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A pathway to circular economy: Developing a conceptual framework for complex value assessment of resources recovered from waste

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ABSTRACT

The transition to a circular economy, where the value of resources is preserved in the technosphere, must be supported by policies and operational decision-making based on evidence. Existing methods used to provide this evidence (e.g. LCA, LCSA, CBA) are not robust enough to adequately address the creation and dissipation of systemic and multidimensional value that spans the social, environmental, economic and technical domains. This study proposes a novel, conceptual approach that seeks to assess how complex value is created, destroyed and distributed in resource recovery from waste systems. This approach expands beyond conventional methods of estimating value. It combines scientific and engineering methods with a socio-political narrative grounded in the systems of provision (sop) approach, and provides a comprehensive, analytical framework for making the transition to a resource-efficient future. This framework has the potential to connect bottom-up and top-down approaches in assessing resource recovery from waste systems, and address systemic challenges through transparency and flexibility, while accounting for the dynamic and non-linear nature of commodities flow and infrastructure provision in the overall system. This creates the pathway towards circular economy, and lays the foundations for future advances in computational and assessment methodologies in the field of RRfW.

1. Introduction

Global material extraction has grown to more than three times what it was four decades ago (Schaffartzik et al., 2014), and shows little sign of slowing down (Wiedmann et al., 2015). This expansion in material use is largely attributed to the prevailing take-make-use-dispose form of resource mismanagement, which depletes our stock of finite resources, causes serious damage to the capacity of our planet to continue to provide a safe habitat (Steffen et al., 2015), and generates continuously increasing amounts of waste (Schandl et al., 2016). The recent 'Global Waste Management Outlook' (GWMO) commissioned by UNEP estimated that 7–10 billion tonnes of solid waste are generated annually from urban households, commerce, industry and construction activities alone (UNEP and ISWA, 2015). Ultimately, this poses a severe threat to the stability of the global economy and ecosystems (Park and Chertow, 2014; Prendeville et al., 2014).

Regulation and policies that attempt to disrupt wasteful paradigms by mandating safe disposal and recycling of materials often fail, because of their poor enforcement and application, disparities in regulations between separated jurisdictions, and blatantly illegal movements of waste; all of which contribute to loss of valuable material that may vary from one place to another (EEA, 2012). Besides regulations and the degree to which these are enforced this variation might also be a result of the collection and reprocessing infrastructure in place; the price of primary material, the presence of markets and demand for secondary resources (materials and fuels) (ISWA, 2015); and the level of accessibility to discarded material and the potential profit made. For example, price volatility of commodities is likely to increase demand for high quality secondary (i.e. waste derived) materials in the informal waste recycling systems (waste picking) of the Global South (Velis et al., 2012b), where a human-powered fast response between demand

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and supply of secondary resources exists; whereas in the Global North, recycling infrastructure systems are supply-driven to meet statutory policy targets irrespective of demand (ISWA, 2015). In both cases, the lack of physical and/or market infrastructure to support the uptake of recyclable materials, and/or the low demand as opposed to oversupply, means that substantial amounts of waste are either not targeted for resource recovery, or are exported to global secondary material supply chains (Velis, 2015). This can have questionable environmental and public health implications; an unsettling trade-off which has been largely disregarded to date (Velis, 2014).

The loss of economic value embedded in lost materials, and their improper disposal (due to e.g. illegal dumping, open burning, or where informal recycling processes thrive) may also contribute to environmental degradation and associated health impacts (EEA, 2012). Take for example the waste electrical and electronic equipment (WEEE). Because of the diversity of materials from which most of the WEEE is made of, and the hazardous nature of some of these, their pre-treatment and recycling needs to be carried out in purpose-built facilities. Construction and operation of such facilities in the EU can be associated with high labour costs and stringent health and safety regulations; as such, WEEE is often donated/sold to low-income countries where labour costs are lower for 'reuse', or is (illegally) exported for recycling operations (Breivik et al., 2014). Lack of effective environmental legislation enforcement in these countries means that WEEE may often end up in low-quality landfills with a high probability of this waste being poorly managed (e.g. by acid leaching or open burning) (Probst et al., 2016). When the hazardous materials used in WEEE products leak into the environment, this can lead to potentially serious and persistent environmental threats, and to the serious detriment of local or global communities (Breivik et al., 2016). In such a case, economic and environmental impacts are minimised in the EU, at the cost of increased negative environmental and social impacts elsewhere; highlighting that current resource recovery systems may have hidden impacts, often divorced in time and space.

Until there is a method for identifying, estimating, evaluating and trading-off visible and hidden benefits and impacts – i.e. positive and negative changes in the social, environmental, economic, and technical domains of value – poorly-informed decisions and inappropriate interventions will continue to be made. A more sophisticated method for assessing systems from the extraction to the recovery and management of materials, components and products (MCPs) is required to gain insights on how to best preserve and recover the multi-dimensional 'complex value' of resources, defined herein as measurable benefits (positive value) and impacts (negative value) in the environmental, economic, social and technical domains (Iacovidou et al., 2017b). Such an approach could allow better support of policy and decision-making processes, preventing unintended consequences and problem-shifting; benefiting concurrently the society, economy and the environment by delivering global optimal resource recovery scenarios; and catalysing the development of new business opportunities that exploit previously overlooked residual value hiding in waste MCPs.

Therefore, this paper aims to present a new, innovative approach and framework called Complex Value Optimisation for Resource Recovery (CVORR) that seeks to assess how complex value is created, destroyed and distributed in resource recovery from waste systems. This approach looks beyond end-of-pipe solutions, examining both upstream and downstream parts of the waste producing system. The need for, and the development of this new approach are described in this paper through three sub-sections in which we:

- review some of the major issues pertinent to the concept of resource efficiency and sustainable resource management, and their evolution into the resource recovery from waste (RRfW) approach within the circular economy (CE);
- expand on the limitations of existing approaches for impact analysis, assessment and evaluation, e.g. life cycle assessment (LCA) and cost-benefit analysis (CBA), to holistically address RRfW systems, and highlight the need for adapting and expanding existing sustainability assessment approaches in order to better inform decision- and policy-making;
- address the key challenges related to measuring and evaluating aspects of complex value.

Then, the CVORR approach is presented and the framework that governs this approach is discussed regarding its potential to provide guidance for and stimulate cooperation between all actors in the RRfW system, creating the apropriate ground for moving towards a functioning CE.

2. Background

2.1. Evolution of the context of resource recovery from waste

Building on several decades of sustainable resource management initiatives that focus on primary and waste-derived resources, there is now an abundance of guiding principles, approaches and strategies that seek to remedy both the inefficient and unsustainable consumption of primary resources, and the improper management of waste, a comprehensive list of which can be found elsewhere (Glavič and Lukman, 2007; Lukman et al., 2016). Indicatively these include *dematerialisation; factor 4 and factor 10; eco-efficiency; zero waste; eco-effectiveness; cradle-to-cradle dynamic;* and *industrial ecology and symbiosis*, all of which have been developed on the basis of reducing resource production and consumption, and promoting sustainability.

A review of some of these guiding principles and approaches (in *Supplementary Materials*), suggests that the concept of sustainability is becoming more coherent; however their application is limited to the contexts in which they have been developed. Some approaches put more emphasis on reducing the amount of resources entering the waste stream and of their associated environmental impacts (e.g. through redesigning components and products, or altering the production and consumption processes across all stages of MCPs lifecycle), while others put more emphasis on increasing resource value retention. The latter approaches are developed based on the principle that MCPs are 'technical or biological nutrients' circulating in closed loops, where nothing is wasted but instead channelled to different processes depending on MCPs remaining properties and characteristics. This distinction between minimising material throughput and wastage, and maximising retention of material value has led to the development of the continuum presented in Fig. 1. As shown in Fig. 1, *dematerialisation* and *zero waste* focus on the mono-dimensional value of "quantity of material". This may be a useful proxy for some environmental impacts, but a broader concept is needed for evaluating long-term sustainability. Both *factor 4* and *factor 10* connect human wealth and well-being with resource productivity (Schmidt-Bleek, 2008; von Weizsäcker et al., 1997), but omit to account for the resource recovery at the end of MCPs lifecycles. Improved efficiency in the use of primary resources, as described by the principle of *eco-efficiency*, can cause rebound effects (Hertwich, 2005) that in the medium- to long-term lead to an increase in the global primary resource consumption; an effect known as the "Jevons paradox" (Holm and Englund, 2009). For instance, energy efficiency measures at the micro level can lead to increased economic growth and

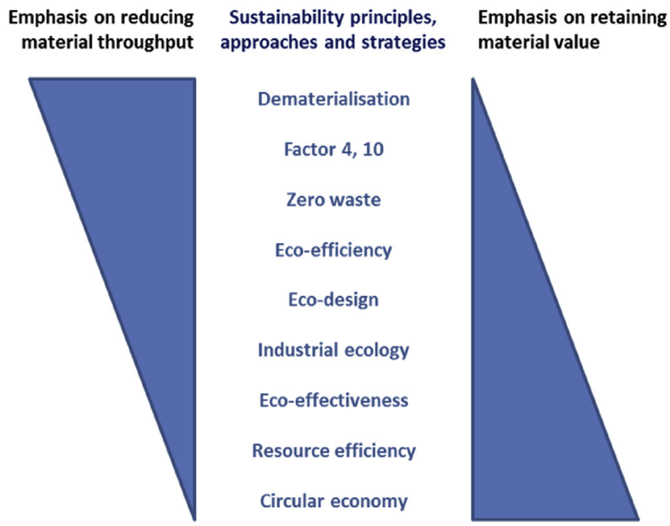

Fig. 1. Continuum of some sustainability approaches that emphasise resource management based on reducing material throughput and those based on retaining material value.

thus higher energy use at the macro level (Herring, 1999); other documented rebound effects include the introduction of low-energy light bulbs leading to people counterproductively having the lights switched on for longer, therefore leading to increased energy consumption (Azevedo, 2014).

Industrial ecology (IE) and *industrial symbiosis* (IS) are well-suited for enabling systemic thinking and modelling (Frosch, 1992; Graedel and Allenby, 2003), but their emphasis on closed-loop production processes is focused on particular environmental advantages that can also yield unexpected disadvantages. These may include added costs that exceed the benefits obtained, especially if the regulatory system within which a firm operates does not fully internalise the costs of air and water pollution or waste disposal (O'Rourke et al., 1996). In addition, the focus on energy and materials flows distracts from the optimisation of processes that foster waste minimisation, and instead operate on the basis of nurturing the connections between industries/businesses for yielding economic advantages and ensuring industry/business stability (Esty and Porter, 2005). Although these approaches provide useful contexts and guidelines for improving resource efficiency and management at a sectorial and national economy level, they do not fulfil the need for systemic analyses that provide a multi-dimensional perspective on the creation, destruction and dissipation of value associated with MCPs in complex social and political contexts.

The CE concept addresses some of the limitations of the above ideas, and attempts to synthesise their most promising aspects. CE is not a new economic model, but a commitment – through promoting reuse, repair, refurbishment, recycling, product design and manufacture, and fostering system eco-effectiveness – to prevent MCPs, and their technical properties, from being dissipated into waste (Fig. 1). This concept spurs valuable thinking around eliminating waste, decreasing primary resource dependency and increasing resilience over time (Genovese et al., 2015). It involves identifying and implementing pathways through manufacture, use, reuse and recycling processes that drastically reduce or even eliminate the generation of wastes (Bourguignon, 2016; Ellen MacArthur Foundation, 2014; European Commission, 2015).

Nonetheless, most resource recovery operations have a primary focus on preventing harmful materials from being disposed of in landfills, and protecting the local environment from the release of hazardous compounds. However, the activities involved in the reprocessing of these materials might be associated with the use of additional resources and associated pollution (as discussed for the case of WEEE above); the impacts of which are at best unclear (Wäger et al., 2011). Similarly, recycling is often presented as automatically reducing greenhouse gas (GHG) emissions, yet the energy required for the reprocessing of recovered materials may or may not involve GHG emissions that justify the savings (Turner et al., 2015). For example, recycling a PET bottle provides a net benefit in GHG of 1.5 tonnes of CO_2-e per tonne of recycled PET (Hopewell et al., 2009), whereas the recycling of paint was found to contribute more to GHG (86 kg CO_2-e per tonne) compared to its primary production (Turner et al., 2016). A true CE must consider these multidimensional benefits and impacts at the system level, rather than just focus on perceived/theoretical benefits justified by single-dimension approaches.

Consequently for RRfW to become realised as a key component of the transition to CE, a multidimensional evaluation framework is required. Assessments of RRfW processes that focus only on the combination of economic and environmental factors manifested through subsidies, taxes, regulation and market forces can distort the sustainability of the system, because of the lack of a whole-system perspective (i.e. that takes into account environmental, societal, economic and technical aspects, and of the unintended or neglected consequences in other systems or dimensions). The current conception of CE and the institutional and political frameworks in which it has been developed do not allow explicit analysis of value creation and dissipation in multiple dimensions and systems.

As such, a comprehensive analytical framework that can assess the degree to which circularity is optimal for different products, components and materials, according to the geographical location and diversity of processes and technologies used, as well as the political, institutional and socio-cultural context in which these overlap, needs to be developed. We will, in Section 3, present a novel framework as an initial response to addressing these challenges.

2.2. Models and approaches for impact assessment and valuation

Various impact assessment frameworks and methods have been used to support decision-making in wide-ranging contexts across different domains of value. The approaches reviewed herein take a systemic perspective and include *Material Flow Analysis (MFA), Life Cycle Assessment (LCA)* and its various extensions, *Life Cycle Sustainability Assessment (LCSA), Environmentally Extended Input-Output Analysis (EEIO),* and *Cost Benefit Analysis (CBA)* (Table 1). Together, these span the full spectrum of categories of sustainability assessment outlined by Sala et al. (2015) and are widely applied in waste management contexts (Allesch and Brunner, 2014). Each approach has been developed in its own context, reflected in the scope, focus and orientation (in terms of goals and outputs) of the problems they address (Sala et al., 2015). A functional scope can be based on the scale of a single product or service provided, or it can take the wider boundaries of the function provided by a single factory, geographical area, or geopolitical unit, e.g. nation state. Such systemic scopes are appropriate when making comparisons with targets also defined systemically, such as global temperature change, national CO_2 emission reduction targets or regional unemployment rates.

A more detailed analysis of the strengths and weaknesses of the above approaches is described in *Supplementary Materials (SM)*.

2.3. Key challenges to be addressed

Reflecting on the above methods, it appears that no robust,

Table 1
Key strength and major shortcoming of sustainability assessment methods.

Method	Strength	Weakness
MFA	Mass conservation principle - all material flows are accounted for throughout the product lifecycles.	No consideration of the creation or destruction of complex value.
LCA	Environmental impacts assessment over a product's life-cycle (i.e. from extraction to final sink).	Lack of transparency due to aggregation of values onto a single domain; struggles with multifunctional processes that produce multiple products.
LCSA	Holistic evaluation based on the integration of environmental (LCA), economic (LCC) and social (sLCA) impacts.	Difficulties in keeping system boundaries consistent and in integrating the three methods; no explicit consideration of value creation and destruction within the technical domain.
EEIO	Analysis of the full supply chain based on environmental and economic impacts associated with resource consumption based on all market exchanges.	No consideration of: a) trade-offs amongst environmental and economic aspects of industrial processes; b) value creation and destruction within the social and technical domains.
CBA	Identification of expected monetary or monetised costs and benefits of proposed initiatives interventions and policies across economic, social, and environmental domains over a specified time.	Monetisation of costs and benefits and their aggregation onto a single domain and a measurement unit; devaluation of future costs and benefits (through discounting).

integrated, multidimensional assessment method spanning social, environmental, economic and technical domains have yet been developed, appropriate for contexts of RRfW. Optimisation of RRfW systems require an assessment method with systemic scope (as those described above) that must (i) capture more layers of detail than MFA, (ii) demonstrate greater transparency and flexibility than LCA tools, (iii) retain a higher resolution of industrial processes, (iv) capture the social effects of projects and policies, (v) have a far more astute understanding of the complexity of value than CBA, (vi) be capable of tracking the technical value of resources (we expand on this idea below), (vii) recognise interactions between foreground and background systems (i.e. those systems within and outside the system boundaries, respectively), viii) account for the dynamic and non-linear nature of commodities flow and infrastructure provision in the overall system, and (viiii) understand the socio-political dynamics of the system under scrutiny.

In short, this will require an assessment framework and associated methodology with all the aspirations of any comprehensive sustainability assessment, but with a specific understanding of how multidimensional value is created and destroyed in contexts of RRfW. In this section, we discuss five aspects of this challenge.

2.3.1. Defining, measuring and optimising complex value

Creation and destruction of complex values in RRfW systems are inherently linked to the social and physical infrastructures that provide products and services to societies. These are distributed and captured non-uniformly across space and time and among the various actors involved in the system. They are underpinned by the transformation of material properties and products and their associated, actual or perceived, functionality/utility (Hall and Roelich, 2016).

In an assessment context, the values that the assessor deems important are implicit in (i) the problem framing and (ii) the choice of value metrics; the measurable quantities chosen to represent the dimensions and aspects of value of interest (Sala et al., 2015). However, to allow for transparency and democratic accountability those values need to be made explicit. As described in Section 2.2, existing RRfW assessments generally focus either upon a single domain of value (e.g. LCA to assess the environmental performance), or they collapse many values onto one dimension (typically monetary, as in CBA). Integrating results across domains from different, potentially inconsistent models, can also be problematic (Millward-Hopkins et al., 2018). Occasionally, economic and environmental assessments are integrated without collapsing values in this way (Vadenbo et al., 2014), but important trade-offs in values — such as potential social impacts of increasing recycling rates via exports to places of very low environmental and public/occupational health standards (Velis, 2015) — remain obscured.

In this sense, current RRfW sustainability assessments lag somewhat behind assessments in other contexts (Iacovidou et al., 2017b). Our framework thus aims to synthesise and build upon valuable work from other contexts.

2.3.2. Maintaining/transforming the technical value of resources

When components and products reach their end-of-life (EoL) stage, they may still contain significant technical value that can be recovered. Often this manifests through material properties, i.e. physical properties of products, components thereof or materials from which these are made; hence, decisions made at this stage are important and may be affected by many considerations (i.e. engineering, business, environmental, and societal factors) (Iacovidou et al., 2017b; Ziout et al., 2014). Seemingly negligible changes in chemical composition in percentage by mass terms (e.g. via contamination by surface adhesion or absorption) can cause step-changes in technical value. For example, pulverised fly ash (PFA) can be used as a low-carbon cement replacement provided it meets technical standards (BS EN 450) including a chlorine (Cl) concentration of <0.1%. Co-firing of coal with low-carbon fuels, such as solid recovered fuel, with typically tolerable Cl content of 0.5% wt. dry mass for power plants (Velis et al., 2012a) may under certain conditions (e.g. high substitution rates) lead to Cl concentrations in PFA that breach permitted limits (Sarabèr, 2012) rendering PFA unusable for concrete production. Cultural factors can also determine whether technical value is retained or destroyed, especially when dealing with materials used in food-related systems (i.e. defining avoidable vs unavoidable food waste).

Assessment methodologies should also be able to recognise that retention, transformation or loss of inherent technical value embedded in MCPs (as well as associated values in other domains) often depends on the processing operations available. This requires a different set of technical metrics associated with technologies and processes, i.e. technological advancement, reusability, mass/technical recyclability, remanufacturability, and their relevance and applicability to the recovery of MCPs (Iacovidou et al., 2017b). For example, recycling processes can often be responsible for material quality loss which relates to changes in the technical properties of a waste material (e.g. the shortening of fibres during paper recycling). Technical values may also interact with economic values, such as the market substitution ratio which reflects the ability of the market to substitute an amount of primary material with its secondary counterpart of a given technical quality (Turner et al., 2016).

The preservation of the technical value of flows is thus a necessary means to creating social and economic wellbeing and development. An appropriate set of technical values should thus be defined and monitored so that systems can be evaluated from a cradle-to-cradle perspective to determine how these values can be best preserved/transformed (Iacovidou et al., 2017b).

2.3.3. System boundaries, dynamics and scale

RRfW systems are inherently dynamic and non-linear (Clavreul et al., 2013). New technologies and materials are developed, capital stocks degrade, customers' preferences change, and previously abundant resources become depleted. This dynamic evolution of both the commodities in circulation and the infrastructure through which they pass presents a challenge to robust decision-making in resource management. This challenge must be better understood if solutions for resource recovery problems are to be found.

The issue for assessment methodologies is two-fold: (i) stocks of materials and infrastructure in the system must be included in analysis alongside flows, and (ii) prospective changes in exogenous determinants of system behaviour must be forecasted, potentially for a set of different potential future developments (Messner et al., 2006). Examples of the first issue include the availability of critical materials essential for low carbon technologies (Busch et al., 2014; Dawson et al., 2014), and the sunk costs in energy from waste plants that incentivise the continuing production of their feedstock (Chong et al., 2016). Examples of the second include the changing consumer demand for plastic bags following the introduction of a mandatory charge, and the reduction in household waste generation and/or increase in recycling rate when pay as you throw (PAYT) schemes are implemented (Watkins et al., 2012). Current assessments, however, are typically static and/or deterministic, and neglect both systems evolution in time and non-linear behaviour (Allesch and Brunner, 2014).

The issue of scale/time and level of detail of analysis is inherent into any modelling/accounting and measurement effort. Systems and process engineering has made considerable progress in defining such challenges.

2.3.4. Data gathering and uncertainty

Garbage in, garbage out — the assertion that models can only ever be as good as their inputs — is a well-known adage in modelling. Any complex value assessment will likely encounter significant difficulties when gathering data that relates metrics to the flows, stocks and processes within a system. Such data is inevitably patchy, uncertain and/or restricted by commercial sensitivity, and this is particularly true for future projections and analyses in the social and economic domains. Assessment methodologies should therefore have comprehensive, transparent strategies for accounting for uncertainty and assessing its impact on the robustness of evaluations.

2.3.5. Political economy and socio-political framework

Public and private decisions influencing resource and waste management take place: within the framework of historically contingent socio-political institutions (e.g. liberal democracy, consumer society, atheistic/humanistic/hedonistic values prevailing); under conditions of the contemporary political economy (e.g. highly financialised, globalised, and deindustrialising capitalistic market systems); and the expectations and speculations of actors as to how these institutions and conditions will evolve. Resource and waste management options cannot realistically be analysed, forecasted and evaluated without understanding these elements. Evidence of the serious limitations of the standard neo-classical economic theory with respect to ecological and sustainability challenges is increasingly recognised, and hence we must draw from non-standard (heterodox) approaches to political economy and economics. This will provide decision-makers with a less abstract, more realistic and practical appreciation of economic, social, societal and governance processes that are essential to understand and reform resource and waste management patterns throughout supply chains.

Thereby, in this study we explore the application of the systems of provision (sop) approach in RRfW systems. The sop approach was originally developed for understanding consumption systems in a "vertically" integrated way (Fine and Leopold, 1993) i.e. along — and not cross-cutting — the commodity specific supply chain; '*how they variously connect production to consumption through distribution, wholesaling, retailing, and in the organisation and meaning of consumption itself within the household*' (Fine, 1997). More recently the sop approach has been expanded to analyse issues cross-cutting to parallel — but connected — sops of final consumer goods, such as infrastructure (Brown and Robertson, 2014), and financialisation (Bayliss et al., 2013). This seems to be a promising way forward to conceptualising sustainable management of natural resources or RRfW, and thereby to examine and understand the generic and sop specific aspects of the political economy relevant for optimising complex values of such systems. However, at this point in time it cannot be excluded that it is more useful to conceptualise RRfW as a separate system of provision (of secondary raw materials and a cleaner environment).

A further advantage of sop is that it is open to, or rather prefers, a multi-dimensional approach to value assessment, contrary to CBA as explained above. It also goes beyond the simplistic state-market dichotomy that is a concept of limited analytical power, especially in the waste sector. This open-ended nature of the sop approach means that it is suitable to inform all stages of our assessment framework; from understanding the current functioning of production and consumption systems, operationalising performance criteria to reconfiguring systems and selecting more appropriate metrics.

3. Methodology: the CVORR approach

In this section, we describe the conceptual CVORR framework that aims to synthesise the most relevant of the above mentioned approaches and hence expand existing sustainability assessments into the context of RRfW. The framework, illustrated in Fig. 2, is separated into three distinct phases namely, system synthesis, system analysis and system refinement, and combines scientific and engineering methods with an astute socio-political narrative grounded in reality. It utilises quantitative, technical methods while recognising the importance of qualitative descriptions and the incommensurability of complex values; measurable benefits (positive value or changes in value) and impacts (negative value or changes in value) in the environmental, economic, social and technical domains.

Upon selection of the resource recovery system, the selection, appraisal and evaluation of the suite of complex values that govern the RRfW system that is to be assessed is realised, following the various stages of the framework, as illustrated in Fig. 2, and described below:

Material flow analysis and conceptual value assessment: This stage involves a preliminary design of the RRfW system by making high-level inferences as to the most significant flows, processes and (changes in) complex values associated with it. The system is conceptualised via standard methods of MFA, which involve specifying system boundaries, foreground processes, inflows, intermediate flows, outflows, and stocks. Although this conceptualisation is rooted in engineering and environmental accounting, elaboration at both sectorial and wider political economy analysis (sop; as described above) levels, and consideration for the institutional context within which resource recovery systems are embedded in, can inform an improved system set-up and definition of its boundaries. These are also informed by the inflows (outflows)

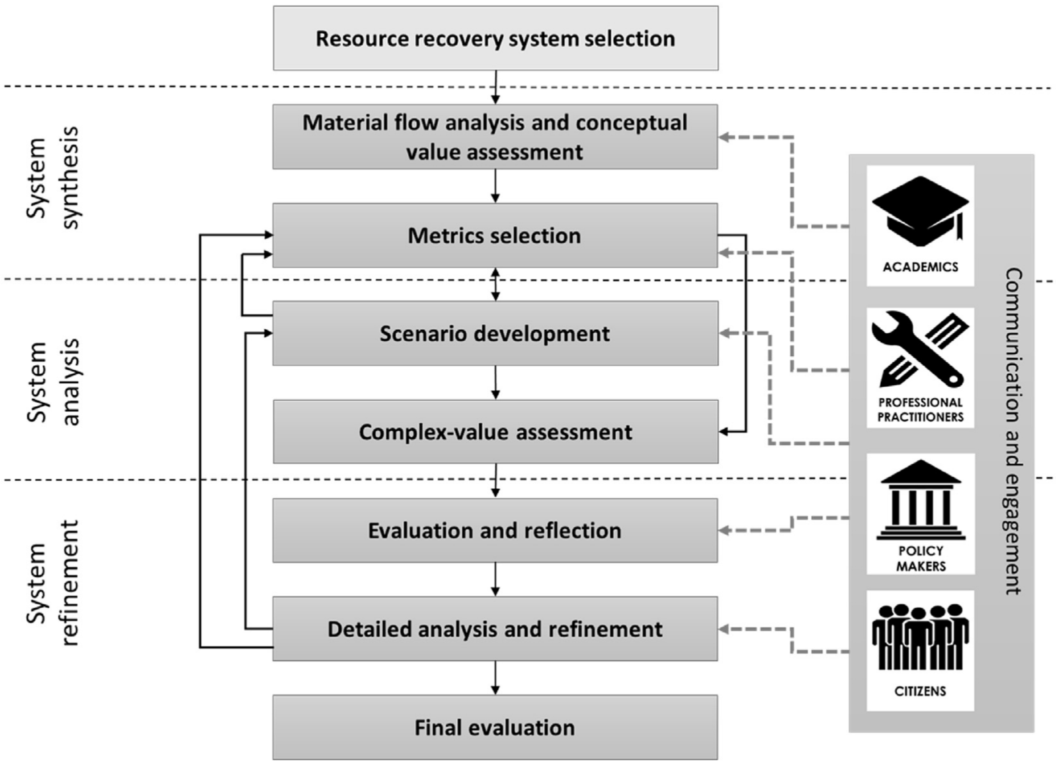

Fig. 2. Framework for complex value optimisation for resource recovery (CVORR).

origins (destinations), their physical characteristics, and how these affect the various institutions that govern their production, distribution and consumption, as well as by how the various actors, their interests, ideologies and social practices are influencing the system's functioning and evolution. Engagement with policy makers, industry, citizens, etc. is a fundamental aspect of the success of this step.

Metrics selection: This step is undertaken in parallel with *scenario development*, with each informing the other. Metrics selection involves compiling a comprehensive list of metrics suitable for capturing important changes in complex value that are expected to occur under the scenarios explored. The selection should be sufficient to provide *necessary*, yet not *excessive*, coverage of value change within the impacted domains of value. Each user has to set and justify their own set of metrics against the RRfW system they want to assess, yet selection of metrics from all four domains of value is a precondition for using the CVORR approach. Depending on the values included in the analysis, metrics can be quantitatively or qualitatively estimated. It is recognised that capturing important dynamics under system (re)configurations will require different sets of metrics for different systems and, potentially, and under very specific situations also different system boundaries for different metrics. Technical values in particular may be bespoke to certain systems and even to specific components within the same system. An operational metrics-selection framework is a key element in supporting the use of the CVORR framework and constitutes one of the topics of our future work.

Scenario development: Scenarios are designed to explore the impacts of business-as-usual systems, but also the dynamics of value change behind proposed policies, interventions, and systemic reconfigurations. This could include changes in: design and production processes or waste collection activities; regulation of waste collection, processing or disposal; products lifecycle via resale, repair, refurbishment or collection of MCPs; and/or cooperation between normally disparate actors in supply chains. Consequently, this stage draws heavily from ideas embedded in CE, such as those of IE and IS, cradle-to-cradle and eco-effectiveness, that form the foundation for considering wider social and economic benefits/impacts as well as political barriers and opportunities. Important dynamics driving the system must be clearly understood, in order to inform scenarios (interventions to be considered and appropriate time-steps and time-horizons to be implemented), and to undertake the modelling itself, as detailed below.

Complex-value assessment: This stage involves gathering data for the chosen metrics by drawing upon databases from outputs of LCA and EEIO (Iacovidou et al. 2017b), and modelling how value is transferred, transformed, created and destroyed across the system. The modelling utilises a bespoke, integrated, multidimensional assessment model that we describe elsewhere (Millward-Hopkins et al., 2018). Its integrated nature allows simulated changes in social, environmental, economic or technical values to drive the dynamics of the physically-based material flow layer, both temporally and spatially.

Evaluation and reflection: This is the penultimate stage of the framework which involves evaluation of complex value outputs and reflection upon these outputs and of the scenarios investigated, in order to enable refinement of the system design. Reflecting on the results may open further questions that should be raised for ensuring a comprehensive evaluation of the system, such as the following:

- Where are the trade-offs in value, and who wins and who loses?
- Can these trade-offs be eliminated or only managed?
- Are there (known) hidden values that remain?
- Have system boundaries been drawn widely enough to enclose all significant processes?

- If not, can they realistically be extended, or can *foreground-background* interdependencies be understood in another way – for example, via dynamic embodied values in the inputs?

Detailed analysis and refinement: This stage involves refining the system design by reflecting upon the scenarios that are to be investigated and selecting the appropriate metrics. This step necessitates a repeat of *Metrics selection* and *Scenario development* steps so that additional metrics can be considered and/or further scenarios can be designed.

Final evaluation: Finally, complex value outputs are evaluated. Rather than collapsing environmental, economic, and social metrics onto a single dimension, multi-criteria decision analysis (MCDA) is utilised as a heuristic tool to aid transparent decision-making.

In Section 3.1, we present a simple example to demonstrate the usefulness of an open, iterative, and pluralistic approach (as we propose here) for the complex task of efficiently recovering resources from waste.

3.1. Application of CVORR methodological framework using the generation and use of pulverised fly Ash (PFA) as case study

The generation of PFA by the coal-based power production sector (Drax) and its subsequent use by the concrete and cement industries in the UK, presents an important example of where the waste output of one production process becomes the resource input of another. However, co-firing of low-carbon fuels such as biomass and solid recovered fuel (SRF) with coal - emerged as one of the most important interventions in power plants owing to air pollution (e.g. CO_2, NO_x and SO_2 emissions) reduction, and the recovery of value from materials of poor technical quality that would otherwise end-up in landfills - may compromise the quality of PFA due to their relatively higher chlorine content (e.g. for SRF it can be around 1% wt.) compared to that of coal, thereby affecting PFA's end uses (Iacovidou et al., 2017a). As such, analysis and assessment of the advantages and potential trade-offs that may occur from such changes in the RRfW system is required to assess the potential dissipation and/or creation of value. Following the key steps of CVORR framework the following analysis has been performed:

Material flow analysis and conceptual value assessment: For the Drax example system, an initial conceptual model was designed that linked the UK coal-based power production sector to the UK concrete and cement industries, accounting for flows in and out of the system and between the processes within it (Fig. 3a). Then a conceptual (qualitatively) analysis of the systemic impacts of the co-firing intervention was also designed in order to consider both upstream and downstream impacts along with policy and economic drivers (Fig. 3b). Our primary interest was the (rarely discussed) downstream impacts on the construction industry of a shift from coal to low-carbon fuels including biomass and SRF.

The MFA was then constructed, after taking into account the impacts on material flows of the technical value of the ash, and the changes in carbon and particulate emissions and profits were calculated across the scenarios and time horizon (see Fig. S1 in *Supplementary Material*).

Metrics selection and scenario development: For this system, it was clear that the key environmental metric considered should be *carbon emissions*, given that this is the metric the co-firing intervention aimed to reduce. To capture the downstream impacts that our scenario (co-firing intervention) intended to explore, the diffusion of *chlorine* through the system was considered, and related this to a technical value, namely the *'value' of the secondary combustion products* (i.e. ash; *low*, *medium*, or *high*). In the social domain, several systemic effects of power generation, e.g. the emission of particulate matter and the work accidents in the various industries – domestically and abroad, may influence health outcomes. To account for these health outcomes, *particulate emissions*, was incorporated in the analysis as the relationship between biomass fuels and these emissions has long been debated; finally *profits* was selected as a generic economic metric.

Complex value assessment, evaluation and reflection: When evaluating the results, it was interesting to observe the scale of reduction in high quality ash available to the UK concrete and cement industries from the UK power production sector. This provoked us to undertake an exploratory investigation into the alternative provision of fly ash, which revealed a potential for this product to be internationally traded from major coal burning European countries such as Poland and Turkey.

Detailed analysis and refinement: To explore the implications of importing fly ash from other counties, we refined the system (shown in Fig. 3b) by adding a further potential inflow to the system (imported PFA) (as shown in Fig. 4) and formulated an additional scenario. In this scenario we added another metric, i.e. *mortality,* to estimate and allocate a proportion of the impacts of coal-combustion abroad to the final destination of the combustion by-product (i.e. PFA). We then repeated the mass-balancing and complex value analysis before undertaking final analysis and evaluation of our results.

Final evaluation: The results highlight *inter alia* that potential new international trade links may induce further offshoring of environmental and social impacts, but this essentially depends on the accounting convention applied to allocate indirect impacts. A detailed description of the analysis performed and evaluation of the results can be found elsewhere (Millward-Hopkins et al., 2018).

4. Discussion

Current waste management policy and practice is striving to depart from linear approaches and move towards sustainability, with efforts being largely concentrated on the recovery of resources from waste. At present, such efforts are usually based on the consideration of environmental and/or economic values, linked by the national and trans-national environmental legislation and its desirable and undesirable impacts on the economy, which poorly account for unwanted effects in other domains of value (i.e. social and technical). In addition, ill-understood factors arising from micro-scale methodological details of individual production or waste management facilities, and peoples' consumption and disposal patterns, is delivering misleading messages to businesses, policy and decision-makers leading to implementation of frequently ineffective measures. In this context, RRfW can rarely be optimised objectively, as there are typically incommensurable values and trade-offs.

To address the challenge of sufficiently describing, monitoring, forecasting and evaluating all significant values and trade-offs in an integrated and holistic manner, the CVORR approach has been developed. This approach sets out the key steps required for developing a dynamic, flexible, fully transparent valuation approach that goes beyond upstream and downstream processes involved in RRfW systems, making trade-offs explicit and eliminating partial and/or double-counting. Through this novel way of assessing RRfW systems, CVORR can provide guidance as to where successful interventions (i.e. changes to, elimination of, or collaboration between processes) can be made, in order to enable the transition to more sustainable and long-sighted systems of production and consumption.

CVORR is intended to provide a valuable approach for all stakeholders involved in MCPs value chain, as it can be used to assess the efficacy of multiple proposed interventions upstream

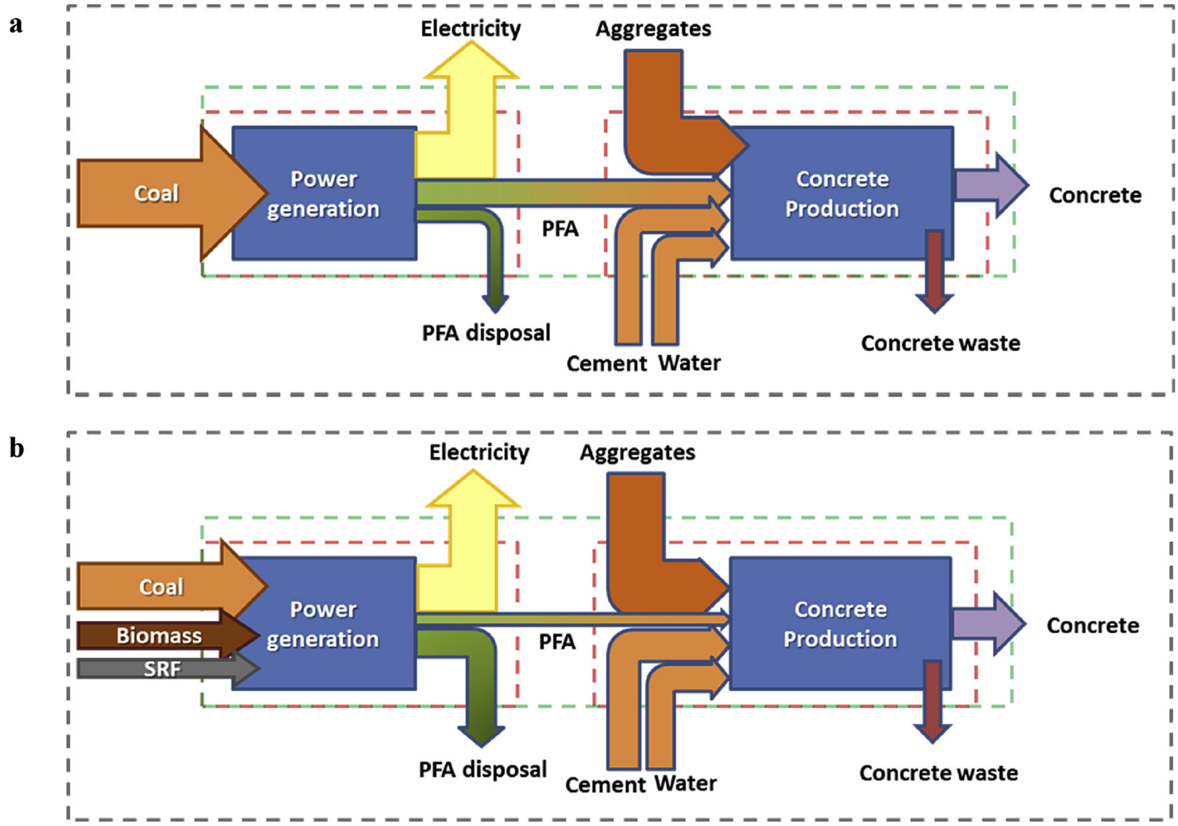

Fig. 3. Coal based power production (a) with maximum PFA recovery and use and (b) with minimal PFA recovery and use due to co-firing intervention.

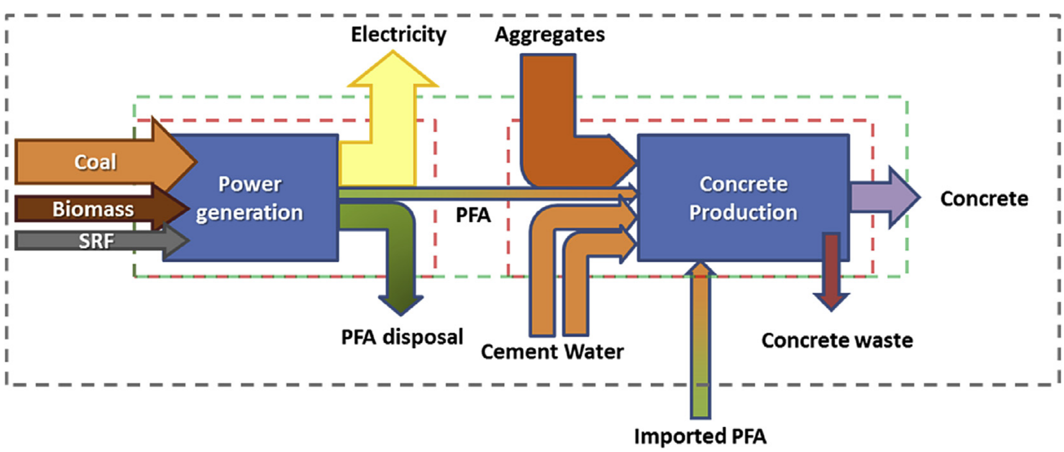

Fig. 4. Additional scenario of importing PFA.

(e.g. at the MCPs design stage) and downstream (e.g. in waste collection and reprocessing systems) of the RRfW systems. Through this multi-dimensional evaluation of interventions, CVORR will be able to support sound decision-making and help in identifying the interrelationships between different parts of the system, which can ultimately be exploited to optimise the system as a whole, and identify, attribute and distribute the multi-dimensional value generated to all stakeholders involved. This will provide opportunities for new CE business models to be developed, leading to increased employment and human well-being.

In terms of policy impact, CVORR has the potential to showcase how changes in the political and legal framework can result in the better management of resources at different levels of the economy (e.g. local and organisational to national/international levels). In particular, it can be a useful instrument to policy makers and regulators to understand how different values interact, and make informed changes in relation to the planning and environmental legislation associated with resource recovery and management; i.e. provide the right economic incentives, taxes and fines to support these changes. This would ensure that environmental legislation is not inadvertently causing upstream or downstream destruction of value, neither is it leading to unethical shifts of environmental and/or social impacts to less economically developed countries, but instead guiding transformative changes that foster multiple benefits for the environment, society and economy. Some current legislation is driven by dogma or lobbyists who either have an agenda, or do not have the analytical tools to fully assess their proposals. The CVORR approach will aim to provide clarity in these matters and prevent these voices from gaining advantage.

Finally, the CVORR approach recognises that the result of government and private sector actions 'in silos' delivers short-term solutions that create more problems and fragment knowledge. To address this sectoral short-termism, CVORR will be demonstrated at several levels, from incremental changes to radical interventions, aiding its adoption both by the commercial and regulatory sectors while stimulating communication between the two sectors. This will provide the means to promote common interests and reduce conflicts that often arise from mutual misunderstanding of motives. As well as providing professionals and industry with the capability to analyse the value of processes and practices in place, CVORR will provide the public with a more sophisticated view of specific and general waste management issues, and increase their awareness as to how they can support RRfW. Incubating a fertile ground for communication and cooperation between all RRfW stakeholders is considered to be a key precondition for CVORR's successful implementation, as it is the only way to uncover a trajectory of interventions that can initiate the transition from currently ill-performed RRfW practices to more integrated and sustainable systems.

Assessment of RRfW processes over time and space and across system boundaries requires a whole-system approach that is based on a coherent analytical framework, and a metrics selection guidance that is transparent, easy to understand, and scalable to different system boundaries. We acknowledge that for CVORR to be successful in implementing this approach it needs to avoid i) promoting vague and overly optimistic goals, ii) including metrics that delve into excessive detail, and iii) aggregating values into a single dimension. We also acknowledge that much could be gained by promoting socially, economically, and politically integrated ways to observe, assess, and evaluate multi-dimensional value. Future work involves trialling the implementation of this framework, and creating a fora for discussion and debate with a broad range of actors and interested parties across the RRfW community. This would enable us to refine the CVORR framework, making it useful for all actors involved and providing the right signals for moving towards sustainable development, and creating a viable and evidence based pathway to CE.

5. Conclusions

A paradigm shift in RRfW requires approaches that move beyond end-of-pipe solutions that focus on narrowly defined and politically, geographically and/or time-restricted environmental and human health protection. It requires approaches that can assess and evaluate complex value simultaneously in the environmental, economic, social and technical domains, and can provide the mechanisms that enable radical and systemic interventions to become mainstream. The CVORR approach, by adopting a whole-system perspective, provides a comprehensive analytical method for calculating and communicating multi-dimensional outputs, essential to support informed decision-making. Fundamental aspects that the CVORR approach will grasp include: identification of where resource-related values are created, lost or dissipated within the system; exemplification of potential loops based on CE goals; mechanisms to capture and redistribute different dimensions of values along the full supply chain (upstream and downstream); assessment of the political and legal framework within which the RRfW system interacts; and assessment of the effects of interventions on the performance of the RRfW systems, allowing an evidence-based transition to CE to become realised.

An underlying requirement of CVORR is to bring government, civil society and private sector actors involved in RRfW together, establishing a collaborative environment where RRfW systems can be holistically assessed. This systemic approach has the potential to account for the specificities of each process and the ideologies and interests of each actor involved in those processes, in order to identify the social institutions and mechanisms that must be created alongside technological interventions to enable optimisation of the RRfW processes. Only then can the synergies between processes upstream and downstream of the point where waste is generated, and the user-system interrelationships can become understood, promoting innovative and radical interventions. We conclude that the CVORR approach is not only needed for moving us closer to sustainability, but to increase the resilience of the nascent circular economy and lay the narrative foundations for future computational and assessment methodologies in the field of RRfW.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jclepro.2017.09.002.

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