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Heat integration in processes with diverse production lines: A comprehensive framework and an application in food industry

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HIGHLIGHTS

- A new practical heat integration framework was developed for complex and diverse production lines.
- Heat recovery was maximised by direct and indirect heat integration at zonal and factory levels.
- A novel approach to stream data extraction was proposed to account for both stream capacity and availability.
- A case study was carried out on a multi-product confectionery factory.

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ABSTRACT

Heat integration is a key measure to improving energy efficiency and maximising heat recovery. Since the advent of Pinch analysis in the 1980s, direct and indirect integration approaches have developed in separate domains with very few examples where both approaches are utilised together to maximise heat recovery. This paper presents a novel decision-making framework for heat integration in complex and diverse production lines, with the aim to provide the user with a step-by-step guide to evaluate all heat recovery opportunities through a combination of direct and indirect heat integration. This framework involves analysis at both the zonal level and the factory level. The proposed framework was applied to a case study based on a confectionery factory in the UK that manufactured multiple products across a diverse range of food technologies. It demonstrates that the framework can effectively identify the significant streams to be considered in the heat integration analysis, and address practical factors such as diverse production times, geographical proximity, and potential of compromise to product quality when the direct and indirect heat integration opportunities are proposed and assessed both within and between production zones. This practical framework has the potential to benefit the wider food industry and beyond.

1. Introduction

The rise in industrial energy prices over the past decade [1] and interest in environmental sustainability has seen many food manufacturers – the largest manufacturing sector in the UK – focusing on energy reduction as a top priority [2]. The food industry, with 9340 food factories in the UK, is a major energy user accounting to about 14% of energy consumption by UK businesses [3,4]. While this represents a rather significant proportion of industrial energy use, improving the energy efficiency of food factories can be a complicated endeavour given the diversity of the food products manufactured and the technologies employed.

The food industry is a broad sector that manufactures a wide range of products that can be categorised [5], for example dairy, cereals, confectionery, fish, eggs, soups, beverages, food supplements, fruits and vegetables. Taking the confectionery category as an example, there are a range of product types that form this category, for example, chocolate, cocoa powder, hard and soft candy, nougats, marzipans, and chewing gum. For each product type, there are a number of specialised food processing technologies,

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such as ovens, cookers, dryers, and extruders that form part of a process chain that also includes machines for example conveyors, screw feeders, pumps, and packaging equipment, which together are called a production line within a factory. A single factory may contain multiple production lines for a product category or, in some rare cases, multiple product categories. The diversity of production lines, production and operation type can vary which is dependent on the factory, company and the business models for different products (e.g. core or seasonal production; batch, continuous or semi-continuous operation). As a result, the energy profiles vary not only at a factory-level but across the different product categories. Furthermore, any energy efficiency considerations for a food factory will have to be made within limits imposed to product quality and safety [6]. Developing an effective approach to improving the energy efficiency of such processes will not only be significant for the food industry but also for other sectors sharing similar attributes, such as the pharmaceutical industry.

There are various options open to food processing factories to enhance their energy efficiency, including, of course, major investment in energy saving machinery. But such major investment is often prohibitive, especially because it could result in a loss of production as the new equipment is installed and operators trained. Heat recovery by heat integration known as Pinch analysis [6] is another key measure that can be taken to improving energy efficiency by a combination of direct and indirect approaches. Since the advent of Pinch analysis during the 1980s, the research field of energy integration has addressed both continuous and batch processes using the dominant mode of evaluating heat recovery opportunities via superstructure-based optimised Heat Exchanger Network (HEN) model by mathematical programming [8–13] rather than graphical techniques [7,14–16]. The mathematical programming based approach has major practical limitations for users in industry who are not necessarily equipped with adequate knowledge of the mathematical techniques and/or the software. As a result, the more common approach in practice is based on the use of graphical techniques for carrying out Pinch analysis and design, which are often applied for targeted areas in a factory that focuses on either direct or indirect heat exchange by first building the data bottom-up at a process-level; several heat integration studies have demonstrated energy savings of 10–45% from process retrofitting [7,17–21]. Outside the food industry, Pinch analysis has been applied at a total site scale [22] for the steel, chemicals and petroleum sectors [23–25]. Despite these achievements, the food processing industry has not been forthcoming to use such an approach at both a targeted area and factory level primarily due to [26–29]:

(1) Low financial returns that can be gained from capturing low grade heat (typically 50–140 °C).
(2) Diverse thermodynamic profiles from different food categories.
(3) Material quality compromise due to the involvement of thermally sensitive or hazardous streams, and integration of intrusive technologies.
(4) Non-continuous (i.e. batch or semi-continuous) operation.
(5) High levels of fouling and complex rheologies of many process streams.
(6) Narrow process conditions range, for example tight temperature control due to material quality compromise.
(7) Small number of streams available for heat integration.
(8) Integration complexity that can result from diverse production lines and elaborate heat exchanger networks.
(9) Seasonal operation resulting from different business models for different product types.
(10) Lack of data and understanding, including inadequate knowledge of energy profiles of different production lines.
(11) Lack of resource (e.g. time, people, finance) to conduct a factory-wide heat integration assessment.

While acknowledging these challenges, there are nonetheless significant opportunities for the food processing industry to improve energy efficiency, reduce costs and Greenhouse Gas (GHG) emissions and optimise heat recovery systems by applying heat integration as a retrofit for mature factories. This is because historically food factories on the whole have not systematically searched for heat recovery opportunities at a factory-wide level encompassing multiple production and utility areas. Instead, a more common practice has been to focus directly upon targeted areas in the factory where heat recovery is perceived to be the highest [18]. However, this does not provide a holistic assessment of heat recovery options. Pinch analysis, on the other hand, has obstacles in practice that include the following:

(1) it requires the collection of a large amount of data e.g. mass and energy flows that depends on the scale and complexity of the industrial system being investigated;
(2) it requires reliable and accurate stream data extraction to conduct a high-quality pinch study;
(3) the study can be laborious and time consuming;
(4) analysis requires expert knowledge and judgements;
(5) it has been predominantly applied for continuous operations with direct heat exchange; and
(6) there is a lack of clarity, rationality and procedure in handling a mixture of direct and indirect heat exchanges in complex and diverse factories.

The research described here sought to address these challenges by investigating the scope and practicality of heat integration within and between production areas that are complex and diverse. It aimed to develop a clear, rational and practical pinch analysis framework, which incorporates industrial experience and allows industrial users to explore both direct and indirect heat exchanges in diverse multi-plant industrial systems.

In the remainder of this paper, a new heat integration framework that can be applied for discontinuous, diverse multi-product, multi-plant factories is proposed in Section 2. Section 3 presents a case study at a confectionery factory in the UK, to show how the proposed framework works in practice. The case study has been included primarily for illustrative purposes and to allow a critical discussion of the framework, but it does also yield some interesting data. Discussions on the framework and the case study are made in Section 4, before the conclusions are given in Section 5.

2. Material and methods

2.1. Overview of the proposed framework

The development of the new methodological framework presented here is based on Pinch analysis from the techniques developed by Linnhoff March [17], Sadre-Kazemi and Polley [30], and upon the experiences drawn from different factories. The technique developed by Linnhoff March [16] lays out the general principles of the Pinch methodology and is concerned principally with continuous processes for direct heat exchange. In contrast, the technique developed by Sadre-Kazemi [30] is concerned with Pinch analysis for batch processes with the utilisation of indirect heat exchange to compensate for different operation time windows for heat exchange. In this current work, these two techniques are combined and adapted with additional decision events and steps identified to develop a single practical framework that can