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Fully integrated modelling for sustainability assessment of resource recovery from waste

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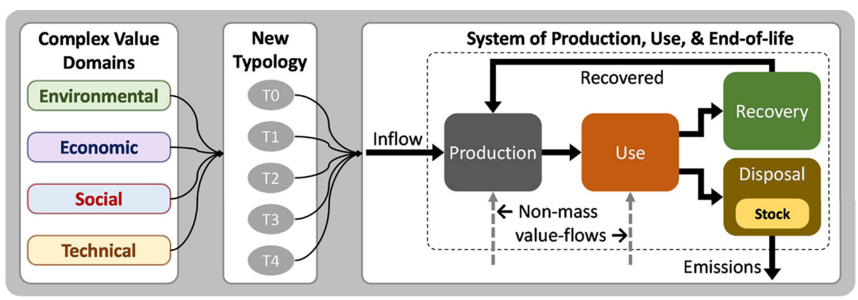
HIGHLIGHTS

- We develop a multidimensional model for assessing resource recovery systems.
- Social, environmental, technical and economic domains of value are fully integrated.
- We propose a new typology for metrics better suited to integrated modelling.
- We apply the model to a case linking electricity and concrete/cement production.
- Interdependencies between domains and temporal dynamics can be modelled.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper presents an integrated modelling approach for value assessments, focusing on resource recovery from waste. The method tracks and forecasts a range of values across *environmental*, *social*, *economic* and *technical* domains by attaching these to material-flows, thus building upon and integrating unidimensional models such as material flow analysis (MFA) and lifecycle assessment (LCA). We argue that the usual classification of metrics into these separate domains is useful for interpreting the outputs of multidimensional assessments, but unnecessary for modelling. We thus suggest that multidimensional assessments can be better performed by integrating the *calculation methods* of unidimensional models rather than their *outputs*. To achieve this, we propose a new metric typology that forms the foundation of a multidimensional model. This enables dynamic simulations to be performed with material-flows (or values in any domain) driven by changes in value in other domains. We then apply the model in an *illustrative* case highlighting links between the UK coal-based electricity-production and concrete/cement industries, investigating potential impacts that may follow the increased use of low-carbon fuels (biomass and solid recovered fuels; SRF) in the former. We explore synergies and trade-offs in value across domains and regions, e.g. how changes in carbon emissions in one part of the system may affect mortality elsewhere. This highlights the advantages of recognising complex system dynamics and making high-level inferences of their effects, even when rigorous analysis is not possible. We also indicate how changes in social, environmental and economic '*values*' can be understood as being driven by changes in the *technical value* of resources. Our work thus emphasises the advantages of building fully integrated models to inform conventional sustainability assessments, rather than applying hybrid approaches that integrate outputs from parallel models. The approach we present demonstrates that this is feasible and lays the foundations for such an integrated model.

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1. Introduction

The increasing recognition that human activities are seriously impacting on the planets capacity to support civilisation (Rockstrom et al., 2009) has led to a wide range of strategies to decarbonise and dematerialise the global economy. Achieving such significant changes will require (IPCC, 2014) more efficient production processes, more sustainable consumption patterns, radical reductions in energy and material use and waste generation, enhanced recovery of resources, and a socio-political environment amenable to such a transition (Bailey and Wilson, 2009).

The limited remaining scope for improvements in technological-efficiency of individual production-processes (Allwood et al., 2012) makes it essential for environmental impacts and material demands of production and consumption to be considered systemically. This *lifecycle* thinking is central to concepts such as *Sustainable Consumption and Production* (SCP) (Lebel and Lorek, 2008) and *Circular Economy* (Gregson et al., 2015), and to various established methods for environmental impact assessments such as *Life Cycle Assessment* (LCA) (Guinée et al., 2011), *Material Flow Analysis* (MFA) (Cencic and Rechberger, 2008), *Environmental Cost-Benefit Analysis* (ECBA) (Atkinson and Mourato, 2008) and *Environmentally Extended Input-Output Analysis* (EEIOA) (Barrett et al., 2013).

However, it has always been recognised that sustainability assessments must look beyond environmental impacts to consider a concept of sustainability encompassing all three primary domains of value: environmental, social and economic (UNCED, 1992; Zamagni et al., 2013). Accordingly, a number of methods have been developed (Sala et al., 2013b) that typically apply techniques similar to LCA in other domains, such as *Social Life Cycle Assessment* (sLCA) and *Life Cycle Costing* (LCC). Over the past decade, researchers and practitioners have worked to unify these into *Lifecycle Sustainability Assessment* (LCSA) (Guinée et al., 2011; Kloepffer, 2008; Sala et al., 2015). The purpose of these developments has been to create a robust and comprehensive sustainability assessment methodology that addresses three key challenges:

1. the need for systemic approaches that combine a lifecycle perspective with a triple bottom line accounting of impacts;
2. a recognition of the interdependencies between environmental, economic and social domains of value; and
3. the ability to capture the disparate and potentially conflicting perspectives of stakeholders required for transparent decision support.

The operationalisation of LCSA frameworks remains an ongoing project with relatively few practical implementations (Onat et al., 2017; Sala et al., 2013a, 2013b).

In contexts of Resource Recovery from Waste (RRfW), integrated social, economic and environmental assessments of different system configurations are rare (Chong et al., 2016). However, to fully understand the impacts and benefits of maximising resource recovery, it is essential that systemic assessment methodologies are developed that consider interdependencies, synergies and trade-offs between different domains.[1] As in sustainability assessments more generally, attempts to maximise environmental and/or economic outcomes are not always compatible with desirable social outcomes (Velis, 2015). Developing such methods will allow systems to be designed that help us (i) move away from end-of-pipe solutions and look upstream to consider how production and consumption can be reconfigured such that materials are more easily recoverable, (ii) minimise detrimental impacts and maximise positive ones, i.e. ensuring diverse sets of values are optimised, and (iii) build resilience in the context of the social, political and economic forces and actors motivations that shape the dynamics of such systems.

The *CVORR* project (complex value optimisation for resource recovery) aims to develop such an assessment framework for RRfW systems. We consider *complex value* to be a multidimensional variable, comprising potentially incommensurable sets of individual values. These can display diverse behaviours during modelling and analysis, including complex interdependencies (as described later in Section 3), and they may be quantitative or qualitative. The framework under development is composed of three sequential processes: selection of appropriate metrics, integrated modelling, and a multi-criteria decision analysis of outputs. These are all grounded in a political economy narrative to gain insight into the socio-political context of the system being studied (Brown and Robertson, 2014). The wider framework and metric selection are presented elsewhere (Iacovidou et al., 2017a, 2017b). Here we focus upon the development and conceptualisation of the integrated model. The primary novel contribution of the model is that it offers a typology that brings values across all domains into a common framework. This, in turn, allows for an integrated assessment of complex value in which interdependencies between domains are considered.

In this article, we first outline the broader context of sustainability assessments methods and introduce a simple case study analysing links between the UK electricity-production and concrete industries. Second, we describe the structure of the model, discussing its conceptual and mathematical foundations, the required input data, and our new typology for classifying metrics of complex values. Third, we apply the model to the case study to demonstrate the value of the approach. We then draw our conclusions.

2. Background and methodology

2.1. Conceptual background

The concept of sustainable consumption and production (SCP) has climbed up the global political agenda in recent decades. It now forms the twelfth of the United Nations *Sustainable Development Goals* for 2030 and a crucial aspect is to drastically cut the generation of waste via prevention, reduction, recycling and reuse (UN, 2015). SCP aims to address sustainability in a comprehensive and holistic manner, going beyond engineering and technological solutions to also look at issues such as the dependence of consumption patterns on collective vs. individual psychology and their impacts upon wellbeing (Jackson, 2005).

The goals and value judgements of SCP analyses are particularly explicit, depending broadly upon whether researchers' tend more towards reform, revolution, or reconfiguration of current social, economic and political structures (Geels et al., 2015). Such values are highly relevant to strategies for resource recovery and waste management, as they may determine to what degree intellectual and political resources are directed towards, for example, upstream demand management or downstream waste processing systems. Moreover, they may determine where in the lifecycle of products waste reduction interventions are applied and at what actors they are aimed (households, businesses, etc.). Such values may also affect the design of sustainability assessments more broadly via the choices made when selecting methods, metrics, system boundaries, and allocation coefficients for secondary products (Hanes et al., 2015; Sala et al., 2013b). For example, the monetising of environmental and social impacts in ECBA (Kallis et al., 2013; McCauley, 2006; Millward-Hopkins, 2016) is a contentious approach that opponents have argued is fundamentally incompatible with sustainability science (Anderson et al., 2015).

For environmental assessments in contexts of resource recovery from waste, methods such as MFA and LCA are widely applied (Allesch and Brunner, 2014). Reviews of MFA applied to RRfW have indicated that it is valuable for observing how waste management systems function and understanding the pathways hazardous substances take through systems (Allesch and Brunner, 2015). Bespoke LCA tools have been developed for waste management (easetech, 2017) and reviews of LCA applied to RRfW have highlighted the

[1] Indeed, the very concept of *waste* relies upon a unidimensional mode of evaluation: i.e. a zero or negative economic value, within the contemporary political economy.