A macro level of assessment of material circularity
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Citation
Aguilar Hernandez, G. A. (2021, May 6). *A macro level of assessment of material circularity*. Retrieved from https://hdl.handle.net/1887/3166494

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Title: A macro level of assessment of material circularity
Issue Date: 2021-05-06

Chapter 2

Assessing circularity interventions: A review of EEIOA-based studies

Based on: Aguilar-Hernandez, G.A., C.P. Sigüenza-Sanchez, F. Donati, J.F.D. Rodrigues, and A. Tukker. 2018. Assessing circularity interventions : a review of EEIOA-based studies. *Journal of Economic Structures* 7(14): 1–24. https://doi.org/10.1186/s40008-018-0113-3

Abstract

Environmentally extended input-output analysis (EEIOA) can be applied to assess the economic and environmental implications of a transition towards a circular economy. In spite of the existence of several such applications, a systematic assessment of the opportunities and limitations of EEIOA to quantify the impacts of circularity strategies is currently missing. This chapter brings the current state of EEIOA-based studies for assessing circularity interventions up to date and is organized around four categories: residual waste management, closing supply chains, product lifetime extension, and resource efficiency. Our findings show that residual waste management can be modelled by increasing the amount of waste flows absorbed by the waste treatment sector. Closing supply chains can be modelled by adjusting input and output coefficients to reuse and recycling activities and specifying such actions in the EEIOA model if they are not explicitly presented. Product lifetime extension can be modelled by combining an adapted final demand with adjusted input coefficients in production. The impacts of resource efficiency can be modelled by lowering input coefficients for a given output. The major limitation we found was that most EEIOA studies are performed using monetary units, while circularity policies are usually defined in physical units. This problem affects all categories of circularity interventions, but is particularly relevant for residual waste management, due to the disconnect between the monetary and physical value of waste flows. For future research, we therefore suggest the incorporation of physical and hybrid tables in the assessment of circularity interventions when using EEIOA.

Keywords: circular economy, input-output analysis, waste management, recycling, closing loops, resource efficiency, product lifetime extension

2.1. Introduction

In the early 1990s, the concept of circular economy was proposed by Pearce and Turner (1990) as a model to transform the traditional open-ended economy into an ongoing closed-loop system from a material perspective. Since then, several scholars and practitioners have adopted multiple definitions for circularity (Winans et al., 2017). After considering 114 conceptual frameworks, Kirchherr and colleagues (Kirchherr et al., 2017) define it as an economic system that substitutes product end-of-life with a set of circularity interventions.

Circularity interventions are actions or processes that preserve resources inside the economy (Bocken et al., 2017; Lieder & Rashid, 2016). Such actions are based on three principles (EMF, 2013; Ghisellini et al., 2016):

- Minimizing waste disposal through the use of waste flows as inputs for other economic activities;
- Optimizing material loops through the design of products and services that allows extending product lifetime, reuse and recycling materials at their end-of-life;
- Promoting a restorative environment through the development of renewable energy that decreases material extraction and its environmental impacts.

Implementing circularity interventions has become a prominent topic in sustainability policies (McDowall et al., 2017). For instance, the European Commission presented an action plan for the circular economy in which interventions are related to the design of long-lasting products, material closed-loops at multiple supply chain levels, resource efficiency and sustainable waste management (EC, 2015). Another example is that of the Chinese circular economy initiatives of the 1990s, which seek to prolong product lifetime and to enhance resource efficiency (Geng et al., 2012, 2016). These and other governments have implemented circularity actions as mechanisms to achieve economic prosperity and environmental sustainability (Andersen, 2007; Geissdoerfer et al., 2017; Ghisellini et al., 2016).

In order to maximize the economic and environmental benefits of circularity interventions, it is important to assess their cost-effectiveness. This can be done through the application of analytical methods that assess the impact of particular policies (Elia et al., 2017; Potting et al., 2017). However, there is no recognized framework for measuring how effective a country is in making a transition to circularity (EEA, 2016; Linder et al., 2017). Such an approach needs to integrate indicators with a clear understanding of the circularity mechanism influencing multiple economic activities and their environmental performance (Lieder & Rashid, 2016; Pauliuk, 2018).

The assessment of circularity interventions can be addressed by environmentally extended input-output analysis (EEIOA). In fact, as described further below, EEIOA has been used to evaluate the impacts of residual waste management, reusing and recycling activities, product lifetime extension, and resource efficiency (Duchin 1992; Iacovidou et al., 2017).

Assessing these interventions through EEIOA has in turn required adapting that same framework, leading to the development of new methods. For example, the study of the interdependency between production and waste generation led to the development of waste input-output models (S. Nakamura, 1999). In addition, the analysis of resource use and emissions at country level in relation to potential leakage on a global level (Böhringer &

Rutherford, 2015; WEF, 2014) resulted in the development of multiregional models for assessing the impacts embodied in international trade (Peters & Hertwich, 2009; Tukker & Dietzenbacher, 2013; Wiedmann, 2009). Finally, circularity interventions are usually implemented using financial incentives such as subsidies and taxes, that need to be endogenized to account for all impacts of the policy (Ferrão et al., 2014). The theoretical integration of financial incentives in the waste input-output model was achieved by Rodrigues et al. (2016). Such adaptations of EEIOA framework have been relevant to evaluate the potential impacts of current circular implementation.

To promote the further advancement and implementation of best practices in the use of EEIOA to assess the economic and environmental implications of circularity interventions, it is important to critically evaluate existing studies. To the best of our knowledge no such review has previously been compiled.

We fill this knowledge gap by offering a literature review of EEIOA-based circularity interventions and suggest opportunities for improvement. Chapter 2 proceeds as follows. Section 2.2 describes the data and methods used in the literature survey. Section 2.3 presents the actual literature review, describing how in the past circularity interventions have been addressed, organized around four categories: residual waste management, closing supply chains, product lifetime extension, and resource efficiency. Section 2.4 synthesizes the main methodological aspects of each intervention type. Section 2.5 then discusses the major contributions and limitations as well as opportunities for improvement and Section 2.6 closes with some final remarks.

2.2. Method and data

In order to facilitate the identification of EEIOA-based studies related to circular strategies, we organized circularity interventions based on the resource flow framework proposed by Ellen MacArthur Foundation (2013), Bocken et al. (2016), and Kirchherr et al. (Kirchherr et al., 2017). Given such framework, we then collected 13 keywords that are commonly used to identify circular strategies (Bocken et al., 2017; den Hollander et al., 2017a; Ghisellini et al., 2016). Table 2.1. shows the categories evaluated in this review as well as their definition and corresponding keywords.

Table 2.1. Circularity intervention categories

Intervention category	Description	Based on	Keywords
Residual waste management (RWM)	Related to post-consumption activities where the materials are disposed outside the economy	Ellen MacArthur Foundation (2013) Kirchherr et al. (Kirchherr et al., 2017)	landfill energy recovery waste treatment
Closing supply chains (CSC)	The re-integration of materials at different levels of the supply chain after being used, via for instance product reuse, component re-use, refurbishing, and recycling	Bocken et al. (2016) Ellen MacArthur Foundation (2013) Kirchherr et al. (Kirchherr et al., 2017)	reuse redistribution refurbishment remanufacture recycle
Product lifetime extension (PLE)	Associated with slowing-down the resource use as a consequence of extending lifetime of products, via for instance design for longevity and improved maintenance	Bocken et al. (2016) Kirchherr et al. (Kirchherr et al., 2017)	product lifetime extension maintenance repair

Resource efficiency (RE)	Processes or mechanisms which optimize resource flows by using less resources per unit produced	Bocken et al. (2016) Kirchherr et al. (Kirchherr et al., 2017)	resource efficiency material efficiency

We applied the keywords of Table 2.1 to query online databases of peer-reviewed scientific publications in English (i.e. Web of Science and Scopus) and identified 163 documents that combined “Input-Output Analysis” and at least one term related to circularity interventions when screening title, abstract and keywords. Afterwards we manually examined the content of the documents, restricting our analysis to 47 relevant documents. We then developed a backwards/forwards snowballing process (Wohlin, 2014), identifying additional relevant literature from the citation network. In total we found 93 relevant documents.

In order to identify basic attributes of the selected publications, we collected data on the year of publication and number of citations, circularity intervention covered, and EEIOA model characteristics.

Figure 2.1 shows the number of articles published in each year and the number of yearly citations of all previously published papers. The figure shows that there has been a gradual increase in the number of EEIOA-based studies that assess circularity, with 60% of all relevant literature published in the past five years. Figure 2.2 shows that the majority of studies are focused on the interaction between recycling and waste treatment systems (n[CSC+RWM] = 35). Moreover, residual waste management is the most common intervention, present in 68 study cases, followed by closing supply chains (n[CSC] = 54), product lifetime extension (n[PLE] = 17) and resource efficiency (n[RE] = 13).

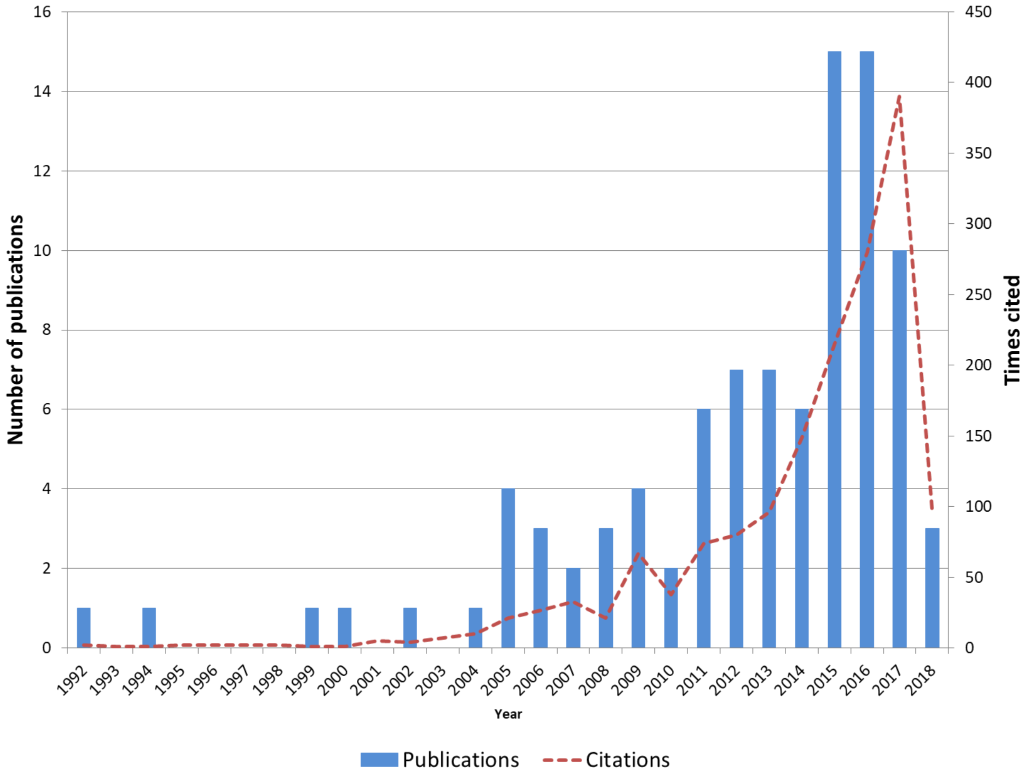

Figure 2.1. Number of publications and citations per year (status on 11 June 2018).

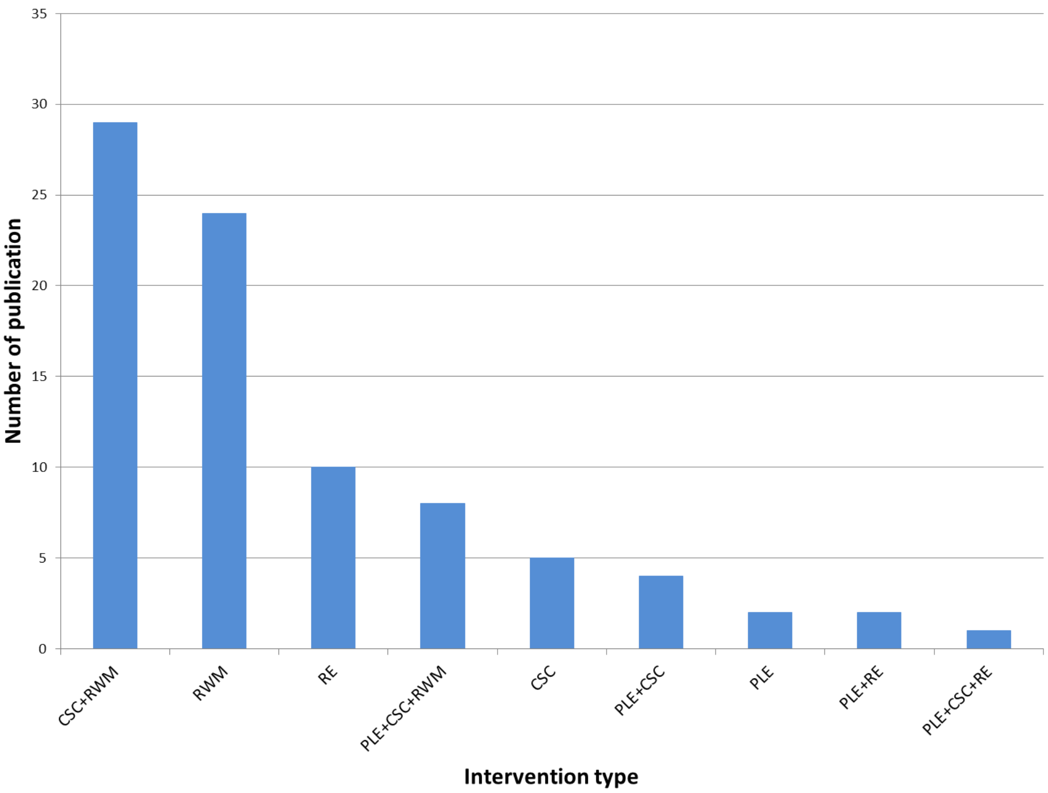

Figure 2.2. Number of publications per circularity intervention category (status on 11 June 2018). RWM = residual waste management; CSC = closing supply chains; PLE = product lifetime extension; and RE = resource efficiency

Table 2.2 presents a characterization of the top-10 most-cited papers. Table 2.3 provides a technical characterization of the type of model and/or approach used in different studies concerning the type of table, units, time and geographical scope. Most studies (88%) use harmonised input-output tables (IOTs), use hybrid units (53%), are focused on a specific year (85%) and are applied to a single country (75%). A detailed list of specific characteristics of the reviewed publication is provided in the supplementary material section.

Table 2.2. Overview of top-10 most cited articles related to the assessment of circularity interventions (status on 11 June 2018)

Reference	Intervention	Region	Sector	IO approach	Outcome	Citations
Wiedmann et al. (2015)	RE	Global	Multi-sectoral	MR EEIOA	Identification of material footprint hotspots at global scale	218
Nakamura & Kondo (2002)	CSC RWM	Japan	Waste management	WIOA	Evaluation of envrionmental impacts of waste treatment policies	146
Ferrer & Ayres (2000)	PLE CSC	France	Remanufacturing	IOA	Evaluation of economic impacts of remanufacturing sector	78
Nakamura et al. (2007)	CSC RWM	Japan	Metals	WIO-MFA	Development of framework for identify material	72

					paths along the supply chain	
Duchin (1992)	RWM	United States	Waste management	IOA	Quantification of waste disposal and income changes for different scenarios	66
Takase, Kondo & Washizu (2005)	RWM	Japan	Households	WIOA	Impacts of household consumption on CO_2 and landfill use	65
Aye et al. (2012)	PLE CSC	Australia	Buildings	Hybrid IO-LCA	Impacts of prefabricated reusable building modules on GHG emission and energy	56
Nakamura & Kondo (2006)	CSC RWM	Japan	Electrical home appliances	Hybrid IO-LCA & IO-LCC	Environmental cost of end-of-life scenarios (landfill, recycling, design for disassembly, and lifetime extension)	39
Kondo & Nakamura (2004)	PLE CSC RWM	Japan	Electrical home appliances	Hybrid IO-LCA	Environmental impacts of end-of-life scenarios (landfill, recycling, design for disassembly, and lifetime extension)	37
Nakamura (1999a)	CSC RWM	Netherlands	Waste management & recycling	WIOA	Effects of recycling, efficiency collection and efficiency technology recycling	36

Table 2.3. Summary of EEIOA model characteristic by type of table, units, time and geographical dimensions

Model characteristic		Number of publications
Table	IOTs	82
	SUTs	11
Units	Monetary	39
	Physical	5
	Hybrid	49
Time dimension	Single year	79
	Time series	14
Geographical dimension	Single region	70
	Multi region	23

Although there are examples of circular intervention assessments at the macro-economic level developed by governments and private institutions in the grey literature (for example, Bastein et al., 2013; Böhringer & Rutherford, 2015; McKinsey&Company, 2016; Pratt & Lenaghan, 2015), most of these studies apply bottom-up methods, computable general equilibrium (CGE) models or other approaches rather than EEIOA (Winning et al., 2017). Apart from the fact that we wanted to focus primarily on the peer-reviewed literature, this was an additional reason to exclude this type of studies to focus in the identification of novel methods and best practices in EEIOA-based cases. Moreover, Chapter 5 will show the application of CGE and other macroeconomic models on assessing the impacts of circularity interventions

2.3. Results and discussion

We now perform a methodological review of EEIOA-based studies which assess residual waste management, closing supply chains, product lifetime extension, and resource efficiency. Each intervention differs in its approach to splitting and extending sectors in the input-output tables, adjusting technical and final demand coefficients, and incorporating hybrid-unit data.

2.3.1. Residual waste management

Nakamura and Kondo (2009; 2002) introduced the harmonized waste input-output tables, which are used to determine the embodied waste of a certain consumption. The waste input-output analysis (WIOA) consists in a hybrid model constituted by economic and physical units in which are represented explicitly the interaction between industries and waste treatment sectors. This model allows to expand EEIOA in relation to the interdependence between goods and waste disposal.

Several studies applied the WIOA model to measure the direct and indirect waste of consumption at national level, such as Taiwan, France, and United Kingdom (Beylot, Vaxelaire, et al., 2016; Jensen et al., 2013; Liao et al., 2015; Salemdeeb et al., 2016). In a study at sub-national scale, Tsukui et al. (2011, 2017) developed an interregional WIOA to quantify the embodied waste generated by consumption patterns in the city of Tokyo. These cases applied a traditional Leontief inverse matrix to estimate the embodied goods and waste of final demand.

By applying monetary supply-use principles in the WIOA framework, Lenzen and Reynolds (2014) developed a method to construct waste supply-use tables. They considered that a supply-use approach has an advantage because it includes the allocation matrix from WIOA model into the accounting system, which enables the simultaneous generation of industry and commodities multipliers (Lenzen & Rueda-Cantuche, 2012). In addition, a supply-use model can distinguish between multiple waste types and treatment methods. The researchers demonstrated that WIOA and WSUA multipliers were equivalents by employing Miyazawa's partitioned inverse method. An application of WSUA was presented by Reynolds et al. (2014), in which the authors assessed the direct and indirect flows of waste generated by intermediate sectors of the Australian economy.

Fry et al. (2016) constructed multiregional waste supply-use tables by using Industrial Ecology Virtual Laboratory as a computational platform (Lenzen et al., 2014). They measured the waste footprint of Australian consumption considering the impacts of imports. The authors also focused on the impacts driven by consumption pattern in each Australian state and territory, which showed the waste footprint at sub-national level.

Similarly, Tisserant et al. (2017) developed a harmonized multiregional solid waste account using coefficients from physical and monetary values from EXIOBASE v2.2.0 (Tukker et al., 2013; Wood et al., 2015). They collected the data from 35 waste treatment services (measured in tonnes) that were used to calculate global waste footprint and identify the main sectors contributors per country. With the outcome of waste footprint, they evaluated the possibility of achieving targets for material recycling proposed by European Commission in the Circular Economy Package (EC, 2017).

By extending satellites accounts, Lin et al. (2013) introduced a wastewater material composition vector that distinguishes the composition of wastewater flows. In addition, Court et al. (2015) incorporated an accounting system for hazards waste materials as an extension of EEIOA.

In a study of landfilling scenarios using waste input-output tables, Yokoyama et al. (2006) created additional sectors of ‘landfill mining’ and ‘gasification’. These activities were evaluated in scenarios of increasing gasification industry demand and adopting new landfill infrastructure. The scenarios required the adaptation of technical coefficients, which imply positive and negative values depending on the interaction between industries. For the final demand, the authors assumed that consumption pattern is proportional to domestic population growth and, then, they fixed the respective final demand values. Their final outcome showed the impacts on CO_2 emissions and waste generation under certain assumptions of sustainable waste management.

Duchin (1990, 1992) proposed an analysis of waste treatment scenarios by adapting technology matrix and final demand values in EEIOA framework. In her studies, the author computed numerical examples and identified waste disposal in final consumption by adjusting final demand values in a static model. This approach described an entire economy in terms of its sectors and their interrelationships, which account for the environmental impacts.

By converting the monetary values of input-output tables into physical units, Nakamura et al. (2007) proposed a material flow analysis (MFA) that uses monetary coefficients to express inter-industrial physical flows. The waste input-output material flow analysis (WIO-MFA) was used to trace the final destination of materials and their specific elements through the supply chain (Nakajima et al., 2013; S Nakamura et al., 2009; S Nakamura & Nakajima, 2005; Ohno et al., 2014). For example, in an analysis of metal industry, Ohno et al. (2016) applied the WIO-MFA to assess the material network of metals and alloying elements. For creating the network, they developed three steps: to disaggregate sectors and convert monetary to physical units; to calculate the technical coefficients; and to multiply the input coefficient matrix with two filtering matrices, which are physical flow filter as a binary matrix for excluding non-physical flows and the loss filter matrix that removes inputs that are related to process waste.

From a product-level perspective, Nakamura and Kondo (2006) evaluated the end-of-life scenarios of electric home appliances, landfilling, shredding, recycling, and recycling with design for disassembly, by combining the WIOA framework and life cycle costing analysis. Reynolds et al. (2016) also demonstrated the use of waste input-output life cycle assessment (WIO-LCA) in the context of New Zealand food waste. They included mass values, economic cost, calories and resources wasted accounts as model inputs. In a recent study, Reutter et al. (2017) combined input-output multipliers with the Australian economic cost of food waste, which can be used to quantify the embodied net surplus of wasted food.

2.3.2. Closing supply chains

To assess 3R's economic activities (recycling, reuse and reduction), Huang et al. (1994) collected data to include these sectors in a supply-use framework. They applied a traditional Leontief approach in which each new industry produces a single economic commodity. By using such assumption, the authors allocated the monetary flows of recycling and reuse sectors in a new supply-use table that allows to analyze policy initiatives related to closing supply chains.

Nakamura (1999) applied a similar principle to create a harmonized industry-by-industry framework that accounts for recycling activities. He represented the flow of goods and services, waste, and pollutants among five industries that include recycling sectors. Such activities were expressed by both physical and monetary units because, in many cases, the market value of waste was not represented in accounting system.

In an analysis of electronics waste recycling, Choi et al. (2011) constructed an EEIOA model that collects data for recyclable end-of-life products and related economic sectors. They considered e-waste values in a satellite account that is connected to recycling sectors in a similar way as primary materials are linked to mining industries. The authors then included a new industry and product categories for recycling activities as well as the adjustment of environmental extension to represent the e-waste flows through the supply chain.

For assessing the economic impact of product recovery and remanufacturing in France, Ferrer and Ayres (2000) incorporated the remanufacturing sector in a harmonized industry-by-industry matrix. This harmonized system was adjusted to consider different demands in labor, energy, primary materials, and inputs from others economic sectors. They assumed that the manufacturing and remanufacturing final demand in physical values were equivalent, however, remanufacturing products have a lower price value. They quantified the impacts of the new sector in terms of market share and labor increase.

Beylot et al. (2016) studied the potential contribution of waste management policies to reduce carbon emissions and resources use. The authors used WIOA obtaining physical units from the French physical supply-use tables. These physical values were used to calculate technological requirement matrices related to waste flows. By considering changes in final demand coefficients, they established scenarios to increase recycling rates and to adopt available best technologies for waste incineration. The scenarios of closing supply chains were extrapolated to evaluate the short-term impacts of recycling policies.

Focusing on the case of Australian consumption, Reynolds et al. (2015) evaluated the effects of non-profit organizations on reducing food waste. In a waste supply-use table, they created a new ‘food charity’ sector, and extrapolated food waste data from government and industry reports by using a top-down estimation method. According to Reynolds et al. (2016), this technique allows to estimate waste flow per industry simultaneously but separately in which each waste flow has a unique composition that is defined by the direct production inputs. Such a relationship is provided by the technology matrix, which is also connected to available waste data to construct the new intermediate sector.

In a study investigating the impact of Portuguese packaging waste management, Ferrão et al. (2014) analyzed the effects of municipal waste and recycling strategies on economic added value and job creation. They described four basic types of recycling materials: paper and wood, plastic, glass and metals. For each material type, they considered that the magnitude of recycling sector relative to the respective non-recycling activity is brought by the ratio of the net payback value to the total amount of intra-sectoral transactions. The researchers adjusted the ratio of recycling and non-recycling materials in order to evaluate waste management scenarios for packaging alternatives.

In an analysis of tire industry, Rodrigues et al. (2016) modified a waste supply-use model to recognize the effects of policies related to closing supply chains, such as extended producers responsibility. In this scheme, waste management is financed by compensation that is represented as producers' fees in terms of waste volume processed. The researchers modeled the flow of compensation fees by introducing the financial requirements of waste management under the adapted waste supply-use table. They also adjusted the coefficients of waste treatment intermediate industries in the technical matrix and introduced an exogenous stimulus that is used to compare a reference scenario and the alternative strategy.

To explore the optimal structure of end-of-life treatment and recycling strategies, Kondo and Nakamura (2005) introduced a model that integrates WIOA into a linear programming analysis (WIO-LP). The researchers replaced the fixed constant values of waste input-output tables with an adaptable allocation matrix that can respond to specific constrains. This approach is generally defined as a minimization problem. For example, Lin (2011) applied the WIO-LP model to analyze the optimal system configuration for reducing environmental loads, such as CO_2 emissions from wastewater treatment. The researcher considered a set of constraints to reduce the amount of a certain type of environmental impacts generated by both producing and waste treatment sectors.

In a recent study, Ohno et al. (2017) evaluated the optimal scenarios of steel recycling for end-of-life vehicles in Japan through the integration of linear programming into a waste input-output material flow analysis. They considered quality-oriented scrap recycling and identified which scenarios can contribute to obtain the maximal potential of recovery for alloying elements.

By using industrial accounts for the Taiwanese economy, Chen and Ma (2015) assessed the linkages of industrial material and waste flows at national level. They rearranged the structure of the accounting system to adopt a framework that resemble the WIOA. This accounting system enables us to identify eco-industrial network patterns, for example, by examining the potential of by-products as inputs for other industries.

2.3.3. Product lifetime extension

In an assessment of the Japanese automobile industry, Kawaga et al. (2008) studied the implications of changing passenger vehicle lifetime. They applied a cumulative product lifetime model that is used to describe the patterns of final consumption. This approach is used to adjust the final demand for the scenarios of extending automobile lifetime. The authors then developed a structural decomposition analysis (SDA) with the new scenarios in order to quantify the drivers of end-of-life automobile between certain periods.

Takase et al. (2005) extended the Japanese household final demand in the WIOA for assessing waste reduction scenarios based on sharing transport services and long-lasting products. These schemes were analyzed by adjusting final demand coefficients. In sharing transportation, for example, the authors explored a scenario in which users replace private cars for the use of train. This scenario was expressed by increasing goods in public transport services and decreasing car industry outputs. They changed the coefficient in each scenario and compared the embodied waste disposal and CO_2 emissions. In addition, they incorporated potential rebound effects, by assuming a fixed budget for final demand and allocating proportionally the remaining budget to all goods in the new consumption portfolio.

In a further study, Kagawa et al. (2015) adapted WIOA framework to the lifetime distribution model, which is used to forecast secondary material flows demand and supply. They incorporated a stationary stock variable in the lifetime distribution analysis and expressed stocks, discarded and newly purchased products in function of time. These variables were inserted in the final demand, which implies a dynamic function that can be used to predict future demand. In a similar way, secondary supply flows were predicted by the disposal of scraps materials at end-of-life.

Shortly after, Nishijima (2017) used an EEIOA integrated to lifetime distribution analysis for quantifying the effect of extending air conditioners lifetime on CO_2 emissions. He calculated the new final demand for household air conditioners by multiplying the production price per air conditioner unit and the number of new air conditioners sold. By adjusting final demand, he performed a structural decomposition analysis to assess the effects of changes final demand, technical and direct CO_2 emissions confidents in air conditioners sectors.

Duchin and Levine (2010) introduced an EEIOA framework for estimating the average number of times that a resource passes through each supply chain stage. They established the principles of transforming input-output tables to an Absorbing Markov Chain (AMC) model based on their mathematical characteristics. For instance, both approaches are matrix-based and can represent transaction flows through different economic activities. The monetary flows from the input-output framework are analogous to the AMC's transition states, which represent the probability of a resource to move throughout sectors.

A key study evaluating AMC attributes is that of Eckelman et al. (2012), in which they argued that the AMC approach lays the first stone from the resource extraction as downstream perspective, instead of the upstream consumption-based approach that it is considered in a traditional EEIOA framework.

In a follow-up research, Duchin and Levine (2013) integrated the AMC into a linear programming model that distinguishes key sections of resource-specific network. This integrated model brought detailed insights about the structure of global resource interaction. Furthermore, the model constrained multiregional factors that were adapted to minimize global resource use to satisfy specified final demand.

In a study investigating the distribution of metals over time along the supply chain, Nakamura et al. (2014) established a IO-based dynamic MFA model that considers open-loop recycling and explicitly takes into account scrap quality and losses at production stage. This approach was constructed by converting the monetary coefficients of input-output tables into physical representation for the MFA model. Their work on MaTrace model was complemented by Takeyama et al. (2016) study of alloying steel elements in Japan. They applied MaTrace framework to demonstrate the potential reduction of alloying elements dissipation.

More recently, Pauliuk et al. (2017) developed the dynamic approach in a multiregional context, which was used to determine regional distribution and losses of steel production throughout multiple lifetime stages. They described their 'MaTrace' model as a supply-driven approach that traces down specific materials in life cycles of multiples products and complement the life cycle perspective, which is compared with other techniques, such as AMC and Ghosh inverse matrix. The researches also introduced a material-based circularity indicator by considering the cumulative mass of material present in the system over a certain time interval in terms of an ideal reference case.

2.3.4. Resource efficiency

In an analysis of material use for Japanese household consumption, Shigetomi et al. (2015) decomposed the household final demand into the consumption expenditures by householder age bracket. The disaggregated expenditures were used to quantify the material intensity of each household group, which represented the material hotspots of final demand. The authors identified the major contributors to the material footprint and projected future consumption trend based on a linear regression model. This analysis assumed that future household size will be proportional to the predicted population growth.

Skelton et al. (2013) explored the impacts of material efficiency on key steel-using industries by the application of multi-regional input-output (MRIO) approach. They focused on an upstream perspective to seek opportunities through the supply chain of steel. A diagonal final demand vector was applied to identify the final destination of steel output from each sector. They assessed the major contributors to the footprint in terms of their potential incentives to implement material efficiency strategies. They measured such incentives in a supply-side approach based on the Ghosh inverse matrix (Miller & Blair, 2009). This method allows to quantify the effects of changing the value added. The researchers performed price changes assuming that carbon tax scenarios are implemented. The fixed prices were applied to the system in order to measure the variation in the share of input expenditure that goes on the steel sector, which expresses the incentives of each industry for incorporating material efficiency practices.

Giljum et al. (2015) analysed geographical trade patterns identifying the embedded materials on a bilateral basis. They extended the MRIO model by adding material extraction data. This dataset was grouped into four broad types: metals, minerals, fossil fuels and biomass. Each classification was used to calculate the domestic material consumption and raw material consumption per country. In the same way, Wiedmann et al. (2015) calculated material footprint time series that were used to represent the changes of resource productivity at global level. They presented a multivariate regression analysis for countries to understand the driving forces of national material footprints. A broader perspective has been adopted by Tukker et al. (2016) who estimated resource footprint considering the indicator dashboard of resource efficiency, which includes carbon, water, energy and land metrics (EC, 2011). The authors correlated each resource footprint to quality life indicators, namely human development index and happy development index, bringing a social dimension to resource efficiency measures.

2.4. Synthesis of EEIOA frameworks on the assessment of circularity interventions

In the following section, we synthesize the findings from the literature review in terms of the current application of EEIOA in a circular economy context. To illustrate the further development and best practices of such methods, we consider a simplified waste supply-use analysis (WSUA) based on Rodrigues et al. (2016). Although we found the application of traditional EEIOA and other hybrid models, we use the waste input-output approach because it shows a suitable framework for creating end-of-life scenarios, which are usually linked to the basis of circular strategies (Kirchherr et al., 2017).

Most of the studies suggested that WIOA can be applied to measure effectively the resource flows of circularity interventions. In addition, WIOA can benefit from a supply-use approach which can express the interaction of products and industries in a higher level of detail (Lenzen & Reynolds, 2014).

Figure 2.3 shows a basic waste supply-use table that contains three main parts: final demand vector (y), technology matrix (A) and intensity vector (b′). The y-vector is subdivided into final consumption of products (y^P) and final waste generation (y^W). The A-matrix is comprised of a set of submatrices that account for the direct requirements of products or services (P), sectors or industries (S), waste (W), and waste treatment or recycling sectors (T). The b′-vector shows the element of direct impact coefficients that correspond to the production intensities of the S and T sectors (e^S and e^T respectively).We can assess the effects of incorporating circularity interventions by adjusting final demand and technology coefficients. Several authors applied changes in y-vector and A-matrix to explore the scenarios of enhancing waste treatment and recycling activities (Beylot et al., 2018; Beylot, Boitier, et al., 2016; for example, Yokoyama et al., 2006). In many cases, representing these sectors would require the extension of intermediate demand to account explicitly for the specific flows of each circular strategy.

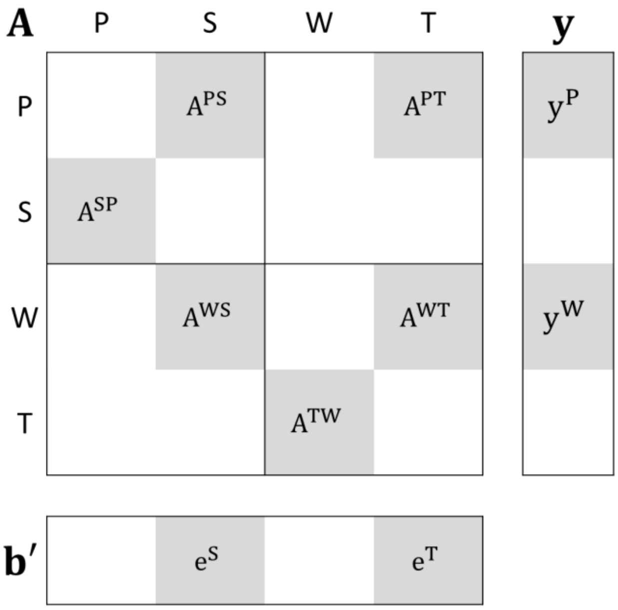

Figure 2.3. Simplified waste supply-use table. y = final demand vector; A = technology matrix; b'= intensity vector. P = product or service, S = sector or industry, W= waste, T = waste treatment or recycling activity. y^P elements are monetary values (M.EURO). y^W elements are physical units (tonnes). A^{PS} and A^{SP} elements are coefficients from monetary units (M.EUR/M.EUR). A^{WS} elements are coefficients from physical and monetary units (tonnes/M.EUR). A^{TW} and A^{WT} elements are coefficients from physical units (tonnes/tonnes). A^{PT} elements are coefficients from monetary and physical units (M.EUR/tonnes). e^S elements represent coefficients from physical values, depending on the environmental pressure, and monetary units (e.g. CO_2 tonnes /M.EUR). e^T elements represent coefficients from physical

values, depending on the environmental pressure, and physical units (e.g. CO_2 tonnes/tonnes). Empty cells contain zeros.

Considering a reference scenario $(\mathrm{y}, \mathrm{A}, \mathrm{b}')$, it is possible to adapt the intermediate flows and final demand coefficients to represent the changes of new circularity actions $(\mathrm{y}^{\mathrm{alt}}, \mathrm{A}^{\mathrm{alt}}, \mathrm{b}'^{\mathrm{alt}})$. We then can calculate the embodied impacts of the reference scenario (m) and the alternative circular strategy ($\mathrm{m}^{\mathrm{alt}}$) by a traditional Leontief inverse (Miller & Blair, 2009), as is shown in equations [2.1] and [2.2]:

$$\mathrm{m} = \mathrm{b}'(\mathrm{I} - \mathrm{A})^{-1}\mathrm{y}; \qquad [2.1]$$

$$\mathrm{m}^{\mathrm{alt}} = \mathrm{b}'^{\mathrm{alt}}(\mathrm{I} - \mathrm{A}^{\mathrm{alt}})^{-1}\mathrm{y}^{\mathrm{alt}}. \qquad [2.2]$$

The net effect of circularity interventions ($\Delta\mathrm{m}$) can be quantified by the difference of m and $\mathrm{m}^{\mathrm{alt}}$ (see equation [1.3]). This net impact could represent a measure for the potential effect of a specific circularity scenario. For example, if we analysed the implications of a certain circularity action on carbon footprint and the net effect would be a positive value (i.e. $\Delta\mathrm{m} > 0$), it means that the alternative circularity scenario has less impact than the reference stage on the embodied carbon emissions. Such avoided impact from the application of a circularity intervention could be used as point of comparison between different scenarios.

$$\Delta\mathrm{m} = (\mathrm{m} - \mathrm{m}^{\mathrm{alt}}). \qquad [2.3]$$

We can synthetize the lessons from the literature to determine which are the best practices for constructing an alternative final demand ($\mathrm{y}^{\mathrm{alt}}$), technology matrix ($\mathrm{A}^{\mathrm{alt}}$), and intensity ($\mathrm{b}'^{\mathrm{alt}}$) that determine the effects of each circularity intervention. Based on the literature review, we then deduce the causality sequence of adapting scenarios for residual waste management, closing supply chains, product lifetime extension, and resource efficiency. The following sub-sections can be used as a reference point for analysing specific scenarios of circularity transition.

We now focus on the description of primary and secondary sequences for each circularity action. Primary sequence refers to the first element of an EEIOA that can be adapted in order to represent the implementation of a circularity intervention. Following a causality chain, the secondary sequence denotes the first order of indirect impacts in response to the primary stimulus. We schematise such sequences in order to demonstrate the adjustment of waste supply-use tables for modelling each circularity alternative. Figure 2.4 indicates casual links as follows: primary sequence (green square, solid line border '—'), secondary sequence (red square, dashed line border '---'), the up arrow ('↑') represents a relative increment of the technical coefficients on A-matrix, the down arrow ('↓') indicates a relative reduction of the technical coefficients on A-matrix, and the up-down arrows ('↑↓') represents sequences in which technical coefficients can be increasing or decreasing in different sectors or industries due to the same causal link. As in Nakamura and Kondo's approach (2002), the A-matrix might contain negative values that show the causality sequence of waste flows thought economic activities. For instance, the inputs of recycling activities can be expressed as negative inputs of treatment sectors that would be required if recycling processes were not available (Shinichiro Nakamura & Kondo, 2002).

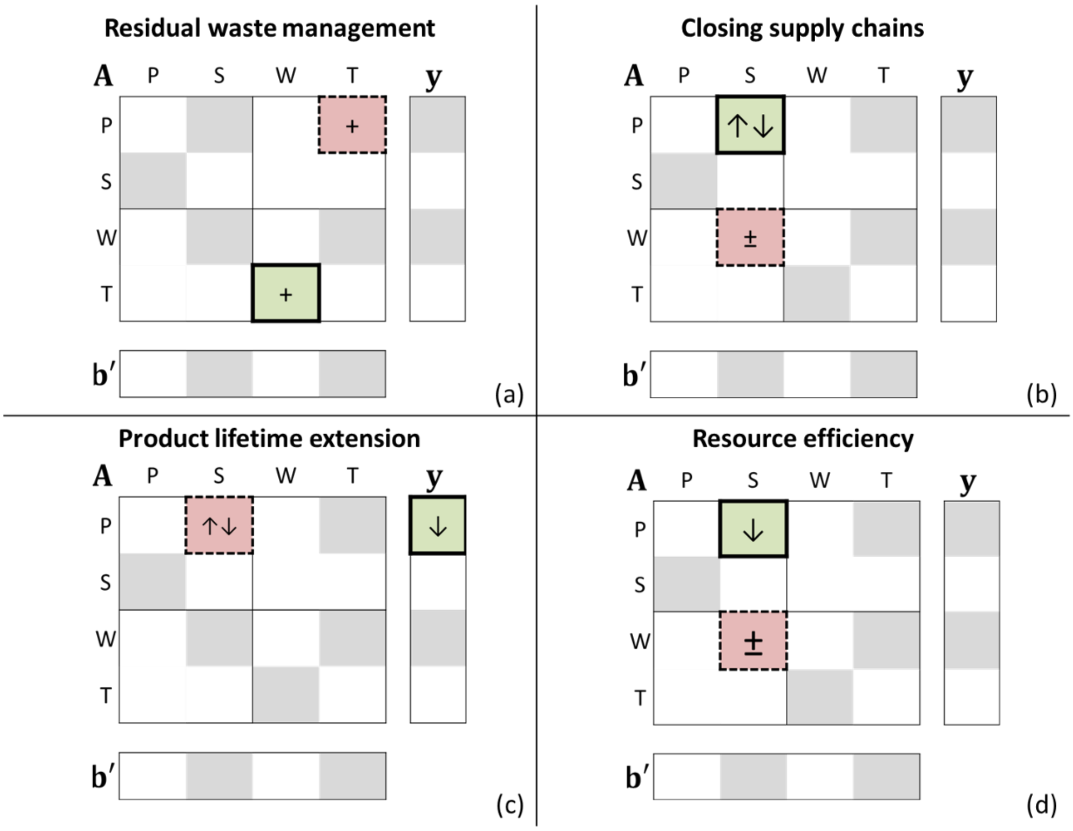

Figure 2.4. Modelling causality sequence of (a) residual waste management, (b) closing supply chains, (c) product lifetime extension, and (d) resource efficiency. y = final demand vector, A = technology matrix, b'= intensity vector. P = product or service, S = sector or industry, W= waste, T = waste treatment or recycling activity. Green square with solid line border ('—') indicates primary sequence, and red square with dash line border ('---') represents secondary sequence. '↑' indicates a relative increase of A-matrix coefficients, '↓' indicates a relative decrease of A-matrix coefficients, '↑↓' indicates a simultaneous change in different sectors or industries caused by the same causal link.

2.4.1. Modelling residual waste management

Residual waste management can be modelled by adjusting the amounts of waste treated by specific waste treatment sectors. Several authors created new waste treatment with improved technology (Beylot, Vaxelaire, et al., 2016; Liao et al., 2015; for example, S Nakamura & Kondo, 2009), which could be added to a waste supply-use table. These activities would require to augment their inputs from the rest of the economy in order to process the quantity of waste established in a specific circularity scenario (Yokoyama et al., 2006).

Figure 2.4(a) shows the causality sequence of changing the A-matrix for reducing waste scenarios. As primary sequence, wasted materials require to be absorbed by waste treatment sectors (↑ in A^{TW} elements). A secondary effect of such action is an increase on the direct requirements of waste treatment sectors in order to satisfy the new intermediate demand (↑ in A^{PT} coefficients). As a consequence of rising production, waste disposal from waste treatment activities and their suppliers are expected to increase (↑ in A^{WT} and A^{WS} elements). This sequence appears to create an ongoing loop where absorbing waste would lead to increase waste disposal in order to process the new residuals. However, disposal would need to be constrained by the processing capacity of waste treatment sectors. In our present framework, we do not focus on how capacity constraints should be modelled explicitly, nevertheless, we consider it to be an important aspect for future studies.

It is important to notice that, in some cases, the causality sequence could not be represented by changes in the A-matrix block. For example, increasing A^{TW} coefficients might not lead to an increment of A^{PT} coefficients directly. Instead, a secondary sequence can be observed in changes on the intermediate demand block of waste treatment inputs.

2.4.2. Modelling closing supply chains

Closing supply chains can be modelled by changing input and output coefficients to closed-loop activities, such as reuse and recycling sectors. These sectors can be represented as new end-of-life systems that would use waste outputs from industries as inputs to generate a usable product for the economy (Chen & Ma, 2015; S Nakamura & Kondo, 2006). In many cases, such new activities would be added to EEIOA in order to model specific material recycling (Choi et al., 2011; for example, Ferrer & Ayres, 2000; C. J. Reynolds et al., 2015).

A common assumption is that closing supply chains would drive the reduction of extracting virgin materials as a consequence of their replacement with secondary circular flows (Ferrer & Ayres, 2000). This substitutional approach can be modelled by the replacement of specific commodities in the use matrix of industries by secondary materials, components, etc. (i.e. ↑↓ in A^{PS} coefficients).

Figure 2.4(b) presents the causality sequence of closing supply chain scenarios. The primary sequence of closed-loop strategies would imply to adapt the use matrix of a specific industry. Assuming that industry (S) would replace a primary product (P') for a secondary material from a recycling activity (P''), then, the coefficients of the A^{PS}-matrix would decrease for the virgin materials (↓ for $a^{P'S}$). Likewise, the direct requirements of S would rise for the input of secondary goods (↑ for $a^{P''S}$). A proportional exchange between P' and P'' can be expressed by monetary terms, if the prices of both products are fixed, as well as by direct substitution in physical units (Ferrão et al., 2014; Ferrer & Ayres, 2000). Following the secondary sequence, we observe the adjustment of waste fractions treated by waste treatment industries (↑↓ in A^{TW} elements). Such an effect is considered because the replacement of P' for P'' could adapt as well the waste generated by industry S, and, then, changing direct requirements from waste treatment sectors in order to dispose the new fractions of waste.

2.4.3. Modelling product lifetime extension

The scenarios of extending product lifetime can be modelled by combining an adjusted final demand and the input coefficients in production sectors, next to probably a higher input of maintenance activities. In general, it is expected that the extension of product lifetime would decrease the quantity of goods consumed by final demand (Kagawa et al., 2009; Nishijima, 2017). Therefore, a primary effect of prolonging product lifetime would involve a reduction of final consumption on a certain product (y_i^P).

Figure 2.4(c) illustrates the causality chain of product lifetime extension. Assuming that a product i is designed to maximise its durability, the demand of such good would expect to decrease (↓ for y_i^P). Although this effect might imply an improvement of environmental performance from reducing the consumption of product i, the potential economic savings could be expended in other goods or services thus obtaining a rebound (Zink & Geyer, 2017).

A possible approach to account for these rebound effects is proposed by Takase et al. (2005). They suggested that the total expenditure of new final demand (x^P) would remain the same as total consumption in the reference scenario (x). By applying their assumption, we can distribute a leftover budget proportionally to the rest of goods and then include a quick estimation for the rebound effect in the alternative final demand (y^{P^*}), as is shown in equation [2.4]:

$$y^{P^*} = y^P \left(\frac{x}{x^P}\right). \qquad [2.4]$$

As a secondary effect, it is possible that extending product lifetime could potentially require the adjustment of the production recipe, which leads to change in the input requirements of industries (Bakker et al., 2014; den Hollander et al., 2017b). However, there are only limited opportunities for consumers to prolong their product's lifetime when the product design is unchanged.

Depending on the product design, some industries might require to increase their material inputs in order to manufacture a more durable product (Murray et al., 2015). This operational adjustment is expressed in figure 2.4(c) by the simultaneous increment and reduction of technology matrix coefficients (in A^{PS}). For example, if a change of the production recipe for obtaining a durable good would require to reduce the input of commodity i and to increase the input of product k, then, we can model such adjustments on the A^{PS}-matrix (by ↑ for $a^{PS}_{k,j}$ and ↓ for $a^{PS}_{i,j}$).

2.4.4. Modelling resource efficiency

In comparison with the previous interventions, resource efficiency is the least studied of circularity actions from an EEIOA perspective (see figure 2.2), and it can be one of the most interesting in terms of future development of EEIOA method. We found that studies related to resource efficiency are mostly focused on the calculation of resource footprint as an aggregated value (for example, Giljum et al., 2015; Tukker et al., 2016; Wiedmann et al., 2015). However, resource footprint by itself does not capture if resource efficiency policies would be beneficial for reducing the extraction material from the environment or if it would contribute to minimise waste disposal. For assessing the impacts of resource efficiency measures, we can consider the effects of such intervention by lowering input coefficients at the same output.

Figure 2.4(d) presents the casual links of resource efficiency actions. In terms of primary sequence, it is possible that the application of material efficiency can lead to reduce the input requirements of economic activities where such intervention is implemented (↓ in A^{PS} coefficients). In a similar sequence as in modelling closing supply chain (see section 2.4.2.), a secondary implication of changes in A^{PS} can be expected in the operational changes of waste treatment, in which the technical coefficients of waste treatment sectors can be adapted as a response of variations in waste disposal (↑↓ in A^{TW} elements). To compare different scenarios, it is important to consider an accounting system in which the A^{PS}-matrix is expressed in physical terms because the use of monetary units as proxy can misrepresent physical reality (Dietzenbacher, 2005).

2.5. Discussion

In this review, our purpose was to critically evaluate the current application of EEIOA on the assessment of circularity interventions. We now focus on the main contributions and limitations of EEIOA in order to bring a possible direction for the development of such method in the assessment of circular strategies.

From the reviewed studies, we found a common agreement on how the assessment of circularity can be benefit from the development of EEIOA in which end-of-life scenarios are integrated. Such models usually are comprised of hybrid-units in which secondary and waste flows can be considered (Lenzen & Reynolds, 2014; for example, S Nakamura & Kondo, 2009). In addition, identifying these flows at multiregional scale has led to a better understanding of the impacts of international trade on resource and waste footprints in specific countries (as in Faye Duchin & Levine, 2013; Fry et al., 2016; Tisserant et al., 2017; Tukker et al., 2016; T. O. Wiedmann et al., 2015).

On the other hand, we observed that a major aspect to develop is the representation of flows as economic transactions. The monetary values of input-output tables could not address effectively the allocation of resource flows because the monetary values per physical units can differ significantly in several supply chains (Weisz & Duchin, 2006). This variation is caused by the assumption of an average price for materials with diverse physical properties and qualities (Tukker et al., 2016).

Price variation could become a critical factor in EEIOA with high sectorial and product aggregation (Wiedmann et al., 2015). It is likely to be a limitation for adequately tracing specific resource flows. For instance, if we assessed the recycling and reuse flows of a specific material such as ‘recovered aluminum’, input-output tables with broad classification of materials and industries (e.g. ‘metal products’ and ‘mining sector’) would assume that the price per physical value of ‘recovered aluminum’ is equivalent to the value of aggregated ‘metal products’. This example shows that a highly aggregated EEIOA could in many cases be too limited to model specific material flows.

To avoid the deficiency in resolution of some EEIOA models’, a reasonable approach could be to disaggregate products and sectors in more detailed categories. The new classification may contribute to monitor specific resource flows in a circular economy model (as shown by Choi et al., 2011; Li et al., 2013). However, disaggregating sectors in EEIOA presents a challenge by itself because sectoral data may not be available at the required level of detail. This is particularly the case in waste input-output frameworks, in which many studies show a limited dataset to split and link waste treatment sectors to the rest of the economy (Salemdeeb et al., 2016).

According to the studies, a lack of data sets for waste and material recovery could represent an issue in terms of waste valuation. Several authors recognized a deficiency for accounting the economic value of waste as this could be lower or absent in the EEIOA model (Liao et al., 2015; S Nakamura, 1999). The lack of economic valuation renders input-output accounts incomplete and, in some cases, leads to the underestimation of the embodied waste generated by final demand. For example, in the study of the Australian waste footprint by Fry and colleagues (2016), waste flows related to overseas production could not be considered due to the lack of waste values in other regions. This led to an underestimation of waste footprint resulting from Australian consumption by at least 1.5 million tonnes.

Underestimating waste generation may be caused by three aspects (Tisserant et al., 2017). First, some waste treatment sectors might not be included in the EEIOA model. Second, a standard EEIOA does not consider informal or illegal activities that could affect the estimation of waste footprint. Finally, EEIOA might not capture some of the flows that are not linked to monetary or physical transactions between sectors (i.e. direct reuse flows). In general, these aspects have an impact on the quality of waste data availability in many countries, which can be a significant source of uncertainty.

To address the lack of specific-sectoral data, proxies that can be used to integrate the values of circular strategies into the EEIOA framework could be estimated. For instance, to identify the patterns of industrial waste disposal, Reynold and colleagues (2016) suggested that the shares of waste generation in New Zealand presented the same trend as others developed economies (e.g. UK and Australia) and, then, used a proxy for the estimation of waste generation. In many cases, this type of assumption introduces uncertainties that may affect the analysis reliability (Ohno et al., 2016). Although the importance of uncertainties is considered in the literature (Wiedmann 2009), most of the reviewed studies mention the level of uncertainty without addressing it in much detail, and it brings a recurrent issue about data reliability of analyzing circular economy interventions with EEIOA.

In terms of modelling circularity scenarios, EEIOA may be of limited use when assessing environmental implications in the future (de Koning, 2018). For example, by fixing technical coefficients of a circular economy scenario, EEIOA cannot capture the volume effects on prices as well as price effects on the use of certain products. Without additional model components (see, for example, Gibon et al., 2015), EEIOA has also limited opportunities to represent changes of energy systems in the future with environmental impacts that are different from the current way of production. Moreover, there is no direct feedback effect from nature to the economy in standard EEIOA, which restricts the assessment of different circularity gains.

2.6. Conclusion

This chapter presented a review of EEIOA-based studies that assessed the economic and environmental implications of residual waste management, closing supply chains, product lifetime extension, and resource efficiency interventions. We evaluated the selected articles based on their methodological characteristics in order to synthesize the main EEIOA-based frameworks used to analyze each circularity intervention. Furthermore, our results led to a point of reference for modelling future circular strategies at macro-scale by applying EEIOA.

By considering a simplified waste supply-use model, we explained the causality sequence of modelling circularity interventions. For residual waste management, a waste treatment action can be modelled by augmenting the values of waste absorbed by a certain waste treatment sector, which in turn requires more inputs from the rest of the economy in order to process the new amount of waste disposal.

Closing supply chains can be assessed by adjusting input and output coefficients for industries that adopt closed-loop strategies, which are related to the replacements of virgin materials with secondary circular flows. In addition, these interventions require to specify new sectors in the EEIOA model if the circular activities are not explicitly expressed.

Product lifetime extension can be modelled by adapting the final demand coefficients by expecting a reduction of final consumption. However, it is important to consider a potential rebound effect of prolonging product lifetime caused by the expenditures on other product or service categories from the savings on final demand. Furthermore, modelling product lifetime extension might involve accounting for potential changes of the production recipe of durable goods.

Resource efficiency intervention can be analyzed by reducing input coefficients while maintaining the output. Such action could minimize the input requirements of economic activities in which the intervention is applied, and it can be used to model the structural changes in a technology matrix caused by resource efficiency strategies.

We observe that the development of waste input-output analysis (WIOA) will dominate the assessment of circularity transition, because it is the most suitable framework to link the flows of waste and the rest of the economy in an EEIOA system. However, WIOA is constrained by the monetary flows in EEIOA (S Nakamura & Kondo, 2009), which can be considered a major limitation for the analysis of circular strategies, especially in the case of residual waste management, due to the lack of valuing waste. This challenge can be avoided by future applications of physical and hybrid tables that can be used to analyze the potential impacts of material efficiency and secondary flows more accurately (Tisserant et al., 2017).

The recent development of hybrid-unit input-output and supply-use tables, in which tangible products and waste types are expressed in physical units (i.e. mass) and service sectors in monetary units (for example, Merciai & Schmidt, 2018), will advance the modelling of circularity interventions in a consistent framework. In addition, detailed sectoral data could enable the assessment of circular strategies such as re-use, remanufacturing, and refurbishment (EMF, 2013). Combining both aspects, hybrid tables and detailed production data, would allow an improvement of current EEIOA models for assessing the economic and environmental implications of a circularity transition.

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