CIRP Annals - Manufacturing Technology xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

Energy characterisation and benchmarking of factories

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ARTICLE INFO

Keywords:
Energy efficiency
Factory
Energy benchmarking

ABSTRACT

Energy efficiency is imperative for enhancing the competitiveness of today's manufacturing. Benchmarking can provide guidance for developing improvement strategies, which requires energy characterisation to determine the current performance, reference points and improvement potentials. However, the present developments in energy benchmarking cannot be applied to a wide range of manufacturing industries. Therefore, this paper presents a generic methodology to characterise the energy efficiency at a factory level and to derive the reference points for benchmarking. A case study is used to demonstrate the validity and applicability of the proposed method.

1. Introduction

Energy and the associated emissions are of great concerns in today's world. The manufacturing industry, in particular, is affected from this since manufacturing sector consumes nearly one-third of the global energy generated [1]. Improving energy efficiency in manufacturing can be considered as a pragmatic and an attractive solution, because it assists manufacturers to address the mentioned concerns as well as reducing their production cost, ultimately enhancing their competitiveness in the market.

In order to systematically improve the energy efficiency, it is essential to identify improvement potentials and to monitor the progress at the factory level. One approach is to derive references or targets through benchmarking which is a well-established management tool [2,3]. The present development in energy benchmarking for factories is mainly based on industrial surveys for a specific sector. For example, the Energy Star® industry programme uses statistical analysis to determine a probabilistic frontier for automotive industries [4]. The BEST (benchmarking and energy savings tool) uses a bottom-up approach to compare each unit process with a hypothetical best process from a sector-specific survey (e.g. iron and steel industry) [5]. However, those methods are limited to available industry surveys which require great efforts and need to be updated regularly. In addition, it is often unfair to compare with an external practice due to the variety of products, processes and factories.

Alternatively, benchmarking can be performed through the comparison with a theoretical limit [2]. In the context of energy benchmarking, the concept of minimal/theoretical energy requirements can serve as an unbiased reference for a given manufacturing system. Therefore, this paper aims to develop a generic methodology to derive such reference points for a given factory.

2. Analytic approach and its limitation

In order to provide the theoretical background, the analytic approach from a thermodynamic perspective is first discussed in this section. This approach is based on 'exergy' that has been defined by Sciubba and Wall [6] as 'the maximum theoretical useful work obtained if a system S is brought into thermodynamic equilibrium with the environment by means of processes in which the S interacts only with this environment'.

Gutowski et al. [7] introduced an exergy framework for manufacturing systems. Under this framework, all types of input and output streams (e.g. energy, material, waste) can be converted into a unified form, exergy. Also, this quantification offers the opportunity to estimate the minimal/theoretical energy requirement for producing one unit of product. However, this approach requires a significant amount of detailed information, which limits its applicability.

To further explore the required efforts, an exemplary case is presented, which is an aluminium remelting facility in Australia. Firstly, all main input and output streams were identified through a material and energy flow analysis. The amount of the input energy, input material, output product, and by-product (i.e. slag) was obtained from the company database, whereas the exhaust gas from the furnace was estimated theoretically. In addition, it is necessary to obtain the chemical composition and physical status (e.g. temperature, altitude) of each stream to derive the exergy coefficients. Then, the exergy due to system loss (e.g. radiation) was calculated based on the exergy balance as Eq. (1):

$$\sum Ex_m + \sum Ex_{en} = \sum Ex_p + \sum Ex_w + \sum Ex_l \quad (1)$$

where all quantities with Ex refer to the exergy, and subscripts m input materials, en input energy streams, p output product streams, w waste streams, and, l aggregate loss in the system.

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http://dx.doi.org/10.1016/j.cirp.2017.04.010
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Finally, the minimal/theoretical exergy requirement, *MExR*, was calculated as Eq. (2). Notably, the waste streams are considered unavoidable for a given technology or process (e.g. exhaust after burning gas):

$$MExR = \sum Ex_{en} - \sum Ex_l = \sum Ex_p - \sum Ex_m + \sum Ex_w \qquad (2)$$

Fig. 1 illustrates the normalised results of the exergy analysis for the exemplary case. It suggests that the current system requires a minimal of 1.53 GJ to produce 1 tonne (T) of molten aluminium.

Although the exergy analysis has been successfully applied to the exemplary case, it has failed to be extended to the entire rolled aluminium factory. Following lessons and limitations have been identified for this exergy analysis:

a. It is essential to acquire particular state change of the material/product streams throughout the entire system (both chemically and physically). This information is often not measured or recorded in the factory.
b. Exergy analysis is relatively straight for thermal and chemical processes, but not for other processes, such as machining, forming, assembly, etc.
c. The complexity of material compositions further limits the application of the exergy analysis to primary material industries. For complex products, such as vehicles, it is nearly impossible to estimate the MExR through this method.

Therefore, this calls for an alternative approach to estimate the MExR, which overcomes above limitations and challenges.

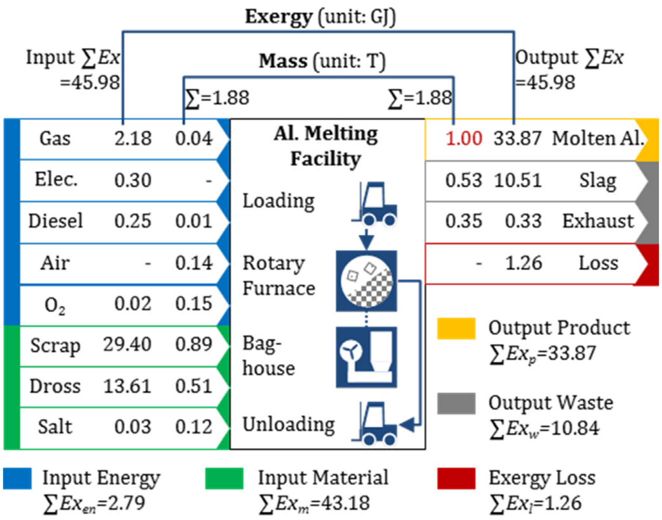

Fig. 1. Exergy analysis for producing 1 T of molten aluminium in the studied case.

3. Alternative approach: empirical characterisation

Unlike analytic approaches, empirical modelling uses observations and statistical analysis to characterise the relationship between cause (i.e. variables) and effect (i.e. responses). The derived relationship can be potentially used to estimate the theoretical limit [8]. It is often used in conjunction with Design of Experiments (DOE), and has been successfully adapted to characterise the energy efficiency of unit processes [9]. However, it is not directly applicable at a factory level. The reasons are twofold: one is that there are numerous potential factors; the other one is that it is impossible and costly to run scheduled experiments at the factory level. For example, Dehning et al. conducted a survey for the automotive industry, and identified a number of potential significant factors [10]. However, it does not address the dynamics within a given factory. As a result, a modified empirical approach is developed and explained in the following sub-sections.

3.1. Identification of main variables

Firstly, a number of observations need to be collected to provide sufficient evidence for statistical analysis. To be more specific, a monthly record of each measured stream is recommended to be obtained for a minimal one-year period. Using the same exemplary case in Section 2, the past 16-month records have been gathered and then normalised for each working day of a month. Then, a matrix scatterplot between the main input streams and output streams is generated by using MATLAB®. Fig. 2 shows the results of the exemplary case. It can be observed that the rate of molten aluminium has a strong proportional correlation with input materials and input energy, as highlighted in red. As a result, the product output rate can be used to characterise the input energy.

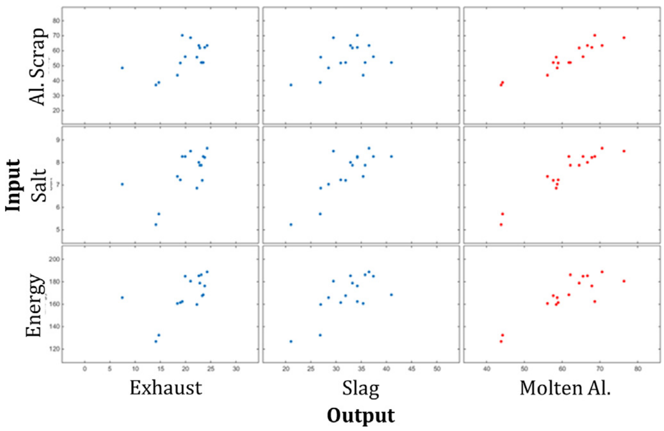

Fig. 2. Scatterplot of monthly input and output streams for the exemplary case.

3.2. Determination of the model form

Prior to the regression analysis and model-fit, the exergy analysis (presented in Section 2) is used to derive the model form for a theoretical ideal scenario, as detailed below:

i. The exergy balance (Eq. (1)) can be converted to address the input energy streams as Eq. (3)

$$\begin{aligned} Ex_{en} &= Ex_p - Ex_m + Ex_w + Ex_l \\ &= ex_p \cdot p_{out} - ex_m \cdot m_{in} + ex_w \cdot w_{out} + Ex_l \end{aligned} \qquad (3)$$

where all quantities with ex refer to specific exergy, and p_{out}, m_{in}, and w_{out} refer to the amount of output product, input materials and output waste respectively.

ii. Then, Eq. (3) can be normalised over a specified duration as a rate balance equation, and can be expressed by Eq. (4).

$$\dot{Ex}_{en} = ex_p \cdot \dot{p}_{out} - ex_m \cdot \dot{m}_{in} + ex_w \cdot \dot{w}_{out} + \dot{Ex}_l \qquad (4)$$

iii. To express the exergy requirement for producing one unit of product, Eq. (4) can be divided by the product output rate, $\dot{p}_{out}$. Then, the specific exergy requirements, *SExC*, can be depicted as Eq. (5).

$$\frac{\dot{Ex}_{en}}{\dot{p}_{out}} = SExC = ex_p - ex_m \cdot \frac{\dot{m}_{in}}{\dot{p}_{out}} + ex_w \cdot \frac{\dot{w}_{out}}{\dot{p}_{out}} + \frac{\dot{Ex}_l}{\dot{p}_{out}} \qquad (5)$$

iv. According to the bill of material, a constant input material to output product ratio, as well as waste to product ratio can be expected in an ideal scenario. The scatterplot in Fig. 2 also suggests a linear trend between the input materials (Al. scrap and salt) and output product (Molten Al). This implies that the sum of first three terms in the right-hand side of Eq. (5) can be considered as a constant and can be denoted as C_o as