Total Site Heat Integration in Carbon Neutral Industrial Manufacturing – A Systematic Mapping Study

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Carbon neutral operations are becoming important owing to tightening of greenhouse gas (GHG) emissions restrictions and increasing social corporate responsibility. Circular economy and total site integration are current hot topics, requiring resource-efficient industrial processes; this can be achieved with waste heat transfer and process integration. This study comprises a systematic mapping of research into waste heat transfer across total sites, with the goal of providing a structured overview of the research area to identify and quantify existing research. Fiive research questions are used to determine the publication landscape; the distribution of research categories, themes, modelling methodologies (Pinch, mathematical optimisation, hybrid); and the quantifiable benefits of waste heat transfer in terms of utility reduction, based on case studies. This work is expected to benefit researchers in understanding the research patterns and directions of total site heat integration, and in identifying the research gaps. Future work includes using the identified popular graphical modelling method of Pinch analysis for process integration of a medical device manufacturing site.

1. Introduction

Corporate social responsibility and business strategy are drivers for industrial enterprises to reduce their greenhouse gas emissions to approach carbon neutrality (Olatunji et al., 2019). This often entails the following steps: calculating carbon emissions, improving process efficiency, integrating processes, power purchase agreements, investing in renewable technologies, and offsetting unavoidable carbon emissions. Focussing on the early action steps of improving process efficiency and integrating processes reduces the financial investment of the later steps and the final emissions to be offset.

Industrial waste heat can be recovered using various Process Integration (PI) methodologies. Pinch Analysis is a graphical PI approach based on thermodynamic principles, and is insight-based and user-friendly with easily interpretable solutions; however, its scope is limited to technological parameters (Klemeš and Kravanja, 2013). Mathematical programming optimises multiple objectives simultaneously, including emissions and economic criteria; however it is not well received in industry as advanced knowledge is required for understanding (Klemeš and Kravanja, 2013). Hybrid modelling may benefit from the advantages of both methodologies (Klemeš and Kravanja, 2013). Current PI applications include Total Site Heat Integration (TSHI) and its extension, locally integrated energy sectors, in which communities share resources between industrial, commercial, and residential zones to reduce regional reliance on utilities (Perry et al., 2008). TSHI appears to be an important step towards achieving global carbon emissions targets and moving beyond these targets to carbon neutrality. The future of energy efficient industrial manufacturing should focus on Waste Heat Integration as a form of industrial symbiosis in the circular economy as a way to mitigate climate change.

The study objective is to analyse the research trends and classify the existing studies regarding TSHI in carbon-neutral industrial manufacturing; this was achieved by systematically reviewing relevant papers in a systematic mapping (SM) process. SM is a structured methodology that yields an overview of the research area by prioritising a broad range of studies at the expense of in-depth analysis of the individual studies (Petersen et al., 2008). It provides a visual presentation of the results, and identifying research gaps. To the best of the authors knowledge, no such papers have been published in the field of TSHI; this paper aims to address this gap in the research.

Section 2 of this paper describes the SM methodology; Section 3 presents the research questions; Section 4 details the search process and presents a visual summary thereof; Section 5 describes the screening of the publications; Section 6 describes the keywording process; Section 7 presents and discusses the results; and Section 8 concludes the SM research and details how the knowledge gained from this SM will be applied in future work.

2. Systematic mapping methodology

The SM methodology used in this study and outlined in the following sections is based on the five process steps defined by Petersen et al. (2008), as shown in Figure 1.
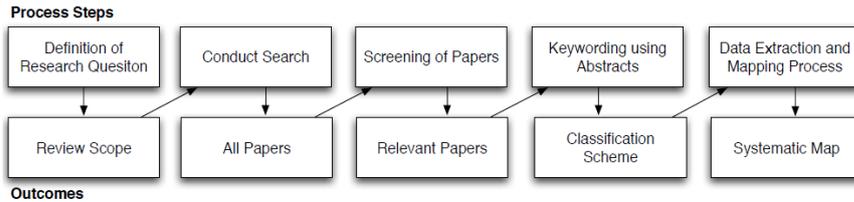

Figure 1: Systematic mapping process (Petersen et al., 2008)

2.1 Step 1: Research questions

Table 1 shows the five research questions (RQ) and their motivations as the foundation of this SM.

Table 1: Definition of research questions

No.	Question	Motivation
RQ1	What is the publication landscape of waste heat transfer across total sites?	Topic progression and relevance
RQ2	What research categories are being contributed?	Maturity of topic
RQ3	What research themes are being contributed?	Distribution of knowledge within topic
RQ4	What modelling methods are being contributed?	Current direction of modelling
RQ5	What are the quantifiable benefits of waste heat transfer across total sites in terms of utility reduction, based on case studies?	Quantify reason for focus on topic

2.2 Steps 2-3: Selection of relevant studies

A complete repository of relevant publications was created using the selection process outlined in Figure 2 and described in the following sub-sections. Step 2 comprised the initial search and the filtering of the publications; and step 3 comprised two screening phases.
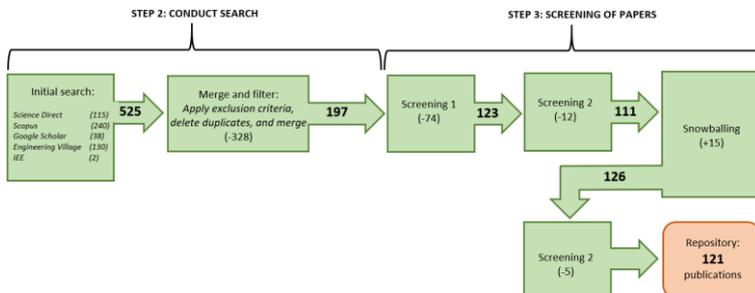

Figure 2: Flowchart of publication selection process

Step 2: Conduct search

Five databases were searched to capture the majority of the applicable published work, using search strings on the research topic and questions. The publications were filtered in the searches by applying exclusion criteria

(non-English) and inclusion criteria (subject area—Energy, Chemical Engineering, Engineering, Chemistry). The filtered papers were downloaded and saved in the reference management software Mendeley, which was used to screen the papers. The initial search and filtering strategy (shown in Table 2) yielded 525 results. Then, the publications from each database were merged into a single database, and duplicate publications and those not available in full text were removed. Further publications that were not initially filtered out according to the required exclusion criteria (because of the limited search functionality of the database) were removed. A total of 194 publications progressed to the screening phases.

Table 2: Search strategy

Database	Search
Science Direct	Metadata: 'Heat' AND Total Site'; Full text:'Process Integration' OR 'Pinch'
Engineering Village	Metadata: 'Heat' AND Total Site'; Full text:'Process Integration' OR 'Pinch'
IEEE	Metadata: 'Heat' AND Total Site'; Full text:'Process Integration' OR 'Pinch'
Scopus	Metadata: 'Heat' AND Total Site'; Full text:'Process Integration' OR 'Pinch'
Google Scholar	allintitle: ("Pinch methodology" OR "Pinch analysis" AND 'heat') OR "total site heat integration"

Step 3: Screening of papers

The publications were passed through two screening levels. The titles and abstracts were reviewed in the first screening phase, and the introductions and conclusions were reviewed in the second screening phase. A total of 108 publications passed through the screening levels. For snowballing, the most recent modelling paper (Möhren et al., 2021) and review paper (Klemeš et al., 2018) were reviewed to check for relevance of cited studies. Each identified study was analysed according to the criteria of the second screening phase to check its relevance. After snowballing and screening, there were 121 publications, which comprise the repository of publications for analysis in this SM.

2.3 Step 4: Keywording using abstracts

Each paper was categorized according to relevant key words to gain a basic understanding of the contribution. These keywords were used to define the research categories (RQ2) and themes (RQ3).

2.4 Step 5: Data extraction and mapping process

Microsoft Excel was used to record the data extraction process, and Google Colab was used to extract and plot the data according to the defined categories.

3. Results

The results for each research question are shown in the following sub-sections.

3.1 RQ1: What is the publication landscape of waste heat transfer across total sites?

Figures 3a, b, c, and d show the publication distribution per year, and the highest contributing countries, institutions, and publications. The concept of Total Site (TS) was introduced by Dhole and Linhoff in 1993 (Dhole and Linnhoff, 1993) (excluded from this study owing to lack of availability for download), but it was not until 1997 that the first relevant paper (meeting this SM criteria) regarding Total Site Profiles and composite curves for various industrial applications was published (Klemeš et al., 1997). The research accelerated rapidly in 2010, reaching a peak in 2015; the publications in this year were contributed by seven countries, indicating that this peak was not the result of an intensive study by a single institution. The contributions have declined in recent years; the low number of publications in 2020 and 2021 far may be partly attributed to the COVID-19 pandemic. The geographical distribution of the research can partly be explained by the early training of prominent researchers at The University of Manchester, who further developed research in this field as they took up new academic postings globally (Klemeš et al., 2018). Researchers at the Centre for Process Integration (CPI) at the University of Pannonia in Hungary collaborated with those at the University in Maribor in Slovenia in developing the TS methodology (Klemeš et al., 2018). Further collaboration from the CPI may have led to the high contributions from Malaysia, as many of these were co-authored by the head of this research group. With the exception of China, the publications from each country are limited to a single institution, indicating that the research is primarily driven by researcher interest rather than country-specific policies or incentives. Chemical Engineering Transactions is the most prolific source title with 28 publications, with Energy following with 23 publications. The lack of relevant conference papers can be attributed to there seemingly being only one well-established global conference with a specific focus on process integration—The Conference on Process

Integration for Energy Saving and Pollution Reduction, currently in its 24th year, and selected papers from this conference are published in Chemical Engineering Transactions.
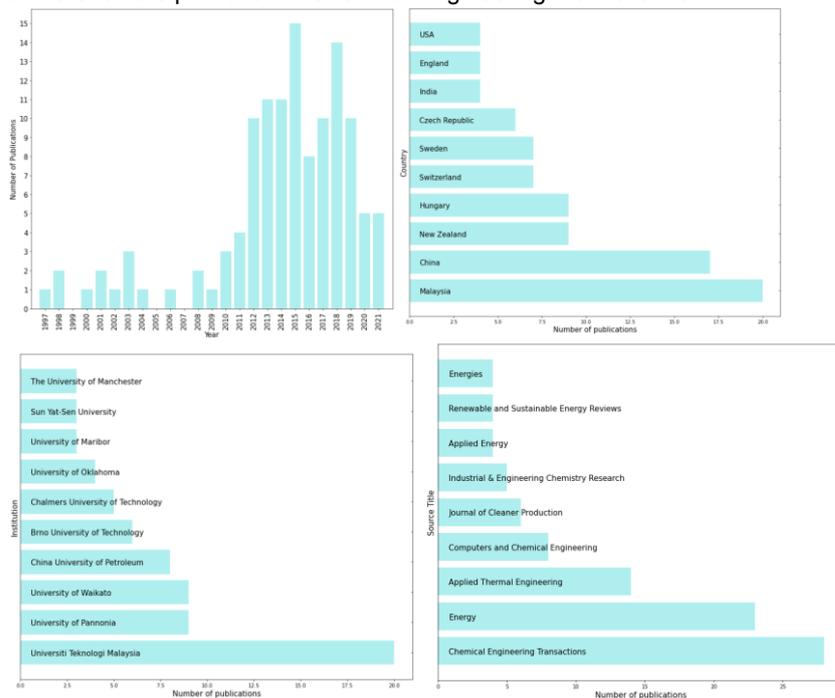

Figure 3: Publication distribution per (a) year, (b) country, (c) institution, and (d) source title.

3.2 RQ2: What research categories are being contributed?

The publications were categorised based on key words derived from the abstracts and the abstracts themselves, using an engineering-specific classification system that classifies papers according to their type of engineering task; solution papers propose novel approaches, evaluation papers research existing techniques to identify their use and associated problems, philosophical papers propose novel conceptual frameworks, and opinion papers offer the author's thoughts on a particular subject (Wieringa et al., 2006). The overall distribution and distribution per year are shown in Figure 4a and 4b. The publications are predominantly solution papers, indicating a focus on developing methodologies to model heat integration across total sites. Heat integration for individual processes (not relevant in this SM) is well-established and provides a solid foundation for TS analysis; this may account for the lack of philosophical papers as the existing frameworks may have been used, and the focus of TSHI could have progressed straight to methodologies. The low contribution of evaluation publications is likely because the majority of the solution publications include evaluations of their methodologies by means of case studies, and these are not recorded as standalone evaluation publications as this is not their primary contribution. This high number of methodologies is expected since the research topic is broad and considers different parameters relating to TSHI, as addressed in RQ3. Different methodologies are also tailored towards specific industries with common process equipment requirements.
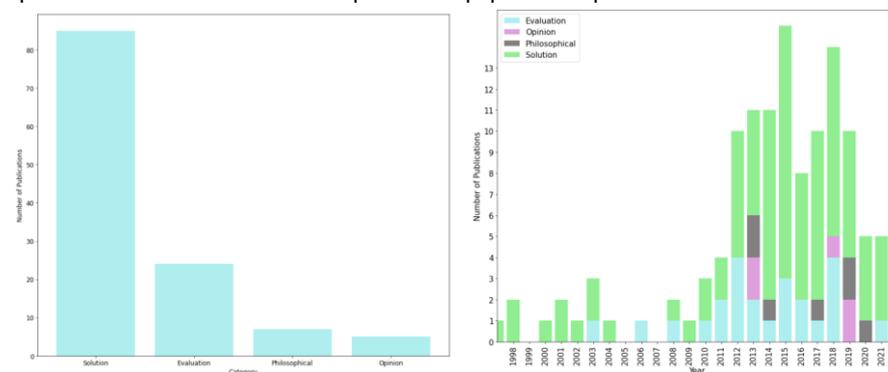

Figure 4: Distribution of research classification categories; (a) overall and (b) per year

3.3 RQ3: What research themes of are being contributed?

Figure 5a shows the research theme distribution per year. The majority of publications focus on heat, as expected from the search strings derived from the goal of this SM. The 'Multiple' theme comprises publications that include additional parameters for integration and optimization in conjunction with heat; these are broken down into the main themes in Figure 5b, where 'Heat' represents papers that focus on heat only. The proportion of publications considering multiple factors has increased in recent years, likely because total sites can be large and complex with many practical issues, and thus it may be more practical to consider heat more holistically.
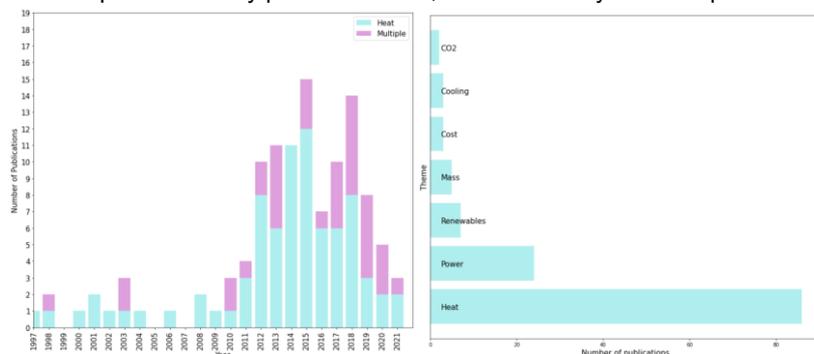

Figure 5: Distribution of research themes; (a) per year and (b) overall

3.4 RQ4: What modelling methods are being contributed?

The overall distribution and distribution per year of the modelling methods are shown in Figure 6. The Pinch method comprises all Pinch and Pinch-based graphical approaches, which make up the majority of publications. This is expected since Pinch was already a well-established method of heat integration when the TS concept was conceived. Graphical approaches have maintained a good proportion of the publications in recent years. Mathematical optimization and hybrid methods are becoming more popular as they consider the practical factors and cost considerations of total sites; this is important for total sites as they have a considerable impact on whether the TSHI methods are adopted.
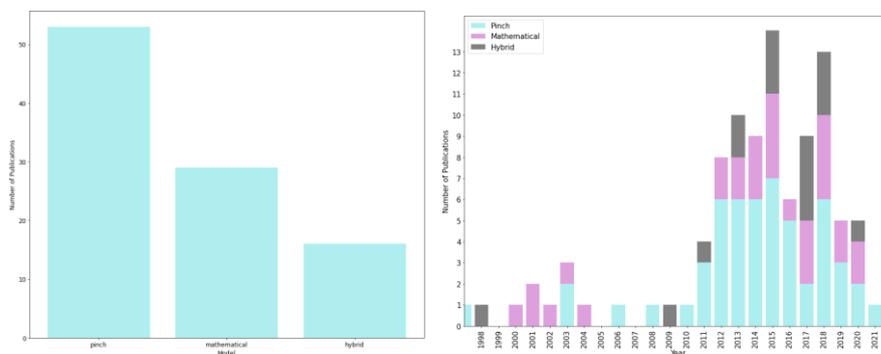

Figure 6: Distribution of modelling methods; (a) overall and (b) per year

3.5 RQ5: What are the quantifiable benefits of waste heat transfer across total sites in terms of utility reduction, based on case studies?

The reductions in heat energy reported in the case studies of total sites are shown in Figure 7, categorized by industry. The majority of studies focused on petrochemical sites. The most common energy reduction based on the studies analysed is 20 – 30 %, which is in line with typical energy savings reported for Heat Integration of total site and individual processes (Klemeš et al., 2018). There is a broad range of values owing to a number of factors relating to sites, e.g. industry type, site layout, distance between specific processes, method of heat transfer between sites (direct or indirect), and initial level of heat recovery incorporated into the original design in the case of retrofit scenarios. Moreover, the reduction in some studies is based on current consumption of existing plants, and in other studies is is based on theoretical consumption of new sites without heat integration. Thus, there is no basis for comparison between studies, and this figure merely reflects typical values that can be achieved by recovering waste heat across total sites.
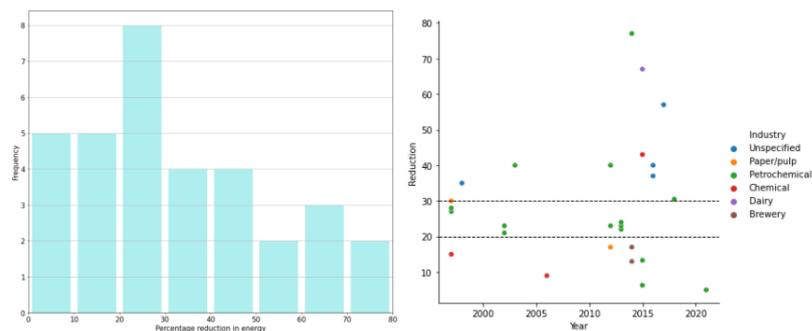
Figure 7: Reduction in heat energy (a) overall and (b) by industry

4. Conclusions and Future Work

This paper maps the literature regarding TSHI and provides a thorough overview of the research topic. The research indicates that TSHI can achieve significant energy reduction and is becoming an increasingly important research topic globally, with numerous methodologies under development to address the various complex factors that affect total sites. Although mathematical and hybrid modelling techniques are increasingly used, graphical methods remain the predominant modelling method. The knowledge gained will be used to inform an efficiency-and circular-economy-centred roadmap to carbon neutrality for an industrial site of a multinational company with stringent GHG emission goals and high corporate social responsibility. Specifically, the graphical method of Pinch Analysis will be used for the Process Integration step of the roadmap.

Acknowledgments

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