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Thermal profile construction for energy-intensive industrial sectors

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Abstract:

Industrial plant data are difficult to find in academic literature for a number of reasons such as confidentiality, and thus intentional masking, or problem size reduction. These common practices limit the ability of researchers to apply novel methods to real cases and understand energy consumption of real industrial plant instances. This is especially pertinent in the field of process integration, as realistic representations of real processes form the basis for the application of novel technologies. Few efforts have been made in this area [1, 2] demonstrating the added value of these profiles; thus, a clear methodology is required for constructing such energy consumption profiles. The method proposed in this work defines an approach for constructing the heat profiles of major industries in a generic way. Parameterized models of several major European industries are presented for defining specific production/plant instances based on contextual specificities to represent different production pathways. The profile construction methodology is described for several situations of data access. Confidentiality issues are addressed by different anonymization techniques such as aggregation, statistical treatment, or by using data which are already publicly available. In this work, data were gathered from real plant operations and validated at higher levels using public information. Although the potential applications and implications of these profiles are clear, two cases are presented to exhibit adaptation of the parameterized models to specific instances and profile use for process integration problems. Varying the model parameters represents different plant instances and thus yield different integration solutions for the major process industries included in this work.

Keywords:

Industry, pinch analysis, composite curves, process, generalization, mixed integer linear programming, process integration, heat integration, industrial symbiosis, generic profile, eco-industrial network

1. Introduction

Heat generation and utilization accounts for approximately 25% of energy consumption among European industries and is particularly relevant in major and fundamental process industries such as refining and production of steel and cement. In some industries, process heating can account for 95% of total consumption, depending on the technology employed [3]. Heat integration within and between processes forms the basis of efficient plant design in many industries. Expanding the scope beyond plant design to consider inter-plant integration—one concept captured by industrial symbiosis—requires understanding and representation of heating and cooling requirements in neighboring industries. Generic thermal profiles for energy-intensive industries therefore provide several elements with high impact in both academic and industrial settings:

1. Understanding the minimum heating and cooling requirements of process industries provides energy targets and benchmarks. While these benchmarks are often difficult to reach practically, they provide an indication of the current operating efficiency relative to the maximum energy recovery (MER), and potential improvements toward this goal.

2. Providing opportunities for academics to apply novel process integration methods on realistic cases.
3. Providing a means of communication between industries to enable industrial symbiosis, circular economy and efficient use of resources between industries. This requires communication of concepts between industries which are unfamiliar with each other; thus, generic thermal profiles are an initial step to communicate basic process information without disclosing sensitive or confidential data.

Composite curves with heat integration, and not the state of the art, are presented in this paper as heat integration measures should first be realized within plants before considering interfaces with others. This encourages internal targeting and optimization within sites with the express objective of improving internal heat recovery and integration before considering external connections. This promotes the idea that industries should not 'sell their inefficiency' (excess heat) but rather should maximize the internal opportunities and then seek synergistic opportunities with other processes/industries. This work presents a step-by-step method for generation of generic thermal sector profiles for a variety of energy-intensive industries adapted to varying degrees of available data. It further demonstrates the benefits of such profiles for pre-feasibility assessment of inter- and intra-sectoral symbiosis and energy saving measures.

2. Methodology

2.1. General methodology

Creating heat profiles for energy-intensive process industries requires a systematic methodology to ensure that practitioners use consistent approaches to define models which can then be validated and reused by others. Thermal profiles in this work are presented using composite curves which are one component of pinch analysis, commonly used in industry and academia to assess potentials for industrial heat integration. Composite curves provide a description of the process requirements in terms of heat loads and temperatures found within the process. Further information on composite curves and pinch analysis can be found in the literature [4–8].

Top-down and bottom-up approaches can both be used for constructing generic thermal profiles and both approaches are briefly discussed in the following sections. The choice between the two approaches depends on data access, where a bottom-up approach is preferred when detailed process data are available and the top-down approach can be used in their absence. Figure 1 depicts an overview of the methodology followed in this study, covering both thermal profile (model) construction and generation of integration cases. The individual steps are detailed in the noted sections. Regardless of the approach used, thermal profiles are constructed by reducing the heat demand for each process to specific requirements (based on feedstock or product flowrate) and related to the stream temperature and heat load requirements. Process modularization is completed by identification of the major transformative steps and their associated boundaries, thus resulting in a set of modules (sub-processes) which are stored in a *modelbase*. Scaling production volumes and combining modules according to existing or prospective scenarios enables creation of representative thermal profiles of plants, sectors and combined sectors. This flexible approach enables generic representation of existing plant configurations and exploration of potential integration opportunities within and between plants or sectors.

2.2. Definition of process boundaries

Defining process unit or sub-unit boundaries is important for the generic process description which presents the input and output flows as interfaces for integration. The process boundaries for generic heat profile construction should be drawn around the elements which contribute to a major transformative step in the process while all streams and equipment contributing to this transformation are included. Since the thermal requirements for units are defined in specific terms (i.e. per mass of

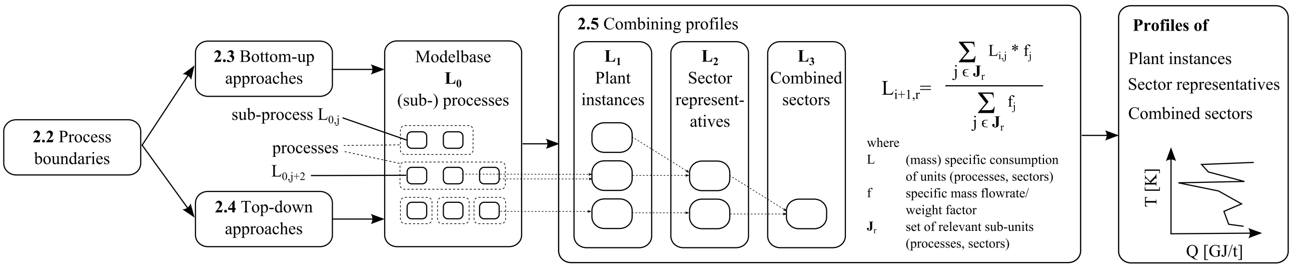

Fig. 1. Methodology for thermal profile generation and use

feedstock or product), the main stream which is processed or produced should be used as the reference. Definition of boundaries requires engineering experience and process knowledge. Several examples of such a selection are presented in Section 3 where the boundaries between sub-processes are identified in the block diagrams.

2.3. Bottom-up approach

Bottom-up approaches rely on gathering primary data from functioning plants in the pertinent industrial sector. The profiles are intended to capture a generic profile and thus care must be taken to differentiate specificities of individual plants from typical operations. Ideally, many individual plants provide data which permit identification of the ubiquitous process units in the sector. Analysis and use of data from a single plant can also be used, though the practitioner should be familiar with the sector to assess whether the single plant is representative of the sector. Data gathering efforts initially focus on understanding the process operation, identification of the main transformative steps, identification of the main energy consuming units and finally collecting the pertinent data. The steps proposed here build from previous work in total site analysis [9]. When data are available for this approach, profile construction should be guided by the following steps:

- Understand the overall process and major transformations which occur.
- Decompose the process into useful sub-processes (modules, see Section 2.2).
- For large/complex plants, identify the main energy consumers within sub-processes [10].
- Identify thermodynamic requirements (temperature levels, flowrates, heat loads) of the main energy consumers from measurements and using data reconciliation [1] when possible, or available published data.
- If thermodynamic requirements cannot be identified, use utility data (as last option).
- Perform data treatment:
  - If data from multiple plants are available: average/nominal requirements should be used.
  - If data are confidential, apply anonymization techniques.
- Normalize energy requirements using mass flowrates to obtain specific requirements for the basis unit considered.
- Construct the model using the identified temperatures and mass-normalized enthalpies (adding enthalpy differences in temperature intervals).
- Verify the model obtained with high-level data sources such as the best available techniques (BAT)/best available techniques reference documents (BREFs) documents published by the European Commission [11], or other reliable data sources. The verified model can be added to the modelbase.

2.4. Top-down approach

Top-down approaches are also valid for construction of thermal profiles and should yield a similar result, though the deep details accessible for plant operators cannot be leveraged. High-level data such as the BAT/BREF documents from the European Commission [11] serve as a starting point and provide some process details, depending on which sector is being assessed. When data from real plants are not available, the top-down approach can be used to construct a generic profile using the following steps:

- Understand the overall process and major transformations which occur.
- Identify the main energy consumers.
- Decompose the main *energy consuming* processes into useful sub-modules (see Section 2.2).
- Understand the functions of each main consuming process.
- From reference textbooks, technical reports and other public documents, define the process requirements for each process in terms of temperature levels, heat loads and mass flowrates.
- Normalization, model construction, verification and addition to the modelbase can be completed as in Section 2.3.

2.5. Combining profiles

Construction of generic thermal profiles for major process industries is intended to provide insight into typical operations of the industry and the requirements (or excess) heating and cooling therein. Once available, instances of plants can be constructed by combining sub-processes according to the mass flowrates and the requirements of each sub-process. Thermal profiles of the sector can thus be generated by combining the plant instances which represent the facilities in a specific sector or by amalgamating the respective sub-processes in the correct quantities as indicated in Fig. 1. Combinations of sectors, toward concepts of industrial symbiosis through sharing of thermal resources, can be analyzed by combining plant instances from different sectors or sector representative profiles. The potential for heat integration between disparate sectors can thus be estimated for any sectors which are represented in the modelbase. The following section presents thermal profiles for a refinery, cement plant and modularized dairy process as representatives in their respective sectors.

3. Industrial heat profiles

3.1. Refinery

While often considered to be within the chemical industry, refining of crude oil represents a basic and energy-intensive process within the broader array of chemical processes. Thus, the thermal profile for refining is presented here as a fundamental building block within the chemical industry. The product slate from the chemical sector is extremely varied and thus additional efforts are required in the future to construct representations for the remaining and highly-varied production processes in this sector.

Figure 2, adapted from [1] depicts the main processes in a typical refinery. Each sub-process in the refinery performs a specific separation or conversion function to yield a single, or specific mixture

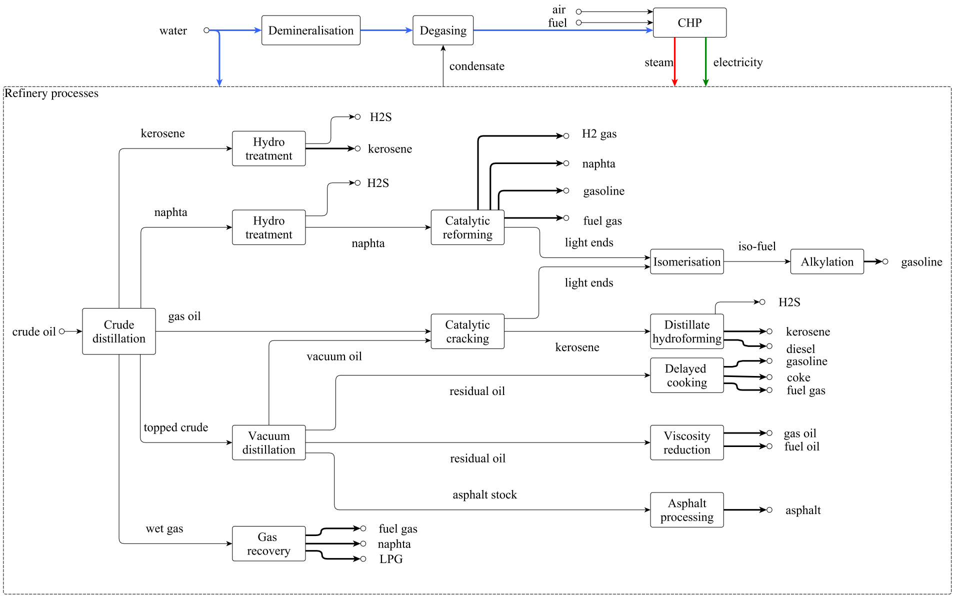

Fig. 2. Simplified representation of refinery operations, indicating principle sub-processes

of, hydrocarbon compounds. The first sub-process, the crude distillation is the most important and energy-consuming part of the refinery. Crude oil is heated to coarsely separate the component hydrocarbons in the first step of the refinery, crude distillation. Since the products of crude distillation feed the other processes and the boiling points of compounds within the crude oil cover a broad spectrum from low (<30°C) to high temperatures (>400°C). Information on the various refinery sub-processes can be found in the many literature references on the subject of oil refining.

In most refinery processes, heating is required to evaporate the bottom streams of the distillation columns (in separation units) or to increase the temperature of the reactants to reach the reaction temperature (in conversion units). Likewise, cooling is required to condense the overhead streams of distillation columns and cool product streams. Typical refinery sites employ combined heat and power (CHP) units to co-generate heat and electricity. Heat is then distributed to the plant through a steam network while electricity is distributed throughout the refinery to drive overhead aerocoolers, pumps and compressors.

The thermal profile for heat-integrated refining operations is shown in Fig. 3 which demonstrates the most efficient thermal operation of a refinery with the maximum amount of heat recovery between processes. State-of-the-art refineries practice heat integration to some degree as the primary operating cost is fuel self-consumption/purchase to produce the heat required for the various sub-processes. The theoretical minima of hot and cold utility consumptions for refinery operations are shown to be 0.88 GJ/t and 0.99 GJ/t of crude oil input, respectively. Most of the heat must be supplied at moderate to high temperatures (200 - 600°C) with excess heat being exhausted at low temperature.

The profile was constructed using the bottom-up approach and verified using high-level data as discussed in Section 2.3. Plant data from multiple refineries were gathered, focusing on the major heating and cooling demands in each refinery unit. The refinery thermal profile was first published in [1, 12] and was subsequently improved by adding data over time to result in the more recent iterations found here and in [2].

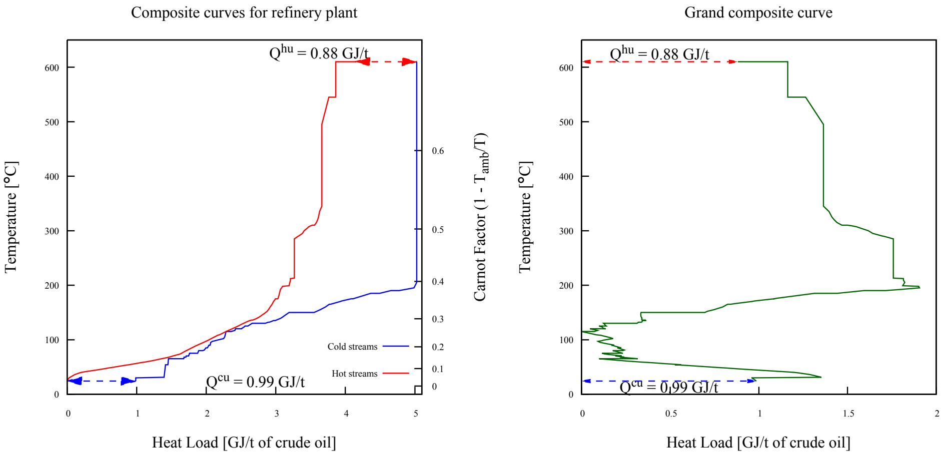

Fig. 3. Composite curves of a heat-integrated refinery

3.2. Food and Beverage – Dairy

Within the food and beverage sector, as with the chemical industry, the production slate is very wide and almost impossible to comprehensively model. As with the definition of process boundaries, the major products within the sector must be defined so as to pragmatically construct a sufficient representation. For highly-varied production sectors such as this, advantage can be gained by understanding common production processes (regardless of the products) and using key stream parameters such as heat of vaporisation, specific heat and flowrate to vary the profile. Common processes such as concentration, cooking, and dehydration show similar thermal profiles, regardless of the product, and thus could be used as analogs between products to construct approximate profiles from these elementary modules. Several dairy processes are detailed in this work, though a comprehensive profile library for the food and beverage sector would permit greater exploration of the potential for intra- and inter-site integration and optimization.

The dairy industry concerns all conversion processes of raw milk into milk-based products. Figure 4 indicates the two primary conversion routes in the dairy sector, which are production of cheese and production of fresh dairy products such a yogurt and butter. During both cheese and fresh dairy production, raw milk is initially centrifuged to produce cream and skimmed milk. In cheese production, rennet is combined with milk to initiate curdling. The resulting curds may further be merged with cream, followed by forming, refining and packaging. The generated whey is dried and exported as a co-product.

Some fresh dairy products are created from cream, such as butter, while others are manufactured from skimmed milk, such as milk powder/concentrated milk, ultra-high temperature (UHT) milk, and most types of yogurt and desserts. The main conversion steps involve heating, mixing, and refrigeration.

Production of iced cream is treated separately since it requires a variety of ingredients. The main steps involve homogenization and pasteurization, followed by aging and freezing.

Each dairy product has different thermal requirements as indicated by the average consumption in EU dairies shown in Table 1. Typical dairy plants combine several processes mentioned here in varying quantities based on plant structure and market demand. Therefore, representing a single, generic sector representative dairy plant is rendered impossible by variable production ratios. The thermal profile for each product is thus presented separately in Fig. 5 and can be combined to reflect any plant instance. The modular representation provided herein could also be used to optimize the design of an integrated dairy process, setting production rates to efficiently reuse heat between the production units. The main routes considered in this work are based on previous studies [13, 14], which were derived from industry data in addition to reference documents for the best available techniques in the food, drink and milk industry [15]. Thus, the profile is constructed using a bottom-up approach augmented using high-level data from other sources.

Table 1. Average consumption values in EU dairies ([15], 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

3.3. Cement

In cement production, lime- or calcium silicate-based minerals are major constituents for cement and enter the process by passing through phases of drying and grinding. The thermal energy requirement for drying is typically supplied by the hot gases recovered downstream. Thus, the raw materials are transformed into powder with low relative humidity as feed for the clinkerization reaction.

Production of clinker is the key process in cement production and current production is often completed in two successive processes of pre-calcination and pyro-processing. Pre-calcination consists of heating the raw material from 50 °C to 850 °C, at which temperature the calcination reaction takes place converting the calcium carbonate ($CaCO_3$) into calcium oxide (CaO) and CO_2. The calcined material is then heated to 1450 °C in the pyro-process (kiln), producing clinker. In both sub-processes, the thermal requirement is satisfied by external fuel input which ranges from conventional fuels such as coal, to dry sewage sludge and fuels derived from by-products or wastes of municipal or industrial processes. Electricity is used throughout the plant to drive the mills and kiln, to run blowers connected to the milling units and the systems for clinker transportation and crushing. A simplified diagram of the process is shown in Fig. 6

As mentioned previously, some level of heat integration is already common in the cement industry, facilitated by the high reaction temperature for clinker formation allowing heat exchange from clinker cooling and exhaust gases to the other processes. The cement heat profile therefore yields a

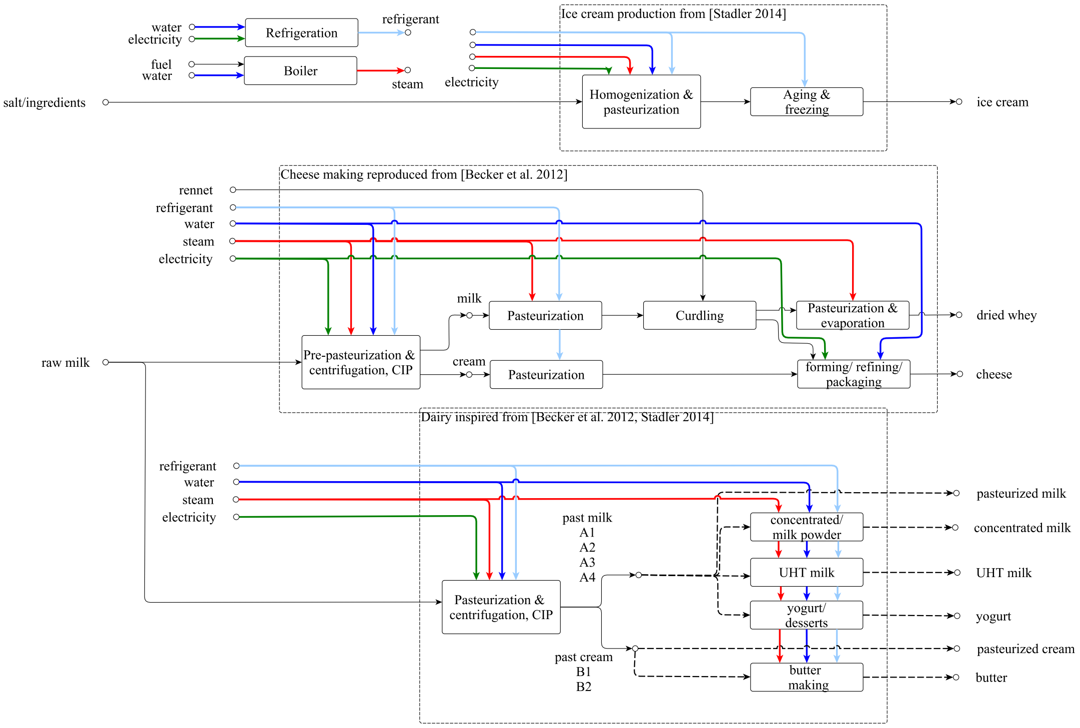

Fig. 4. Flowchart of the dairy industry, adapted from [13, 14]

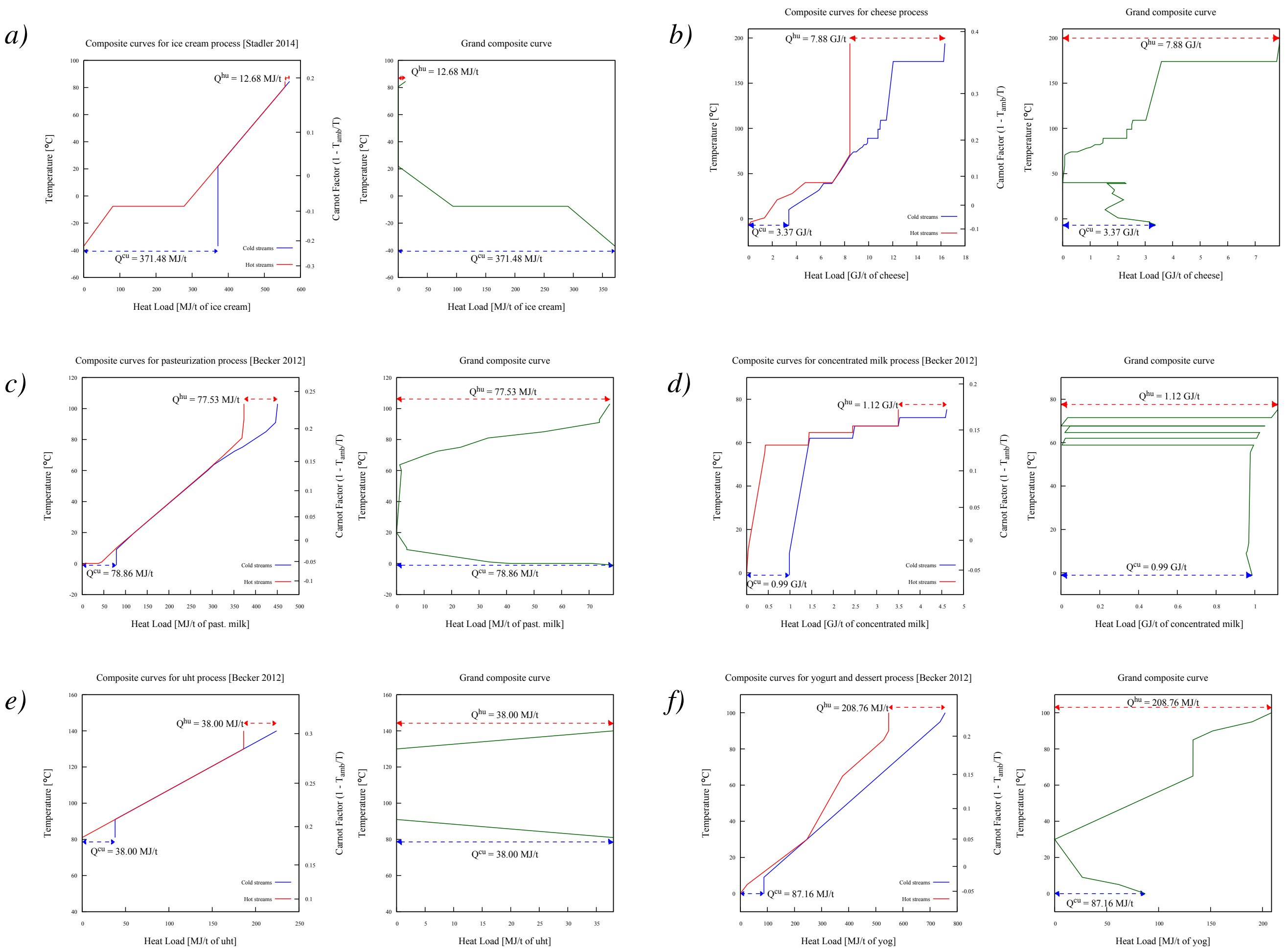

Fig. 5. Composite curves of heat-integrated dairy processes: a) Iced cream, b) Cheese, c) Pasteurisation, d) Concentration, e) Ultra-high temperature milk, f) Yogurt

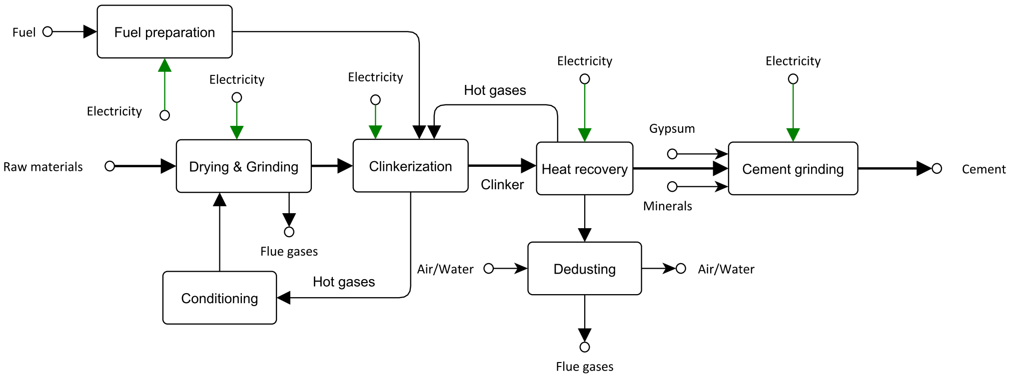

Fig. 6. Simplified representation of cement production, indicating the main sub-processes

threshold problem which encourages few opportunities for improvement on the state of the art, when considering integration within the plant itself. However, large quantities of waste heat available at moderate temperatures, as seen in Fig. 7, provide exploitation opportunities for process integration and industrial symbiosis.

The cement profile was constructed using a bottom-up approach, collecting data from several European sites to identify the major generic processes and energy consumers. Additional verification was provided by comparison with published studies [16–18] to ensure coherence with accepted practices regarding cement production.

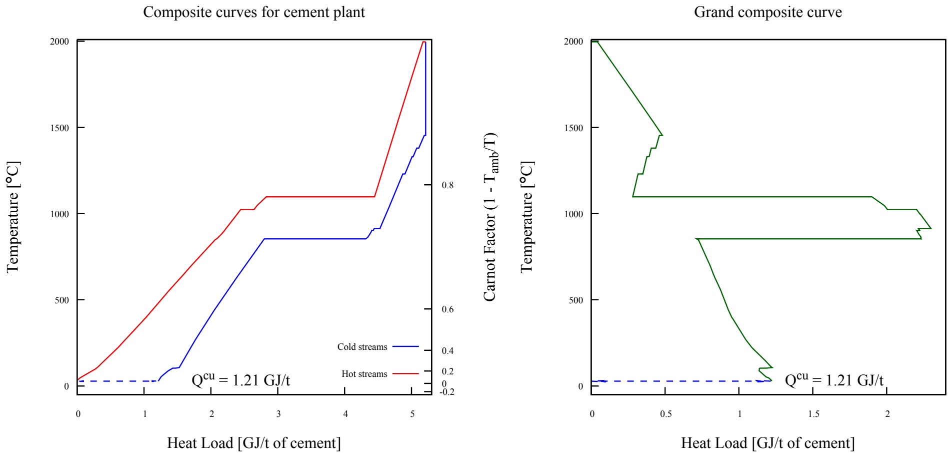

Fig. 7. Composite curves of a heat-integrated cement plant

4. Applications

4.1. Combining production: generation of plant instances

Typically-coupled production, especially from a single feedstock, requires the combination of individual processes to more closely represent the realistic state of a production facility. In doing so, a different representation of the thermal profile is created, based on the productivity of the component processes. Various production combinations related to internal and external influences thus change the representation, and therefore the integration options for a sector representative. To illustrate this point, the components of a combined dairy facility presented in Section 3.2 are combined with a different production slate and the resulting thermal profiles are shown in Fig. 8. Typical production ratios were used to define two scenarios for exhibiting this application; the first based on the EU consumption mix shown in Table 1, and the second on the original plant instance [14]. This illustrates the differences from varying the components and production volumes when creating profiles for different plant instances.

4.2. Inter-sectoral (industrial) symbiosis

In addition to the exploration of possibilities within processes, integration between sectors exhibits the synergistic matches between profiles which yield overall improvement in the energy efficiency of the system, maximizing the utility of the heat provided. An example of heat integration between industries is provided here to show the potential applications for exploring these possibilities. Synergistic process couples already exist in some sectors, though commonly based on material integration, such as ammonia/urea or refinery/petrochemical clusters. Industrial symbiosis activities are also initiated or built on these bases such as in [20, 21]. Energy, and especially heat, were historically inexpensive; as such, the potential for thermal integration between disparate processes received little attention. The focus in this work is on construction of realistic thermal profiles which have broad applications such as representing the thermal potentials within processes and the interfaces to integrate with others. As an example of the latter, the cement industry from Section 3.3 is combined with that of the refinery from Section 3.1. The thermal profile of a combined refining/cement-making operation is shown in Fig. 9. The potential for integrating heat between the processes is logical since the cement process has excess heat available above the refinery pinch temperature. As such, the thermodynamic potential of integrating the two processes is considerable, with the cement production capable of supplying most of the refinery's heating requirements. The minimum cold utility requirement for cement production

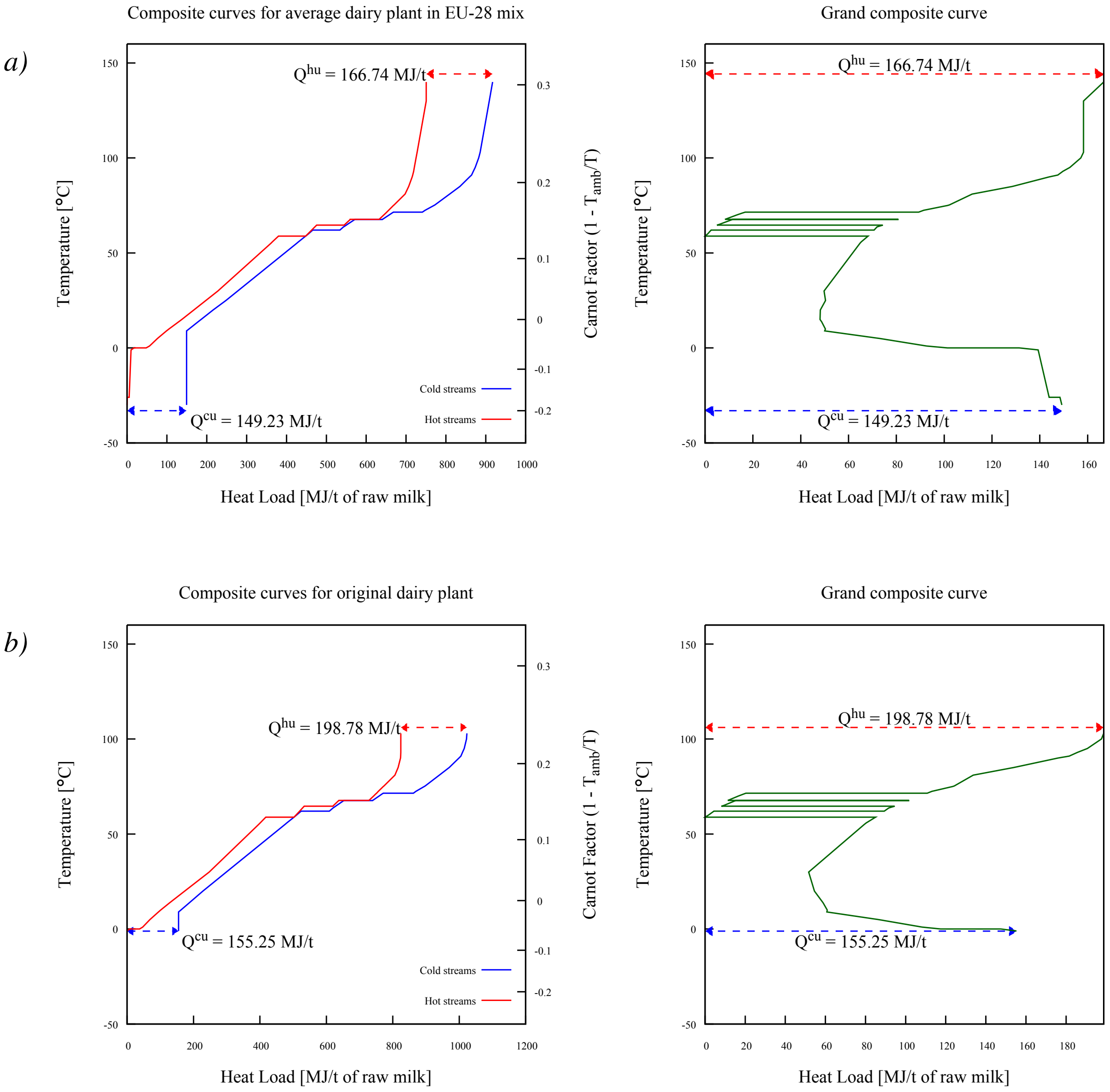

Fig. 8. Composite curves of a heat-integrated dairy with a) plant instance representing the EU consumption mix and b) original plant instance. Data from Table 2 and Figure 4

Table 2. EU average plant instance, mass fractions and flowrates

Process	Inlet	Fraction %	Outlet	Fraction %	Mass flow rate $kg_{product}/s$
past., centri. & CIP	raw milk	100	past. milk	89	8.9
			past. cream	11	1.1
A1	past. milk	25	past. milk	100	2.23
A2	past. milk	18	conc. milk	43	0.69
A3	past. milk	25	UHT milk	100	2.23
A4	past. milk	32	Yog. & dess.	100	2.85
B1	past. cream	31	past. cream	100	0.341
B2	past. cream	69	butter	100	0.759

European milk consumption from [19], 2015: cheese 36%, butter 29%, cream 13%, drinking milk 11%, milk powder 4%, fresh products 7%;(*) Assumption: 50% of drinking milk is UHT
Original plant [14] cheese 0%, butter 0%, cream 11 %, drinking milk 14%, milk powder 20%, fresh products 55%

was reported in Section 3.3 to be 1.21 GJ/t and the minimum hot and cold utility requirements for the refinery were reported in Section 3.1 as 0.88 GJ/t and 0.99 GJ/t, respectively. The standalone hot and cold utility consumptions would therefore total 0.88 GJ/t and 2.2 GJ/t, respectively. Combination of the profiles shows elimination of the hot utility and the combined cold utility requirement reduced to 1.32 GJ/t with the equivalent production. Technical problems such as how to recover and transfer heat between the two processes are not solved by such an approach but incentivized process industries may embark on the steps to explore such options, given the large potential.

4.3. Process integration applied to a sector representative

The purpose behind constructing generic thermal profiles for major industrial sectors is to explore opportunities to integrate the thermal requirements within plants and processes to ensure the maximum energy utilization. Thus, by representing processes in a generic way, opportunities for integration within and between plants/sectors can be discovered. Using the dairy industry from Section 3.2 with the heat pump superstructure published in [22, 23] yields the optimal heat pump integration for the sector representative.

Utility integration for an average EU dairy plant instance described in Section 4.2 was conducted. The MER case with standard utility integration (boiler, cooling water, standard refrigeration cycle [24]) was compared to an improved case with options of a heat pump superstructure [22, 23, 25]. The results indicate the optimal utility integration includes additional mechanical vapor re-compression and heat pumping as shown in Section 3. Using a sector representative profile of a dairy plant therefore yields generic opportunities in the sector. If many typical operations are consistent with the generic profile, specific heat pump configurations can be used as solutions for improving the energy efficiency of dairy production. Table 3 shows the results of heat pump integration compared to the MER case with standard utility integration for a dairy plant instance representing the average EU production mix

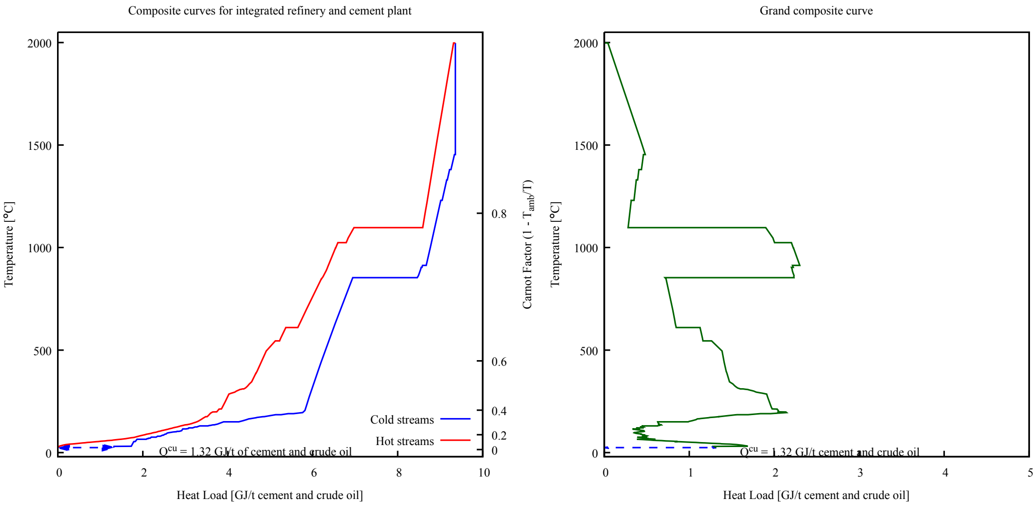

Fig. 9. Composite curves for refinery and cement combined production

(thus a sector representative). The heat pump superstructure applied on this profile yields a 42.3% decrease in natural gas consumption and a 36.6% decrease in cooling water consumption at the cost of increasing the electricity consumption by 33.6%. The total annualized cost of this solution was found to be less than the MER case which already realized internal heat integration possibilities. From the analysis with a sector representative, the potential for heat pumping in the dairy industry is clear and warrants further investigation on specific installations.

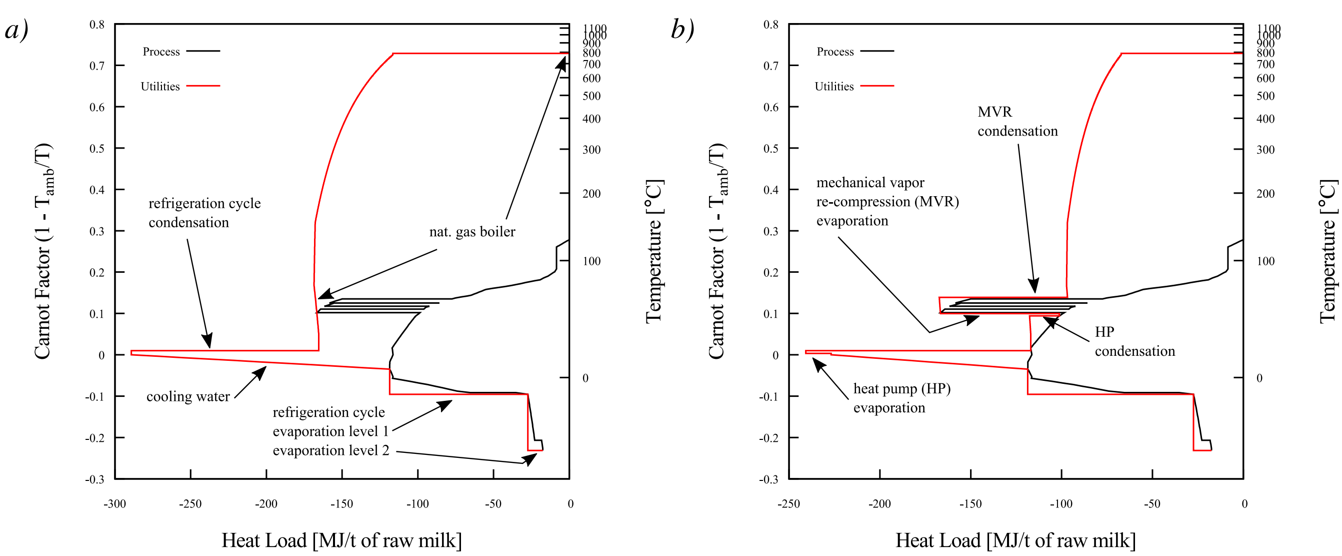

Fig. 10. EU average plant instance with utility integration a) MER and utility integration (UT), b) Heat pump superstructure (HPS)

Table 3. Results of heat pump integration to EU average dairy plant.

	Electricity \$/y	Natural gas \$/y	Cooling water \$/y	Compressors \$/y	ΔHEN \$/y	TAC \$/y
MER & utility integration (UT)	69 270	309 330	29 380	0	0	407 980
Heat pump superstructure (HPS) [22, 23, 25]	92 580 (+34 %)	178 500 (-42 %)	18 640 (-37 %)	27 660	60 060	377 440 (-7.5%)

UT assumed to represent a real plant, based on comparison with real plant data of a different configuration and adaptation of the ΔT_{min} = 5 K, [14, 23]; Reference utilities:[24] Electricity price 0.122 \$/kWh, nat. gas price 0.068 \$/kWh, operating time 2500 h, annualization factor 0.13; Compressor installed cost $1.33 \cdot 1.5 \cdot 1500 \cdot 160^{0}.1 \cdot (E_{comp}[kW])^{0.9}$ [\$ 2010, \$/€exchange rate 2010: 1.33]; HEN installed cost estimation Taal et al. [26] ([27]), CS-SS $\left(8500 + 409 \cdot (A/N)^{0.85}\right) \cdot N$ [\$ 2003], where A and N are the total estimated area and number of connections, respectively; HEN: retrofit estimation, ΔHEN = $\mathrm{HEN_{HPS}}$ - $\mathrm{HEN_{UT}}$; All cost functions are updated with the CEPCI

5. Conclusions and outlook

A methodology for constructing thermal profiles of process industries is presented as a solution for several academic and industrial barriers. Construction of realistic and generic thermal profiles of major process industries enables application of process integration methods in realistic settings, defines energy targets for industry and provides a common vocabulary and platform for communication between industries.

This method was applied to construct thermal profiles in several industrial sectors and the application/utilization of these profiles was demonstrated by showing flexible construction for processes with varying production pathways, thermal integration potential of disparate processes and process integration within an industry to identify generic process improvements.

This approach therefore enables generation and use of typical industrial profiles which permit the exploration of integration opportunities within and between major process industries. Process integration applications within a sector representative dairy operation showed improvement in the total annualized cost of production and reduction in energy consumption by considering a heat pump superstructure, increasing the electricity consumption by 33.6% to reduce the hot and cold utilities by 42.3% and 36.6%, respectively. Theoretical heat integration between the cement and refining profiles showed elimination of hot utilities and improvement in cold utility consumption by 0.9 GJ/t compared to MER representations of the two independent operations.

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