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An exergy based approach to resource accounting for factories

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A B S T R A C T

Resource accounting is widely practiced to identify opportunities for improving the sustainability of industrial systems. This paper presents a conceptual method for resource accounting in factories that is based on the fundamentals of thermodynamics. The approach uses exergy analysis and treats the factory as an integrated energy system comprising a building, its technical building services and manufacturing processes. The method is illustrated with a case study of an automotive cylinder head manufacturing line in which the resource efficiency of this part of the factory is analysed for different energy system options relating to heating ventilation and air conditioning. Firstly, the baseline is compared with the use of a solar photovoltaic array to generate electricity, and then a heat recovery unit is considered. Finally, both of these options are used together, and here it was found that the non-renewable exergy supply and exergy destruction are reduced by 51.6% and 49.2% respectively. Also, it was found that a conventional energy analysis would overestimate the resource savings from reducing the hot water supplied to the heating system, since energy analysis cannot account for energy quality. Since exergy analysis accounts for both energy quality and quantity it produces a different result. The scientific value of this paper is that it presents an exergy-based approach for factory resource accounting, which is illustrated through application to a real factory. The exergy-based approach is shown to be a valuable complement to energy analysis, which could lead to a more resource efficient system design than one based on energy analysis alone.

1. Introduction

There is both increasing global competition for scarce natural resources and increasing pressure on industries to waste fewer of them. Research into industrial sustainability is one response to these trends and there is a range of approaches to this subject (Gutowski, 2011). One approach to industrial sustainability is 'resource efficient manufacturing' which implies improving a manufacturing system thus producing the same product using fewer natural resources. To calculate a factory's resource efficiency, it is necessary to account for all the resources flowing through its manufacturing systems, including materials and various forms of energy. When considering the energy flows, the most common approach is based on the first law of thermodynamics, which leads to the concept of an energy balance. This can be considered an established method of resource accounting (Bakshi et al., 2011), with the equivalent technique for material flows being the mass balance.

Henningsson et al. (2004) use mass and energy balances to calculate the financial savings that from improving resource efficiency in the UK food industry. Duflou et al. (2012) review methods used to improve resource efficiency in discrete part manufacturing including more of the industrial system than merely the factory, showing that a more holistic approach allows identifying greater opportunities for resource reuse, so that the analysis impacts more on waste reduction and resource efficiency. Similarly, Evans et al. (2009) suggest that a 'whole systems thinking' approach is well suited to the current challenges of industrial sustainability. An example of whole systems thinking is the approach taken by Ball et al. (2012) in which the concept of resource flows within manufacturing is extended to include the resources used in the factory building too. They argue that an analysis of both the factory building (and its building services) and the manufacturing processes within it can identify opportunities for improving resource efficiency that might otherwise be missed. Resource optimization tools in manufacturing commonly focus on discrete events (such as plant breakdown events, order arrivals or process completions),

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Nomenclature

c_{air}	Specific heat capacity of air
c_{water}	Specific heat capacity of water
$\dot{E}_{electrical}$	Electrical energy flow rate
$\dot{E}x_{in}$	Total exergy flow rate into the system
$\dot{E}x_{out}$	Total exergy flow rate out of the system
$\dot{E}x_{supply}$	Non-renewable exergy supply rate
$\Delta\dot{E}x_{wa}$	Water flow exergy supply rate
$\dot{E}x_{elec}$	Electricity supply rate
$\dot{E}x_{dest}$	Non-renewable exergy destruction rate
$\dot{E}x_{in-air}$	Factory space supply air flow rate
$\dot{E}x_{out-air}$	Hot air supply rate delivered by the HVAC system
$\dot{E}x_{recov}$	Exergy recovery rate
$\dot{E}x_{PV,HVAC}$	Photovoltaic power supply to HVAC system
$\dot{E}x_{totalelec}$	Total electricity demand rate of the factory
$\dot{E}x_{gains}$	Rate of exergy gains to the HVAC system from factory components
$\dot{m}_{air}$	Mass flow rate of air
$\dot{m}_{outside}$	Mass flow rate of supply air
$\dot{m}_{wa}$	Mass flow rate of water
T	Temperature of air or water stream
T_0	Weather temperature

Acronyms

AHU	Air handling unit
BMS	Building management system
DOAS	Dedicated outdoor air system
HRU	Heat recovery unit
HVAC	Heating ventilating and air conditioning system
IE	Industrial ecology
TBS	Technical building services
UH	Unit heaters
WAGES	Water, air, gas, electricity and steam.

whereas analysis of building energy systems focus on continuous energy flows. Since factories comprise both buildings and process plant, optimization tools that combine the two show great potential for resource savings (Oates et al., 2011; Herrmann and Thiede, 2009). Despeisse et al. (2012a) present a conceptual model that takes a whole system perspective on factory analysis, illustrating this with a case study (Despeisse et al., 2012b), similar work being carried out by Chen et al. (2014).

Studies based on mass and energy balances such as these exclude any notion of resource consumption since we know that during mass and energy transformations, both matter and energy are always conserved. Such techniques may quantify wasted resources but they cannot distinguish between the quality (or usefulness) of primary flows and those flows that we may label ‘waste’. The notion of waste itself is problematic since the waste from one factory may sometimes be regarded as the feedstock for another, a key insight of industrial symbiosis. Unlike mass and energy, exergy (a thermodynamic quantity based on the 2nd law of thermodynamics) is consumed during transformations and can therefore be used to account for the quality as well as the quantity of mass and energy flows. Exergy destruction can rightly be regarded as a form of waste.

The exergy of a thermodynamic system is defined as “The maximum theoretical useful work (shaft work or electrical work) obtainable as the system is brought into complete thermodynamic equilibrium with the thermodynamic environment while the system interacts with this environment only” (Tsatsaronis, 2007). It is a property of both the system and the environment when both are considered as part of a composite system (Bakshi et al., 2011). Exergy can be calculated for both energy and mass flows, representing variation of a flow from the equilibrium environment. Resources that are at the equilibrium state are considered to have no useful potential. Therefore, exergy can be used to account for mass and energy flows of varying quality levels using common units to quantify their usefulness. This gives exergy analysis an advantage over the use of mass and energy balances when analysing natural resource flows. As a result, the method is quite mature in the field of environmental science, a short summary of relevant exergy research follows.

Wall and Gong (2001) list the different types of exergy that exist in nature and show how the concept of exergy can be used to measure human impact on the environment, leading to the development of exergy-based environmental indicators. Szargut et al. (2002) also use an exergy based indicator to measure the impact of manufacturing on the environment as an ‘ecological cost’ that is based on the cumulative consumption of non-renewable exergy. Here, the distinction between renewable and non-renewable exergy consumption is important, the latter being seen as a proxy for resource depletion. Gößling-Reisemann (2008) also measures the depletion of the earth's natural resources by the consumption of non-renewable exergy. Connelly and Koshland (2001) use exergy to measure resource consumption and an evolutionary analogy to assess industrial system sustainability. They define industrial sustainability according to two key principles: increasing the proportion of exergy from renewable sources, and reducing the exergy destroyed by the industrial system.

Rosen (2009) show theoretically how exergy analysis can be used to quantify the impact of technology on the environment. Exergy analysis is used by Dewulf and Van Langenhove (2005) to develop environmental sustainability indicators to make quantitative comparisons of different technologies, using these indicators to compare solid waste treatment technologies. Exergy-based indicators have also been used in a decision support tool for power plants (Zvolinschi et al., 2007) and to analyse the impact upon sustainability of different designs of a gas turbine (Granowskii et al., 2008). A much studied large industrial system is the Kalundborg eco-industrial park in Denmark (Jacobsen, 2006) where resource efficiency is maximised by integrating the material and energy flows between the different organisations of the park. Valero et al. (2012) carried out the first exergy analysis of Kalundborg showing how exergy could be used as an indicator for resource efficiency in industrial symbiosis. A similar approach can be used to account for resources at a national scale, as shown by Chen et al. (2006) who use exergy to measure the resource efficiency of China. Further applications of exergy analysis to industrial sustainability can be found in review articles, such as those by Boroum and Jazi et al. (2013) and Sciubba and Wall (2010). Together, these studies suggest that exergy can be used to measure industrial sustainability at any scale.

It is appropriate at this stage to consider the usefulness of exergy analysis to manufacturing, in particular its application to the material and energy flows within and between the processes and building services of a factory, to explore any possible benefits compared to the traditional approach of mass and energy balances.