

## Original article

## Industrial waste heat recovery: A systematic approach

Elliot Woolley<sup>a</sup>, Yang Luo<sup>b</sup>, Alessandro Simeone<sup>c,\*</sup><sup>a</sup> Centre for Sustainable Manufacturing and Recycling Technologies (SMART), Wolfson School of Mechanical, Electrical and Manufacturing Engineering, Loughborough University, Loughborough LE11 3TU, UK<sup>b</sup> Research Centre for Carbon Solutions (RCCS), Institute of Mechanical, Process and Energy Engineering, Heriot-Watt University, Edinburgh EH14 4AS, UK<sup>c</sup> Intelligent Manufacturing Key Laboratory of Ministry of Education, Shantou University, Shantou 515063, China

## ARTICLE INFO

## Keywords:

Energy efficient manufacturing

Heat recovery

Decision support

## ABSTRACT

Globally one third of energy consumption is attributable to the industrial sector, with up to fifty percent ultimately wasted as heat. Unlike material waste that is clearly visible, waste heat (WHE) can be difficult to identify and evaluate both in terms of quantity and quality. Hence by being able to understand the availability of waste heat energy, and the ability to recover, there is an opportunity to reduce industrial energy costs and associated environmental impacts. A waste heat energy recovery framework is developed to provide manufacturers with a four step methodology in assessing production activities in facilities, analysing the compatibility of waste heat source(s) and sink(s) in terms of exergy balance and temporal availability, selecting appropriate heat recovery technologies and decision support based on economic benefits. The economic opportunity for industrial energy recovery is demonstrated in an industrial case study. The applicability of the framework for wider industrial application is discussed.

## Introduction

The need for improved energy efficiency in manufacturing is unquestionable. Responsible for one third of global energy demand [1] and set against the backdrop of increasing consumption and depleting energy-rich fossil-based fuels, it is likely that the future will bring increased energy prices and both short and long-term energy insecurities. This is not an ideal situation for manufacturing and a response to this threat is urgently required.

For manufacturers to reduce reliance on fossil-based fuels and at the same time reduce environmental impact of their activities there are two basic options: the use of renewable energy systems or the reduction of energy consumption. The incorporation of renewable energy technologies is an increasingly attractive option as prices fall but are not suitable for all locations and investment costs can still be prohibitive. The alternative, reducing energy demand, can be divided into three further options: a reduction in total activity (e.g. [2]); better energy management (e.g. [3]); and recovery and use of waste energy (e.g. [4]). A reduction in total activity can occur without detrimental impact on the profitability of a company [5] but requires a significant change to the business model and is not suitable for all company types [6]. Energy management has been explored at a number of manufacturing levels [7] and has been shown to be suitable for long, medium and short-term energy consumption improvements. Energy recovery and use is founded

on the principle that energy is never actually consumed, it is only converted from one form to another, and so there is a potential to capture this and utilise it as an energy supply. This is best conceptualised when considering the lifecycle of energy within a plant (Fig. 1), where energy (typically waste heat) can be recovered closed loop (reused back into the same process) or extended loop (recover into the energy supply of the facility). Recovered energy, in effect, replaces the need for a proportion of final energy demand by a facility.

The amount of useable energy is defined by its exergy, the component of energy that can be used to carry out work within a system. Additionally, most 'waste' energy available within a system is in the form of heat (Fig. 2) which is typically of lower exergy than stored chemical or electrical energy for example. Whereas energy within a system remains constant, the amount of exergy always decreases and so energy recovery must be undertaken in a well-informed manner to minimise exergy loss and maximise benefits. The objective of this work is therefore to create a framework for the identification and classification of waste heat energy within a facility and to provide a decision support tool to enable plant managers to make informed decision on the type of technology required to capture and harness waste heat energy.

This paper begins with a brief review of current industrial energy management and recovery used within industrial production facilities, before defining a framework for evaluating opportunities for reuse and recovery of energy within industrial environments. Both quantitative

\* Corresponding author.

E-mail address: [simeone@stu.edu.cn](mailto:simeone@stu.edu.cn) (A. Simeone).

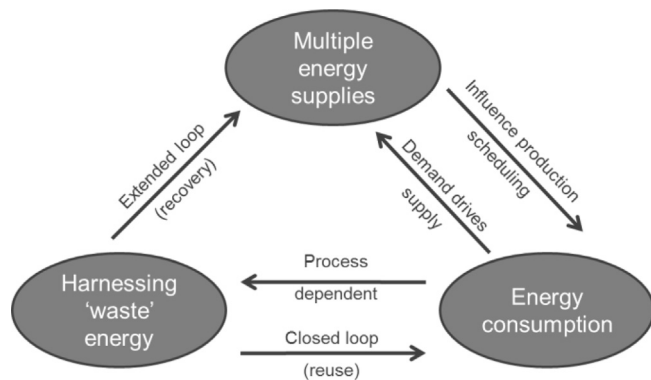


Fig. 1. Life cycle of energy in a manufacturing facility.

and qualitative descriptors are defined and a process established for the comparison of available sources and sinks. Primarily targeted for discrete production, the approach is also applicable to continuous processing. A decision support process is described and demonstrated via an industrial case study. The suitability of the framework is discussed in the context of industrial applications.

### Literature review

Energy efficiency is often overshadowed by economic efficiency, particularly when it comes to decision making within industrial environments. It is true that not all energy efficiency improvements are beneficial economically (i.e. they may require significant investment) [9] but there are a wide range of energy efficiency improvements that can be made across a manufacturing facility, of which some should certainly lead to cost savings within acceptable time periods. Within manufacturing energy using activities can be categorised under six levels, five of which (turret, machine, machine cell, facility and enterprise) have been described by Vijayaraghavan and Dornfeld [10] while a sixth level, business strategy, has been proposed [7] to incorporate ramifications from longer term decision making. A vast amount of literature exists describing various approaches for reducing energy consumption across these manufacturing levels (see [11;12] for example). The levels are useful for focusing and categorising energy management efforts, and can be adopted for describing the possibility of energy recovery. On whichever level energy is used there is the potential for energy recovery, be it from the heat generated from the friction of material removal from a work piece at the turret level, or the heat generated by the compressor pumps for pneumatic lines powering a facility. However, in terms of energy recovery, the number of these

manufacturing levels is too great (e.g. there is little difference between waste energy generated at the process level and at the cell level) and in practical terms waste energy at the enterprise level would be too dispersed to harness (although some technologies exist (e.g. [13]) and the business strategy level becomes irrelevant. In addition, there is the potential to recover heat directly from a product which has been recently processed (e.g. a freshly cast engine block). Therefore, instead of the manufacturing levels described by [9], which are highly useful for analysing energy inputs into a system, it is useful to adopt a set of terminologies defined by Rahimifard et al. [14] called the *3P perspective* referring to Plant, Process and Product. Developed for energy modelling, these three perspectives can also be used to define potential output sources of WHE and are useful for identifying possible waste heat flows within a manufacturing facility (between the different perspectives). In general, the highest temperatures, but smallest amounts of waste heat are available directly from the product, with the lowest temperatures, but greatest amount of heat being available at the plant level. This implies that suitable sinks for waste heat recovery (WHER) are unlikely to be found at a lower level, but could be identified at the same or higher levels (Fig. 3). The three opportunities for energy recovery then are for it to be reused for the same purpose recovered for another use within the factory or reutilised for energy storage or power generation (i.e. electricity).

Given this backdrop of energy recovery technologies and the 3P perspective for WHER, it has been identified that there is need to create an economic model that successfully 'bridges' available WHE sources with suitable, potential WHE sinks [15]. In support of this, it has been shown that it is more economical to recover heat for transfer to a sink rather than to invest in heat pumps or convert the heat into other forms such as electricity [16]. It is also preferable to reuse the heat in the same process, or a sink in the immediate facility, to avoid the cost of pipework, ducts and auxiliary equipment which themselves, also lead to thermal losses. Further, heat exchangers have been proposed as one of the best systems for recovering WHE energy [17,18], and for these, there needs to be an emphasis on matching heat sources with heat sinks. Such research supports the idea of reusing WHE energy within the same level (shown in Fig. 3) and where this is not possible, cascading it to the next level.

Energy recovery has been investigated for a range of different industrial sectors including aluminium casting [19], steel production [20], low grade heat from the food manufacturing [21] and district heating [22] with many other sectors, such as cement, glass, chemicals and ceramics having been highlighted as ideal for low grade energy recovery [23].

Clearly, this is an active area of investigation and the number of installation of WHER technologies continues to increase [24]. However,

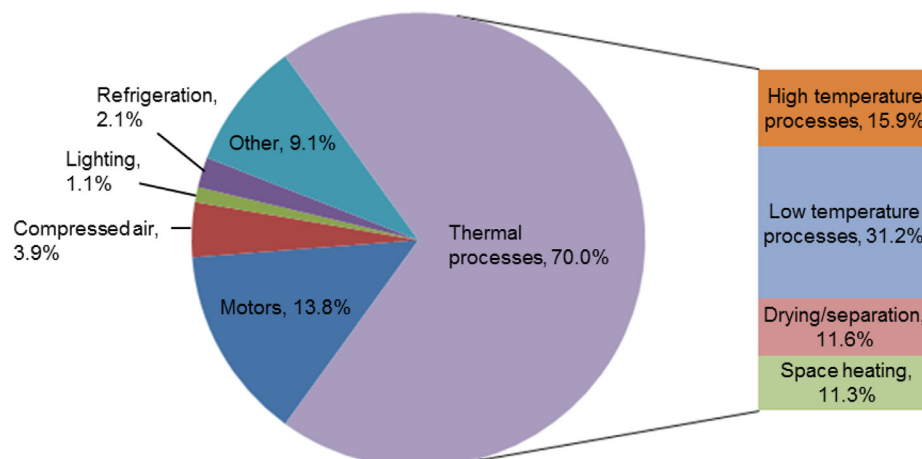


Fig. 2. 2016 Energy consumption in UK manufacturing industry by type (Data from Department of Business, Energy and Industrial Strategy, [8]).

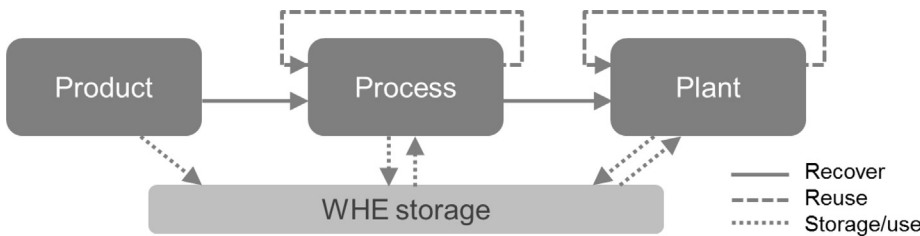


Fig. 3. 3P perspective for WHE.

there does not appear to be a core methodological approach to the assessment of potentials for recovery of WHE energy and the perceived complexity could be regarded as a barrier to implementation. The work presented in this paper seeks to establish a systematic approach to assessing and appraising potential options for WHE energy recovery within industry.

### Waste heat recovery framework

The task of identifying and assessing opportunities for recovery of WHE energy within manufacturing facilities can be quite complex, particularly if the solution with the most benefit (e.g. energy saving, return on investment) is to be selected. Given the large size and complexity of many manufacturing facilities, it is not straight forward to understand which are the most suitable WHE energy sources, and where might the potential sinks be. Even if these can be identified, the process of assessing compatibility (e.g. temporal and energy availability) between a number of sources and sinks can be highly complicated [28]. And finally, even if these assessments can be made, the selection of the most appropriate technology from the broad range of options available is difficult.

In this respect there is a need for a structured, assisted methodology to enable the relevant managers to be able to undertake assessments and inform decision making regarding investment in energy recovery technologies. In this research a structured framework has been devised in order to collect, collate, assess and produce relevant data to support industrial investments in WHE energy technologies. The structure of the framework is derived from a survey-assess-decide approach which has been proposed for the proposed for the waste management sector [25,26] and is an extension of the work presented in [27]. The framework is in four distinct phases which can be summarised by the following and is shown in Fig. 4:

1. Survey of WHE sources and potential sinks in facility.
2. Assessment of WHE quantity and quality.
3. Comparison of key parameters from a database of available technologies.
4. Decision support and recommendations.

These individual stages are further described in the following sections with respect to the information flow required to inform investment decisions within manufacturing business.

In addition their structure around information flow lends the framework to implementation via a computerised system which has three main advantages: potential for a user-friendly interface, competent handling of complex, multi-parameter calculations (including use of neural networks) and ability to store and look-up data from large databases.

#### Survey of waste heat sources in facility

The first stage of the framework requires a site survey to be undertaken to establish the most likely thermal sources and sinks which may be utilised for energy recovery. Information should be recorded at the product, process and plant perspectives for the largest WHE producing activities (these will normally be known to the site managers),

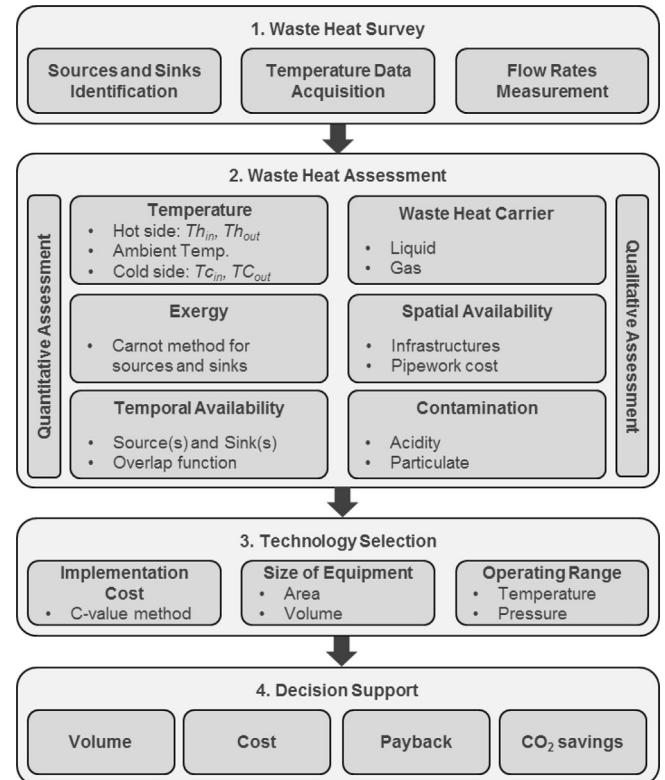


Fig. 4. Framework for energy recovery assessment.

the number of sources identified being commensurate with the size and activities of a facility. Data acquired from this step will be both numerical and descriptive which is then fed into the next stage of the framework for conversion and categorisation into standardised descriptors (see Table 1) that can be interpreted by a decision making algorithm. During the survey, potential sinks for the WHE energy should be identified and the descriptions recorded accordingly. It is preferable to identify at least as many potential sinks as sources to increase the opportunity for recovering more WHE energy. WHE surveys should be carried out prior to making any new decisions on recovery of WHE within a facility and periodically (e.g. annually) to ensure the continued relevance and function of any installed WHER systems.

Table 1

The descriptors used in the waste heat recovery framework.

|                                 |  |
|---------------------------------|--|
| <i>Quantitative descriptors</i> |  |
| Temperature difference          | Between source and potential sinks   |
| Available energy (exergy)       | Component of energy available to carry out work  |
| Temporal availability           | Profile of available energy with respect to time   |
| <i>Qualitative descriptors</i>  |  |
| Carrying medium                 | The solid or fluid within which the waste heat resides as it leaves a process or service |
| Spatial availability            | Description of accessibility of waste heat   |
| Risk of contamination           | Indication of special requirements for treatment of waste heat energy                    |



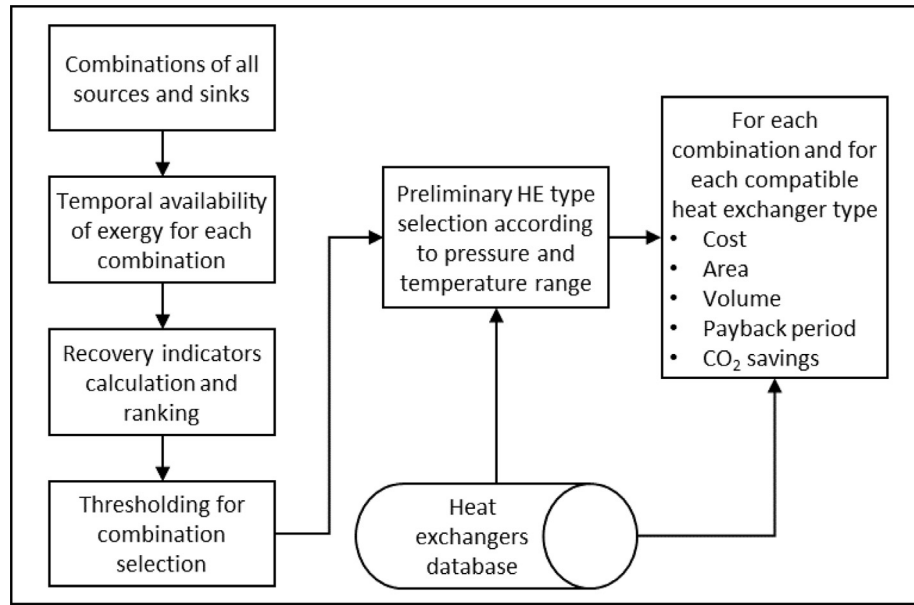


Fig. 5. Computation Module created in MATLAB®.

Table 3

Sources and sinks combinations list for a two sources and two sinks scenario.

| # | Sources column      | Sinks column    |
|---|---------------------|-----------------|
| 1 | Source 1            | Sink 1 + Sink 2 |
| 2 | Source 1            | Sink 2          |
| 3 | Source 1            | Sink 1          |
| 4 | Source 1 + Source 2 | Sink 1 + Sink 2 |
| 5 | Source 1 + Source 2 | Sink 2          |
| 6 | Source 1 + Source 2 | Sink 1          |
| 7 | Source 2            | Sink 1 + Sink 2 |
| 8 | Source 2            | Sink 2          |
| 9 | Source 2            | Sink 1          |

$c_p$  = specific heat capacity  $\left[\frac{\text{J}}{\text{kg}\cdot\text{K}}\right]$ ,

$[0, T]$  is the time window defined by the user in the previous stage.

The exergy values of source and sink can be calculated as the integral of the power over the time window taken into account, as reported in the formulas below:

$$Exergy_{source} = \int_0^T Power_{source}(t) dt \quad (3)$$

$$Exergy_{sink} = \int_0^T Power_{sink}(t) dt \quad (4)$$

#### Temporal availability

In order to compute the recoverable energy it is necessary to consider the temporal availability of WHE energy with respect to the required energy by the sink. Therefore an Overlap function  $O(t)$  for a given combination of source(s) and sink(s) is defined as follows:

$$O_{source,sink}(t) = \begin{cases} Power_{sink}(t), & Power_{sink}(t) < Power_{source}(t) \\ Power_{source}(t), & Power_{sink}(t) \geq Power_{source}(t) \end{cases} \quad (5)$$

The recoverable energy, i.e. exergy, for a given combination of source and sink is defined as the integral of the Overlap function over the time window  $[0, T]$

$$Exergy_{source,sink} = \int_0^T O_{source,sink}(t) dt \quad (6)$$

Once the exergy for combinations of sinks and sources can be established, then it is possible to proceed with a comparison between the different possibilities for WHER within a facility (e.g. as shown in Table 3 (sinks and sources)). An example of overlap function and exergy plot is reported in Fig. 6 for combination #1 (source No.1 matched with sink No.1 + sink No. 2). In order to assess the recoverability of the WHE, a series of indexes has been devised and can be calculated:

The Recovery Index,  $RI$ , is defined as the ratio of recoverable energy ( $Exergy_{source,sink}$ ) to total available energy ( $Exergy_{source}$ ) in the specified time window, representing the maximum fraction of source energy that it is possible to capture,

$$0 < RI_{source,sink} = \frac{Exergy_{source,sink}}{Exergy_{source}} < 1 \quad (7)$$

The Waste Index,  $WI$ , is defined as the ratio of unrecoverable energy to total available energy in the specified time window,

$$0 < WI_{source,sink} = 1 - RI_{source,sink} < 1 \quad (8)$$

Utilisation Index,  $UI$ , is defined as the ratio of recoverable energy to total available sink ( $Exergy_{sink}$ ) in the specified time window, representing the percentage of the energy required by sink that is met from the source.

$$0 < UI_{source,sink} = \frac{Exergy_{source,sink}}{Exergy_{sink}} < 1 \quad (9)$$

Using these indexes, it is possible to then rank the possible source and sink combinations based on the fraction of energy that could be recovered as shown in Table 4.

The list of combinations is ranked according to the Recovery Index and the Utilisation Index. These indexes are useful for determining the best match between sources and sinks for WHER, but not necessarily identifying the pairings that recover the most energy. In this respect the results should be considered in conjunction with the outputs of the Overlap function.

#### Selection of appropriate technology

The types of suitable technology for a particular scenario will depend on the specific properties of WHE source. It is essential to define the selection criteria for the available heat recovery technologies which consist of four predominant properties: heat transfer mechanism,



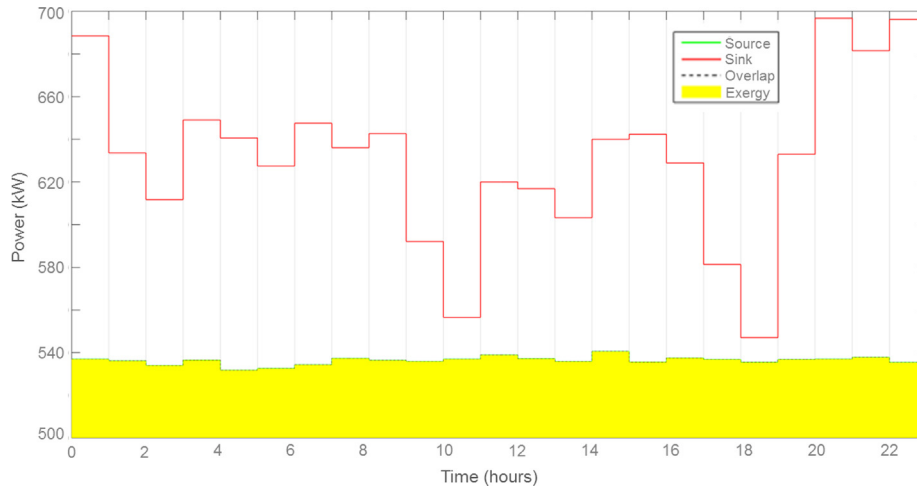


Fig. 6. Exergy and temporal availability plot for source No.1 matched with sink No.1 + sink No. 2.

Table 4

Combinations ranking according to the RI followed by the UI.

| Sources             | Sinks           | RI    | WI    | UI    |
|---------------------|-----------------|-------|-------|-------|
| Source 1            | Sink 1 + Sink 2 | 1.000 | 0.000 | 0.905 |
| Source 2            | Sink 2          | 1.000 | 0.000 | 0.512 |
| Source 2            | Sink 1 + Sink 2 | 1.000 | 0.000 | 0.322 |
| Source 1            | Sink 2          | 0.891 | 0.109 | 0.838 |
| Source 1 + Source 2 | Sink 1 + Sink 2 | 0.874 | 0.126 | 0.953 |
| Source 1 + Source 2 | Sink 2          | 0.742 | 0.258 | 0.875 |
| Source 1            | Sink 1          | 0.544 | 0.456 | 0.950 |
| Source 2            | Sink 1          | 0.509 | 0.491 | 0.494 |
| Source 1 + Source 2 | Sink 1          | 0.320 | 0.680 | 0.978 |

medium of WHE carrier, size of the equipment and operating temperature range. With the defined properties of WHE and heat recovery technology, matching and comparison can be carried out.

The results from the WHE quantity and quality assessment can be used to filter the range and number of technology options from a list contained, for example, within a database. This process yields a list of feasible technology solutions which score similar in the comparison of criteria. The output results of this stage are useful in the next stage of the framework, which carries out environmental and economic analysis methods to further compare between the selected technology solutions to support decision making. In the current work, environmental analysis extends only to carbon foot printing as a suitable and common proxy.

In this research a database was extracted from ESDU 92,013 Selection and costing of heat exchangers [29] to provide detail on a range of potential heat exchangers that could be used to link WHE sources and sinks. It is recognised that for wide scale uptake of the current methodology, up-to-date databases of suitable energy recovery technologies would need to be developed, maintained and made available. In this respect a hub-style approach to data processing and database provision may be most feasible for the described methodology.

In order to exclude the non-compatible heat exchanger types, three conditions must be verified simultaneously:

$$P_{\text{source}} < P_{\text{max}}|_{\text{HEtype}} \quad (10)$$

$$\min(T_{c,\text{in}}(t)) > T_{\text{min}}|_{\text{HEtype}} \quad (11)$$

$$\max(T_{h,\text{in}}(t)) < T_{\text{max}}|_{\text{HEtype}} \quad (12)$$

where the maximum pressure,  $p_{\text{max}}$ , and the operating temperature limits,  $T_{\text{min}}$  and  $T_{\text{max}}$ , are reported in Table 5 for the heat exchanger types included in the database.

Table 5

An example selection of compatible heat exchangers types for each combination of source(s) and sink(s).

| HE type         | $p_{\text{max}}$ (bar) | $T_{\text{min}}$ (°C) | $T_{\text{max}}$ (°C) |
|-----------------|------------------------|-----------------------|-----------------------|
| Air cooled      | 500                    | 0                     | 600                   |
| Double pipe     | 300                    | −100                  | 600                   |
| Brazed plate    | 16                     | 0                     | 200                   |
| Plate fin       | 100                    | −273                  | 150                   |
| Printed circuit | 1000                   | 0                     | 800                   |
| Shell and tube  | 300                    | −25                   | 650                   |
| Welded plate    | 60                     | 0                     | 700                   |
| Plate           | 10                     | −25                   | 175                   |

Table 6

Compatible heat exchangers for the various source and sink combinations.

| Solution # | Sources  | Sinks           | Technology      |
|------------|----------|-----------------|-----------------|
| 1          | Source 1 | Sink 1 + Sink 2 | Air cooled      |
| 2          | Source 1 | Sink 1 + Sink 2 | Double pipe     |
| 3          | Source 1 | Sink 1 + Sink 2 | Printed circuit |
| 4          | Source 1 | Sink 1 + Sink 2 | Shell and tube  |
| 5          | Source 1 | Sink 1 + Sink 2 | Welded plate    |
| 6          | Source 2 | Sink 2          | Air cooled      |
| 7          | Source 2 | Sink 2          | Double pipe     |
| 8          | Source 2 | Sink 2          | Printed circuit |
| 9          | Source 2 | Sink 2          | Shell and tube  |
| 10         | Source 2 | Sink 2          | Welded plate    |

Each combination of source(s) and sink(s) will ideally be compatible with one or more heat exchanger types. The compatible heat exchangers for the current example are listed in Table 6.

#### Decision support and recommendations

It is of interest to manufacturers to be able to evaluate the potential impact of their decisions. A financial analysis calculates both the annualised net financial benefit and overall payback period. For small scale WHER technology with low capital cost, a rough estimate of the economic return should be sufficient to justify investment, whilst for larger WHER systems with integrated components, where there is a high capital cost, a full appraisal should be carried out.

Environmental considerations utilising this method are currently limited to impacts associated with the direct displacement of current energy supply (e.g. in terms of CO<sub>2</sub> reduction), but wider lifecycle impacts may also be of interest. Production, installation, maintenance and disposal of heat exchangers, for example, may have a non-

negligible impact in applications where energy recovery is at a low level or where the displaced energy already has a low carbon footprint.

Once the compatible heat exchangers types have been identified, in order to estimate the cost and other relevant parameters, the heat load,  $Q$ , needs to be ascertained for each potential solution. For this purpose, it is possible to define the following parameters:

Source related parameters:

- $\alpha$  = Flow rate density
- $\beta = \max(T_{h,in})$
- $\gamma = \min(T_{h,out})$

Sink related parameters:

- $\varphi = \text{mean}(\text{Flow rate density})$
- $\varepsilon = \min(T_{c,in})$
- $\delta = \max(T_{c,out})$

$Q$  is readily determined from the enthalpy change of the hot stream:

$$Q = \alpha \cdot \rho_{\text{source}} \cdot C_{p,\text{source}} \cdot 1000 \cdot (\beta - \gamma) \cdot RI \quad (13)$$

For a constant overall heat transfer coefficient and for constant specific heat capacity of the fluid streams, the mean temperature difference is equal to the logarithmic mean temperature difference given by:

$$\Delta T_m = \frac{(\beta - \delta) - (\gamma - \varepsilon)}{\log_e \frac{\beta - \delta}{\gamma - \varepsilon}} \cdot F_T \quad (14)$$

where  $F_T$  represents the logarithmic temperature difference correction factor.

At this point, it is possible to calculate the Cost Factor,  $C$ , as reported by Hewitt and Pugh [23] by accessing the database using the  $\frac{Q}{\Delta T_m}$  ratio value:

$$C = \exp \left\{ \log_e C_1 + \frac{\log_e (C_1/C_2) \log_e [(Q/\Delta T_m)/(Q/\Delta T_m)_1]}{\log_e ((Q/\Delta T_m)_1/(Q/\Delta T_m)_2)} \right\} \quad (15)$$

where  $C_1$  and  $C_2$  are the  $C$  values (retrieved from a database for all the heat exchanger types for a given value of  $\frac{Q}{\Delta T_m}$ ) of the particular hot and cold side streams pairing at  $(Q/\Delta T_m)_{\text{lower}}$  and  $(Q/\Delta T_m)_{\text{upper}}$ , respectively. The subscripts 1 and 2 correspond to the upper and lower bound values of the database [29]. This  $C$  value method allows the comparison between heat exchangers with respect to heat duty ( $Q$ ) and the available temperature driving force ( $\Delta T_m$ ), which are related to the process specification.

In the comparison shown in Table 7 below, where values of  $Q/\Delta T_m$  is assumed to be 3000 W/K, therefore the lower and upper bound levels of 1000 and 5000 are chosen. Based on the corresponding  $C_1$  and  $C_2$  values, using a double-pipe heat exchanger as an example, the overall  $C$  value is determined as follows:

**Table 7**  
Cost of heat exchangers per typology.

| Heat exchanger type | $C_1$ & $C_2$ values (£/(W/K)) |                           | Overall $C$ value | Costs (£)               |
|---------------------|--------------------------------|---------------------------|-------------------|-------------------------|
|                     | $Q/\Delta T_m = 1000$ W/K      | $Q/\Delta T_m = 5000$ W/K | £/(W/K)           | $Q/\Delta T_m \times C$ |
| Double-pipe         | 2.8                            | 1.4                       | 1.74              | 5220                    |
| Shell-and-tube      | 4.89                           | 1.56                      | 2.24              | 6720                    |
| Printed-circuit     | 12                             | 3.6                       | 5.28              | 15,840                  |
| Welded-plate        | 5.6                            | 2.54                      | 3.26              | 9793                    |

$$C = \exp \left\{ \log_e 2.8 + \frac{\log_e (2.8/1.4) \log_e [(3000)/(1000)]}{\log_e (1000/5000)} \right\} = 1.74 \frac{\text{£}}{\text{W/K}} \quad (16)$$

It is also possible to calculate the heat exchanger area as follows:

$$A = \frac{Q/\Delta T_m}{U} \quad (17)$$

where  $U$  = heat transfer coefficient, retrieved from the database through logarithmic interpolation. The cost of several different heat exchangers for the present example are shown in Table 7.

An important parameter for heat exchanger selection is the heat exchanger volume  $V$  ( $\text{m}^3$ ), calculated as follows:

$$V = \frac{A}{\sigma} \quad (18)$$

where  $\sigma$  = Surface area per unit volume, retrieved from the database [ $\text{m}^2/\text{m}^3$ ].

Finally, it is possible to predict the financial payback period based on the cost of the heat exchange, the expected auxiliary costs,  $C_{aux}$ , and the expected annual cost saving,  $C_{as}$ :

$$P_b = \frac{(Q \cdot C) + C_{aux}}{\Delta T_m \cdot C_{as}} \quad (19)$$

Decision makers within industry are thus able to use the outputs of this methodology to support strategic investments in WHER technologies in conjunction with other relevant factors which may apply to specific manufacturing plants and industrial sectors. Again, it is appreciated that for industrial application, the empirical model described could be seen as rather complex and inaccessible for some potential users, however the method could be implemented by external expertise either through consultancy or via other commercial or governmental schemes. Issues with in-house skills, access to metering equipment and relevant databases would therefore be overcome.

## Case study

The following industrial case study is provided to demonstrate the applicability and benefit of the presented WHER framework. The study is concerned with the operation of a cupola within an engine casting plant. The data used comprises of original data from a commercial company and from published literature which has been referenced where the desired information was not available from the company.

An initial survey of the casting process revealed four main sources of heat loss:

- Heat losses from the exhaust discharge.
- Heat transported out of the equipment by the load conveyors.
- Radiation losses from openings, hot exposed parts.
- Heat carried out by the excess air used in the burner.

WHE losses from the exhaust were considered the highest priority due to the high temperature gas discharge which varies from as low as 13 °C to as high as 578 °C (for the observed period). Combustion products themselves, generated from well-designed and well-operated modern burners using gaseous and light liquid fuels, are relatively clean and do not contain particles or condensable components that may require filtering before discharging into the atmosphere. However in this particular case, since the furnace uses coal as its main fuel as well as a reaction reagent, the combustion products may react with materials used in the construction of downstream WHER equipment and potentially create problems if not treated appropriately. Potential issues include chemical reaction of exhaust gases and their solid or vapour content with the materials used in the WHER. Many of these problems are compounded by the high temperature of the exhaust gases and uneven flow patterns of the hot gases.

During the survey two potential sinks for the WHE from the exhaust were identified (based on location and heat requirement). These sinks were pre-heating of the combustion air for the cupola and a heat supply for the molten iron holding tank.

Data has been recorded over a one week period, but for some of the data (e.g. exhaust temperatures) the reporting time was not regular and so the data was interpolated to provide a resolution of one minute. The production campaign is weekly and begins late on a Sunday to warm up the furnaces ready for production on Monday morning. Eight 10 h shifts (two per 24 h) are conducted during the production campaign which ends on Thursday for cleaning and maintenance.

$Q_1$  values can be calculated using equation (20). For the exhaust gas, there is clearly no specific pre-defined value for  $C_p$  and so this was determined based on the gas composition. Information regarding the flow rate of the exhaust gas was not available and so this was calculated from the flue-gas stack effect analysis:

$$\dot{V} = CA \sqrt{2gH \frac{T_i - T_o}{T_i}} \quad (20)$$

where:

$\dot{V}$  = flue-gas flow-rate,  $\text{m}^3/\text{s}$

$A$  = cross-sectional area of stack,  $\text{m}^2$

$C$  = discharge coefficient (taken as 0.7)

$g$  = gravitational acceleration at sea level,  $9.807 \text{ m/s}^2$

$H$  = height of stack,  $\text{m}$

$T_i$  = absolute average temperature of the flue gas in the stack,  $\text{K}$

$T_o$  = absolute outside air temperature,  $\text{K}$

The equation assumes that the molar mass of the flue gas and the outside air are equal and that the frictional resistance and heat losses are negligible. Hence, the flow-rate was calculated as  $18.05 \text{ m}^3/\text{s}$ . An excerpt of the data recorded for the source and two sinks is presented in Fig. 7.

As can be seen from Table 8, there are three potential combinations for coupling sink and sources in this study. The second option can be discarded based the grounds of low energy recovery ( $\text{RI} = 0.139$ ). Despite the variation in  $\text{RI}$ , the  $\text{UI}$  for all options is close to 1, indicative that the waste energy available from the source largely exceeds that required by the two sinks for any period of time for which data has been recorded.

The exergy amount is calculated based on the inlet and outlet temperature of the WHE source and sink provided by the manufacturer. Each combination of source and sink(s) will be compatible with one or more heat exchanger types. The compatible heat exchangers for the potential solution *Source 1* with *Sink 1* plus *Sink 2* (which has the highest  $\text{RI}$ ) are listed in Table 9 alongside their estimated costs, evaluated using the C-value method [30].

The result of the application of this framework to the current case

**Table 8**

Potential combinations for coupling sink and source.

| Sources  | Sinks           | RI    | WI    | UI    |
|----------|-----------------|-------|-------|-------|
| Source 1 | Sink 1          | 0.472 | 0.528 | 0.999 |
| Source 1 | Sink 2          | 0.139 | 0.861 | 0.999 |
| Source 1 | Sink 1 + Sink 2 | 0.611 | 0.389 | 0.999 |

study reveals that provided sufficient space is available a shell and tube heat exchanger would provide the best return on investment for the casting plant, whilst an air-cooled heat exchanger may be an option if spatial restrictions apply. Any potential  $\text{CO}_2$  savings can be calculated based on the displacement of energy requirements for the pre-heating of the combustion air for the cupola and a heat supply for the molten iron holding tank.

The calculation of the recovery indexes is typically based on large datasets and so less susceptible to data variability. The calculation of the  $C$  value is important for the accuracy of the calculation of economic payback time and should therefore be devised carefully when compiling a database of heat recovery technologies.

The case study provides evidence of the applicability of the presented framework to an industrial problem and therefore such an analysis can be used during technology selection for optimised energy recovery and financial payback assessment.

## Concluding discussion

The recovery of WHE energy in industry is potentially more economically viable than the installation of renewable energy technologies and other mechanisms for reducing overall energy consumption across a facility. Because of the often low-tech solution required to harness the energy, the approach is generally accessible for most companies and payback times can be relatively short (of the order of two years). However identifying the best opportunities for energy recovery within a facility is not straight forward and the work presented here provides a structured process for analysing energy outputs, comparing potential sources and sinks and selecting and evaluating energy recovery technologies.

The four stage framework presented here offers a piecemeal approach to selecting the most appropriate solution for a particular scenario and is therefore suited to industrial application. The survey requires the skill level currently commonplace in most manufacturing industries, whilst the second stage (assessment of WHE quality and quantity) is more complex. Of particular difficulty in this stage is the exergy and temporal analysis and to this end, a piece of software has been coded in MATLAB® to assist with the comparison between sinks and sources, and to generate the WHER indexes. These indexes have

| Cupola Exhaust (Source1) |             |             |                  | Cupola Pre-Heating (Sink 1) |             |            |                  | Holding Tank Heat Supply (Sink 2) |             |            |                  |
|--------------------------|-------------|-------------|------------------|-----------------------------|-------------|------------|------------------|-----------------------------------|-------------|------------|------------------|
| Stream medium            |             | Exhaust gas |                  | Stream medium               |             | Air        |                  | Stream medium                     |             | Air        |                  |
| Th_in (°C)               | Th_out (°C) | T_amb (°C)  | Flow Rate (m³/s) | Tc_in (°C)                  | Tc_out (°C) | T_amb (°C) | Flow Rate (m³/s) | Tc_in (°C)                        | Tc_out (°C) | T_amb (°C) | Flow Rate (m³/s) |
| 27.24                    | 27.24       | 27.24       | 18.0485          | 27.24                       | 27.24       | 27.24      | 13.24            | 27.24                             | 27.24       | 27.24      | 6.75             |
| 27.22                    | 27.22       | 27.22       | 18.0485          | 27.22                       | 27.22       | 27.22      | 13.24            | 27.22                             | 27.22       | 27.22      | 6.75             |
| 27.20                    | 27.20       | 27.20       | 18.0485          | 27.20                       | 27.20       | 27.20      | 13.24            | 27.20                             | 27.20       | 27.20      | 6.75             |
| 27.18                    | 27.18       | 27.18       | 18.0485          | 27.18                       | 27.18       | 27.18      | 13.24            | 27.18                             | 27.18       | 27.18      | 6.75             |
| 27.16                    | 27.16       | 27.16       | 18.0485          | 27.16                       | 27.16       | 27.16      | 13.24            | 27.16                             | 27.16       | 27.16      | 6.75             |
| ...                      | ...         | ...         | ...              | ...                         | ...         | ...        | ...              | ...                               | ...         | ...        | ...              |
| 538.43                   | 171.72      | 21.98       | 18.0485          | 21.98                       | 291.91      | 21.98      | 13.24            | 21.98                             | 200.21      | 21.98      | 6.75             |
| 538.42                   | 171.71      | 21.99       | 18.0485          | 21.99                       | 291.90      | 21.99      | 13.24            | 21.99                             | 200.20      | 21.99      | 6.75             |
| 538.41                   | 171.71      | 22.01       | 18.0485          | 22.01                       | 291.89      | 22.01      | 13.24            | 22.01                             | 200.19      | 22.01      | 6.75             |
| 538.40                   | 171.70      | 22.02       | 18.0485          | 22.02                       | 291.88      | 22.02      | 13.24            | 22.02                             | 200.18      | 22.02      | 6.75             |
| 538.39                   | 171.70      | 22.03       | 18.0485          | 22.03                       | 291.87      | 22.03      | 13.24            | 22.03                             | 200.17      | 22.03      | 6.75             |

**Fig. 7.** Sample of recorded data for Source 1 and Sinks 1 and 2.



**Table 9**  
Compatible heat exchangers for the selected combination.

| Heat exchanger type | $C_1$ value (£/(W/K)) | $C_2$ value (£/(W/K)) | Overall $C$ value (£/(W/K)) | Costs (£) | Area (m <sup>2</sup> ) | Volume (m <sup>3</sup> ) | Payback period |
|---------------------|-----------------------|-----------------------|-----------------------------|-----------|------------------------|--------------------------|----------------|
| Shell-and-tube      | 0.62                  | 0.35                  | 0.54                        | 217,020   | 1773                   | 35.9                     | 2 y 1 m        |
| Double-pipe         | 0.35                  | 0.35                  | 0.35                        | 341,770   | 1794                   | 35.9                     | 4 y 9 m        |
| Printed-circuit     | 0.87                  | 0.74                  | 0.75                        | 787,600   | 1054                   | 2.1                      | 4 y 8 m        |
| Air-cooled          | 1.12                  | 1.12                  | 1.12                        | 450,120   | 907                    | 1.8                      | 2 y 7 m        |

been shown to be useful in selecting the most appropriate matches between sources and sinks.

Stage three of the framework requires a database of available technologies to compare with the source-sink matches. In this work a database relating only to heat exchangers was utilised (by importing to MATLAB®) which has limited the potential solutions in the case study. However, with the generation of other databases (e.g. for thermoelectric devices, heat engines, storage devices), the capability of the present framework could be much increased. The generation of such databases is not too onerous a task provided sufficient information is available from the commercial field, although they would need to be maintained to ensure that the most up-to-date technologies are included for assessment.

It should be realised here that in the case of the utilisation of energy storage technologies, the temporal availability of energy plays a less important role since sources and sinks do not need to match so closely in this respect. However the alignment of availability and requirement will determine the type and size of energy storage needed. In general, the use of energy storage will still require some form of energy conversion technology.

The final stage of the framework uses the potential energy recovery from the technology and its predicted purchase and maintenance costs to calculate a financial payback period. The CO<sub>2</sub> saving is deducible from the type and amount of energy predicted to be displaced within the facility.

Given the framework described in this research, there are three scenarios where using this decision support tool could be utilised to improve overall plant energy efficiency:

- Recovery of WHE energy within an existing manufacturing plant (demonstrated in the present case study);
- Implementing WHER within a reconfigurable manufacturing system (where regular analysis and system changes would be required);
- Process design stage of a manufacturing system with WHER consideration.

It is considered therefore that the framework could be widely applicable to old and new facilities alike and provides a method for relatively quickly deciding upon whether energy recovery might be a suitable investment and more specifically which technologies would be most suitable for various scenarios. The framework could be considered onerous to potential users if relevant skills, energy meters and/or data does not already exist within a company, and for these reasons it is suggested that application of the WHE assessment method could be implemented by a third party.

There are some technical limitations to the framework in its current format which could direct further development:

- The life-cycle environmental impact of energy recovery technologies are not considered in the current framework – only the energy/CO<sub>2</sub> savings to the host organisation – therefore true environmental benefits/deficits are not revealed.
- The framework relies on historical (or simulated) data to match sources and sinks and determine the most appropriate technologies for energy recovery. This works best for facilities that operate consistently over long periods of time and less well with highly dynamic

facilities which might for example run short and varied production campaigns (e.g. such as those described by Industrie 4.0).

- The software which has been created to help implement the framework still requires some expertise (in MATLAB®) to operate, and so for distributed use, further developments are required in addition to the generation of up-to-date energy recovery technology databases.

## Acknowledgements

This work was supported by the Engineering and Physical Sciences Research Council (EPSRC) UK [grant number EP/I033351/1].

## References

- [1] International Energy Agency. World energy outlook 2012. Paris: IEA Publications; 2012.
- [2] Sorrell S. Reducing energy demand: a review of issues, challenges and approaches. *Renew Sustain Energy Rev* 2015;47:74–82.
- [3] Seow Y, Rahimifard S. A framework for modelling energy consumption within manufacturing systems. *CIRP J Manuf Sci Technol* 2011;4(3):258–64.
- [4] Vallack H, Timmis A, Robinson K, Sato M. Technology innovation for energy intensive industry in the United Kingdom. York: Low Carbon Futures; 2011.
- [5] Tukker A. Eight types of product service system: eight ways to sustainability? Experiences from SusProNet. *Bus Strategy Environ* 2004;2004(13):246–60.
- [6] Neely A. Exploring the financial consequences of the servitization of manufacturing. *Oper Manage Res* 2008;1(2):103–18.
- [7] Woolley E, Sheldrick L, Arinez J, Rahimifard S. Extending the boundaries of energy management for assessing manufacturing business strategies. In: 11th Global Conference on Sustainable Manufacturing. Berlin, Germany. 2013.
- [8] Department of Business, Energy and Industrial Strategy. [https://www.gov.uk/government/statistics?keywords=&topics%5B%5D=all&departments%5B%5D=department-of-energy-climate-change&from\\_date=&to\\_date=](https://www.gov.uk/government/statistics?keywords=&topics%5B%5D=all&departments%5B%5D=department-of-energy-climate-change&from_date=&to_date=) 2016 [accessed 15.01.2018].
- [9] Chiaroni D, Chiesa M, Chiesa V, Franzò S, Frattini F, Toletti G. Introducing a new perspective for the economic evaluation of industrial energy efficiency technologies: an empirical analysis in Italy [Internet]. *Sustain Energy Technol Assess* 2016;15:1–10.
- [10] Vijayaraghavan A, Dornfeld D. Automated energy monitoring of machine tools. *CIRP Annals – Manuf Technol* 2010;59(1):21–4.
- [11] Woolley E, Seow Y, Arinez J, Rahimifard S. The changing landscape of energy management in manufacturing. In: Moya BL, Pous J, editors. *Greenhouse Gases*. Rijeka: InTech; 2016.
- [12] Caggiano A, Marzano A, Teti R. Sustainability enhancement of a turbine vane manufacturing cell through digital simulation-based design. *Energies* 2016;9(10):790.
- [13] Jadhao JS, Thombare DG. Review on exhaust gas heat recovery for I.C. engine. *Int J Eng Innovative Technol* 2013;2(12):93–100.
- [14] Rahimifard S, Seow Y, Childs T. Minimising embodied product energy to support energy efficient manufacturing. *CIRP Annals – Manuf Technol* 2010;59(1):25–8.
- [15] Department of Energy and Climate Change. The future of heating: meeting the challenge. London: DECC; 2013.
- [16] Law R, Harvey A, Reay D. Opportunities for low-grade heat recovery in the UK food processing industry. *Appl Therm Eng* 2012;53(2):188–96.
- [17] Kaushik SC, Reddy VS, Tyagi SK. Energy and exergy analyses of thermal power plants: a review. *Renew Sustain Energy Rev* 2011;15(4):1857–72.
- [18] Khodami R, Abbas Nejad A, Ali Khabbaz MR. Experimental investigation of energy and exergy efficiency of a pulsating heat pipe for chimney heat recovery [Internet]. *Sustain Energy Technol Assess* 2016;16:11–7.
- [19] Solheim A, Moxnes BP, Vamraak K, Haugland E. Energy recovery and amperage increase in aluminium cells by active cooling of the anode yokes. In: Bearne G, Dupuis M, Tarcy G, editors. *Light metals*. New Jersey: Wiley; 2009.
- [20] McKenna RC, Norman JB. Spatial modelling of industrial heat loads and recovery potentials in the UK. *Energy Policy* 2010;38(10):5878–91.
- [21] Atkins MJ, Walmsley MRW, Neale JR. Integrating heat recovery from milk powder spray dryer exhausts in the dairy industry. *Appl Therm Eng* 2011;31(13):2101–6.
- [22] Chen Q, Finney K, Li H, Zhang X, Zhou J, Sharifi V, et al. Condensing boiler applications in the process industry. *Appl Energy* 2012;89(1):30–6.
- [23] Carbon Trust. Heat recovery. London: Carbon Trust; 2011.

- [24] Markets and Markets. Waste Heat Recovery System Market by Application (Preheating and Steam & Electricity Generation), End-Use Industry (Petroleum Refining, Metal Production, Cement, Chemical, Paper & Pulp, and Textile) - Global Trends & Forecasts to 2021. 2016.
- [25] Del Borghi A, Gallo M, Del Borghi M. A survey of life cycle approaches in waste management. *Int J Life Cycle Assess* 2009 Nov 1;14(7):597–610.
- [26] Garcia-Garcia G, Woolley E, Rahimifard S, Colwill J, White R, Needham L. A methodology for sustainable management of food waste. *Waste Biomass Valorization* 2017 Sep 1;8(6):2209–27.
- [27] Luo Y, Woolley E, Rahimifard S, Simeone A. Improving energy efficiency within manufacturing by recovering waste heat energy. *J Therm Eng* 2015;1(5):337–44.
- [28] Simeone A, Luo Y, Woolley E, Rahimifard S, Boer C. A decision support system for waste heat recovery in manufacturing. *CIRP Annals Manuf Technol* 2016;65(1):21–4.
- [29] ESDU. 92013 Selection and costing of heat exchangers. London: ESDU International; 1994.
- [30] Hewitt GF, Pugh SJ. Approximate design and costing methods for heat exchangers. *Heat Transfer Eng* 2007;28(2):76–86.