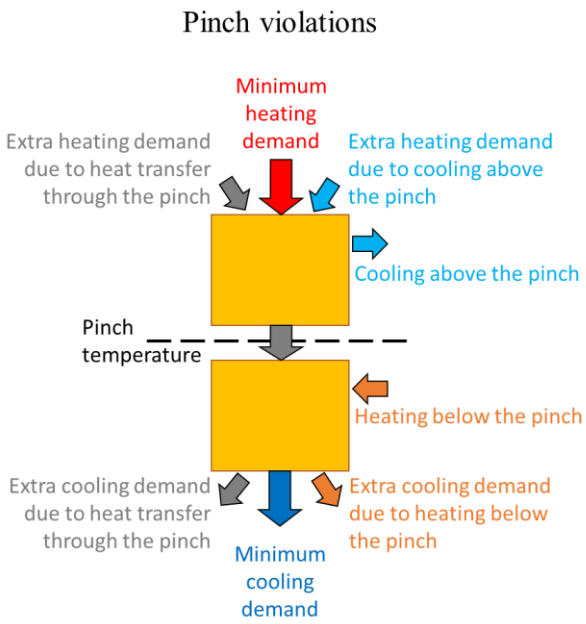
2.2 HEAT INTEGRATION – PINCH ANALYSIS

Pinch analysis (or pinch technology, pinch methodology) is a collection of methods and tools that can be used to analyze and improve the energy efficiency of industrial heat recovery systems. The pinch analysis framework provides tools and methods for quantifying the minimum heating and cooling demands for a process, for defining optimum temperature levels for external heating and cooling utilities, for designing heat exchanger networks, and for guiding thermal integration of energy intensive unit operations like distillation columns. There are methods for designing new heat exchanger networks (grassroot or greenfield design) as well as for analyzing and improving existing networks (retrofit design).

2.2.1 Fundamental principles

From the basics of thermodynamics, we know that heat that is removed from a process or stream at a high temperature can be used to heat another stream with a heating demand at lower temperature. The fundamental principle of pinch analysis is that the process is divided into two temperature regions, one with a deficit and one with a surplus of heat. Above a certain temperature level, called the pinch temperature, the process has a net demand of heat, while below the pinch temperature, the process has a net surplus of heat. Based on this knowledge, the three golden rules of pinch analysis can be formulated:

- Do not transfer heat across the pinch
- Do not cool above the pinch
- Do not heat below the pinch



To break one of these rules is termed a pinch violation, which leads to greater than minimum energy use. Pinch violations in existing heat exchanger networks can be seen as inefficiencies, by which high temperature levels are not utilized optimally for heating of cold process streams (or vice versa – low temperatures are not utilized optimally for cooling of hot process streams). Consequently, measures that reduce or eliminate pinch violations, will lead to energy savings.

In retrofit situations, i.e. when existing processes are analyzed for identification of improvement measures, the following steps should be completed:

- Definition of the system: The aims and constraints strongly influence the way data is extracted and also at the same time give guidelines to the stream data extraction.
- Collection of stream data from, e.g. process computers: Start and target temperatures and heating/cooling demands for each heat source and heat sink.
- Choice of the minimum allowed temperature difference for heat exchange, ΔT_{min}.
- Pinch calculations: Minimum process heating and cooling demands, maximum potential for heat recovery and pinch temperature.
- Identification of current use of heating and cooling utility from available process data.
- Identification of pinch violations in the existing heat exchanger network.
- Proposals for new designs of the heat exchanger networks to eliminate pinch violations.

2.2.2 Composite curves

A common graphical tool in pinch analysis is the composite curves, see Figure 1. The cold composite curve is constructed by combining temperature and load characteristics for all heat sinks, i.e. for all streams that need to be heated (cold streams). This implies that the cold composite curve shows the net heating demand for the process as a function of temperature. The hot composite curve is constructed correspondingly. Both composite curves are plotted together in a temperature/heat load diagram. The region where the two curves overlap shows the potential for heat recovery. The diagram also shows the minimum hot and cold utility demand ($Q_{H,min}$ and $Q_{C,min}$) for a given ΔT_{min}. The pinch is the point on the temperature axis where the distance between the curves is equal to ΔT_{min}.

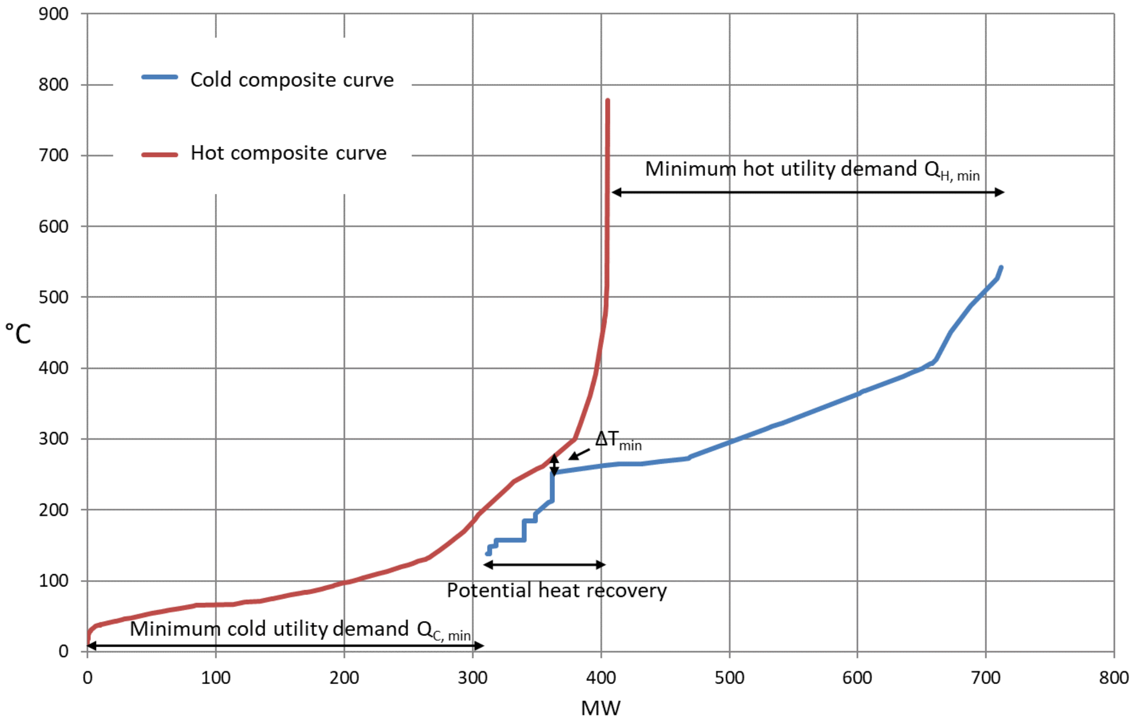


Figure 1. Composite curves, which show the minimum temperature difference approach at the pinch, the minimum heating and cooling demands, and the maximum potential for heat recovery.

A greater value of ΔT_{min} implies larger temperature differences for heat exchange and consequently lower demands for heat transfer area and lower capital costs. On the other hand, the potential for heat recovery is reduced (the curves cannot be shifted as close together), which leads to higher energy demand and higher operating costs for energy.

2.2.3 Retrofit of existing heat exchanger networks

Rebuild or revamp of existing heat exchanger networks is usually referred to as heat exchanger network retrofit. Possible retrofit options include addition of heat transfer area, use of heat-transfer enhancements, installing new exchangers, and/or relocating existing heat exchangers to reduce the hot and cold utilities required.

Methods for energy analysis of existing heat exchanger networks involve the identification and evaluation of inefficiencies in the current network, heat-saving modifications to reduce these inefficiencies, and the selection of the most promising modifications, i.e., the most profitable ones with acceptable operability. Methods for heat exchanger network retrofit can be broadly categorized into optimization-based approaches and insight-based approaches. The optimization-based methods are highly complex, and evaluation of the quality of solution may be difficult in practice considering possible trapping in local optimum and inevitable model and parameter uncertainties. Therefore, in practice, the insight-based approaches such as pinch analysis are still the most widely used for industrial applications – also for retrofit; see (Li & Chang, 2017) for a recent example. In pinch analysis, the insights from graphical tools such as composite curves are used to calculate energy targets. Heuristics are then applied for network design to achieve these targets.

The main advantages of insight-based methods such as pinch analysis are their simplicity, their graphical representation, and the possibility of the design engineer to interact and influence the solution process. However, difficulties in data extraction, practical targeting and redesign of the network are still encountered using pinch analysis, not the least in retrofit situations.

In retrofitting, the existing equipment constrains the opportunities for cost-efficient integration. Consequently, information about the existing heat exchanger network should be included in the analysis. The advanced composite curves (Nordman & Berntsson, 2009) which are based on the classical pinch curves, include information about the actual placement of heaters and coolers in the existing heat exchanger network. A new insight-based method that has the advantages of pinch analysis in terms of user interaction and graphical visualization tools, and also overcomes some of the problems with data extraction and representation of the existing network has recently been proposed (Bonhivers, et al., 2016).

Nevertheless, approaches based on pinch analysis are still the most widely used in industry. The basic method for heat exchanger network retrofit involves identification and reduction of pinch violations. When the potential for energy savings has been determined (current energy demand minus theoretical minimum energy demand) and the pinch temperature has been identified, it is possible to identify which existing heat exchangers that violate the pinch rules, or in other words, where the inefficiencies in the heat exchanger network are. In the next step, proposals for how to eliminate the pinch violations are sought, for example, by installing new heat exchangers or by enlarging the heat transfer area in existing units. This last step typically requires experience and is guided mainly by thermodynamic principles and heuristic rules.

2.2.4 Further reading about pinch analysis

For more information about pinch analysis, we refer to the easily accessible and pedagogic material that has been developed by Natural Resources Canada. Their reports describe the basics of the methods and provide examples of successful applications in the oil refining industry and other sectors. The following link is a good entrance:

http://www.nrcan.gc.ca/energy/efficiency/industry/processes/systems-optimization/process-integration/pinch-analysis/5525

2.3 CONTROLLABILITY OF HEAT EXCHANGER NETWORKS

2.3.1 Optimal operation and control of heat exchanger networks

Operation of heat exchanger network has several objectives: to satisfy the target temperatures of the streams, to minimize the utility cost, and to achieve a satisfactory dynamic behavior, i.e. stable operation and smooth transitions (Glemmestad, 1997). Generally, the most important control objective is to keep the target temperatures at their specified setpoints, or within specified boundaries. This is required to guarantee proper downstream operation. The most important disturbances are typically, variations in flow rates and supply temperatures.

In the heat exchanger network, a number of inputs that can be manipulated are needed to add enough degrees of freedom for regulatory control and optimization. The most common types of manipulated inputs are illustrated in Figure 2 and consist of:

1. Utility Flowrates
2. Bypass fraction
3. Split fraction
4. Process Streams flowrates
5. Exchanger area (e.g. flooded condenser)
6. Recycle (e.g. if exchanger fouling is reduced by increased flowrates).

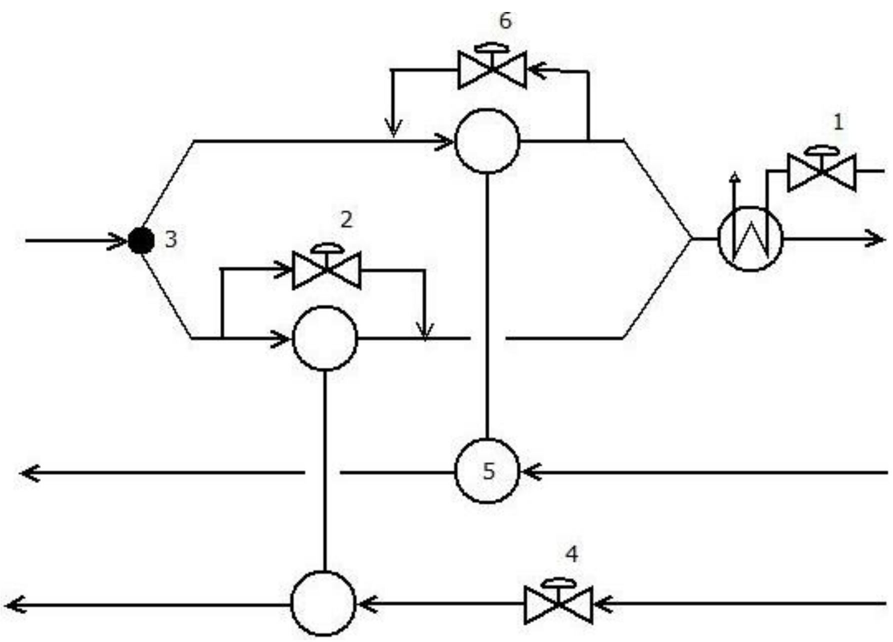


Figure 2. Possible manipulated inputs in heat exchanger networks (Escobar, et al., 2013).

The first two options are the most generally used for regulatory control. The duty of a utility heat exchanger, e.g. a heater or cooler, that is placed as the last heat exchangers on a process stream can be manipulated to control the outlet temperature of the stream with a fast and direct effect, and with no interaction with other control loops. However, in a well heat-integrated system, not all streams have a utility exchanger. Consequently, bypasses are also required in the control structure.

A heat exchanger system is a typical example of a so-called multiple input multiple output (MIMO) system, where the same manipulated input (e.g. a bypass valve) may affect multiple outputs (e.g. target temperatures) or conversely the same output is affected by multiple inputs. Potentially, these interactions may be quite strong, something that is a common issue in industrial process systems. The control of multivariable systems requires more complex analysis than single-variable systems. However, the concept of a decentralized feedback control system in which each input is used to control one output only, is the simplest approach to multivariable control design. There are three major advantages to using a decentralized feedback control system: flexible operation, simple design, and failure tolerance (Tellez, et al., 2006). Decentralized control systems are dominating in the application of heat exchanger networks, and here we also assume that the heat exchanger networks will be controlled this way.

The selection of suitable input-output pairings of bypasses, utility heat exchangers and target temperatures is a challenging problem because of its combinatorial nature. The controllability is strongly dependent on both the network configuration and control structure selection.

2.3.2 Controllability index based on interaction measures for input-output pairing

From the heat exchanger network design perspective, a controllability index is desired for comparison of different heat exchanger network designs at an early conceptual design stage. Consequently, such a controllability index should be easy to calculate and, ideally, it should be a function of the network's topology primarily and not depend on a particular control strategy or set of manipulated variables.

Measures of controllability (or more specifically output controllability) can describe different aspects of the control performance of a process, for example, interaction between control loops or disturbance rejection, see e.g. (Mathisen, et al., 1991) (Wolff, et al., 1992). Interaction measures are commonly used for input-output pairing, that is, for selecting which manipulated variables should be used to control which controlled variable. Good pairings provide a fast and direct effect between the manipulated and controlled variable, with no interaction with other control loops. The interaction measure consequently also provides one view of the controllability of the system.

The relative gain array (RGA) is a tool that is commonly used both as an interaction measure for input-output pairing, and as a basis for controllability assessment of heat exchanger networks. The RGA is a matrix in which each value represents one possible pairing of manipulated and controlled variables. For an input u_i and an output y_j, the effect on y_j of changing u_i, i.e. $\partial y_j/\partial u_i$ is denoted as the gain. For a system with interactions with other control loops, the steady-state gain will change depending on whether the other loops are open (i.e., their manipulated variables are constant and the control valve openings fixed) or the other loops are closed with perfect control (i.e., the controlled variables are constant and the controllers are in automatic mode and on setpoint). The values of the RGA matrix are calculated as the ratio of the steady-state gain with the other loops open, and the steady state gain with the other loops closed, hence, the relative gain. This means that a value of one represents a case where closing the other control loops does not affect the gain between the particular input and output variables, or in other words, there are no interactions between this control loop and the others and the pairing should be preferred. Values of the relative gain that are far from one means there are large interactions in the system. Especially, pairings for which the relative gain becomes negative should be avoided.

The condition number, which is calculated from the RGA has been used as a measure of controllability of heat exchanger networks. However, the condition number, like any interaction measure, by definition, depends on the available manipulated inputs, that is, it depends essentially on the choice of which heat exchangers should be equipped with by-pass valves, and which of these should be used for regulatory control. The condition number is therefore not a measure of the controllability of the heat exchanger network itself, but rather of the heat exchanger network and a given set of control equipment (the latter essentially referring to the by-pass valves since utility heaters and coolers and stream splits are given by the network design). From a conceptual design point of view, each new heat exchanger network should be designed using the best set of manipulated variables. Hence, a controllability index for a heat exchanger network can be defined as the best value of the chosen controllability measure obtained for all possible combinations of manipulated variables. (Westphalen, et al., 2003).

Another important issue in the controllability analysis of heat exchanger networks is the identification of subnetworks. A subnetwork is defined as an independent set of streams that are heat-integrated. Because the heat exchangers of one particular subnetwork can never be selected to pair with an outlet temperature of a stream located in a different subnetwork, interactions should be evaluated for each subnetwork separately. If, in a given network, all but one subnetwork show good controllability, the subnetwork with poor controllability impacts the control performance of the whole heat exchanger network, and therefore, the controllability index of the whole network should relate to the worst value of the controllability indices obtained for all subnetworks. (Westphalen, et al., 2003).

For heat exchanger network controllability analysis, measures based on the RGA, or modifications of it, have been the most common. However, the RGA has several shortcomings, and other interaction measures have been proposed that overcome some of the problems with RGA. There are, consequently, reasons to consider using other interaction measures as a basis for controllability assessment of heat exchanger networks.

2.3.3 Interaction measures

While the RGA is relatively simple to use, it relies on steady-state properties and can therefore be inappropriate for evaluating dynamic systems, for example, related to delays due to long piping distances. Relatively recently a new group of input-output pairing methods that accounts for system dynamics have been introduced, namely the gramian based methods. This group includes the Σ_2 method (Birk & Medvedev, 2003), the participation matrix (PM) (Conley & Salgado, 2000) and the Hankel interaction index array (HIIA) (Wittenmark & Salgado, 2002). The result from applying one of these methods is an interaction matrix with numbers representing how much each input affects each output.

However, the gramian based methods differ from the RGA and its variants in that they suffer from issues of scaling. In other words, the results of the methods vary depending on how inputs and outputs are scaled. Generally, all inputs and outputs are scaled to have equal range. In this project, however, it has been shown that this can lead to incorrect pairing (see Example 2 in Section 3). Instead, alternative scaling methods utilizing the row and/or column sums of the original interaction matrices have been applied and tested in a statistical assessment. In this project it has been demonstrated that especially the so-called Sinkhorn-Knopp scaling algorithm ranked higher compared to other methods (Bengtsson, et al., 2018).

3 EXAMPLES

In this section, two examples are presented that illustrate some of the shortcomings of commonly applied methods for heat integration and controllability assessment for heat exchanger networks.

In the first example, some difficulties associated with using the pinch representation of the heat exchanger network as a starting point for the dynamic analysis are illustrated.

The second example demonstrates a case when the recommended pairing of controlled and manipulated variables (more specifically the pairing of bypass valves and target temperatures) in a heat exchanger network differs depending on which interaction measure, and which input-output scaling the analysis is based on. It also discusses why, as a consequence, it is problematic to base a controllability measure on just one such interaction measure without knowing whether this is the most appropriate one for the application.

Example 1

Challenges of using pinch analysis models for controllability assessment

The example is taken from the Preem case study (see e.g. (Åsblad, et al., 2014)). One of the process units studied was the ICR (isocracker). The pinch analysis was carried out using Aspen Energy Analyzer, which provides a first check of what is referred to as 'controllability status' of the network design. This controllability status is simply based on a degrees of freedom (DOF) analysis of the system, but already here, the analysis fails.

For the ICR, the pinch network representation of the existing network results in a controllability status: "The network cannot be controlled". A closer look on the degrees of freedom analysis reveals that one of the sub-networks of the process consists of 1 unit (heat exchanger), 2 streams, 0 loops and hence -1 degree of freedom. Considering that the model is supposed to represent a real heat exchanger network, which is known to operate without any controllability problems, we can assume that there are problems with the representation of the real system.

Two of the subsystems from the ICR are shown in their pinch representations in Figure E1-1. Two streams are heat exchanged in a so-called "perfect match". Obviously, we cannot control the target temperatures of both the hot and the cold streams involved in the heat exchange.

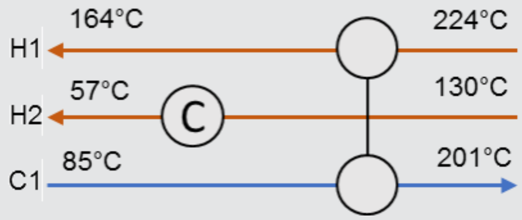


Figure E1-1. Pinch representation of two small subsystems of the ICR heat exchanger network.

A closer look at the process around these subsystems reveals that the hot stream is the overhead from a flash separation vessel (see Figure E1-2). This stream is first mixed with water, before it is further cooled by air coolers in which the target temperature can be controlled. In pinch analysis, heat capacity flow rates are assumed to be constant. Changing heat capacity flow rates need to be handled through linearization. Because the flow of the hot stream in this example is changed due to the mixing with water, it had to be represented as two separate streams in the pinch analysis. However, there is no need for target temperature control of the first stream.

The cold stream is compressed recycle gas. Also this stream will be mixed with another stream (make-up H_2-gas), before it is further heated in a series of heat exchangers and finally a furnace. Consequently, there is no need to control the target temperature of this stream out from the heat exchanger either.

The example shows the necessity of having a more extended representation of the process when analyzing controllability than what is suitable for the pinch analysis. Looking only at the pinch representation of the heat exchanger network will imply that important information for the controllability assessment is lost. By going back to a more complete process model, it is possible to see, for example, whether several pinch streams are directly connected, and it is possible to see which temperatures that need to be controlled.

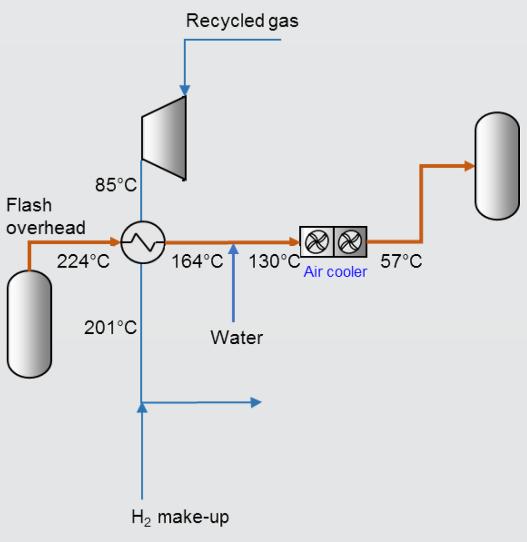


Figure E1-2. Process flowsheet diagram showing the pinch streams from Figure E1-1. and their connections to the surrounding process.

Comment regarding the pinch model:

The handling of the hot superheated stream as two streams in the pinch analysis is not ideal for the steady-state analysis either. There are no process requirements to mix the water at exactly 164°C. By setting the existing outlet temperature from the heat exchanger as the target temperature of the stream, the design is to some extent locked in to the existing design. To really be able to optimize the network, the target temperature should be regarded as a soft target, which in turn affects the start temperature for the next stream. There are no direct ways of representing this for the pinch analysis, but some form of iterative approach should be possible. In this specific case, it is probably not of interest to change the existing heat exchanger, since it transfers a large amount of heat without violating the pinch rules, and it efficiently utilizes the temperature of the hot stream (the temperature difference on the hot side of the heat exchanger is about 23°C, which should be considered quite low).

Example 2

Differences in input-output pairing using different interaction measures

This example illustrates a case where the RGA suggests a different recommended paring of controlled and manipulated variables in a heat exchanger network compared to the results obtained using other interaction measures (IMs) (see Section 2.3.3 for more background on IMs). Since the choice of IM may affect the recommended input-output pairing it becomes problematic to base a controllability measure on one such IM without knowing if it yields the best control configuration. So for example, it may be problematic to use the commonly applied RGA-based controllability index (see Section 2.3.2) if the RGA does not yield the best pairing. While the gramian based IMs are promising alternatives to the RGA, not the least because they account for dynamics in the system, these suffer from issues with scaling, which is also illustrated in the example.

The example heat exchanger network can be seen in Figure E2-1. The goal is to control the output temperatures T1 to T4 using bypasses on the hot side of the heat exchangers U1 to U4. T5 is assumed to be controlled further downstream so it does not need to be controlled here.

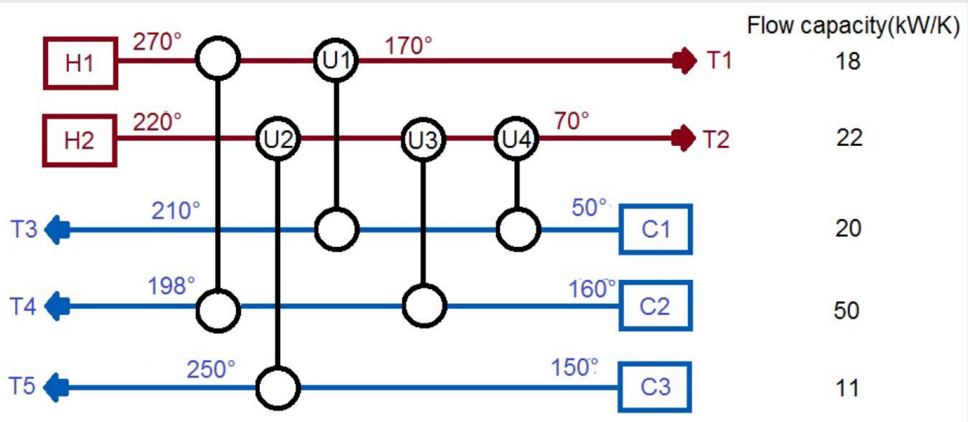


Figure E2-1. The heat exchanger network analyzed in the example.

The heat exchangers were modelled as series of mixing tanks, as described in Section 4.5. The complete system model was implemented in Matlab/Simulink and linearized with the bypasses on U1 to U4 as inputs and the temperatures T1 to T4 as outputs. More details about the model parameters and assumptions can be found in (Bengtsson, et al., 2018).

On the linearized model, different input-output pairing algorithms were applied. The three gramian based methods mentioned in Section 2.3.3, i.e., PM, HIIA and Σ_2, as well as the classical RGA and the more recent ILQIA (Halvarsson, 2010), which is based on LQG control with integral action, were used to derive decentralized control schemes. The recommended pairing for each method is shown in Table E2-1, which shows that the three gramian based methods all suggest the same pairing.

Table E2-1. The results for the pairing suggestions for the heat exchanger network.

	RGA	**PM**	**HIIA**	Σ_2	**ILQIA**
T1	U3	U1	U1	U1	U1
T2	U4	U4	U4	U4	U4
T3	U1	U2	U2	U2	U3
T4	U2	U3	U3	U3	U2

It is also evident that the gramian based methods give a result different from that of ILQIA and RGA. To compare the methods, decentralized PI control schemes were implemented and the controllers were automatically tuned on the open loop subsystems using different values for the tuning parameters (for more details, see (Bengtsson, et al., 2018)). Each of the control configurations was then simulated, with a reference step of two degrees on the desired output temperature of streams H1, H2, C1 and C2, and with a step disturbance of negative two degrees on the input temperatures of the streams H1, H2, C1 and C2. Flow rate disturbances were also evaluated. For assessment the quadratic mean deviation from the reference was devised as a cost, allowing comparison of the different pairing schemes. The results are presented in Table E2-2.

A few conclusions can be drawn from the results. Firstly, it can be seen that for aggressive control schemes (represented by low values of the tuning parameter η), all controller schemes fail, resulting in an undamped oscillatory system. This is not unexpected as there are clear limits on the actuators (they cannot bypass more than 100% of the stream or less than 0%), and therefore the controllers need to be somewhat cautious. However, the control configuration suggested by the gramian based methods yields a worse control for the best tuning (marked by bold and blue in the table) than the ones recommended by the RGA or ILQIA, with a minimum cost of 3 235 as opposed to 1 788 or 990.

Table E2-2. Costs for different controller tuning parameters η.

η	RGA	Gramian based methods	ILQIA
1	235 065	342 149	263 431
2	136 606	210 002	204 696
3	95 950	126 502	156 832
3,5	61 002	83 096	120 940
4	28 570	63 220	101 968
4,5	16 528	41 376	85 213
5	7 595	16 443	69 522
5,5	**1 788**	4 771	53 765
6	1 966	3 533	35 830
6,5	2 154	3 282	21 232
7	2 344	**3 235**	9 054
7,5	2 537	3 274	1 570
8	2 732	3 358	**990**
10	3 526	3 897	1 064
15	5 568	5 706	1 687

To examine why, we look closely at the interaction matrices from the gramian based methods. In these matrices the rows correspond to the target temperatures T1-T4, and the column to the input bypasses U1-U4. Consequently, a number in the matrix represents some kind of measure of how strongly the manipulated input variable of that column affects the target temperature of that row.

$$PM = \begin{bmatrix} 0.15 & 0.00046 & 0.56 & 0.13 \\ 0 & 0.000014 & 0.0023 & 0.55 \\ 0.058 & 0.00084 & 0.00052 & 0.017 \\ 0 & 0.0091 & 0.026 & 0 \end{bmatrix}$$

$$HIIA = \begin{bmatrix} 0.16 & 0.0084 & 0.097 & 0.15 \\ 0 & 0.0015 & 0.018 & 0.29 \\ 0.1 & 0.011 & 0.009 & 0.054 \\ 0 & 0.032 & 0.063 & 0 \end{bmatrix}$$

$$\Sigma_2 = \begin{bmatrix} 0.17 & 0.000035 & 0.0054 & 0.0038 \\ 0 & 0.0000039 & 0.00081 & 0.81 \\ 0.0051 & 0.00003 & 0.0000072 & 0.00022 \\ 0 & 0.00036 & 0.0086 & 0 \end{bmatrix}$$

As can be seen, all the values in the second columns are small compared to the largest values in the other columns. This means that when choosing elements from the matrix little importance is given to the second column. In other words, little importance is given to which temperature should be controlled by U2. The reason for this is that U2 is not particularly well suited for control compared to the other inputs, and therefore the values in its column are lower. However, one can still clearly see that the IMs suggest that U2 is much better suited for controlling T4 than T3, but as can be seen in Table E2-1, none of the gramian based measures recommend this pairing, while both non-gramian based methods do. Similarly, we see that the third and fourth rows contain considerably less interaction than the other rows. Hence less emphasis is placed on selecting a good actuator for T3 and T4.

It can be argued that this is a matter of scaling. However, all the inputs, being bypass percentages, are scaled from 0 to 1 as is the general convention to resolve the issue of input scaling for the gramian based methods (Salgado & Conley, 2004). Moreover, all the outputs are tested with identically sized reference steps, hence can be seen to be properly scaled. However, in this case this scaling scheme appears to be insufficient. In (Castano Arranz & Birk, 2009) a scaling for the Σ_2 method is suggested, where each element in the IM is divided by the sum of all the elements in either its column or row. This seems an attractive proposition to resolve this issue as it ensures that either each input or each output is given equal weight. If we scale the PM, Σ_2 and HIIA interaction measures with these methods, we get the configurations shown in Table 3.

Table E2-3. The results for the pairing suggested by different methods using column or row scaling.

	RGA & PM and HIIA with column scaling & all gramian based methods with Sinkhorn-Knopp scaling	**Σ_2 with column scaling & ILQIA**	**PM and HIIA with row scaling**	**Σ_2 with row scaling**
T1	U3	U1	U2	U1
T2	U4	U4	U4	U4
T3	U1	U3	U1	U2
T4	U2	U2	U3	U3

As can be seen in Table E2-3, when column scaling is applied we get the same control configurations as recommended by either the RGA or the ILQIA and consequently a lowered cost according to the assessment. However, with row scaling we get a new configuration for the HIIA and PM. Testing with this configuration yields worse results than the other configurations.

A third option tested in this project is to ensure that the IMs rows and columns all sum up to the same value, and hence all inputs and outputs are given equal weight. This is done by alternatively scaling the elements by row and column sum, which is known as the Sinkhorn-Knopp algorithm (Sinkhorn & Knopp, 1967). In this case, it turns out that this new scaling method gives the same configuration as the RGA (see Table E2-3), which, while not being the configuration with the lowest cost, still yielded a considerably better result than the configuration recommended by the unscaled gramian based measures. This is the same configuration obtained when scaling the PMs' or HIIAs' IM by column. However, for the Σ_2 method, column scaling yielded a configuration with a lower cost.

This example illustrates how different IMs and different scaling methods can yield different recommendations for the control structure of a heat exchanger network, which in turn will affect the attainable control performance of the design. This, in turn, makes it problematic to base a controllability measure on one of these interaction measures without knowing that the proposed input-output pairing also yields the best controllability of the system.

In order to find a more general conclusion and recommendation regarding the scaling of the gramian based methods, a statistical assessment of a large number of randomly generated MIMO models was performed in the project. This assessment showed clearly that the approach based on the Sinkhorn-Knopp consistently ranked better than the others and therefore seems promising for further developments (Bengtsson, et al., 2018).

4 PROPOSED APPROACH FOR DESIGN AND CONTROLLABILITY ASSESSMENT OF HEAT EXCHANGER NETWORK RETROFITS

The approach for design and controllability assessment of heat exchanger network retrofits that is proposed in this report is based on the idea of using existing methods and tools for heat integration and dynamic analysis, and combine them with new methods developed within the project for interaction/controllability analysis.

For most of the steps suggested there are existing methods and tools that can be used. For some steps, in particular for the controllability analysis, there is still a need for further method and tool development. Before a complete assessment framework can be presented, there is also a need to develop information protocols for knowledge transfer between the steps.

Below, an overview of the step-wise approach is presented. More detailed descriptions and advice on the individual steps are provided in the following sections. Existing tools that can be used for modelling, analysis and design are suggested and discussed in Section 5.

1. **Process description**
   Collect information from, for example, process flowsheet diagrams and process and instrumentation diagrams regarding flows that need heating or cooling, existing heat exchangers, furnaces, steam heaters, water and air coolers, placements of measurements and control valves
2. **Data extraction**
   a. Definition of the system based on the aims and constraints
   b. Collection of data for the pinch analysis
   c. Adjustment of the pinch representation for the dynamic assessment
3. **Pinch analysis**
   Determine targets for minimum energy demand and identify inefficiencies in the network using pinch analysis
4. **Retrofit design**
   Design retrofit proposals for energy savings
5. **Dynamic modelling**
   Construct dynamic models of the heat exchanger network retrofit designs
6. **Controllability analysis**
   Assess interactions/controllability of the alternative design proposals

Note that before the analysis starts with Step 1, the aim and constraints for the assessment need to be carefully defined, since these will determine appropriate system boundaries for the process, and thereby the requirements on the data extraction. The aim and constraints might also influence the retrofit design as well as the control objectives.

4.1 PROCESS DESCRIPTION

It is necessary to realize that although the focus of the design and assessment is a heat exchanger network, information about the process should be collected with widened system boundaries in mind. The role of the hot and cold process streams in the overall process, and their connections to reactors, separations units or storage tanks are crucial to understand the control objectives for the system and the sources of disturbances. Well-defined aims and constraints for the assessment are a key for describing the process in an appropriate way.

4.2 DATA EXTRACTION

4.2.1 Collection of data for the pinch analysis

The primary step in a heat integration study is to produce heat and mass balances for the plant. In a real process plant this can be a significant challenge. The amount of information available from plant measurements, data acquisition systems and simulation models of a process can be very large, at the same time as other important information remains unavailable and needs to be estimated or assumed. Much of the data available is likely to be irrelevant for the analysis, which makes it necessary to identify and extract only the information that is actually needed.

Furthermore, because data sometimes need to be obtained from poor estimates or design specifications that are not met in actual operation, or due to measurement errors, inaccuracies and simplified models of the real process, usually heat and mass flow data simply do not balance. To avoid serious inconsistencies and achieve a reliable data set, data reconciliation techniques are often clearly needed. Such techniques have been applied and tested for the Preem refinery (Murcia Mayo, 2015), which showed that despite the use of such computational tools a number of difficulties are still likely to remain. Experience from process integration studies shows that data collection can be a major part of the work (Natural Resources Canada, 2003).

4.2.2 Adjustment of the pinch representation for the dynamic assessment

It is reasonable to assume that data collection is and should be a major time-consuming part of any project involving process modelling, and this needs to be considered regardless of what type of analysis – steady-state or dynamic – is intended. In the report “Good advice for integrated design in the process industry” (in Swedish) from the project INPROASIT (Björk, et al., 2016) about integrated design in the process industry, it is argued that the work of modelling a process based on historical data consists of up to 80% of data cleansing such as validation and filtration of data. The report even states that if less time is used for this kind of work, there is reason to be suspicious. Another thing that is stressed in the report from INPROASIT is that automation, computing and control competency should be included in the project work from day one, which is a statement that is strongly supported in this work.

As shown by the example in Section 3, it is difficult to base the dynamic modelling and analysis directly on information from the pinch analysis only. Not only will additional data be needed for the dynamic analysis, but there is also a demand for changing the system boundaries, and handle non-linearities in different ways. The following list presents some major additions needed for the dynamic analysis compared to the pinch analysis:

Additional data for single heat exchangers

Time constants or parameters used to calculate or estimate time constants such as heat

exchanger volumes and fluid densities.
Note that for existing heat exchangers, geometrical parameters such as the volume for each fluid, are known. During conceptual design, these need to be computed from assumptions of standard types of heat exchangers.

Data for the piping between heat exchangers
The apparent dead-time in the pipes is essential for the dynamic controllability assessment. Pipe residence time and pipe model order determines the apparent dead-time in the pipes.

Widened system boundaries to include the control system.
Placement, size and dynamic characteristics of by-pass and other valves. Placement and dynamic characteristics of sensors.

Widened system boundaries to capture the interconnections between streams
The dynamic model need to consider if and how individual streams from the pinch analysis are connected to each other and to other type of process equipment. Several pinch streams might be better represented as one connected stream in the dynamic model. A common reason is that the pinch analysis requires a piece-wise linearization of streams with non-constant heat capacity flow rate. The connection to other parts of the process are required to understand and determine the control objectives.

Two alternative ways of handling the information transfer, regarding process interconnections from the pinch analysis results to the dynamic analysis, are suggested:

A. Build the dynamic model directly from the original process description and modify it according to the retrofit suggestions generated in the pinch analysis and design.
B. Build the dynamic model from the pinch representation, but add the basic connections between streams, such as direct connections (one stream in reality that has been modelled as two or more streams in the pinch analysis due to non-constant heat capacity flow rates) or non-isothermal mixing, and include these in the dynamic model.

In both cases, additional data is needed to describe the dynamic characteristics of the individual units in the network.

4.3 PINCH ANALYSIS

For the pinch analysis, see Section 2.2.

4.4 RETROFIT DESIGN

There are normally several alternative retrofit design solutions for a given heat exchanger network retrofit problem. Usually, the larger the industrial problem is, the more alternatives exist. In theory, the optimum design is the one with lowest total annualized cost; the main components of this cost are the cost of new heat exchangers, additional area in existing heat exchangers, piping and hot and cold utility. In practice, these costs cannot be accurately calculated during the conceptual design phase, and various assumptions and estimations have to be made. At the same time, it is common that there exist several alternative designs with only marginal differences in total annualized cost. Realizing the usually large uncertainties in the cost estimates and the small differences in cost between alternative designs, there are strong reasons to base the design choices on other criteria such as operability and controllability.

Consequently, it is desirable to use a retrofit design method that generates, not only one theoretically optimal design, but a number of near-optimal alternative solutions that can be further evaluated with respect to, for example, controllability.

4.5 DYNAMIC MODELLING

In order to assess the controllability of a heat exchanger network, for example, using methods based on interaction measures as described in Section 2.3.2, a dynamic model of the heat exchanger network is needed. In the model of the complete network, dynamic models of the heat exchanger units are essential building blocks.

The dynamic characteristics for the individual heat exchangers are determined by flow configuration and time constants related to holdups of energy on the hot side, cold side and in the heat exchanger walls. Heat exchangers are usually modelled such that each fluid is modelled as a series of ideally mixed tanks (see Figure 3). These lumped models offer mathematical simplicity, but also have physical resemblance to shell-and-tube heat exchangers with baffles, see also (Mathisen, et al., 1994).

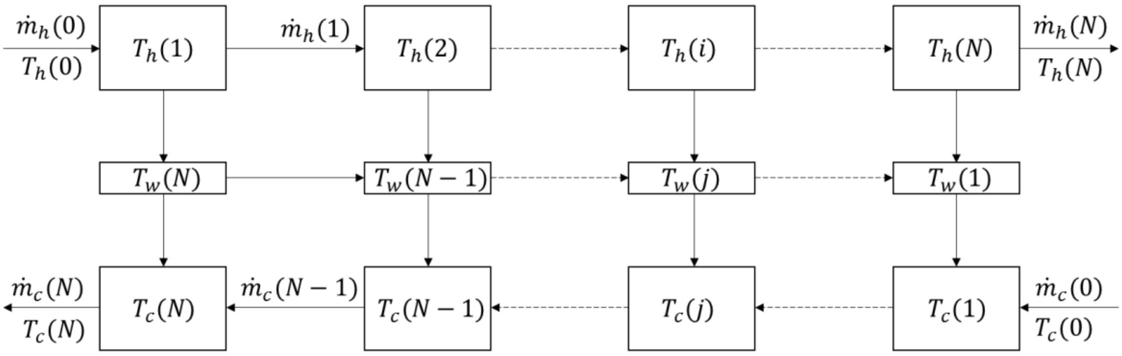


Figure 3. Multi-cell model of one heat exchanger. Based on (Mathisen, et al., 1994).

The differential equations for heat exchangers along with their derivations can be found in (Mathisen, et al., 1994). The cited paper assesses different model features and provides modelling recommendations and examples of typical values for critical parameters. Among other things the appropriate number of mixing cells (model order) is discussed and recommendations are given for minimum and maximum number of cells. A typical number of cells that is mentioned is N=6.

The main components in a model of the complete heat exchanger networks are the heat exchangers, bypasses and pipes. The pipes, like the heat exchangers, are modelled as ideally mixed tanks in series and by time delays. Pipe residence times should be included to predict the apparent dead-time; the pipe dead-time may well exceed the dead-time in the heat exchangers. The model of the heat exchanger networks should also include the dynamics of sensors and actuators. Time constants for control valves and thermocouples are often between 2 and 10 seconds, which can be compared with typical values for heat exchanger between 0.1 and 60 seconds.

A challenge when modelling heat exchanger networks is that the state-space models easily tend to become very large since each multi-cell heat exchanger is represented by N states for each fluid plus one for the bypass, and a complete industrial network can contain a large number of heat exchangers.

4.6 CONTROLLABILITY ANALYSIS

As illustrated in Example 1, it is not always straight-forward to simply take a pinch model of a heat exchanger network to analyze it from a controllability perspective. Without information about how the streams are connected to each other and to the rest of the process, control objectives and disturbance sources are difficult or even impossible to determine. Furthermore, knowledge about the placement of existing and potential new bypasses are essential for the controllability assessment, but not included in the pinch representation. The establishment of a good process description of the heat exchanger network with these aspects included (Step 1), dramatically improves the transition from the retrofit design solutions (Step 4) to the dynamic modelling and controllability assessment (Steps 5 and 6). If the process description is adequate, it is likely to provide sufficient information to "translate" pinch solutions into appropriate dynamic models.

As discussed in Section 2.3.2 and illustrated in Example 2 of Section 3, there are many challenges involved in defining a reliable controllability measure. More work is needed before a heat exchanger network controllability index or similar can be suggested. However, the methodology described by (Westphalen, et al., 2003) (see Section 2.3.2) seems to provide a good framework that could be used once one or more appropriate controllability measures have been defined.

For a defined heat exchanger network design (stream data, utility data, and topology):

1. Identify all subnetworks
2. For each subnetwork
2.1. Identify all combinations of manipulated variables.
2.2. Apply *a selected interaction measure* to define the best combination of controlled and manipulated variables.
2.3. Calculate the controllability index of the subnetwork based on the selected interaction measure for the best combination of manipulated variables.
(Further research needed here)
3. Define the controllability index of the network as the worst value of the controllability index obtained for all subnetworks.

Another approach for controllability analysis could be to visualize the interactions in the heat exchanger network. This could, for example, be achieved by using the software ProMoVis (Birk, et al., 2014), in which the interactions can be visualized with weighted graphs that shows the significance of the connections between manipulated and controlled variables by the thickness of the edges (Castaño Arranz & Birk, 2012). This gives an enhanced visual understanding of the process. Systems that might be difficult to control could, for example, have no or very weak connections (thin edges) from all manipulated variables to one or more controlled variable, or some manipulated variables could have very strong connections (thick edges) to several controlled variables, meaning that they could be difficult to control independently.

5 EXISTING TOOLS

This section presents examples of tools that are currently available to complete the central steps of the proposed methodology. In some of the mature areas, a variety of tools exist, in which case a selection has been made.

Considering that different tools are needed for the various steps of the methodology, appropriate interfaces are needed for model and data transfer. Excel and/or Matlab could serve as these communication interfaces, and would also allow for data manipulation, analysis and visualization of intermediate and final results. Consequently, tools and software used for pinch analysis, heat exchanger network design, dynamic modelling and controllability assessment should preferably allow for integration either directly or via Excel, Matlab or other established standards.

For the process description and extraction of process data, i.e., the first steps of the proposed methodology, a combination of information sources and tools are usually needed. Process flowcharts and data logs from process control systems are essential resources that need to be complemented by qualified assumptions and estimations from process operators and process engineers, additional measurements and subsequent error detection and data reconciliation techniques. The control and data management systems used in the industrial plant determines which software to use, but typically the results can be exported to spreadsheet format (e.g. Excel), which provides further arguments for other software to be used to be compatible with data import/export in this format.

5.1 TOOLS FOR PINCH ANALYSIS AND RETROFIT DESIGN

With the long history of pinch analysis, a number of tools have been developed over the years. Many of these are simple tools, mainly built for educational purposes. Several tools for basic energy targeting are available as Excel calculations spreadsheets or Excel VBA applications, online calculations tools, Matlab programs, or stand-alone software. More advanced and extensive software also include heat exchanger network design and optimization, and most of these are commercial. Table 1 presents a non-exhaustive guide to some of the software:

Advanced pinch software has also been developed by CanmetENERGY (Integration) and Process Integration Ltd (PINCH-int and i-Heat). However, licenses are only available for limited groups.

It can be concluded that software for retrofit design of heat exchanger networks based on systematic and reliable approaches are few. A variety of systematic and semi-automated methods for heat exchanger network retrofit have been suggested, see (Sreepathi & Rangaiah, 2014) for a review. However, these are yet to be implemented in well-tested software packages.

One of the partners in this project, CIT Industriell Energi, has developed their own Excel add-in for pinch calculations, Pro-pi. The main functionalities include energy targeting, generation of pinch curves and manual heat exchanger network design. Although a non-sophisticated tool, the advantage of being an in-house development allows for further development, customization and provides a possibility to test the implementation of controllability assessment techniques in a pinch analysis tool.

Table 1. Software for pinch analysis.

Software	Company	Type	Free	Network design	Retrofit
Heatit	Pinchco	Excel add-in	Yes	No	No
Kemp book spreadsheet	Elsevier	Excel spreadsheet	Included in (Kemp, 2006)	No	No
Aspen Energy Analyzer	AspenTech	Stand-alone program in the AspenOne product portfolio	No	Manual and automatic	Manual and automatic
PinCH	*	Stand-alone	No	Manual	Manual
Simulis Pinch	ProSim	Excel add-in	No	Automatic	Automatic
Einstein Energy	*	Stand-alone	Base version – Yes Plus version – No	Manual and automatic	Manual
Pro-pi	CIT Industriell Energi	Excel add-in	Yes	Manual	Manual

* The Lucerne University of Applied Sciences and Arts - Engineering and Architecture, with the support of the Swiss Federal Office of Energy (SFOE) and the "Energie-Agentur der Wirtschaft" (EnAW)

** EINSTEIN has been developed since 2007 in a collaboration of more than 20 institutes and companies in the Framework of the European projects EINSTEIN (2007-2009) and EINSTEIN-II (2010-2012) and several national and regional projects in Spain, Catalonia and Austria.

5.2 Tools for dynamic modelling

Various tools can be used to implement the dynamic model of a heat exchanger network as outlined in Section 4.5. Examples of such modelling tools are Simulink, Modelica and Aspen.

Simulink, developed by MathWorks, is a graphical programming environment for modeling, simulating and analyzing dynamic systems. Its primary interface is a graphical block diagramming tool and a customizable set of block libraries. Its tight integration with the rest of the MATLAB environment is a clear advantage when integrating the dynamic modelling into the step-wise heat exchanger network controllability framework.

There are a number of open-source as well as commercial modeling and simulation environments based on the free Modelica modeling language, such as OpenModelica, JModelica and Dymola. The open Modelica language allows for integration with other analysis tools, but efficient modelling usually requires access to good model libraries, which are typically owned by commercial companies.

Within the AspenONE Product Portfolio, there are also possibilities for dynamic modelling. This would allow for an easy integration with models built with some of the products within the Aspen suite, and usually easy import and export of input data and results. The drawback is, depending on the particular Aspen product, that model import/export is not straightforward, and the opportunities to customize models and analysis tools are limited.

5.3 TOOLS FOR CONTROLLABILITY ANALYSIS

This report has described how interaction measures may be used as a basis for defining a measure of controllability (see Section 2.3.2) – or at least of certain aspects of controllability – of a system such as a heat exchanger network. More work is needed in this area, and consequently, no tools exist that are ready to use for direct assessment of the controllability of a heat exchanger network.

However, a promising tool for analysis of process interactions has been developed that could have a potential also for the analysis of heat exchanger networks. ProMoVis (Birk, et al., 2014) is a software environment which can visualize an interconnected process system and analyze it using control structure selection methods based on various interaction measures. ProMoVis is also able to visualize analysis results together with the process using a graphical representation (Castaño Arranz & Birk, 2012). ProMoVis is implemented as either a standalone software or as a version which can run within Matlab. For the re-use of existing models a Modelica interface is under development.

So far, ProMoVis has not been used to analyze a heat exchanger network, but it has been applied to similar types of processes, see (Castaño Arranz, et al., 2015). The main challenge is the large model size, which has made it difficult to import the model. If this problem can be overcome, ProMoVis seems to be a promising tool for controllability assessment of heat exchanger networks.

Example 3

ProMoVis Application

ProMoVis has been used for analysis of the secondary heating system of a pulp and paper mill (Castaño Arranz, et al., 2015). This application lies close to the application of heat exchanger networks, which is discussed in this report and is therefore thought to serve as a good illustration of the potential for using ProMoVis for this type of system.

Like heat exchanger networks, the secondary heating systems are heat recovery systems that include a large number of heat exchangers. In terms of steady-state energy efficiency improvements, the secondary heating systems are also commonly modelled as a heat exchanger networks and analyzed using heat integration tools such as pinch analysis, see e.g. (Persson & Berntsson, 2010), (Nordman & Berntsson, 2006). In addition to the heat exchangers, however, secondary heating systems also include water tanks which are central for the operational control of the system. From a controllability perspective there are, consequently, a few important differences compared to a heat exchanger network. In addition to target temperatures, the water levels in the tanks are also controlled variables. Furthermore, the actuators are not bypass valves over heat exchangers, but valves controlling the flows into and out from the water tanks.

Figure E3-1 shows the ProMoVis screenshot of a simplified model of the secondary heating system of a pulp and paper mill, with the corresponding notation summarized in Table E3-1.

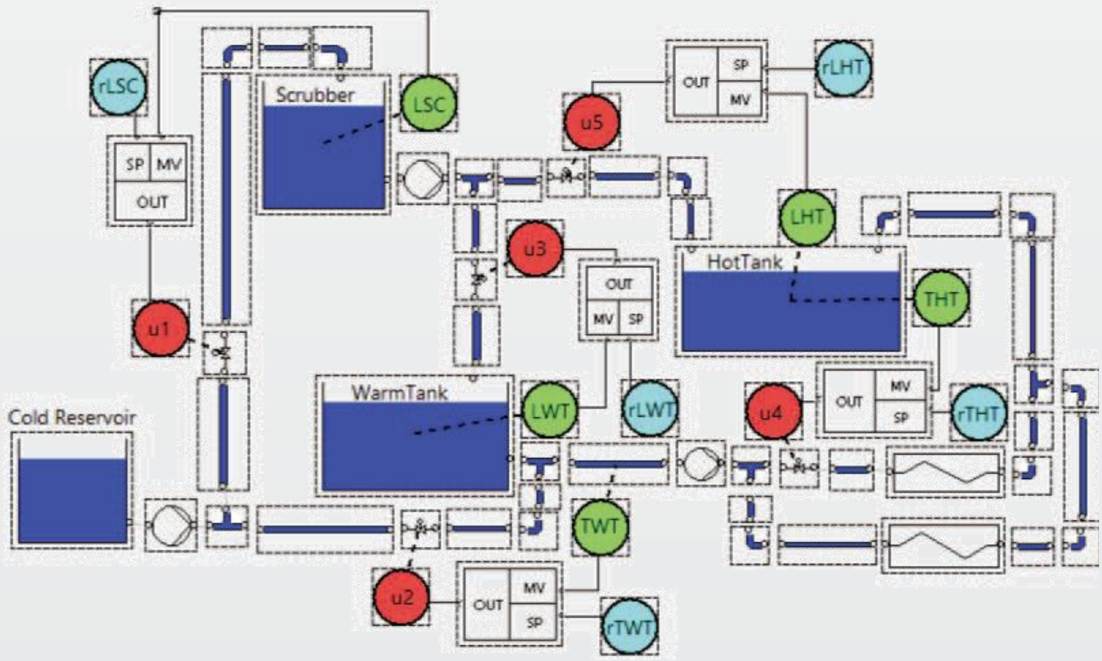


Figure E3-1. ProMoVis screenshot for the Secondary Heating System. Red variables represent control actions on actuators, green variables represent sensor measurements, and blue variables represent selected setpoints for the sensor measurements. The controller blocks receive a sensor measurement (MV) and a desired setpoint (SP), and send a control action to an actuator (OUT).

Before the analysis of the control system, this process was controlled with the set of controllers and input-output pairings illustrated in the figure: $u1 - LSC$, $u2 - TWT$, $u3 - LWT$, $u4 - THT$, $u5 - LHT$. However, this control structure presented severe problems during operation.

Table E3-1. Description of control system variables.

Name	Description
u1, u2, u3, u4, u5	Valve control actions
LWT	Level of Warm Tank
LSC	Level of the scrubber
LHT	Level of Hot tank
TWT	Temperature at the exit of Warm Tank
THT	Temperature inside Hot Tank
rLWT	Reference for LWT
rLSC	Reference for LSC
rLHT	Reference for LHT
rTWT	Reference for TWT
rTHT	Reference for THT

The analysis of interactions in this process is visualized using weighted graphs in Figure E3-2. The control configurations (input-output pairings) suggested by the analysis methods applied in ProMoVis can be compared with the existing control configuration illustrated in Figure E3-1. Some important conclusions from the graphical results in Figure E3-2 can be drawn.

- Existing input-output pairings:
    - u2-TWT: The effect of u2 on TWT is very low (thin edge).
    - u3-LWT: The effect of u3 on LWT is insignificant (no edge was depicted).
- Interactions between non-paired variables:
    - u4-LWT: The control action u4 has a strong impact on LWT.
    - u5-THT: The control action u5 has a strong impact THT.

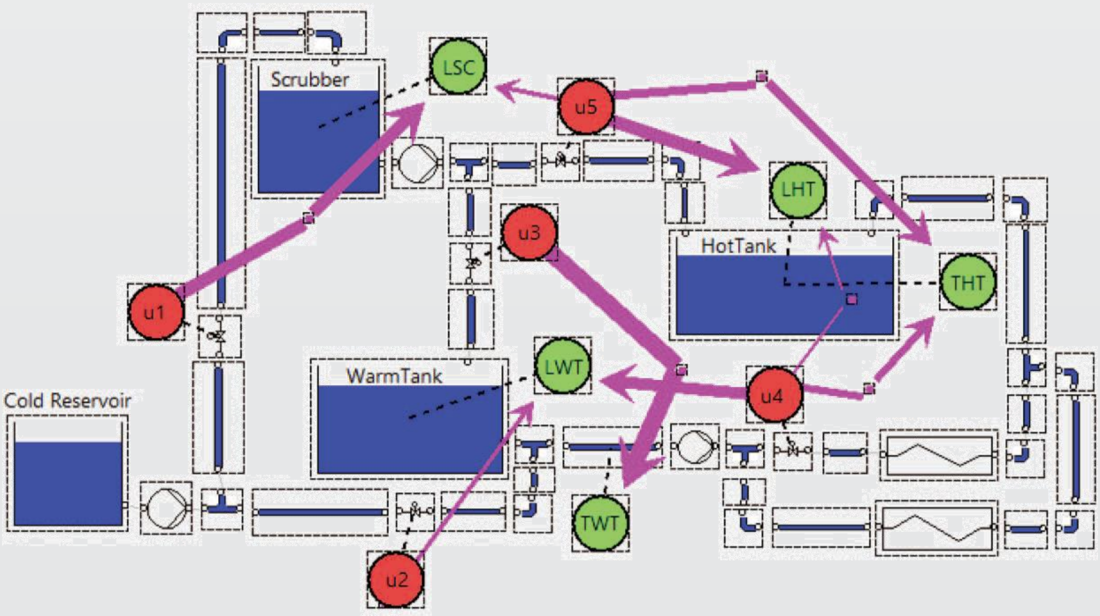


Figure E3-2. Graphical analysis of the Secondary Heating System using weighted graphs. A threshold of 0.1 was placed such that the insignificant edges are neglected in the representation. ProMoVis screenshot.

The combined use of different interaction measures indicates that using u3 to control LWT and using u2 to control TWT will result in very poor performance, since there is very low impact of these actuators on their corresponding measurement, and there are additional perturbations from other control loops. The results from the analysis indicates that instead it would be appropriate to use u2 to control LWT and use u3 to control TWT, which is completely in contrast to the existing configuration.

6 FURTHER DEVELOPMENT NEEDS

This report describes the major steps needed in a structured and systematic approach for evaluation of controllability of heat exchanger networks in the design stage. In the research project MoveDynE, work has been done to identify, evaluate and to some extent improve the basic methods needed for controllability analysis of heat exchanger networks. Nevertheless, further efforts are needed in a number of important areas before a complete controllability assessment framework can be achieved, and in the long term, before a toolbox with integrated design and analysis tools can be developed.

6.1 DEFINING A CONTROLLABILITY INDEX FOR HEAT EXCHANGER NETWORKS

As been discussed in this report, it is not obvious how to define controllability. A controllability index can be based on an interaction measure. This would be in line with the controllability assessment methods based on RGA that are the most commonly applied today. However, even if one chooses to limit controllability to be a measure of the interactions in the system, there are many alternative interaction measures that could be applied, and each one has strengths and weaknesses. There remains a need to evaluate which interaction measure could be best suited for heat exchanger networks, and which, at least in relation to other measures, gives the most reliable and relevant result. Moreover, the interaction measure, which is in the form of a matrix, needs to be evaluated through some mathematical operation in order to arrive at a single, scalar controllability index. How to do this is also a question for further research. Consequently, an adequate controllability index for use in heat exchanger network design still remains to be defined. More work is also needed on how to evaluate the usefulness, appropriateness, and accuracy of such a controllability index.

However, in this project, work in this direction has begun. Drawbacks of using the traditionally applied controllability index based on RGA have been identified, and alternatives to the RGA have been evaluated. Insights about the strengths and weaknesses of different interaction measures have been presented, and the knowledge for continuing the effort to define a better controllability index for heat exchanger networks has been improved.

6.2 GENERIC DYNAMIC MODELS FOR HEAT EXCHANGER NETWORKS

For an integrated design and controllability assessment tool to be useful, some level of built-in support would be needed to formulate dynamic models representing alternative heat exchanger network designs. Steady-state pinch models are easily modelled in existing tools for pinch design. Pre-defined Simulink model blocks for heat exchangers and relevant components, templates for creation of complete networks, and/or some kind of automatic model generation based on user input about the heat exchanger network design could be used to aid the modelling, thereby avoiding that the user is required to formulate the dynamic models from scratch.

As discussed in Section 4.5, the dynamic models, and the development of a model library with model templates and unit building blocks, also need to be extended to include important dynamic characteristics of the system in the form of pipe apparent deadtimes, actuator and sensor dynamics, and possibly also wall capacitance.

6.3 HEAT EXCHANGER NETWORK MODEL IN PROMOVIS

As discussed in Section 5.3, the tool ProMoVis should be a valuable tool for visualization of results from the analysis of interactions in a heat exchanger network, and thereby provide one perspective on the controllability of a design in a graphical illustration. Currently, however, it has not been possible to import the model of the heat exchanger network into ProMoVis due to the model size. Despite the rather small heat exchanger network that has been modelled, the many states used for each single heat exchanger results in an extensive number of states for the model as a whole.

Model simplifications, or new possibilities for model import to ProMoVis in the future may be needed to overcome these difficulties.

6.4 INTEGRATED TOOLBOX

Undoubtedly, major efforts are required, and significant gaps remain to be filled, to be able to integrate the complete proposed approach for design and controllability analysis of heat exchanger networks into a unified framework and toolbox.

In addition to the development needs related to individual assessment steps, there is an apparent need for appropriate protocols for information transfer and conversion of models between the different tools. The challenge in information flow handling is likely to be the difference in relevant system boundaries for the various models and methods. The protocols, routines and templates used for information flow should ensure that information that is needed for the dynamic assessment in the later steps of the methodology is not lost during the first design steps. As shown in Example 1, taking the pinch model directly as an input for the dynamic model and controllability assessment is likely to be misleading.

7 REFERENCES

Alhammadi, H. Y. & Romagnoli, J. A., 2004. Process design and operation: Incorporating environmental, profitability, heat integration and controllability considerations. In: P. Seferlis & M. C. Georgiadis, eds. *The Integration of Process Design and Control*. Amsterdam, the Netherlands: Elsevier, pp. 264-305.

Bengtsson, F., Wik, T. & Svensson, E., 2018. Resolving issues of scaling for gramian based input-output pairing methods. *To be submitted.*

Birk, W., Castaño Arranz, M. & Johansson, A., 2014. An application software for visualization and control configuration selection of interconnected processes. *Control Engineering Practice,* 26, pp. 188-200.

Birk, W. & Medvedev, A., 2003. *A note on gramian-based interaction measures.* Cambridge, UK, 2003 European Control Conference, 1-4 September 2003.

Björk, A., Fridén, H., Tönnerfors, E. & Andersson, S., 2016. *Goda råd för integrerad design inom processindustri,* Stockholm, Sweden: IVL Svenska Miljöinstitutet.

Bonhivers, J.-C., Moussavi, A., Alva-Argaez, A. & Stuart, P., 2016. Linking pinch analysis and bridge analysis to save energy by heat-exchanger network retrofit. *Applied Thermal Engineering,* 106, pp. 443-472.

Bristol, E., 1966. On a new measure of interaction for multivariable process control. *IEEE transactions on automatic control,* 11, pp. 133-134.

Castano Arranz, M. & Birk, W., 2009. *New methods for structural and functional analysis of complex processes*. Saint Petersburg, Russia, 18th IEEE International Conference on Control Applications, 8-10 July 2009, pp. 487-494.

Castaño Arranz, M. & Birk, W., 2012. New methods for interaction analysis of complex processes using weighted graphs. *Journal of Process Control,* 22, pp. 280-295.

Castaño Arranz, M., Birk, W. & Asplund, P., 2015. *Control configration selection for integrating processes using graphs.* Sidney, Australia, 2015 IEEE Conference on Control Applications, 21-23 September 2015.

Conley, A. & Salgado, M. E., 2000. *Gramian based interaction measure.* Sydney, Australia, 39th IEEE Conference on Decision and Control, 12-15 December 2000, pp. 5020-5022.

Escobar, M. & Trierweiler, J. O., 2013. Optimal heat exchanger network synthesis: A case study comparison. *Applied Thermal Engineering,* 51(1-2), pp. 801-826.

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

Glemmestad, B., 1997. *Optimal operation of integrated processes - Studies on heat recovery systems* [PhD thesis]. Porsgrunn, Norway: Telemark Institute of Technology.

Halvarsson, B., Carlsson, B. & Wik, T., 2009. *A new input/outpu pairing strategy based on linear quadratic gaussian control.* Christchurch, New Zealand, IEEE International Conference on Control and Automation, 9-11 December 2009.

Kemp, I. C., 2006. *Pinch Analysis and Process Integration - A User Guide on Process Integration for the Efficient Use of Energy.* 2nd ed. Oxford, UK: Butterworth-Heinemann.

Knight, P. A., 2008. The Sinkhorn-Knopp algorithm: convergence and applications. *SIAM Journal on Matrix Analysis and Applications*, 30(1), pp. 261-275.

Li, B.-H. & Chang, C.-T., 2017. *Retrofitting Industrial Heat Exchanger Network based on Pinch Analysis.* Taipei, Taiwan, 6th International Symposium on Advanced Control of Industrial Processes, 28-31 May 2017.

Luyben, M. L., 2004. Design of industrial processes for dynamic operability. In: P. Seferlis & M. C. Georgiadis, eds. *The Integration of Process Design and Control.* Amsterdam, the Netherlands: Elsevier, pp. 352-374.

Mathisen, K. W., Morari, M. & Skogestad, S., 1994. *Dynamic models for heat exchangers and heat exchanger networks.* Graz, Austria, Computers and Chemical Engineering, pp. S459-S463.

Mathisen, K. W., Skogestad, S. & Wolff, E. A., 1991. *Controllability of heat exchanger networks.* Los Angeles, US, AIChE Annual Meeting, November 1991.

Murcia Mayo, C., 2015. *Process stream data analysis: Data reconciliation and gross error detection for process integration studies* [MSc thesis], Göteborg, Sweden: Chalmers University of Technology.

Natural Resources Canada, 2003. *Pinch Analysis: For the efficient use of energy, water & hydrogen,* CanmetENERGY, Natural Resources Canada.

Nordman, R. & Berntsson, T., 2006. Design of kraft pulp mill hot and warm water systems-A new method that maximizes excess heat. *Applied Thermal Engineering*, 26(4), pp. 363-373.

Nordman, R. & Berntsson, T., 2009. Use of advanced composite curves for assessing cost-effective HEN retrofit I: Theory and concepts. *Applied Thermal Engineering,* , 29, pp. 275-281.

Persson, J. & Berntsson, T., 2010. Influence of short-term variations on energy-saving opportunities in a pulp mill. *Journal of Cleaner Production,* 18(9), pp. 935-943.

Salgado, M. E. & Conley, A., 2004. MIMO interaction measure and controller structure selection. *International Journal of Control,* 21(2), pp. 367-383.

Seferlis, P. & Georgiadis, M. C. eds., 2004. *The integration of process design and control.* Amsterdam, the Netherlands: Elsevier.

Seferlis, P. & Georgiadis, M. C., 2004. The integration of process design and control - Summary and future direction. In: P. Seferlis & M. C. Georgiadis, eds. *The integration of process design and control.* Amsterdam, the Netherlands: Elsevier.

Sinkhorn, R. & Knopp, P, 1967. Concerning nonnegative matrices and doubly stochastic matrices. *Pacific Journal of Mathematics*, 21(2), pp. 343-348.

Slolely, A., 2006. Heat integration steps can present control problems. *Chemical Processing*, September 2006.

Slolely, A., 2009. Will You Really Realize Energy Savings? - Heat integration may deliver complications instead of expected benefits. *Chemical Processing*, September 2009.

Slolely, A., 2010. Control challenges can pinch energy savings - Heat integration can make achieving effective control more difficult. *Chemical Processing*, November 2010.

Sreepathi, B. K. & Rangaiah, G. P., 2014. Review of Heat Exchanger Network Retrofitting Methodologies and Their Applications. *Industrial & Engineering Chemistry Research,* , 53(28), pp. 11205-11220.

Svensson, E., Eriksson, K. & Wik, T., 2015. Reasons to apply operability analysis in the design of integrated biorefineries. *Biofpr,* 9(2), pp. 147-157.

Tellez, R., Svrcek, W. Y. & Young, B. R., 2006. Controllability of heat exchanger networks. *Heat Transfer Engineering*, 27(6), pp. 38-49.

Westphalen, D. L., Young, B. R. & Svrcek, W. Y., 2003. A controllability index for heat exchanger networks. *Industrial & Engineering Chemistry Research*, 42(20), pp. 4659-4667.

Wittenmark, B. & Salgado, M. E., 2002. Hankel-norm based interaction measure for input-output pairing. *IFAC Proceedings Volumes*, 35(1), pp. 429-434.

Wolff, E. A., Skogestad, S., Hovd, M. & Mathisen, K. W., 1992. A Procedure for Controllability Analysis. In: Perkins, J. D., ed, *Interactions Between Process Design and Process Control*, London, UK, IFAC Workshop, 7-8 September 1992.

Åsblad, A. et al., 2014. *Pinch analysis at Preem LYR II – Modifications* [report], Göteborg, Sweden: Chalmers University of Technology.

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