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Towards a coherent multi-level framework for resource accounting

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ABSTRACT

With increasing resource scarcity and environmental impacts resulting from inefficient resource utilisation, accounting for resource consumption along the life cycle of a product or service becomes critical for designing production–consumption systems. This work aims at developing a coherent framework for resource accounting to support the evaluation of alternatives for production and consumption activities. The framework provides an understanding of resource utilisation at unit, process, inter-process and production–consumption levels within a system. The multilevel characteristic of this framework allows a comprehensive and holistic view of a system with the potential to reveal how decisions at one level would affect other levels of the system. Based on such a multilevel view, a unique adaptation of the Cumulative Exergy Resource Accounting method is proposed to quantify resource consumption associated with both technological and natural processes. This work also differentiates between and accounts for the operational resource consumption in resource extraction, agriculture and manufacturing and for the capital resource consumption for providing machinery and infrastructure. This is a practical framework for resource accounting that can be used by process engineers and local planners to support decision making regarding alternative system designs, gain insights on the performance of a production system and devise design options including retrofits for improving the overall resource efficiency of a system. By revealing the resource consumption through each system layer, the framework provides a robust and transparent way to capture effects of decision making during design or retrofitting of processes in order to find the most efficient design options. In addition, the framework can be applied to support research in other areas such as those addressing the social, cultural and business perspectives of resource management. Finally, a case study on the production and consumption of sugarcane ethanol is used to illustrate the features of the proposed framework. The framework proved useful in assessing the effects of design decisions at the various levels, such as choosing between molecular sieve and azeotropic distillation at the unit level, adoption of water recycling at the process level, and bagasse exchange flows at inter-process level. The proposed systematic approach has given insights into how changes in resource consumption occur at different levels.

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1. Introduction

Natural resources are the ultimate source of all the goods and services to meet human needs (e.g. food, energy, water). With world population reaching 7 billion people (USCB, 2013) and continuing upwards, and overall standards of living rising, there is inevitably a subsequent increase in the consumption of natural resources. There are mounting concerns that the supply of key resources such as energy, water and materials would be insufficient to meet the needs of a rising world population. Resource scarcity has also led some commodity prices to rise significantly while depletion of fossil fuels has will contribute to rising energy prices (Krautkraemer, 2005). Furthermore, inefficient use and over-exploitation of resources have adverse impacts on the local environment and contribute to climate change (Allwood et al., 2011; Huijbregts et al., 2010). In this context, improving resource efficiency by producing, processing and consuming Earth's limited resources in a sustainable manner while minimising impacts on the environment from the overall life cycle of the resource (UNEP, 2012) can bring significant economic benefits and boost

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competitiveness (EC, 2013). Appropriate tools and techniques are required for the realisation of these benefits. Resource accounting becomes thus an important approach that can be used to assist decision making and system design, gain insights into the performance of a production system and devise options for improving resource efficiency while minimising impacts on the environment.

Extensive work has been done on resource accounting, including particularly those studies based on exergy as reviewed by Gaudreau (2009). Exergy, defined as the maximum available energy to do useful work, is a thermodynamic measure of energy quality and a more insightful indicator of resource consumption as compared to energy and mass (Amini et al., 2006). It is a universal quantity that can represent a wide range of material and energy streams, the contribution of non-energetic resources (e.g. labour), ecological products and services (Hau and Bakshi, 2004) and the environmental impacts of pollutants (Jorgensen, 1997) as opposed to mass and energy based methods (Ukidwe and Bakshi, 2004). The most widely acknowledged exergy based methods for resource accounting which adopt a Life Cycle Assessment (LCA) approach include (a) Cumulative Exergy Consumption (CEC) by Szargut et al. (1988) which accounts for the material and energetic exergy resource inputs from extraction to industrial manufacture of the product/service, (b) Industrial Cumulative Exergy Consumption (ICEC) which is similar to CEC but focuses on industrial systems (Ukidwe and Bakshi, 2007; Zhang et al., 2010), (c) Extended Exergy Accounting (EEA) which is an extension of Szargut's CEC and additionally accounts for non-energetic resources such as money, labour and environmental remediation costs for zero environmental impact by technological processes (Sciubba, 2001), (d) Ecological Cumulative Exergy Consumption (ECEC) which is based on ICEC but extends its boundary to account for the total exergy consumed in ecological processes for the production of natural resources as well as for assimilating pollutants (Hau and Bakshi, 2004) using the concepts of emergy (Odum, 1996) and (e) Cumulative Exergy Extraction from the Natural Environment (CEENE) developed by Dewulf et al. (2007) which offers a more comprehensive accounting of all natural resources including land use; the latter has been overlooked in the other resource accounting methods. More recent applications of exergy based methods include its use in LCA to assess alternative soil remediation technologies (Rocco et al., 2015), attempts to include economic and environmental factors in ECEC of industrial processes (Yang et al., 2015) and the extension of the classical Economic Order Quantity (EOQ) model to include sustainability factors such as labour, capital and environment based on EEA approach (Jawad et al., 2015).

Besides, previous studies, especially those by Hau and Bakshi (2004), Yi et al. (2004) and Liao et al. (2012), have recognised the need for a multilevel analysis for resource accounting, based on exergy and with emphasis on the system boundary, as opposed to a narrow analysis focused on individual processes which might shift the resource consumption impacts to other parts of the value chain of the product or service. A methodological framework has been developed by Hanes and Bakshi (2015a, 2015b) to address analyses at different scales. However, the existing studies do not offer a detailed multilevel analysis of the processes and flows pertaining to resource consumption at the various levels of a particular system. Such analysis is required to reveal how a resource, before and after being processed at different stages, flows within the system, which is essential for the identification of potential synergistic integration with flows linked to other products or services in the system. Furthermore, previous studies have not focused on a holistic quantitative study encompassing at the same time ecosystems (i.e. natural processes), production, and consumption of desired product or service (i.e. human systems). In particular, the consumption side of a product or service has largely been overlooked. Additionally in terms of scope it can be observed that the resource burdens of constructing plant, equipment and machinery have also been largely overlooked in existing resource accounting methods, with the importance of quantitatively accounting for these resources rarely studied. Finally, while the most recent studies on resource accounting have attempted to include a wide range of resources, the admissibility of the inclusion of money and potential double-counting of labour and money resources are still highly controversial (Rocco et al., 2013).

This work will attempt to address the above shortcomings by proposing a coherent framework for resource accounting. Conceptually, a framework that articulates the key aspects such as system boundary, types of flows and processes, principles for determining resource consumption to avoid ambiguity and double-counting, and multiple levels of analysis will be presented. Building on the conceptual framework, a quantitative approach to resource accounting based on the concept of cumulative exergy consumption will be described. The scope of the proposed framework is to assess resource consumption from a technical perspective and aims to provide support for decision making at the technical level of interest to process engineers and inform decision-makers in industry, government or non-government organisations particularly for the purpose of strategic planning, product design or redesign. In addition, the framework has the potential to provide solid "physics" to support future research that focuses on the social, political, cultural and business aspects of this area, as well as wider environmental and economic performance. One of the major limitations of the approach is the uncertainty associated with the data on cumulative exergy of the components in the system. Data uncertainty appears to be a common limitation to holistic approaches to resource assessment (Brown and Ulgiati, 2010; Yang et al., 2010). In a practical application, it may be addressed by a careful combination of quality sources of cumulative exergy consumption data, possibly supplemented by other types of data sources such as LCA databases. Besides, this approach currently does not take into account the full range of environmental impacts such as climate change effects, toxicity and impacts of monoculture on biodiversity and offers no indication on resource depletion. However, by combining the proposed system characterisation and modelling of resource flows with other approaches such as LCA, the wider environmental implications of a system can be assessed. These limitations must be considered when interpreting the results obtained from this approach. The proposed framework will be demonstrated through a case study on the production and consumption of sugarcane bioethanol.

2. Materials and methods

The approach developed in this work has three main parts, comprising (i) a conceptual framework for characterising a system, (ii) a multilevel structure that supports the development of a coherent and transparent resource accounting and (iii) the formulation of resource accounting algebra for the quantitative assessment of resource consumption at the different levels. These parts are explained respectively in sections 2.1, 2.2 and 2.3, and a summary of the key elements of the framework is given in section 2.4.

2.1. Conceptual framework for resource accounting

A system to which resource accounting is applied is defined by (i) the resource-embedded incoming *flows* that enter the system from its *environment*, (ii) the *process* or processes that convert the flows from the environment and (iii) the outgoing flows produced by the process(es) that leave the system and enter its environment.

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