Industrial Heat Pumps, Second Phase

IEA Heat Pump Program Annex 48

Task 3: Application of existing models

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1 Introduction

Task 3 is intended to provide practical guidelines and insights for the *application of existing models* and tools to aid systematic heat pump integration with industrial processes. The goals of Task 3 were principally derived from the conclusions drawn in the preceding IEA Heat Pump Annex 35 [1] Task 2 report.

The Annex 35 [1] Task 2 report was entitled *"Modelling calculation and economic models"*. It provided a detailed and critical review of various heat pump modelling and design tools and an elaborate discussion of the theoretical background behind systematic heat pump integration into industrial processes based on the principles of pinch analysis. The main conclusions drawn from the report allude to the limited dissemination and restricted usability of the available tools. It was found that wide-scale employment is inhibited by the complexity and specific training required for the use of most available tools as well as the theoretical principles behind them.

To overcome these barriers, Task 3 of Annex 48 has addressed three goals.

(1) Dissemination and clarification of the theoretical principles behind industrial heat pump integration in a concise manner (Section 2).
(2) Deriving an easy-to-use set of guidelines for systematic industrial heat pump integration directed at practitioners, which *can be* used in combination with software tools. These are described in Section 4.
(3) Based on the guidelines, application to a real case study is presented in Section 5, in which the application and use of existing software (models) is also demonstrated.

The main content is completed by presenting a consistent comparative analysis of available tools (Section 3).

1.1 Summary of effort

The total efforts undertaken in Task 3 are summarized in four points.

- The theoretical background for systematic heat pump integration with industrial processes was efficiently summarized and presented in a concise manner (Section 2).
- An analysis of available tools was conducted and an overview was provided in a single, comparative table (Section 3).
- An easy-to-use set of guidelines for practitioners was derived that can be used with or without tools and specific training (Section 4).
- Application of existing models/tools to a real case study based on the set of guidelines (Section 4) was presented in Section 5.

1.2 Notations

The notations used throughout the report are described

Cold stream	Process heating requirement
Composite curve (CC)	Representation of composite thermal hot or cold overall process requirements. Vectoral addition of all individual hot/cold stream contributions.
Grand composite curve (GCC)	Derived by subtraction of the cold from the hot CC in each temperature interval. The GCC monitors the process net heating and cooling loads and

	their temperature levels under the assumption of maximum energy recovery or minimum energy requirement (MER).
Hot stream	Process cooling requirement
HEN	Heat exchanger network synthesis
MER	Minimum energy requirement (of a process considering maximum energy recovery)
MILP	Mixed Integer Linear Programming –> optimization technique
Pinch point	Turning point in process thermal demand profile. Above the pinch temperature the process has a net heat requirement (heat sink), below the pinch temperature the process has a net cooling requirement (heat source).
Pinch analysis (PA)	Methodology to identify the true thermodynamic needs of a process, considering heat recovery.

2 Theoretical background

Ideal heat pump integration into an industrial process and estimation of the resulting benefits cannot be conducted without investigating the entire process energy system.

Figure 1 shows an onion diagram representing the hierarchical nature of the process energy conversion system as presented by Kemp [2], following the general approach to process synthesis. The main drivers of industrial processes are chemical reaction and separation steps (R, S), and are thus situated at the core for designing or optimizing a process. The next step addresses internal heat recovery in the process (H) and finally, design or modification of the utility system should be considered (U). Assuming the process chemical reactor and separation systems are of state-of-the-art technologies, *Pinch analysis (PA)* [3] addresses the final two steps in the onion diagram, providing a sound methodology to estimate the maximum heat recovery potential in a process, and the theoretical background for thermodynamically ideal placement of hot and cold utilities.

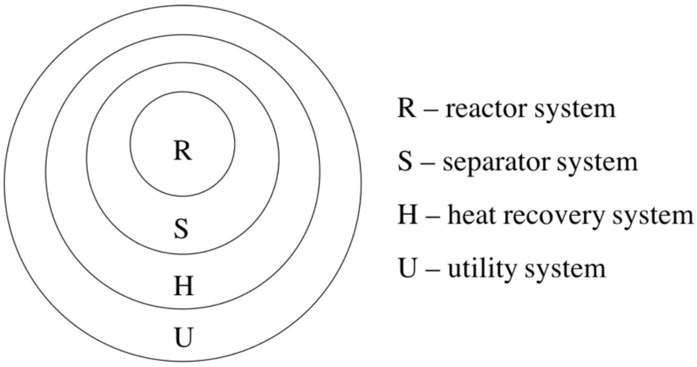

Figure 1 Onion diagram of process synthesis approach, adapted from Ref. [2], Figure 1.3.

This section is based in great parts on the *Context and motivation* chapter from Reference [4]. It introduces Pinch analysis (PA) as a methodology that, as mentioned, allows identification of the heat recovery potential in a process and the recommended utility placement based on the true thermodynamic requirements of a process.

In reality, decision-making is seldom driven by thermodynamic requirements, but rather by economic, safety, and practical concerns. Hence, various additions to classic PA have been provided in research (e.g. by means of cost optimization) [5–7] and in practical tools [8,9].

Pinch analysis is introduced in Section 2.1 with the main rules and conclusions for utility and heat pump placement presented in Sections 2.1.2 and 2.1.3, respectively. This is followed by a short overview of extensions to PA accounting for practical problems (Section 2.2), and a summary and critical review of the methods presented in Section 2.3.

2.1 Heat recovery potential in a process: Pinch analysis (PA)

Pinch analysis is a methodology developed in the 1970s by Linnhoff and Flower [3,10] and extensively discussed by Kemp [2]. It allows estimation of the maximum heat recovery potential in any process with heating and cooling requirements. In industrial settings, this requires decomposition of a site into its thermodynamic requirements. The result is a set of hot (net cooling requirement) and cold (net heating requirement) thermal streams.

The second principle of thermodynamics states that heat can only flow from a source at higher temperature to a sink at lower temperature. Ensuring this thermodynamic feasibility, the heat cascade[1] is derived which allows estimation of the maximum heat recovery potential of an industrial process and the temperature ranges in which external heating and cooling are required. It has to be noted that pinch analysis is traditionally conducted for a time slice, assuming that this represents the process at constant operating conditions. However, different approaches have been developed to address non-constant process operating schedules, such as the time-average approach [11] and so-called multi-time targeting [12]. These are not further discussed in this section, but it is referred to general literature for more information [2].

2.1.1 Minimum approach temperature ΔT_{min}

An ideal heat exchanger is an adiabatic device in which a hot stream transfers energy to a cold stream at lower temperature as depicted in Figure 2. The second law of thermodynamics dictates that a temperature gradient between the hot and the cold stream is required to provide a driving force for heat to flow.

From the principles of pinch analysis (PA), a minimum approach temperature, ΔT_{min}, defines the point in a heat exchanger where the hot and the cold streams exhibit the smallest temperature difference. The position of ΔT_{min} depends on the inclination of the temperature-enthalpy profiles of the hot and cold streams, which are proportional to the inverse product of heat capacity and mass flowrate (mc_p). The optimal minimum temperature difference is conventionally found by optimization which considers the balance between operating and investment cost for heat exchangers. Readers are referred to Refs. [13,14] for the principles and formulation of this problem, which will not be repeated here. Fundamentally, a smaller approach temperature reduces the operating cost due to higher process heat recovery while increasing investment cost related to larger heat exchange area.

In general practice, engineering estimates are often used as values for the minimum approach temperature difference are assumed. For aid in visualisation and to ensure thermodynamic feasibility, the hot (cold) stream temperatures are shifted downwards (upwards) by half of this difference, resulting in what are referred to as *corrected temperatures*.

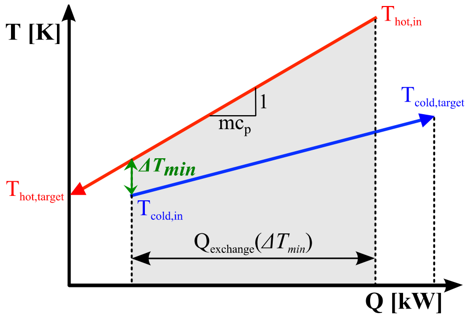

Figure 2 Temperature enthalpy profile of a counter-current heat exchanger to illustrate the ΔT_{min}. Reprinted from [4].

[1] The heat cascade refers to the theoretical concept of successively transferring thermal energy from higher to lower temperatures within a process.

2.1.2 Graphical representation, pinch point, and pinch rules

The hot and cold composite curves (CC) are the main representatives of the process thermal requirements. These are created from the individual hot and cold process requirements (streams). Identifying these thermal streams requires detailed study of the process needs. An example of a hot **composite curve (CC)** generated from the process thermal requirements is illustrated in Figure 3 (b). It is constructed by vector addition of all individual hot stream contributions (shown in Figure 3 (a)) in each temperature interval. The cold CC is constructed similarly, using the cold process streams. The hot and cold CCs represent the total heating and cooling demand of the process. The vertical overlap between the two curves marks the maximum heat recovery potential of the industrial process as shown in Figure 4 (a).

The **grand composite curve (GCC)**, depicted in Figure 4 (b), is derived by subtraction of the thermal load of the cold from the hot CC in each temperature interval. The GCC monitors the net heating and cooling loads and their temperature levels under the assumption of maximum energy recovery or minimum energy requirement (MER). The pinch point is marked by the impingement of the GCC on the temperature (Y) axis. Above, the process exhibits a net heating requirement (heat sink), and below, a net cooling requirement (heat source).

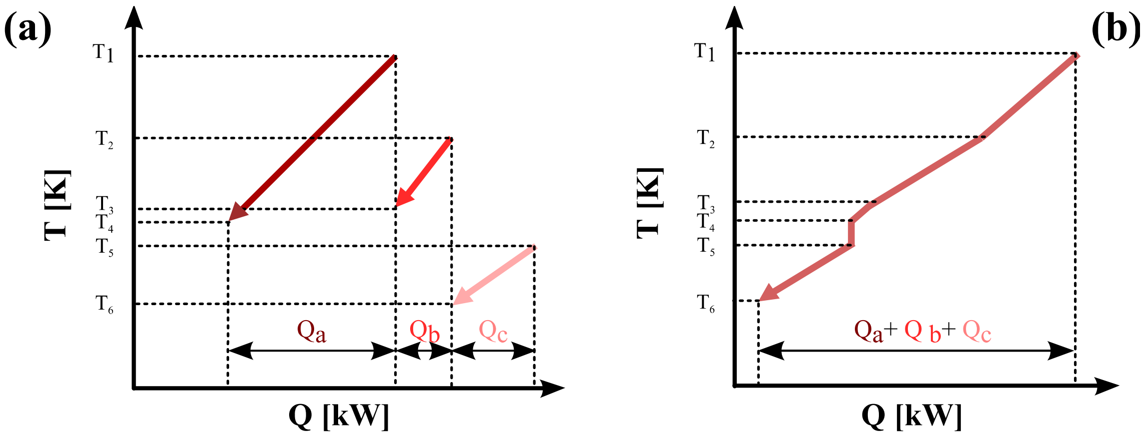

Figure 3 (a) Individual hot streams, (b) hot CC in temperature enthalpy diagram [11].

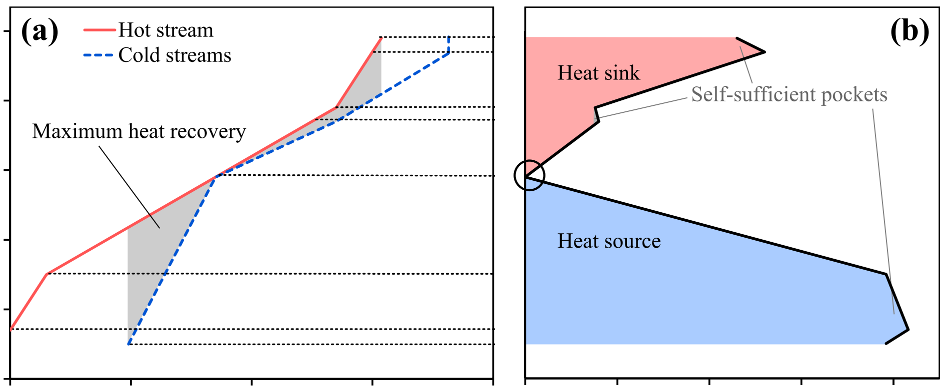

Figure 4 (a) Hot and cold CCs, (b) GCC in temperature enthalpy diagram. Reprinted from [4].

The distance from the temperature axis at the highest and lowest temperature represent the minimum hot (MER_{hot}) and cold (MER_{cold}) energy requirements, respectively.

The pinch point or pinch temperature induces four thermodynamics-based, so-called, ***pinch rules***:

1. Hot utilities should only be installed at temperatures above the pinch (point),
2. Cold utilities should only be placed below the pinch (point),
3. No heat exchange should occur across the pinch (point), and
4. Self-sufficient pockets require no additional heating or cooling.

Violating any of these rules results in an increase of the utility requirements and, hence, a reduction of the process (exergy) efficiency. In the context of pinch analysis, "excess heat" is referred to as the heat available below the process pinch point which represents the process' net cooling demand.

2.1.3 Energetically optimal heat pump placement

This section addresses mechanically driven heat pumps (HPs) due to their widespread application [15]; however, it should be noted that sorption systems present different and interesting integration options but are not within the scope of this section.

Heat pump rules

Rule No. 1 (necessary condition)

Townsend and Linnhoff [13] derived the theoretical foundation for (thermodynamically) optimal placement of heat pumps in an industrial process based on pinch analysis and the pinch rules: heat pumps should always be placed across the process pinch point if energy savings are desired.

In essence, energy savings through *heat pumping* are achieved by

- recovering excess heat from **below the pinch**,
- upgrading it through application of mechanical work, and
- supplying it back to the process **above the pinch** temperature

which is hence referred to as excess heat valorisation or re-use. For practitioners, it is important to recognize that heat pumping entirely above or below the pinch point violates the fundamental tenets of pinch theory. Placed above the pinch, heat pumps act as an electric heater as any heat provided at higher temperature is compensated by an equivalent heat requirement with the only difference due to input of electricity. Below the pinch point, a heat pump necessarily provides a hot stream which directly violates the basic rule excluding hot utility provision below the pinch which, in turn, necessitates a greater consumption of cold utility.

Rule No. 2 (sufficient condition)

It has to be noted that rule No. 1 generates *net energy savings* as long as the coefficient of performance (COP) of the heat pump and the electricity production efficiency are within certain boundaries.

Therefore, in order to assure energy savings, a second rule is defined as:

$$\text{COP (real)} \times \text{electricity production efficiency} > 1$$

Simply stated: the product of the COP and the electricity production efficiency should be greater than unity. For example, if electricity is generated at 50% efficiency (e.g. combined cycle power plant), the heat pump should have a COP of at least 2 to realise net energy savings. This general principle assumes electricity generation from conventional thermal power plants and thus other generation technologies should be considered in accordance with their efficiency in converting primary energy to electricity.

Explanation

If the above-mentioned product is equal to (or less than) 1, the same amount of (or more) heat is required to drive the electricity production than the heat that is delivered by the heat pump. Such a configuration does not bring energetic benefits. The COP for the above-mentioned rule should be calculated as the hot COP if only heat is supplied; and calculated as the combined COP if both heating and cooling are supplied to the process.

The theoretical hot COP can be calculated as follows: $\mathrm{COP}_{h,th}[-] = {T_h[K]}/{(T_h - T_c)[K]}$, while the combined COP is calculated by $\mathrm{COP}_{th}[-] = {(T_h[K] + T_c[K])}/{(T_h - T_c)[K]}$.

Assuming an second-law efficiency of 55%, the real COP is calculated by: COP = COP_{th} x 0.55. Table 1 shows three different real, hot COPs, indicating that a COP of 2 requires the same thermal power plant input as the heat pump condenser delivers. Figure 5 <u>illustrates different COPs between 30°C and various temperature lifts (ΔT). Only temperature lifts above 120K generate a real COP of 2, which illustrates that this case is not particularly common.</u>

Table 1 Comparison compression power and required power plant thermal power for various hot COPs.

COP (hot, real)	-	4	3	2
Heat pump condenser	kW	**100**	**100**	**100**
Compressor power	kW	25	33	50
$\eta_{\text{combined cycle}}$	-	0.5	0.5	0.5
Thermal input of electrical power plant	kW	**50**	**67**	**100**

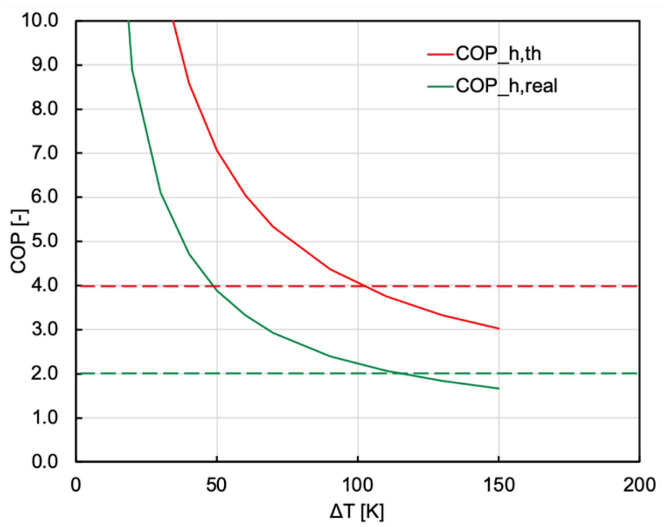

Figure 5 Theoretical and real coefficient of performance (COP) of heat pump (for heating) with evaporation temperature at 30°C, exergy efficiency 55%

As mentioned previously, the COP has a major influence on the performance and energetic gain of the heat pump. One crucial factor which influences the COP of heat pump cycles is the required temperature lift and thus the compression ratio. In the context of industrial excess heat valorisation, the temperature lift is directly linked to the "sharpness" of the pinch, meaning the shape of the process grand composite curve close to the pinch point.

Figure 6 shows the temperature enthalpy diagrams of processes (A) and (B), and the *energetically optimal placement of various compression heat pump systems according to the heat pump rules*.

Process (A) has sharp pinch point with a small temperature lift. While process (B) shows a smooth pinch point with heating and cooling requirements spanning over a range of temperatures. Integration of different mechanical heat pump systems are illustrated, starting from a single-stage, single fluid (inverted Rankine cycle) heat pump in Figure 6 (A) and (B). If a high temperature lift is required as illustrated in Figure 6 (B), the COP of standard (single-stage, single fluid) heat pump cycles can be drastically compromised.

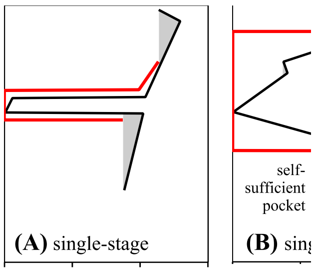

Figure 6 Heat pump integration to process GCC. (A) GCC with "sharp" pinch point & single-stage heat pump (HP), (B) "smooth" pinch point & single-stage HP, (1B) "smooth" pinch point & multi-stage HP, (2B) mixture HP, (3B) inverse Brayton HP.

Three options to overcome this issue are discussed in the literature, which are depicted in Figure 6 (1B-3B).

- (1B) Multi-stage or cascaded heat pump cycles (based on latent heat) with multi-stage compression and/or expansion [16–19], potentially a cascade of cycles.
- (2B) Zeotropic mixture cycles based on (latent heat of) mixtures where the difference in fluid boiling points is expressed in a temperature glide and liquid/ vapor composition shift during evaporation and condensation [20,21].
- (3B) Inverse Brayton cycle heat pumps based on sensible heat release and consumption in the condenser and evaporator, respectively [22].

Single fluid (inverse Rankine) heat pumps can satisfy constant temperature thermal requirements with a single-stage heat pump as well as continuous temperature ranges with help of multi-stage systems at a reasonable COP (above 2). In generating a temperature glide, zeotropic mixtures [20,21] or heat pumps relying on the inverse Brayton cycle [22] may be advantageous for demands spanning wide temperature ranges, but less flexible relative to constant temperature requirements.

This discussion highlights the variety of options which may be considered in order to satisfy the requirements of the process, which are represented by the grand composite curves (GCC) shown in Figure 6. Choosing between options can be simplified by application of optimization algorithms and with the help of tools, which is discussed in more detail in Sections 2.2 and 3, respectively.

2.1.4 Heat pump integration beyond heat pump rules

2.1.4.1 Refrigeration

The rules identified above for energetically optimal placement of heat pumps are also valid for refrigeration cycles which work based on the same principle as heat pumps. Usually, however, the main focus of refrigeration is efficient cooling of the process at sub-ambient temperatures.

If the process pinch point is at high temperature, it may not be reasonable to cross the pinch with the refrigeration cycle. The reason for this is discussed in Section 2.1.3, *Rule No. 2*; however, conclusions should not be drawn prematurely, as shown in the following example.

Figure 7 (a) shows a process with a refrigeration need at -20°C and a pinch point at 54°C. A single-stage refrigeration cycle crossing the pinch between -25°C and 60°C would lead to a real, combined COP of 3.42. However, often, a standard refrigeration cycle would be selected to provide the cooling need and would be placed entirely below the pinch point (evaporation / condensation at -25 / 25°C). This means that cooling water would be required to cool the process below the pinch (but above the ambient temperature) and to cool the condensation stage of the refrigeration cycle.

Applying rule no. 2, the combined COP is above 2 which indicates that heat pump integration could be beneficial. These benefits could also be achieved with a cascaded system as shown in Figure 7 (b). Here, in addition to the standard refrigeration cycle, a multi-stage heat pump is proposed to recover excess heat of the refrigeration cycle and process (adding evaporators at 15 and 35°C), to supply the upgraded heat above the pinch temperature (at 60°C). In this solution the cooling water consumption is drastically reduced which also indicates improved thermodynamic performance of this solution.

These two examples indicate the variety of options which are possible for satisfying the process requirements shown by the GCC, and how complex a consistent analysis without adequate integration tools/methods is. Available methods and tools are discussed in Sections 2.2 and 3, respectively.

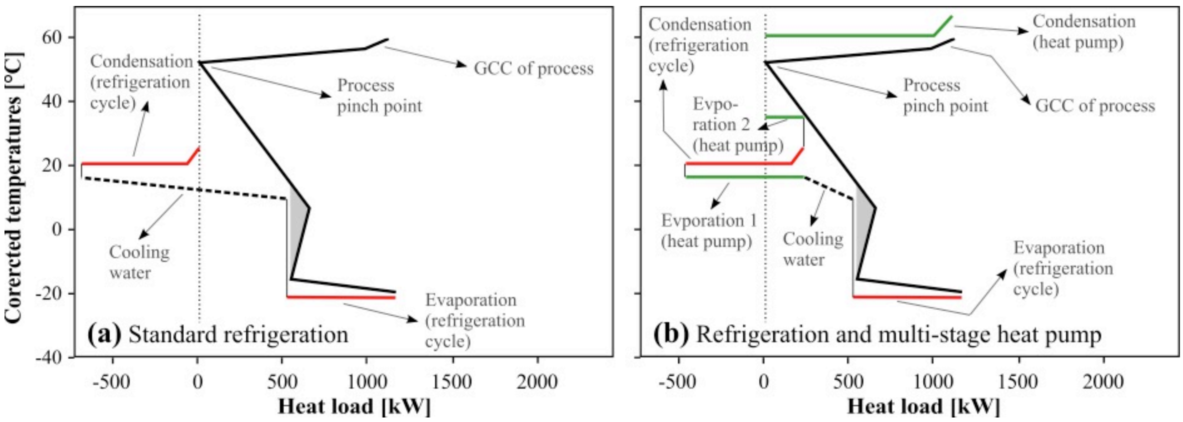

Figure 7 Refrigeration integration to process grand composite curve (GCC) with pinch point at 54°C. (a) Standard refrigeration between -25°C and 25°C, (b) Standard refrigeration and heat pump between 15, 35°C (evaporation) and 60°C (condensation).

2.1.4.2 Pinch violations

Many processes have intrinsic pinch violations for economic or practical reasons, which require cooling above or heating below the process pinch point. In these cases, it is important to understand the purpose of implementation to ensure that it is strictly necessary from the process perspective; however, the heat pump rules may be violated in these specific cases. The following pinch violations may create acceptable heat pump placement against the *heat pump rules*. Their validity, however, needs to be carefully considered.

- **A subambient cooling requirement below the pinch** may require a refrigeration cycle with condensation below the pinch (with heat evacuated to the environment when necessary);
- **A (pinch violating) cooling requirement above the pinch** could be satisfied by a heat pump which may bring energetic advantages compared to a pure cooling utility, because it also provides process heating above the pinch; or
- **A (pinch violating) heating requirement below the** pinch may be satisfied by a heat pump, since it also provides cooling below the pinch.

While these conditions should be avoided wherever possible, some aspects of plant operation surmount energy efficiency measures and thus sub-optimal heat pump integration may be used to satisfy specific requirements **where alternatives are impossible**. The latter two cases are especially rare and should only occur in extremely restricted circumstances; however, heat pumping may yield energetic benefits compared to satisfying rule-violating requirements with alternative utilities.

2.2 Advanced methods for heat pump and utility integration

The above rules and methods address systematic reduction of the energetic requirements of a process. Decision-making in industry, however, is seldom based upon energetic objectives. Other drivers play a major role, including economic and environmental concerns as well as technical constraints and motivational barriers.

Optimization in the form of mathematical programming is a widely-used technique based on systematically scanning various heat pump and utility options to identify the 'best' alternative with regard to selected objective(s). Researchers have published a variety of studies presenting 'superstructure'-based optimization algorithms. 'Superstructure' refers to a generalized model that represents all design alternatives, of which one solution is finally selected during the optimization step.

Papoulias and Grossmann [5] presented an optimization model based on Mixed Integer Linear Programming (MILP) which allows determination of the optimal utility system for an industrial process, considering the heat cascade, to achieve minimum process energy requirement (in agreement with pinch analysis). This approach is generally referred to as **utility targeting** and is adopted by most researchers working on process modelling and optimization.

In a subsequent work, Papoulias and Grossmann [6] presented the mathematical model for designing industrial heat exchanger networks, so that the minimum energy requirements found during the utility targeting could be fulfilled. More information can be found in reviews of this topic [23].

The first comprehensive methodology for optimal *industrial heat pump* design based on the utility targeting principles was presented by Shelton and Grossmann [16,17] in the form of an MILP superstructure. Based on a discrete set of temperature intervals and predefined working fluids, the active presaturators, evaporators, condensers, and their sizes could be optimally determined. Further developments are summarized in [24] where a novel synthesis method and bi-level solution approach was presented which identifies optimal industrial heat pump configurations, considering a comprehensive list of heat pump features comparing their results to various literature cases. More information can also be found in appendix 8.1, where more methods and tools are introduced.

2.3 Summary and discussion

Pinch analysis is a theoretical methodology which identifies heat recovery potential within a process, and with that, the minimum heating and cooling requirements. The pinch rules help to establish recommendations for thermodynamically-beneficial placement of utilities and heat exchangers, while violating the rules results in higher energy consumption and lower efficiency of the process energy system. With help of the pinch rules, Townsend and Linnhoff [25] derived theoretical principles for energetically favourable placement of heat pumps. Two rules were presented in this report indicating that heat pumps should cross the pinch as long as the temperature lift is not large, resulting in a COP which is too low for overall energetic benefits.

Two cases were identified in which the heat pump rules may be, or even must be, violated: (1) refrigeration serves mainly for the purpose of process cooling below ambient temperatures, crossing the pinch can be circumstantially considered; (2) if the process features internal pinch violations, then heat pumping may be considered to satisfy these violations.

The theoretical framework described here is the basis for the practitioner guidelines derived in Section 4; furthermore, most tools described in Section 3 rely on these principles.

The applicability and feasibility of pinch analysis (PA) and its principles is sometimes criticized due to technical and economic constraints which may render design or redesign of a process based on purely energetic targets difficult to attain. Further, it is stated that the use of PA principles requires specific proficiency which inhibits broader usage.

The first aspect of criticism can be faced with the note that it remains the sole method which allows a deep insight and detailed thermodynamic understanding of processes. It offers a holistic view on the process from an energetic/thermodynamic perspective. The second point can be addressed in two ways: firstly, by pointing out that there is a variety of programs and tools (discussed in the next section) available to aid in understanding and using the principles better; and secondly, that understanding of the underlying principles and basic analysis can already provide a starting point (as discussed in Section 4).

3 Industrial heat pump integration tools overview

An analysis of available tools was conducted and an overview is provided in Table 2. The list of criteria as well as the identified properties of the tools were discussed with support staff of the different software packages. The list of considered tools stems from a literature review and the previous IEA Heat Pump Annex 35 [1] Task 2 report and IEA SHC Task 49 [26]. Only tools of which online documentation could be found were considered in this analysis. The considered tools were classified into three categories:

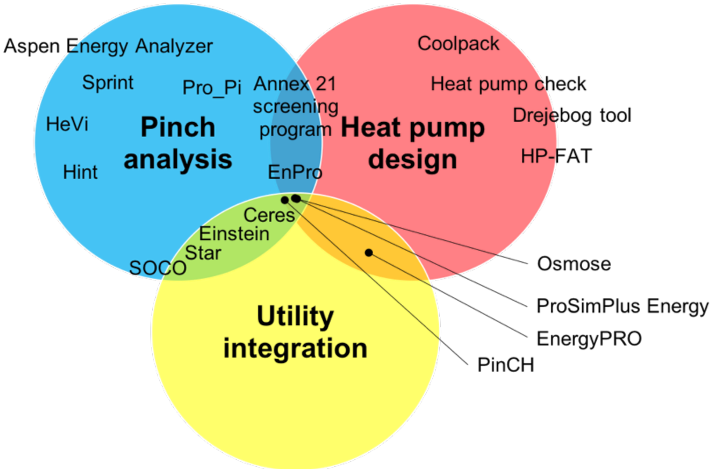

Figure 8 Categories for grouping of relevant tools.

From this overview, four groups were identified and are color-coded in Table 2 accordingly.

- Heat pump design (HP) (marked in red): Tools that aid in designing and planning heat pump systems based on selected operating conditions.
- Pinch analysis (PA) and heat exchanger network (HEN) design (marked in blue): Tools that aid pinch analysis of an industrial process to estimate the heat recovery potential and/or aid in planning and re-designing the heat exchanger network. In these tools, the focus is placed on process heat recovery, not on utility integration.
- PA and heat pump integration (marked in green): Tools which allow analysis of the heat recovery potential through PA and heat pump integration without thermodynamic property calculations.
- PA and heat pump integration (marked in dark green): Same as green, but with thermodynamic property calculations incorporated within the tool.

The licensing of each tool is also noted, indicating whether the tools can be openly accessed, need to be purchased or are utilized in an academic setting. The targeted user type, required proficiency and other criteria are also indicated to better identify which tools should be recommended for various interests.

The ultimate goal of this analysis is to provide a concise overview of the breadth of tools available for various purposes and users. The use of some of the open access tools is discussed in Section 4.1, showing that a combination of certain tools can reach good results and can overcome some barriers of specific tools. Energy auditors, HVAC planners, and heat pump producers are encouraged to try some of the tools to gain deeper understanding of different aspects in industrial heat pump integration. Tools with a free version are especially recommended since they allow study of the matter without an initial investment.

Table 2 Overview of available heat pump tools. User prof. – user proficiency: * - low to ***- high, PA: pinch analysis, HEN: heat exchanger network synthesis, HP: heat pump design, Opt – optimization algorithms. UT: utility integration, ST: steam network, CG: co-generation, ST: solar thermal, TP: thermodynamic property data included. HVAC: heating ventilation and air conditioning, THEE: thermal energy engineering.

Name	Institu-tion	Lan-guage	Latest release	First re-lease	Func-tionali-ties	License	Main use	Inter-face	Targeted user	User prof.	PA	HEN	HP	Utili-ties	In-dustry	Opt.	Comments	Source
Cool-Pack	DTU Copen-hagen	Eng-lish	v1.5	1995	HP	**Open access**	Re-search	GUI	HVAC engineers	** (HVAC)	X	X	✓, multi-stage, TP	-	-	X	(+) tool is mainly developed for heat pump design considering various features, (-) no prcess integration possible	[27]
Sprint	UMIST – The university of Manchester	Eng-lish	2018, v2.9	v1.4	PA, HEN	Aca-demic	Re-search	GUI	students, energy auditors	**	✓	✓	X	X	all	✓	(+) GUI, (-) license required	[28]
Star	UMIST - The university of Manchester	Eng-lish	2018, v2.9	v1.4	PA, UT	Aca-demic	Re-search	GUI	students, energy auditors	**	✓	X	?	SN	all	✓	(+) GUI, (-) license required	[28]
TOP Energy	RWTH Aachen	Eng-lish	2018, v2.8.5	?	HP, UT	Propri-etary	Com-mercial	Flow-sheet	energy auditors, industry	*** (THEE)	X	✓	✓, single-stage	✓	all	X	(+) flowsheet software, simulation (-) no pinch analysis	[29]
PinCH 3.0	HSLU - Lucerne University of Applied Sciences and Arts	Eng-lish	2018, v3.0	2010	PA, HEN, UT	Propri-etary, aca-demic	Indus-try, teach-ing	GUI	energy auditors, industry, students	** (THEE)	✓	✓ (heu-ristic rules)	✓, single-stage (TP)	✓	all	(✓) rule bas-ed	(+) user friendly/GUI, (+) 10 steps to completing PA, tutorials, (+) docu-mentation material & website, (-) proprietary	[30]
Ener-gyPRO	EMD International A/S	Eng-lish, var.	2018, v4.5	?	HP, UT	Propri-etary	Com-mercial	GUI	engineers	**	X	X	✓	✓	X	X	(+) energy system planning with multi-period analysis, (-) proprietary	[31]
HP FAT	Teknologisk Institut	Eng-lish	2018	2016	HP	**Open access**	Re-search	GUI	Researchers, engineers	*	X	X	✓	X	X	X	(+) user-friendly, (+) simple func-tionality, (+) open access, (-)	[32]
Einstein	energyX-perts.NET (E4-Experts GmbH, Berlin, Germany)	Eng-lish, vari-ous	2017, v2.5	2007, v1.0	PA, HEN, UT	**Open access** (v2.4) (v2.5- 850-2800 Euro)	Com-mer-cial/ind ustrial	GUI + flow-sheet	energy auditors, industry	** (THEE)	✓ (no time slices)	✓ (heu-ristic rules)	✓ (black box, no TP)	✓	all (limita-tions above 400°C)	(✓) rule bas-ed	(+) integrated approach, one tool for full energy audit, (+) transparency, (+) open-source version, (+) method for auditioning, (-) User-friendliness of interface could be improved	[9]
EnPro	AEE INTEC, AIT, TUW	Ger-man	2017, v3.0	2017	HP, PA	**Open access**	Re-search	Excel inter-face	process operators, preliminary	* (THEE)	✓ (20 streams)	(✓)	✓, single-stage	ST	all	X	(+) easy to use user interface, (-) not more than 20 process streams can be defined → limited use for industry	[8,33]
ProSim Plus Energy	Prosim	Eng-lish	2017, v3.6.2	?	PA, HEN, UT	Propri-etary	Com-mercial	GUI	energy auditors, industry	*** (THEE)	✓	✓	✓, multi-stage, TP	✓	all	✓	(+) flexible use, wide range of possibilities, (+) thermodynamic property, (-) proprietary	[34]

Drejebog tool	Dansk Fjernvarme	Dan-ish	2017	2017	HP	**Open access**	Educa-tion	Excel inter-face	engineers	*	X	X	✓	✓	X	(✓ rule based)	(+) heat pump integration for district heating, (+) open access, (-) no PA	[35]
As-penEner gyAna-lyzer	Aspen Technol-ogy Inc.	Eng-lish	2015, v34	1981	PA	Propri-etary	Com-mercial	GUI	energy auditors, industry	** (THEE)	✓	✓	-	-	all	✓	(+) easy to use, (+) can be integrated to other ASPEN tools, (-) limited functionalities	[36]
Heat Pump Check	De Kleijn Energy Consultants & Engineers from Druten	Eng-lish	2014, v2.5	?	HP	**Open access**	Educa-tion	GUI (web based)	industry	*	X	X	✓ - single stage	-	-	✓	(+) easy to use, generates best heat pump cycle for specific require-ments	[37]
HeVi	University of Aalto (Finland)	Eng-lish	2008, v0.2.6	2008	HEN	**Open access**	Re-search	GUI	students, researchers	** (THEE)	X	(✓)	X	X	all	X	(+) helps for visualization of HENs, (+) open access, (-) not updated past 2008, no documentation	[38]
Osmose	EPFL- École polytechnique fédérale de Lausanne	Eng-lish	2015	2009	PA, HEN, UT	Aca-demic	Re-search	Script	research-ers, stu-dents	***	✓	✓	✓, multi-stage, TP	✓	all	✓ (UT+ HEN)	(-) No GUI, (-) academic use only, (-/+) General platform, not specific for HPs, but more comprehensive analysis, (+) Optimi-zation algorithms	[39, 40]
SOCO	AEE Institute for Sustain able Technologies	Eng-lish	2014	2014	PA, ST, HEN	Aca-demic	Re-search	GUI	researchers	*** (ST)	✓	✓	?	ST	All	?	(+) focus on multi-period PA for solar energy systems with storage, (-) heat pumping not really consid-ered	[41]
Pro_Pi1 ,2	Chalmers University of Technology, Gothenburg	Eng-lish	2013	2008	PA, HEN	v1 - **open access**, v2 - academic	Teach-ing, re-search	Excel inter-face	students	** (THEE)	✓	(v2 - ✓)	(✓- self-de-fined)	basic	all	no	(+) user-friendly, teaching tool, (-) not design for utility integration, esp. not heat pumps	[42]
Ceres	C.E.S Paristech	Eng-lish	2013	2010	PA, HEN, UT	Aca-demic	Re-search	GUI	energy auditors, students	**	✓	✓	✓ (TP)	✓	all	✓	(+) GUI, (+) optimization, (+) general analysis, (-) proprietary	[43]
Hint	Universidad de Valladol-id (Spain)	Eng-lish	2009	2009	PA, HEN	**Open access**	Teach-ing	GUI	students	** (THEE)	✓	✓	X	X	all	X	(-) not actualized any more, (+) open-source teaching resource	[42, 44]
Annex 21 IHP Screening Program	Heat pump center (HPC)	Eng-lish	1997	1997	HP, PA	Propri-etary - 75 €	Educa-tion	GUI	HVAC engineers	** (HVAC)	✓	X	✓	-	all	X	(+) GUI, screening, (-) Few / outdat-ed refrigerant list, (-) User-handled screening, (-) Unfriendly GUI, data export	[45]
Super-Target	KBC Advanced Technolo-gy (UK)	Eng-lish	?	?	PA, HEN, UT	Not availa-ble	Com-mercial	?	energy auditors (company internal)	***	✓	✓	✓	✓	all, focus on petro-chemi-cal	✓	(+) tool from founder of PA (Lin-nhoff), (-) only for company internal use	[46]
TRIAS-Energet-ica	EURIMA	Eng-lish	?	?	UP	**Open access**	Re-search	Con-cept	urban planners	*	-	-	-	-	-	-	(-) concept for energy-aware urban planning	[47, 48]
KWA heat pump selection screen	RVO (high temperature heat pumps)	Eng-lish	?	?	HP	Not available	?	GUI	industry	*	X	X	✓	-	all	X	(-) neither the tool, nor documenta-tion can be found online	?

Table 2 characterises and provides a summary of many tools, which can be used for studying heat requirements and utilization as well as utility integration opportunities. Pinch analysis forms the foundation of many of these tools and is the exclusive purpose of some.

There is another distinct group which focuses on heat pump design without considering integration with the process or pinch analysis. These tools are often easy to use and function mainly as online calculators built to determine heat pump performance in a specific setting. None of the available tools consider utility integration separately from pinch analysis or heat pump design, which is logical considering that the basic principles of utility integration interact heavily with the other domains.

Overlaps between heat pump design and the other characteristics yield more complex problem formulations which include aspects of the process and/or other utilities. Thus, overlapping domains tend to be less user-friendly which is balanced with the capability of identifying more integrated solutions between the process, heat pumps and other utilities. Several tools are noted in the table to consider all aspects mentioned here, though none are without drawbacks in terms of usability, licensing or breadth. Four tools further include thermodynamic property packages to support heat pumping calculations, though two are strictly for academic use.

4 Practical guidelines

The practical guidelines derived here were inspired from analysis of other guidelines from the IEA SHC Task 49 - Integration Guideline [49] for solar process heat and the industrial heat pump technology guide [37].

The result is a set of guidelines which aid in the data acquisition, analysing the status quo, process heat recovery analysis, optimization and identification of the heat pump integration points. Each point is discussed in greater detail here with an example application in Section 4.1. The relevant steps in which software tools may be useful are identified with asterisk (*); however, all guidelines can be applied without the use of tools.

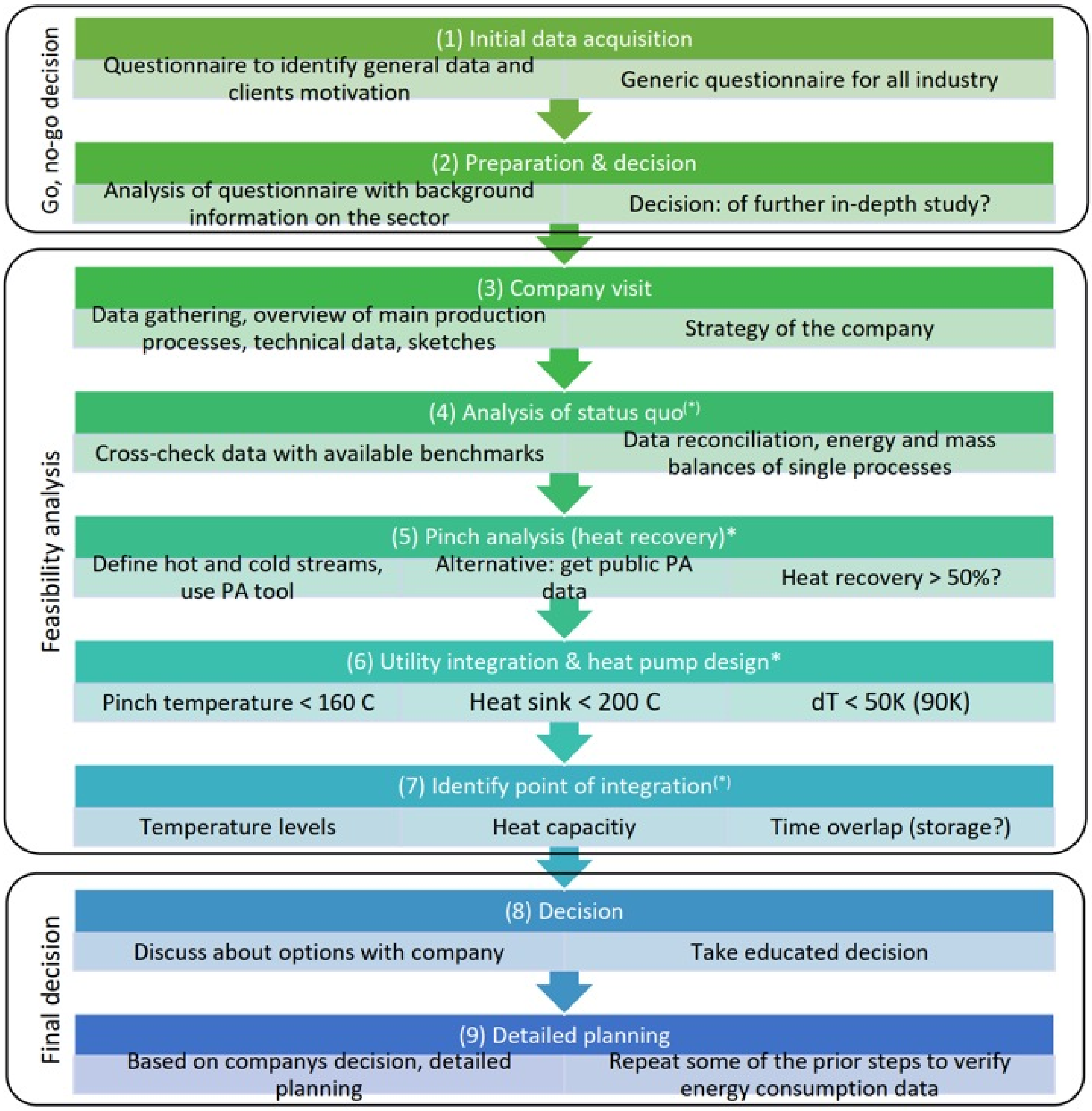

Figure 9 Assessment methodology for industrial heat pump integration.

4.1 Initial data acquisition

The goal of this step is to gain a general overview of the energy bill, the process boundary conditions, and the motivation of the company management to invest in energy efficiency measures. This can be conducted with a general questionnaire, which is not specific to any industrial sector.

Here, the main data of interest are the annual energy bill, plant operating hours and the minimum/maximum temperature levels of the process. Additionally, it may be of interest to identify refrigeration requirements, maximum thermal power demands, and constant temperature requirements. These data are helpful for informing decisions that are made in the following step, based upon the progress and outlook of the project.

The temporal coincidence of heating and cooling demands, such as in continuous processes, form the basis of pinch analysis and is considered to be the case here. Pinch analysis with batch processes is an area of research with many potential strategies to account for differences in operational periods. For considering heat exchange between time steps, storage must be included. Since this discussion would detract from the core methods intended in this report, these aspects are not discussed in further detail.

4.2 Preparation and decision

This step aims at analysing the outcome of the questionnaire and making a decision whether a further in-depth study seems promising. This can be conducted alongside several questions:

- Is there general interest from the company to implement energy efficiency measures?
- Are there refrigeration needs?
- Is the maximum process temperatures below 300°C?

The final decision needs to be made on a case-specific basis; however, the above criteria can provide additional motivation.

4.3 Company visit

The company visit serves for gathering technical data, gain insights to the main production processes and internal dependencies, and to receive or draw sketches of key conversion steps. These data can be further completed by conducting in-depth interviews with process operators and decision makers to identify opportunities for integration potential.

4.4 Analysis of the status quo(*)

The analysis of the status quo serves the purpose of getting a more detailed understanding of the process energy requirements. The aim is to perform a cross-check of the process data with available benchmark values, and to reconcile the data by ensuring that mass and energy balances in the system are satisfied. Data reconciliation is a data preparation and treatment technique which uses non-linear optimization to yield better estimates of uncertain measurements and provide insights where measurements are not reliable or available. Most industrial systems can be treated more easily with the use of software tools, such as Belsim Vali [50] or gProms [51], which supply flowsheeting interfaces and data reconciliation algorithms. Such software are especially useful in large systems where many measurements are available and links between measurement points can easily be overlooked.

These techniques require redundant measurements to effectively reconcile the data and provide statistically 'better' measurements than those read directly from instrumentation. In smaller systems, or if software is not available, data reconciliation techniques can still be applied based on engineering fundamentals of mass and energy balances combined with the appropriate mathematical formulation.

4.5 Pinch analysis (heat recovery)*

The best option for conducting pinch analysis is by using one of the available tools as documented below.

Pinch analysis tools: (Open access) Aspen Energy Analyzer [36], Sprint [28], Hint [42,44], EnPro [8,33], Pro_Pi [42], Ceres [43], Einstein [9], Star [28], PinCH [30], Osmose [39].

Most of these tools require input data in a similar form as presented in Table 5. Of the open source software, the EnPro and Einstein tools were tested. It was found that EnPro is an easy to use tool which does not require much prior training; however, it is limited in the number of streams which can be implemented. Einstein offers a wide possibility of uses, however, the application requires a higher level of knowledge and may require some training.

The outcome of such an analysis should be a set of composite curves: the hot and cold composite curves and a grand composite curve. These curves represent the process minimum energy requirements assuming maximum possible heat recovery, and can be considered as a benchmark of the process. Comparing the benchmark minimum energy requirement to the current energy bill yields the current level of heat recovery of the process.

Alternative to the use of tools: If it is not possible to generate a composite curve e.g. due to a lack of data or time, there are publications which provide indications for typical profiles in various industries, which may be taken as a reference [52] to generate an approximate level of heat recovery in the process. If the level of heat recovery is below 50%, the primary studies should initially focus on heat recovery measures instead of heat pump integration studies.

4.6 Utility integration & heat pump design*

After having created the GCC (or a proxy thereof) in the previous step, this step aims at identifying the correct point of integration of a heat pump and other utilities with the process. The goal is to identify the temperature levels and heat load of the heat pump and other utilities. Satisfying the pinch rules during this step assures that utility placement will still comply to thermodynamic rules and bring energetic benefits to the system in the event of future heat exchanger network redesigns toward maximum heat recovery.

The indications provided in the guidelines provide support to identify whether heat pump integration is feasible.

- Pinch temperature < 160°C?
- Heat sink < 200°C?
- dT < 50K?

The goal is to use the indications above and the information provided in the GCC to identify the temperature and heat load of a heat pump and other utilities. The heat pump pre-design can then be conducted with the help of one of the following tools:

Heat pump design tools: (Open access) Coolpack [27], Heat pump check [37], Drejebog tool [35], EnPro [8,33], Annex Screening program [45], PinCH [30], Osmose [39].

4.7 Identify the point of integration(*)

The point of integration should be identified at this step to proceed with the decision and detailed planning. Therefore, it is recommended to identify heat exchangers, or process units that fulfil the criteria identified in the previous steps. The main points to follow to are depicted below:

- Temperature level
- Heat capacity
- Time overlap (for batch processes)

There are also tools available which may be used to help in finding the adequate points of integration, which are depicted below.

Tools for heat exchanger network design & point of integration: (Open access) Aspen Energy Analyzer [36], Sprint [28], Hint [42,44], EnPro [8,33], Pro_Pi [42], Ceres [43], Einstein [9], PinCH [30], Osmose [39].

4.8 Decision

Many approaches using mathematical or heuristic methods to attain optimal heat pump integration provide a single solution which is suited to the process. Practically, the identifed solution might not be viable and thus providing several ‘good’ solutions is a preferable alternative to a single, ‘optimal’, solution. Providing several solutions leaves flexibility for the decision-maker to choose integration options which account for non-technical factors or to explore possibilities which might be more acceptable to different levels of an organisation. Selecting one or several solutions is required to proceed to the detailed planning phase.

4.9 Detailed planning

Integrating heat pumps with industrial processes requires detailed engineering work following the screening steps which had been carried out until this point. Methods applied for identifying the potential integration options are based on generalised formulae, equipment behaviour and operational characteristics and thus the calculations and design need to be refined in a final step before implementation. Technical, non-technical, economic and environmental calculations should be performed in detail to ensure the best integration of heat pumping in the process, respecting the requirements and constraints of the company which may have been difficult to incorporate at the screening stage.

5 Application of existing models

This section presents the application of existing models, tools, and theoretical principles to a real case study based on the set of guidelines presented in Section 4. Steps marked with an asterisk * may be easier to complete with aid of software tools. Some tools may also be used for the entire set of the guidelines; however, this is not specifically discussed in this section.

5.1 Initial data acquisition

The data acquired from the dairy plant is depicted in Table 3. It highlights that the maximum temperatures do not exceed 100°C, which indicates a great potential for heat pump integration. The operating time indicates quasi non-stop operation of the process apart from short maintenance breaks.

Table 3 Dairy plant data acquisition.

Products	**Pasteurized milk, yogurt, cream**	
Production rate	10	kg/s
Annual operating time	8’000	h
Energy prices	0.081	€/kWh nat. gas
	0.10	€/kWh electricity
Energy resource consumption	2’333	kW nat. gas
	167	kW electricity (refrigeration)
Boiler efficiency	90	%
Energy bill	1’512’000	€ gas
	133’600	€ electricity
	5.7	€/t total
Refrigeration requirement	500	kW
Operating temperature ranges	0	°C (min)
	100	°C (max)
Constant temperature requirements (chemical reactions, evaporation, condensation)	multi-stage evaporation, 60°C	

5.2 Preparation and decision

The operating time is relatively high, representing non-stop operation. The low operating temperatures, multi-effect evaporation system and company interest to improve site energy efficiency bring motivation to continue the analysis in a more thorough manner.

5.3 Company visit

The company visit revealed that heat recovery is already performed to a high degree in the dairy plant. The two main production steps identified were the raw milk pasteurization and centrifugation (process A) to produce pasteurized milk and cream and the concentrated milk production (process B).

The main data can be found on the flowsheet sketches in Figure 10 and Figure 11.

Raw milk enters the pasteurization unit (process A), in which it is heated and then centrifuged to separate high fat content cream from low fat content milk. The pasteurized milk from process A is partially sold and partially processed further to produce desserts and concentrated milk in a multi-effect evaporation system.

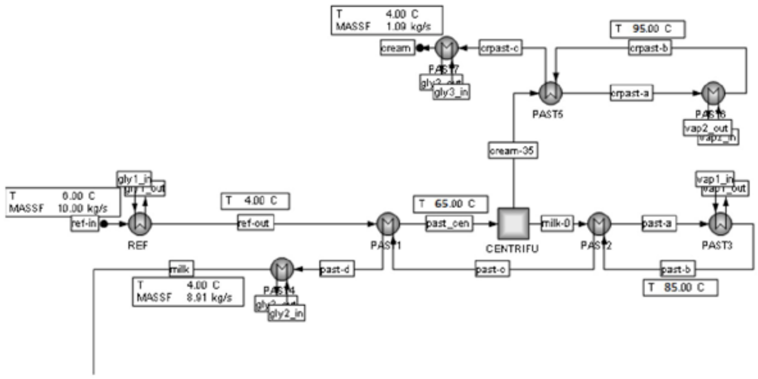

Figure 10 Process A. Pasteurization section with centrifugation for cream and milk separation.

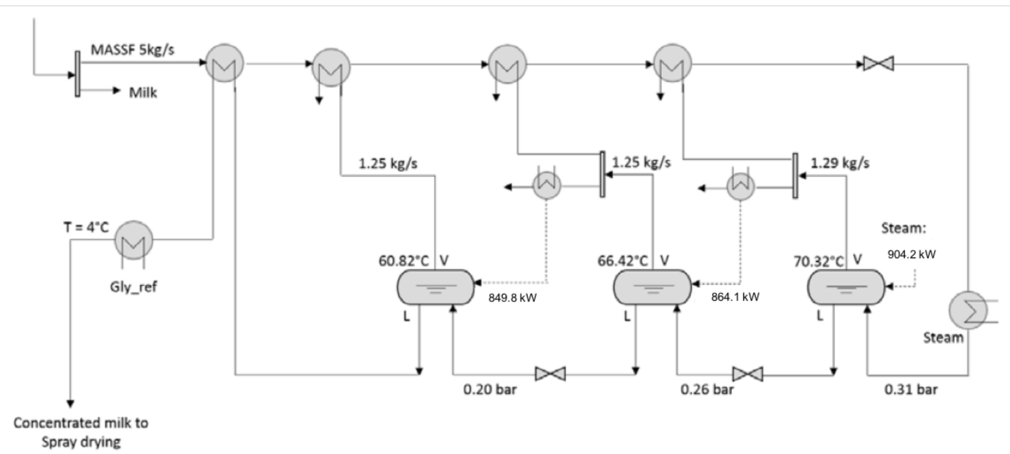

Figure 11 Process B. Concentrated milk production with multi-effect evaporation system.

5.4 Analysis of the status quo(*)

Crosscheck. The process overall specific energy consumption was derived to be 233 kJ/kg (gas) and 17 kJ/kg (electricity). Cross-checking that data with available benchmarks from reference data from the European Union [53] (Table 3.59) reveals that the electricity consumption is below the reference consumption. This was attributed to the fact that the company only reported the electricity consumption from the refrigeration cycles. The specific gas consumption is also at the lower end of the spectrum considering that the plant produces not only pasteurized milk and cream, but also yogurt and concentrated milk.

Table 4 Reference data from the European Union [53] (Table 3.59).

		Milk	Yogurt, others	Cheese	Milk powder	Whey
Fuel	GJ/t	0.18	1.5	4.6	3	20
Electricity	GJ/t	0.15	2.5	2.9	0.1	3.3

Overall, the energy consumption data is in the range of common benchmark values.

In order to analyse the current energy system at more detail, energy and mass balances of the dairy plant were generated. This included generation of a table with heating and cooling requirements needed by the process, depicted in Table 5. Since redundant measurements were not available, data reconciliation could not be performed in this case. The process heating and cooling requirements were modelled based on relatively few measurements, such as the mass flowrates and temperature levels, though only available at several point in the process. The data table was generated based on the following information.

The first process step is **pasteurization** and centrifugation of the raw milk. This requires heating to 66 °C and centrifugation (consuming electricity), which results in separation of milk and cream. Milk is then further heated to 86°C, while the cream is heated to 98°C, resulting in pasteurized milk and cream which are cooled again to 4°C. The heating and cooling requirements of the individual process steps (referred to as process streams) are estimated based on the specific heat capacity and temperature levels. The specific heat capacity of (raw) milk was approximated to be 3.8 kJ/kgK, and that of cream to be 3.4 kJ/kgK. The streams are depicted in Table 5.

Pasteurized milk can be further converted to various products. Fabrication of **yogurt and dessert** requires addition of further ingredients and various heating, storing and cooling steps. In agreement with process operators, both were modelled by assuming heating and cooling requirements between 4 and ≈90°C. The dessert is packaged at 70°C, during which the temperature is assumed to drop to 20°C. For all conversion processes mentioned above, milk properties are assumed with a specific heat capacity of 3.8 kJ/kgK. Concentrated milk is produced in a three-stage evaporation process, at sub-atmospheric pressures between 0.7 and 0.25 bar. Water thermodynamic properties were assumed for partial evaporation. The vapor is assumed to be captured and subsequently condensed and cooled to ambient conditions to harvest the latent and sensible heat.

Products were always modelled to reach operating conditions (4°C) after the conversion steps before being placed in the storage unit. The **storage unit** cooling requirements were modelled at constant temperature and based on data provided by the process operators. The cleaning in place system requires make-up water at 80°C.

Table 5 Hot and cold streams of the dairy process, reprinted from [54], from Becker [11].

Unit	Name	T_{in} [°C]	T_{out} [°C]	$\dot{Q}$ [kW]	$\Delta T_{min}/2$ [°C]	Remarks
Regrigeration	ref	6.0	4.0	76.0	2.0	refrigeration inlet milk
Pasteurization	pasto1a	4.0	66.0	2356.0	2.0	preheating
	pasto2a	66.0	86.0	676.4	2.0	pasteurization milk
	pasto3a	86.0	4.0	2773.2	2.0	refrigeration milk
	pasto4a	66.0	98.0	119.7	2.0	pasteurization cream
	pasto5a	98.0	4.0	351.6	2.0	refrigeration cream
Concentration	eva1	4.0	70.3	504.0	2.0	preheating
	eva2	70.3	70.3	904.2	1.2	evaporation 1.effect
	eva3	66.4	66.4	864.1	1.2	evaporation 2.effect
	eva4	60.8	60.8	849.8	1.2	evaporation 3.effect
	eva5	60.8	4.0	151.5	2.0	refrigeration concentrated milk
	eva6	68.9	68.9	904.2	1.2	condensation 1.effect
	eva7	65.9	65.9	864.1	1.2	condensation 2.effect
	eva9	68.9	15.0	87.8	2.0	condensation 3.effect
	eva10	65.9	15.0	80.8	2.0	cooling condensates 1.effect
Condensates cooling	eva8	60.1	60.1	849.8	1.2	cooling condensates 2.effect
	eva11	60.1	15.0	69.7	2.0	cooling condensates 3.effect
Yoghurt production	yog1	4.0	94.0	1026.0	2.0	heating
	yog2	94.0	10.0	957.6	2.0	cooling
Desert production	des1	4.0	90.0	817.0	2.0	heating
	des2	90.0	70.0	190.0	2.0	cooling
Hot water	hw	15.0	55.0	167.2	2.0	hot water prodcution
Cleaning in place	CIP1a	58.7	70.0	188.6	2.0	maintain temperature CIP1
	CIP1b	65.0	15.0	104.5	2.0	recuperation waste heat CIP1
	CIP2a	67.5	80.0	209.5	2.0	maintain temperature CIP2
	CIP2b	75.0	15.0	125.4	2.0	recuperation waste heat CIP2
Fridge	frig	5.0	5.0	300.0	2.0	maintain storage temperature

5.5 Pinch analysis (heat recovery)*

The dairy process hot and cold composite curves (CC) and grand composite curve (GCC) are presented in Figure 12. The pinch point temperature is observed to be 59°C and the minimum heat requirement is approximately 1.6 MW. Compared to 2.1 MW from the current energy bill yields the current level of heat recovery to be approximately 75%. This is a promising result, indicating that the dairy process is already at a sufficient level of heat recovery.

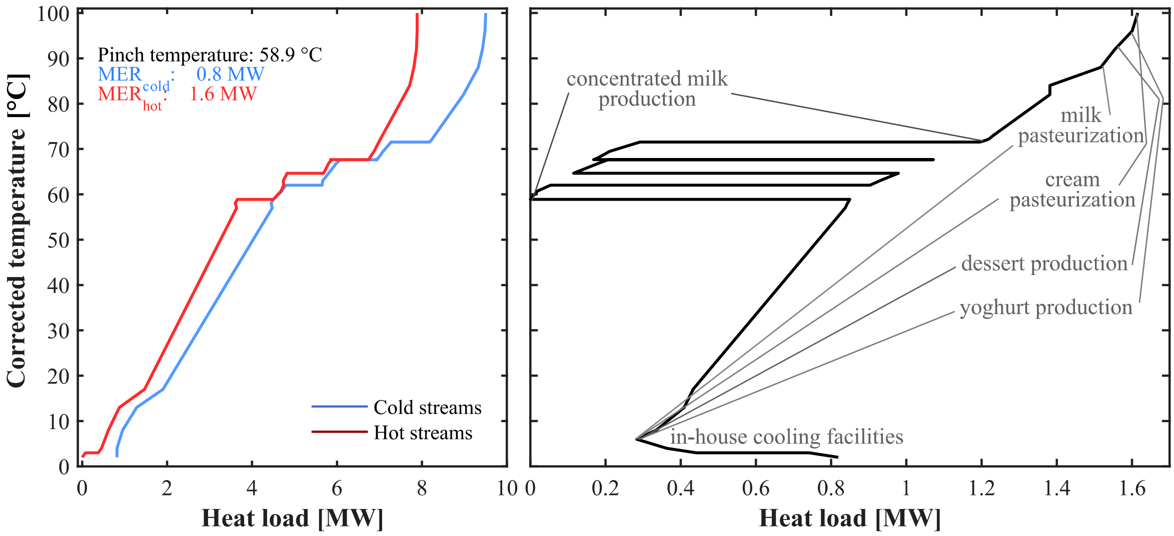

Figure 12 (Left) hot and cold composite curves, (right) grand composite curve of dairy process, reprinted from Ref. [54].

5.6 Utility integration & heat pump design*

Pinch analysis. Figure 13 shows the dairy plant grand composite curve (GCC). The pinch point is created by the multi-stage concentrated milk production unit. A self-sufficient pocket is visible below this region which indicates that the outlet vapor from the third evaporation effect should be partially used for preheating liquid milk. This is currently done in the existing plant, as highlighted in Figure 14.

Applying the pinch rules (1 and 2) to the case study requires heating above 59°C and cooling below this temperature. The pinch temperature is below 160°C, the heat sink is below 200°C, and the temperature lift between heat sink and source is below 50K, which satisfies all conditions described in Section 4.6, suggesting favourable conditions for installation of a heat pump across the pinch. A heat pump across the pinch point temperature, framing the concentrated milk production between 55°C and 75°C, is suggested.

However, there is a self-sufficient pocket, which indicates (according to pinch rule 4) that no additional heating or cooling is required within this region, so a heat pump could only be applied in the region outside the self-sufficient pocket, as shown in Figure 15(a). This analysis, however, excludes the view on the full utility system. The dairy plant also requires refrigeration at 0°C. The condenser of this refrigeration cycle could be used to provide the heat that the steam currently supplies. This would allow for increasing the size of the heat pump across the process pinch point as indicated in Figure 15(b).

This analysis also points to two important conclusions: (1) It is important to always look at the entire utility system, especially considering the refrigeration cycles, to conduct a proper analysis. (2) Pinch analysis (PA) helps to identify saving potentials that generate true benefits. If the marked heat exchanger (in Figure 14), was not already present in the plant, this link might have been easily missed in an analysis without PA, and a heat pump may have been installed which would not have generated any real benefit.

Heat pump design. The heat pump check tool from the de kleijn consultants [37], was tested for the design of the heat pump system across the process pinch point temperature and he results are presented in Figure 16. The tool suggests an ammonia based heat pump between 58°C and 75°C with a COP of 13.5 and a payback period of 1.6 years. Other tools could be used for the heat pump design, but are not illustrated here. Another option would be consideration of direct mechanical vapor recompression of the steam from the third effect evaporator.

These results indicate high economic potential, and support a case to proceed with the analysis.

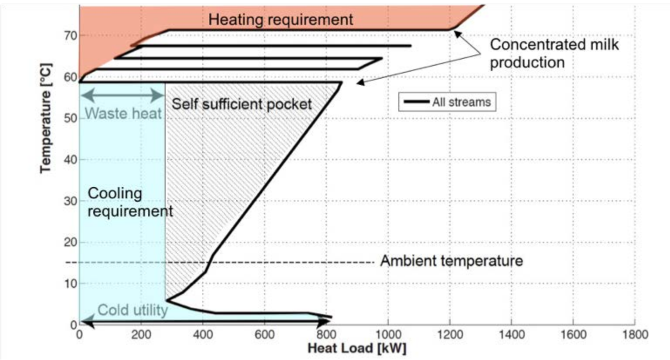

Figure 13 Dairy plant grand composite curve (GCC), from Becker [11].

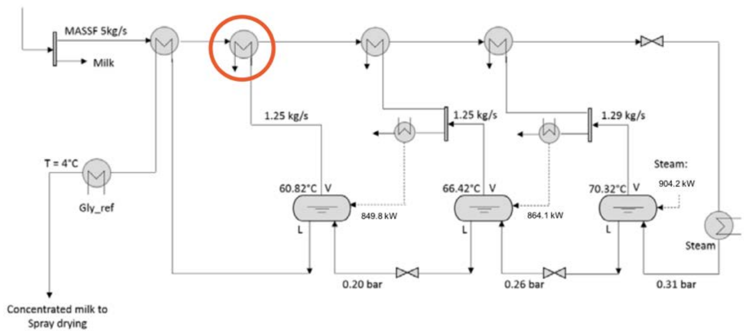

Figure 14 Concentrated milk production.

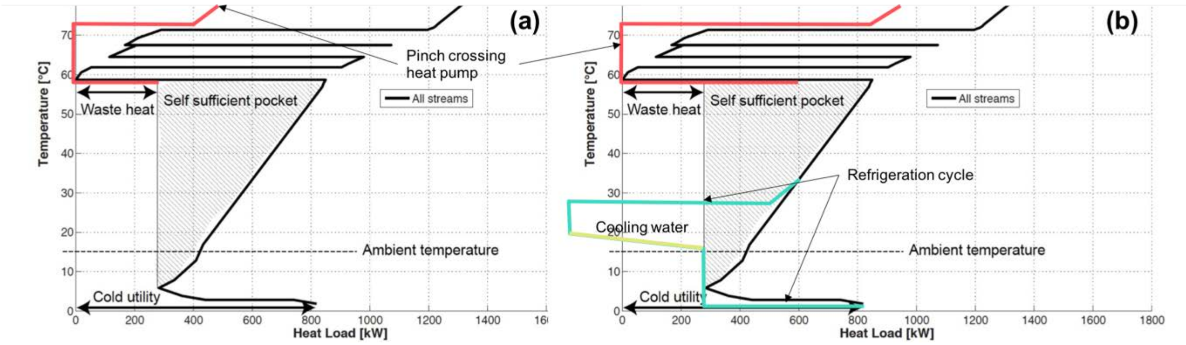

Figure 15 Dairy plant grand composite curve (GCC), from Becker [11], with (a) heat pump, (b) heat pump and refrigeration cycle integration.

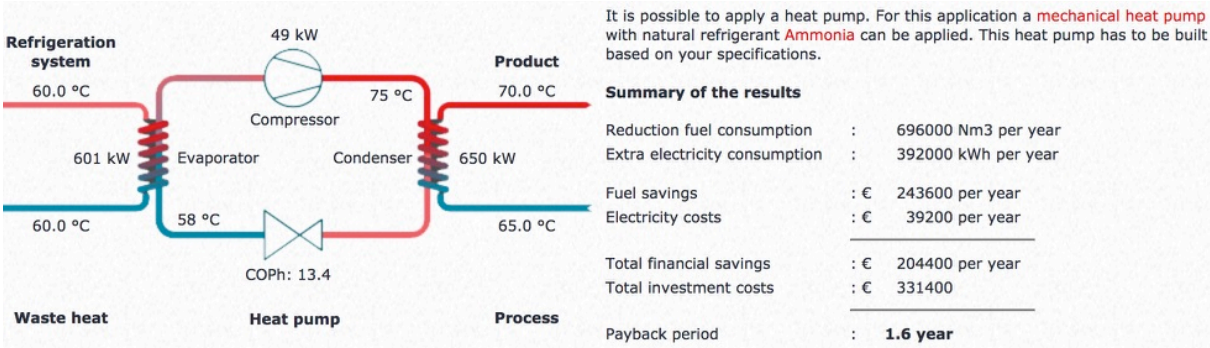

Figure 16 Results of heat pump check tool [37], with 8000 operating hours, 10 ct€/kWh electricity cost, and 35 ct€/m^3 gas cost.

5.7 Identify the point of integration(*)

In the dairy plant, the point of integration has bascially been identified during the previous step, indicating that the steam from the last effect of evaporation should be recovered to partially heat an ammonia heat pump which then can be used to produce steam for the highest effect. The other option would be direct mechanical recompression of this vapor. The temperature levels, heat capacity and time overlap are verified in this case, if it is assured that the refrigeration cycle then provides heating to the liquid milk at lower temperature levels.

5.8 Decision

In the case study, two potential heat pumping options are shown in Figure 15 though other solutions undoubtedly exist. With many solutions, a decision-maker would be required to filter the options based on their own criteria, given insights into the relevant key performance indicators of each. With only two solutions, deciding between the two or to evaluate both options in more detail are viable strategies. Due to preferential elements inherent to individuals or industry, no additional guidance can be given for the remainder of the procedure.

5.9 Detailed planning

The level of detail to implement the solution for the case study would need to be explored here. This analysis has not been completed and thus the exploration of the case study cannot be taken beyond this point.

6 Conclusions

The main motivation for this report was drawn from the previous Annex 35 Task 2 report, concluding that wide-scale employment of models and tools for industrial heat pump integration is inhibited by the complexity and specific training required for the use of most available tools as well as the theoretical principles behind them. Therefore, four main points were identified which needed clarification and dissemination.

The **theoretical background** for systematic heat pump integration into industrial processes was efficiently summarized and presented in a concise manner (in Section 2). Here, it was shown that the process synthesis approach requires that internal heat recovery potential in a process should be considered before utility integration. Further, the principles of pinch analysis (PA) were introduced, providing the insight that heat pumps only bring energy savings if they can be installed across the process pinch point. Additionally, simple rules based on these concepts were presented to aid industries and practitioners in quickly determining good integration potentials for heat pumps.

Several categories of **tools** were identified in this report and a synthesis of the main features of each were summarised in a single comparative table (Section 3). The principal categories are defined as:

- **Heat pump design (HP)** being tools that aid in designing and planning heat pump systems based on selected operating conditions;
- **Pinch analysis (PA)** and **heat exchanger network (HEN) design** which are tools that aid in conducting pinch analysis of an industrial process to estimate the heat recovery potential and/or aid in planning and re-designing the heat exchanger network. In these tools, the focus is placed on process heat recovery, not on utility integration;
- **PA and heat pump integration** tools which allow to analyse the heat recovery potential through PA and heat pump integration without thermodynamic property calculations; and,
- **PA and heat pump integration with property calculations** which is similar as the previous category but including thermodynamic property calculation options inside the tool.

As a next step, an easy-to-use set of **guidelines** for practitioners was derived that can be used with or without tools and specific training (Section 4). These guidelines were explained in more detail with additional practical insights included.

Application of existing models/tools to a **real case study** based on the set of guidelines was presented in Section 5. A dairy plant was discussed, showing a great heat pump potential across the concentrated milk production unit. A preliminary heat pump design was conducted, and yielded a COP above 10, and a payback time below two years. Some open access tools were tested during the case study and insights on their use and expected results were presented.

In summary, a holistic guide for considering heat pump integration with industrial processes was presented with technical detail and insights which are relevant for many levels of plant personnel, consultants and practitioners. Additional resources are provided throughout this report to provide readers with deeper details on many aspects of the approach described herein.

7 Literature

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8 Appendix

8.1 Additional tools

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This appendix gives additional information to the report of Annex 48 Task 3, where an analysis and overview of the available tools for industrial heat pump integration is given. The appendix extends the work of Task 3 with an overview of methods and models developed within the scope of heat pump design, pinch analysis and utility integration from a broader perspective and with more focus on the heat pump cycle design and its integration with the heat sink and source. All models are developed at the Technical University of Denmark, Section of Thermal Energy, and published in scientific journals or conferences. The models are all available for use by others. Some are published on open source repositories. Below a short description of the models is given.

8.1.1 Working Domains

The concept of working domains is to identify and evaluate the feasible operation conditions of a given heat pump system when considering the temperature lifts and sink temperatures. It is originally introduced by Brunin et al. in (Brunin et al., 1997).The method defines feasibility from technical constraints of available refrigeration equipment and a requirement of a positive net present value of the investment compared to a natural gas boiler. When identified, the working domains of the assessed heat pump systems can be compared on both technical and economic performance.
The concept of working domains has been applied in three studies, with focus on high-temperature heat pumps, single-stage vapour compression systems, and ammonia-water hybrid absorption systems, respectively. The models are implemented in Engineering Equation Solver (EES) and Matlab.

- **(Ommen et al., 2015)**
  Five heat pump systems utilising natural working fluids in a single-stage vapour compression system are compared in terms of technical, thermodynamic and economic constraints. The considered natural refrigerants are: R290 (propane), R600a, R744 (CO_2) and R717 (Ammonia), where the latter utilises both low and high-pressure components. One HFC working fluid (R134a) is included in the study for a comparison of the feasibility of natural working fluids. The investigate sink temperatures varies from 40 °C to 140 °C. The feasible working domains are presented graphically, and an optimal solution is determined for each set of sink and source temperatures.

- **(Jensen et al., 2015)**
  The advantages of an ammonia-water hybrid absorption-compression heat pump (HACHP) are investigated based on the same operating conditions and technical and economic constraints as in Ommen et al.. For each operating condition, the ammonia mass fraction and circulation ratio are found by an optimisation of the net present value (NPV). The HACHP working domain is compared to the best available working domain of vapour compression heat pump with natural working fluids. This shows that the HACHP increases the temperature lifts and heat supply temperatures that are feasible to produce with a heat pump.

- **(Bergamini et al., 2019)**
  The thermodynamic performance of various High-Temperature Heat Pumps (HTHP) based on the vapor compression cycle, is compared with natural gas boilers for assessing their technical feasibility and competitiveness as future replacements. Different cycle configurations and natural refrigerants were compared on the coefficient of system performance and exergetic efficiency. The results showed that heat pumps are promising for heat production up to 180 °C. It was found that ammonia was preferred for source temperatures below 60 °C and sink temperatures below 110 °C, and that water is preferable at higher temperatures. The technical analysis revealed that compressor technologies must be further developed for making these solutions competitive.

8.1.2 Further methods/tools

HP Config, published in (Jørgensen et al., 2019)
Many system configurations of large-scale heat pumps (HP) are applicable to a district heating system. The tool analyses eight different vapour compression HP configurations, all utilizing the natural refrigerant ammonia using reciprocating compressors. The analysis focuses on the impact of the HP configuration on the COP and the needed volume flow rate i.e. compressor size. A comparison of the COP and the Lorenz efficiency was done for a combination of 12 different design conditions in terms of sink temperatures and range of different source outlet temperatures. The work is soon to be followed up with an economic comparison of the systems. The models implemented in EES.

Heat pumps with mixtures summarized in (Zühlsdorf, 2019)
Matching the temperature profiles of heat source and heat sink with the working fluid of the cycle during evaporation and condensation reduces the irreversibilities due to heat transfer and thereby increases the performance. Zeotropic working fluid mixtures experience a temperature glide during phase change. The increase in obtainable performance was found to be dependent on the specific boundary conditions. A screening procedure and a belonging model was created to identify promising working fluids for defined applications. The work is developed with a focus on evaluation and comparison on working fluids and different cycle arrangements. The screening procedure and the model has been applied to several applications, including heat recovery from a data center, heat recovery from spray drying processes and booster heat pumps in ultra-low district heating networks. The work is summarized in the Ph.D. thesis of Benjamin Zühlsdorf, and the model Matlab code is available for download at DTU figshare (Zühlsdorf et al., 2018).

HP pinch published in (Jørgensen et al., 2018).
To reach the high temperatures needed in current DH systems, the suggested HP installations become complex systems, where heat transfer between the HP cycle and the heat sink takes place at several temperature levels. With an installation consisting of two, two-stage heat pumps the installation holds 12 different heat exchangers. A study concludes that the chosen heat exchanger networks (HEN) influence the COP. The method applies pinch analysis combined with an optimization algorithm to estimate the highest attainable Coefficient of Performance (COP) with the given HP configuration at the given operating conditions. This COP can be used as a benchmark to evaluate the chosen HEN. The model is implemented in EES.
Dynamic HP model published in (Meesenburg et al., 2019a)
Large-scale heat pumps are expected to play a key role in the future energy system as flexible loads that can be used to balance the electricity grid. However, most large-scale HPs installed are designed for baseload operation and are thus not optimized with regard to dynamic behavior. A one-stage and a two-stage ammonia heat pump were modeled using Modelica, to assess the dynamic behavior and performance during load change. Results indicated that the

limiting factor for how fast the heat pumps may ramp down was condensation in the suction line. To avoid the condensation four different adaptions of the two-stage model were assessed.

Heat source and sink optimization summarized in (Pieper, 2020)
Since the characteristics of different available heat sources for heat pumps differ during the year, it may for larger areas be feasible to exploit more than one heat source. The method and developed optimization model can identify the most economical heat sources and heat sinks to supply an area for a given heating and cooling demand either directly or with a heat pump. Further, the optimal capacity of the production units, as well as the operation for each production unit, will be calculated. The model is implemented in GAMS.

COP estimation in energy planning published in (Pieper et al., 2019)
Energy planning tools often consider a constant coefficient of performance (COP) for large-scale heat pumps (HPs) over the entire year, even though the optimization is usually performed on an hourly basis. In this study, four methods for COP estimations were compared to a detailed calculation of the COP with a thermodynamic HP model. The four considered methods: constant COP, constant Lorenz efficiency, constant exergy efficiency and the method by Jensen et al. mentioned in the two studies above. The comparison was carried out for four heat sources all with yearly variation in temperature. The results show that the Jensen COP estimation method for design conditions provide good approximations compared to a thermodynamic HP model. The results indicate that this method is suitable for the use in energy planning tools. Assuming a constant Lorenz efficiency, constant exergy efficiency or constant COP over the year resulted in large deviations in COP, especially when the operating conditions differ considerably from the design conditions. The model is available as GAMS Code.

Economic feasibility of ultra-low temperature district heating systems by Wiebke Meesenburg published in (Meesenburg et al., 2019b)
Future district heating systems are expected to supply lower temperatures to increase system efficiency, exploit renewable heat sources and be an integrated part of the energy system.
The economic feasibility of three ultra-low temperature district heating (ULTDH) concepts was compared to low-temperature district heating (LTDH), to answer whether it is beneficial to lower district heating temperatures below the level where it is still possible to supply domestic hot water directly. The scope was limited to newly developed district heating networks in Denmark supplied by central heat pump units. To assess the economic feasibility of district heating variants the excel-based district heating assessment tool, published by the Danish Energy Agency, was extended to represent the assessed technologies. The economic feasibility of different DH solutions was compared based on the levelised cost of heat and socioeconomic net present value and evaluated for different central units, building plot ratios and specific space heating demands of the buildings. The tool is available as an Excel spreadsheet.

Smart energy system by Torben Ommen published in (Ommen, 2015).
A detailed system model developed for calculation of the economic and environmental impact of integrating heat pumps in an energy system with a high share of CHP-plants and intermittent electricity production from renewable technologies, e.g. wind turbines. The model is a validated heat and power system model, which features a detailed representation of CHP technology as well as a detailed representation of different heat pump technologies and integration possibilities. The model is implemented in GAMS.

8.1.3 Literature

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8.2 Integration guidelines

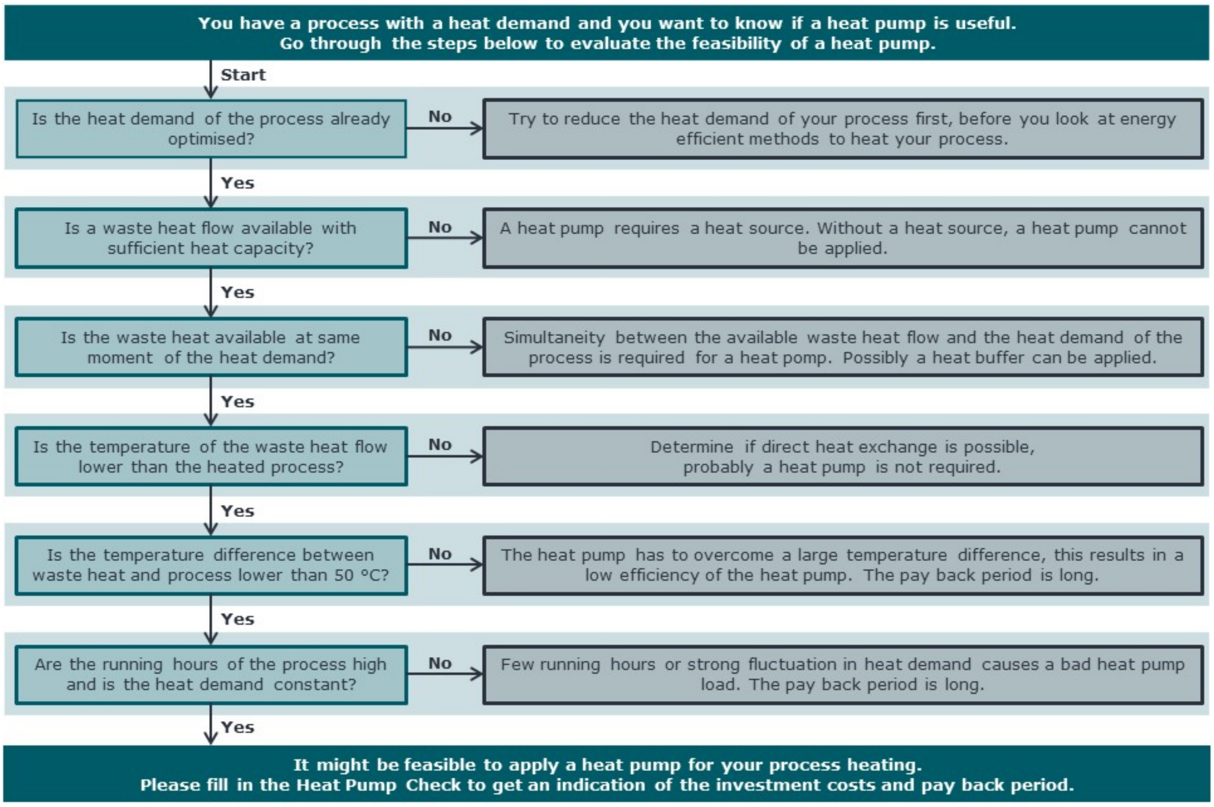

Figure 17 Questionnaire from the feasibility check website for industrial heat pumps [37].

Bastian Schmitt

The effort for identification of suitable integration points for solar heat as well as the number and complexity of possible integration points can vary significantly between industrial sectors and individual factories. To assist with the necessary steps for a feasibility assessment, the methodology illustrated in Figure 4-1 can be used. This methodology can be divided into three main parts: pre-feasibility assessment (steps 1 and 2), feasibility study (steps 3 to 7) and decision/further activities (steps 8 and 9). In the following, the single steps are briefly described.

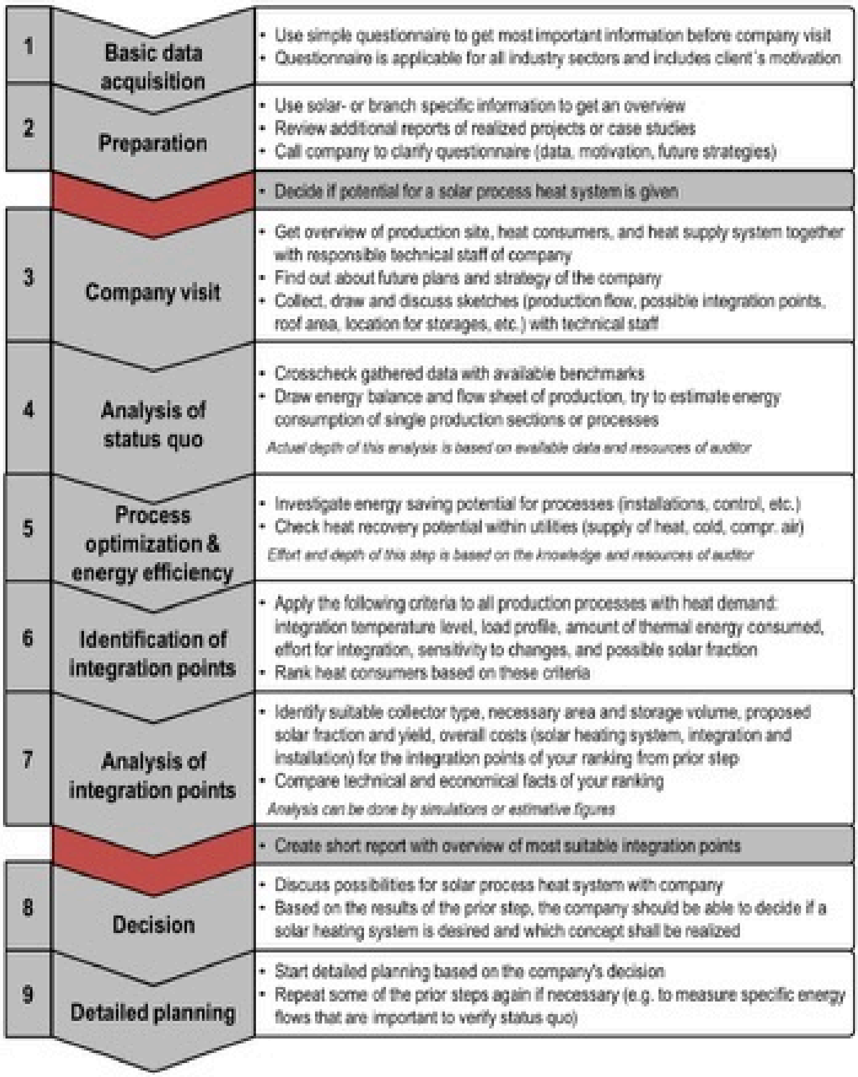

Figure 18 From IEA SHC Task 49 - Integration Guideline [49] for solar process heat.