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Review

Input-output models and waste management analysis: A critical review

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A B S T R A C T

We analyze 78 case studies that applied an input-output (IO) model for waste management analyses. We categorize all IO models into four types (waste extended IO (WEIO), waste IO (WIO), physical IO (PIO) and hybrid IO (HIO)). We then define each model within a waste analysis framework, and carry out a bibliometric analysis. Our comparative analysis is twofold. Firstly, to compare the models conceptually, we analyze and discuss three characteristics of the models – the units of intersectoral flows, the modelling of waste and the relation with mass balance principle. Secondly, we analyze and discuss six criteria pertaining to the functionalities of the models, – the waste generation accounting, the purpose of the modelling, the geographical scale, the temporal dimension, the coupling of the IO models with other methods and the level of details of waste treatment sectors and waste types. Our findings are fourfold. First, there is increasing interest in assessing waste management policies with IO models; WIO models are the most applied ones, followed by WEIO models; PIO models are the least widely applied. Second, WIO models have the most mature analytical framework, and HIO models are conceptually the most powerful. Third, there is no cause-effect link between the conceptual characteristics and the functionalities of IO models. The IO models have been widely used for diverse applications in waste management at economy-wide level, but there is potential for several other applications. Fourth, the main limitation of all models is data related: future efforts should include more effective monitoring and collection of physical IO data and waste data, as well as the development of methods for consistent data mining.

Contents

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1. Introduction

The generation of waste is a symptom of a consumption-based society with production and consumption patterns creating waste. For 2016 it is estimated that only one-third of the generated waste was valorized through recycling and reuse (Kaza et al., 2018). This represents considerable wasted resources. In addition to the depletion of resources as an environmental challenge, the collection, treatment and uncontrolled disposal of waste cause environmental impacts. An estimated 1.6 billion tons of CO2 equivalent greenhouse gas emissions were generated from solid waste management in 2016, which is about 5% of all global emissions (Kaza et al., 2018).

The mainstream endeavor to tackle these issues entails focusing on waste and resource management to transition from a linear model to a circular one, i.e. waste is the core resource for recycled materials as well as for energy and nutrient recovery. Such a transition towards a circular economy model requires efficient, effective, and feasible waste policies and strategies (EC, 2015) that, thus, need to be quantitatively assessed.

This can be done with analytical methods that can be applied at process-level or at economy-wide level. Life Cycle Assessment (LCA) is the most known and recognized process-based method to assess the environmental impacts of a product or a service (Ghisellini et al., 2016).

Regarding the system boundaries, the product system in LCAs is often incomplete when for example cut-off rules are applied to exclude certain inputs. This limitation can lead to an underestimation of the assessed impacts (Suh, 2004). Conversely, Input-Output Analysis (IOA) has broader system boundaries including both, products and services. Indeed, IOA provides an economy-wide system completeness since it links the final demand with all production activities. In this study, we are interested in (i) the waste issues at economy-wide level including economic activities and households and (ii) the environmental and economic impacts of waste management strategies. Thus, the analytical method of IOA matches well with our interest.

The scientific literature distinguishes three main types of IO models: **conventional (monetary) IO** (MIO), **physical IO** (PIO) and **hybrid IO** (HIO) models (Miller and Blair, 2009). The first accounts for intersectoral flows in monetary units (e.g. euro), the second in physical units (e.g. tons) and the latter in a mixed-unit framework, for instance mixing physical and monetary units (Dietzenbacher et al., 2009; Miller and Blair, 2009). None of these models have been developed with the primary aim to assess waste issues and policies. But, since PIO and HIO models include waste data, they are also used to assess waste issues and policies. In contrast to PIO and HIO models, the MIO model as introduced by Leontief (1936) is not designed to take account of waste flows or to assess waste policies, because there is no waste data included.

With the increasing attention to environmental issues, the environmentally extended IO (EEIO) model was developed from the conventional IO model appended with environmental extensions namely: waste, emissions, resources, etc. (Duchin, 1990; Leontief, 1970). An EEIO model thus serves as a tool to assess waste policies if waste generation is part of the extensions. We name such a model as a **waste extended IO model** (WEIO).[1] Further, the framework of EEIO (or WEIO) model has been adapted leading to the development of a new branch of EEIO model, the **waste IO (WIO) model**. The **waste IO (WIO) model** introduced by Nakamura and Kondo, 2002a was developed to connect monetary flows of products and services between sectors with physical waste flows generated and treated. Each of these models: WEIO, WIO, PIO and HIO (explained in section 2 in detail), has been applied in case studies, contributing in investigating waste issues and policies from an economy-wide perspective.

Previous reviews have addressed the assessment of waste management using IO models in the context of circular economy at different levels. For instance, McCarthy et al. (2018) consistently reviewed economy-wide quantitative models such as computable general equilibrium and macro-econometric models to assess the macroeconomic consequences of a transition to a circular economy. The review includes IO models that are used from a macro econometric perspective of circular economy and excluded others which do not represent that perspective, such as (among others) the relevant paper of Nakamura and Kondo, 2002a. Besides, the reviewed IO models are not analyzed in detail. Information on different IO model types and their respective properties is missing. Furthermore, Aguilar-Hernandez et al. (2018) scoped EEIO models that have been used to assess economic and environmental implications of a transition toward a circular economy. There again, the focus of their valuable work is more on EEIO models as one group (known as EEIOA) and the contribution of that group of EEIO models to assess circularity interventions. Hence, although both reviews analyzed studies that used IO models, none have clearly elaborated on the differentiation of types of IO models and their respective contribution to the waste management research in the context of circular economy.

In this work we aim to approach the different types of IO model,

[1] We are conscious that this WEIO is a 'new' or uncommonly named model in the IO community. This neologism appears for the sake of simplicity in categorizing IO models.

including its respective characteristics and functionalities and not considering IO models as one group. To the best of our knowledge this has not been done yet. Comprehensive information is still missing regarding: the role of different IO models in waste management research; the level of methodological and empirical maturity of each IO model; the conceptual characteristics and functionalities of the models and their influence on waste management analyses. Hence, the present review positions itself to fill these lacks, provide a critical summary of the current knowledge and point out areas of future research in order to promote further advancement and implementation of best practices in the use of IO models for waste management analyses.

With this work, we analyze studies that have used WEIO, WIO, PIO and HIO models as tools to assess the environmental and economic impacts of waste policies, with respect to their conceptual characteristics and functionalities. We structure this paper as follows. First, we describe WEIO, WIO, PIO and HIO models in the context of waste management analyses. Second, we present the methodological approach followed for the literature review. Third, we perform a bibliometric analysis of case studies that have used the selected IO models. Fourth, we analyze and discuss the different IO models with respect to their characteristics and their functionalities. Lastly, we outline the main conclusions, findings and perspectives to pave the way for future research on waste management analyses with IO models.

2. Description of models

WEIO, WIO, PIO and HIO models are versions of IO models which cover different aspects of the waste issue and present waste flows in different ways. To manage this diversity of models, we provide a definition of each model with a focus on waste. Such definitions will help to understand the basic principles and fundamental properties of models regarding the representation of waste flows.

2.1. The conventional input-output model with waste extension (WEIO)

An environmentally extended input-output model is generally defined as an IO model where environmental information is added to the IOT. Depending on the type of environmental information (emissions, resources, waste, etc.), the terminology for the EEIO model may vary. The most known and applied model is the EEIO model with emissions as extension which was originally developed by Leontief (1970).

In this paper, we focus on waste flows as environmental extension and define the **waste extended input-output** (WEIO) model as a model consisting of a conventional IOT combined with information on waste generation. Hence, whenever data on waste generation is added as satellite account (eventually next to other extensions) to a conventional IO model, it leads to the so-called WEIO model. In a WEIO model, the only connection between product and waste flows is established by adding waste generation by sectors and by final demand to the monetary product flows in sectors and final demand. The physical use of waste by waste treatment sectors is not considered, nor stock additions. Therefore, the WEIO model cannot follow each waste flow from its generation to its respective waste treatment method (see Fig. 4 A and Table 1 A). It rather focuses on waste generation and the attribution to different sectors and final consumption groups.

2.2. The waste input-output (WIO) model

The first publication on **waste input-output** (WIO) refers to Nakamura (1999). Later, Nakamura and Kondo (2002) formalized and theorized the model with the aim to provide a specific framework of IOA for waste management analysis. In this paper, we define the WIO model as a model that extends the MIOTs with the total net generation of waste, i.e. total waste generated excluding its recycling (see Table 1 B). It shows the different types of waste generated by productive and waste treatment sectors (as positive entry) and additionally shows the use of waste by productive sectors,[2] i.e. waste recycled (as negative entry). Furthermore, in contrast to a WEIO model, a WIO model can allow to follow each waste flow from its generation to its respective waste treatment. The link between generation and treatment is established by the mean of the so-called waste allocation matrix $\boldsymbol{S}$ (Nakamura and Kondo, 2002a). $\boldsymbol{S}$ has the function of linking a waste type (e.g. wood waste) to a waste treatment sector (e.g. incineration), by specifying a treatment proportion – e.g. the share of wood waste that is incinerated. However, this representation of the link between generation and treatment is a step further of the basic representation of a WIO table (in Table 1 B).

In our definition of a WIO model, we distinguish the original WIO model as defined right earlier from the related versions. One is the WIO-MFA model (Nakamura et al., 2007) where a material flow analysis (MFA) is combined with the WIO model. With such a WIO-based model, the authors aimed to estimate the material content of products, i.e. the mass of materials forming products and to trace the final destination of materials and their specific elements through the supply chain. The Waste Supply-Use model (WSU) (Lenzen and Reynolds, 2014) is another version of a WIO-based model. In a typical WIO system, as conceived by Nakamura and Kondo (2002a), waste flows are only represented once, as attributes of the waste treatment sectors. A logical extension of the WIO was to allow two representations of the waste data—waste by type and waste by treatment method—simultaneously presented in one table.

2.3. The physical input-output (PIO) model

The introduction of the material balance principle within the material flow accounting (Kneese et al., 1970) has led to a basic framework for modelling physical flows (product and waste flows). Such groundwork was the basis for a compatible accounting framework for physical aspects of the economy. The SEEA (System of Environmental and Economic Accounting (United Nations, 1993, 2014)) offers an accounting framework of physical aspects of the economy in the form of SUTs. Physical input-output tables (PIOTs) are originally built from these physical SUTs. A PIOT can be seen as the physical equivalent of a MIOT in the SNA (System of National Accounts). All flows in the MIOT that can be measured in mass units are recorded. Sectors providing services as output (that have a monetary value) are not accounted.

In this study, we define a **physical input-output** model as model that measures all flows in physical units: the flows of products, as well as the multiple flows which link the economy and the environment, namely natural resources, emissions and waste flows. Such a model includes waste generated by sectors and final demand, and waste used by waste treatment sectors (see Fig. 4 C and Table 1 C). Physical units can cover a wide range of units: mass, energy, volume, etc., but in this study, by physical units, we refer to mass units since we focus on waste flows (e.g. ton or kg).

[2] The term ‘productive sector’ is used for all sectors except waste treatment sectors.

Table 1
Tabular representation of WEIO (A), WIO (B), PIO (C) and HIO (D) models.

A – WEIO	Sector 1 ··· Sector n	Final demand	Total
Sector 1			
⋮	$\boldsymbol{Z_s} + \boldsymbol{Z_w}$	$\boldsymbol{Y}$	$\boldsymbol{x}$
Sector n			
Value added	$\boldsymbol{v}$		
Resources	$\boldsymbol{R_s} + \boldsymbol{R_w}$		$\boldsymbol{r}$
Supply of waste	$\boldsymbol{Wsup_s} + \boldsymbol{Wsup_w}$	$\boldsymbol{Wsup_Y}$	$\boldsymbol{w_{sup}}$
Stock additions	$\boldsymbol{\Delta S_s} + \boldsymbol{\Delta S_w}$	$\boldsymbol{\Delta S_y}$	$\boldsymbol{\Delta S}$
Use of waste	$\boldsymbol{Wu_w}$		$\boldsymbol{w_u}$
Emissions	$\boldsymbol{B_s}$	$\boldsymbol{B_Y}$	$\boldsymbol{b}$
Total	$\boldsymbol{x'}$		
B – WIO	**Sector 1 ··· Sector n**	**Final demand**	**Total**
Sector 1			
⋮	$\boldsymbol{Z_s} + \boldsymbol{Z_w}$	$\boldsymbol{Y}$	$\boldsymbol{x}$
Sector n			
Value added	$\boldsymbol{v}$		
Resources	$\boldsymbol{R_s} + \boldsymbol{R_w}$		$\boldsymbol{r}$
Net generation of waste	$\boldsymbol{Wnet_s} + \boldsymbol{Wnet_w}$	$\boldsymbol{Wnet_Y}$	$\boldsymbol{w_{net}}$
Stock additions	$\boldsymbol{\Delta S_s} + \boldsymbol{\Delta S_w}$	$\boldsymbol{\Delta S_y}$	$\boldsymbol{\Delta S}$
Emissions	$\boldsymbol{B_s} + \boldsymbol{B_w}$	$\boldsymbol{B_Y}$	$\boldsymbol{b}$
Total	$\boldsymbol{x'}$		
C – PIO	**Sector 1 ··· Sector n**	**Final demand**	**Total**
Sector 1			
⋮	$\boldsymbol{Z_s} + \boldsymbol{Z_w}$	$\boldsymbol{Y}$	$\boldsymbol{x}$
Sector n			
Value added	$\boldsymbol{v}$		
Resources	$\boldsymbol{R_s} + \boldsymbol{R_w}$		$\boldsymbol{r}$
Supply of waste	$\boldsymbol{Wsup_s} + \boldsymbol{Wsup_w}$	$\boldsymbol{Wsup_Y}$	$\boldsymbol{w_{sup}}$
Stock additions	$\boldsymbol{\Delta S_s} + \boldsymbol{\Delta S_w}$	$\boldsymbol{\Delta S_y}$	$\boldsymbol{\Delta S}$
Use of waste	$\boldsymbol{Wu_w}$		$\boldsymbol{w_u}$
Emissions	$\boldsymbol{B_s} + \boldsymbol{B_w}$	$\boldsymbol{B_Y}$	$\boldsymbol{b}$
Total	$\boldsymbol{x'}$		
D – HIO	**Sector 1 ··· Sector n**	**Final demand**	**Total**
Sector 1			
⋮	$\boldsymbol{Z_s} + \boldsymbol{Z_w}$	$\boldsymbol{Y}$	$\boldsymbol{x}$
Sector n			
Value added	$\boldsymbol{v}$		
Resources	$\boldsymbol{R_s} + \boldsymbol{R_w}$		$\boldsymbol{r}$
Supply of waste	$\boldsymbol{Wsup_s} + \boldsymbol{Wsup_w}$	$\boldsymbol{Wsup_Y}$	$\boldsymbol{w_{sup}}$
Stock additions	$\boldsymbol{\Delta S_s} + \boldsymbol{\Delta S_w}$	$\boldsymbol{\Delta S_y}$	$\boldsymbol{\Delta S}$
Use of waste	$\boldsymbol{Wu_w}$		$\boldsymbol{w_u}$
Emissions	$\boldsymbol{B_s} + \boldsymbol{B_w}$	$\boldsymbol{B_Y}$	$\boldsymbol{b}$
Total	$\boldsymbol{x'}$		

Legend
Null
Mixed-unit
Monetary unit
Physical unit
Not accounted

The aim of this table is to show a simplified tabular representation of the reviewed IO model type. The table shows the different flows of goods, services and environmental extensions as recorded in their specific unit.
Capital bold letters indicate matrices, small bold letters indicate vectors. n indicates the number of sectors. Empty cells are null by definition.
The subscripts $\boldsymbol{s}$, $\boldsymbol{w}$ and $\boldsymbol{y}$ stand for productive sectors, waste treatment sectors and final demand respectively.
$\boldsymbol{Z}$: intersectoral flows of goods and services (not coefficients of input requirements of sectors); $\boldsymbol{Y}$: final demand; $\boldsymbol{v}$: value added; $\boldsymbol{R}$: use of resources; $\boldsymbol{Wsup}$: supply of waste plus stock additions; $\boldsymbol{Wu}$: use of waste; $\boldsymbol{Wnet}$: net generation of waste; $\boldsymbol{\Delta S}$: stock additions;
$\boldsymbol{B}$: emissions generated; $\boldsymbol{x}$: total outputs; $\boldsymbol{x'}$: total gross inputs; $\boldsymbol{r}$: total resources; $\boldsymbol{w_{sup}}$: total supply of waste plus stock additions; $\boldsymbol{w_u}$: total use of waste; $\boldsymbol{w_{net}}$: total net generation of waste; $\boldsymbol{b}$: total emissions generated; $\boldsymbol{x'}$: total inputs.

2.4. The hybrid input-output (HIO) model

In the context of IO analysis, the term ‘hybrid’ can refer to (1) combined models such as hybrid IO-LCA that is a fusion of process and IO data as defined in Suh (2004); (2) a combination of IOTs/SUTs in monetary unit appended with environmental accounts in physical unit as for example mentioned by Aguilar-Hernandez et al. (2018). Based on the second definition, WEIO and WIO can be classified as hybrid models, as for example in (Aguilar-Hernandez et al., 2018 p.5): ”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“. A ‘hybrid model’ can also refer to (3) a mixed-unit framework where the data in IOTs/SUTs are expressed in different units: tangible products in mass unit, energy flows in joules and services in monetary unit, regardless environmental accounts, as exemplified by Schmidt et al. (2010) and Merciai and Schmidt (2016). In this study, the term ‘hybrid’ corresponds to the latter definition, and to this extend, we do not consider WEIO and WIO as hybrid models.

Following that, we define a **hybrid input-output** as a model where IOTs/SUTs, recording each input and output of sectors in its most suitable unit (as instantiated earlier), can be appended with environmental accounts covering waste, emissions, resources, etc. In such a model, waste flows are accounted for as waste generated by sectors and final demand, and as waste used by waste treatment sectors (see Fig. 4 D and Table 1 D).

Before closing this section, we briefly describe the use of other environmental extensions, such as emissions and natural resources, because they are relevant for waste management analyses. Some

WEIO model (Barata, 2002; Kagawa et al., 2004) did not include natural resources and emissions while the original version of WIO model included emissions. PIO (Hoekstra and van den Bergh, 2006) and HIO (Schmidt et al., 2010) models have these two extensions in their original structure. Since these extensions can also be added to WEIO and WIO models, we added them in the general representation (see Table 1).

3. Materials and methods

3.1. Bibliometric analysis

We first used Scopus to perform the bibliometric analysis. In the ‘Article title, Abstract, Keywords’ query, we applied each keyword in the first column of Table 2, crossed with each one in the second column. We selected only peer-reviewed scientific publications (journal and conference papers), as well as technical/scientific reports, all written in English. The years covered by the search were publications from 1990 to February 2019. Afterwards, we manually examined the content of the documents, restricting our analysis to relevant case studies that use an IO model for waste management analysis. We then developed a backward snowballing process, strengthened by other search engines, such as Google scholar and Cible + (the Université libre de Bruxelles’ own library system) to identifying additional relevant literature from the citation network. We have identified in total 78 relevant documents that present a case study where an IO model is applied to analyze a waste-related topic.

3.2. Methodological analysis

We defined criteria in order to support the comparison of IO models applied to waste management analysis. We distinguish **three** criteria related to the conceptual characteristics of IO models (presented in section 3.2.1), and **six** criteria related to the functionalities of IO models in case studies (presented in section 3.2.2). This approach highlights conceptual and functional similarities and differences of the four IO models.

3.2.1. Key characteristics of input-output models for waste analyses

The first characteristic refers to the **units of intersectoral flows** of products and services, namely monetary, physical or mixed units. Indeed, the representation of flows in different units is important for waste management analyses, because the unit of flows determines the type of waste management analysis that can be performed with the model. The second characteristic deals with the ability of **modelling waste generation and treatment.** This criterion analyses the applied definition of waste and how each IO model approached waste generation and treatment. The last characteristic concerns the relation with the **mass balance principle**. Kneese et al. (1970) argued that the environmental problems cannot be adequately assessed unless the complete material flow is envisioned with regard to the mass balance principle.

Table 2
List of keywords used for the bibliometric analysis.

Input-output analysis	Waste
Environmentally extended input output analysis	Waste management
Waste input-output	Waste treatment
Waste supply and use	Waste footprint
Physical input output	Recycling
Physical supply and use	Incineration
Hybrid input output	Landfill
Hybrid supply and use	Disposal
Mixed-unit input–output	Energy recovery

3.2.2. Functionalities of input-output models for waste analyses

We define six criteria to analyze the performance of each model based on the applications that have been published so far. The aim is not only to analyze the theoretical functionalities of the model (which model is able to do ‘*what*’), but also to demonstrate what has been practically analyzed based on case studies, i.e. to which extent each model has been used, how often they are used; for which questions they are used.

The first criterion refers to the type of **waste generation accounting** (e.g. waste footprint calculation). The quantification of waste generation is an important functionality of a model since it is a key parameter for waste management analyses. The second criterion describes the **main purpose of a model** – for instance a diagnosis or a scenario analysis – and linked to that, the **type of analysis** that has been performed, for instance environmental or economic. The third criterion targets the **geographical scale**. We distinguish four scales: single- and multi-region, and, subnational and national. The fourth criterion deals with the **time dimension**. We distinguish between static, dynamic non-recursive (mainly referring to projections or time series analysis), and dynamic recursive. The fifth criterion describes the **coupling of IO models** with other methods/models that allows to extend the analysis. The sixth criterion targets the resolution of sectors and products with emphasis on the **resolution of waste types and waste treatment sectors**. This last criterion allows to evaluate the comprehensiveness and level of detail of models for waste management analyses.

4. Results and discussion

In this section, we present and discuss the first part of our findings from the bibliometric analysis, the analysis of models’ characteristics and functionalities. In Section 5 we present the findings that pertain the discussion about improving IO application on waste management strategies.

4.1. Bibliometric analysis

Fig. 1 shows the yearly evolution of the number of publications (blue column) and citations (orange line) from 1990 to 2018. Fig. 1 shows that there is a continuous increase of studies using IO models for waste management analyses. This development demonstrates the growing interest in waste management analyses from an economy-wide perspective.

Fig. 2 shows that 58 (almost 75% of) case studies have measured intersectoral flows of products and services in monetary units and the predominant tables are IOTs. Based on the selected studies, the WIO model is the most applied model type in the literature as also found by Aguilar-Hernandez et al. (2018) followed by the WEIO model type. HIO and PIO models consecutively displays the lowest scores, with no direct application of physical SUTs for waste management analysis.

We provide more bibliometric results in the Supplementary Information.

4.2. Analysis of characteristics of the input-output models for waste analyses

This section presents the results of the comparative analysis based on the three selected properties, namely the units of intersectoral flows, the modelling of waste and the relation with the mass balance principle. Table 3 at the end of this section summarizes this comparative analysis.

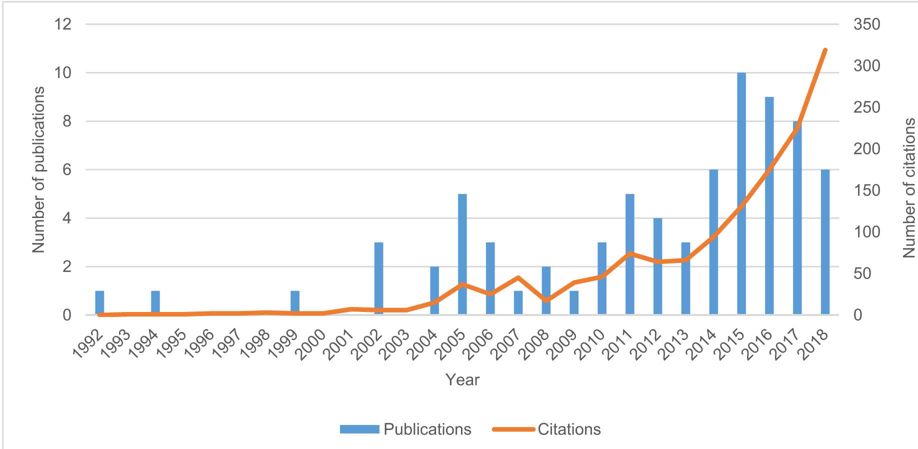

Fig. 1. Number of publications and citations per year from 1990 to 2018.

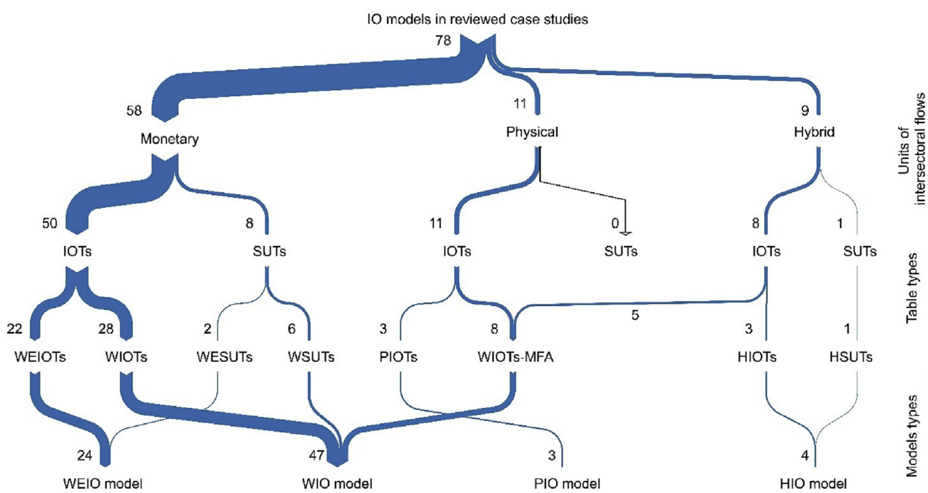

Fig. 2. Number of publications per unit, table type and model type. IOTs: input-output tables; SUTs: supply and use tables; WE: waste extended; P: physical; H: hybrid; MFA: material flow analysis.

Table 3
Summarizing the characteristics of reviewed IO models.

Characteristics	WEIO	WIO	PIO	HIO
1. Units of transactions in the economy	Monetary	Monetary	Physical	Hybrid
2. Modelling of waste				
waste generation	✓	✓	✓	✓
waste treatment	x	✓	✓	✓
input of secondary products to sectors	x	x*	✓	✓
Quality of secondary materials	x	x*	x	x
3. Mass balance principle				
sector balance	x	x*	x	✓
waste balance	x	✓	✓	✓

✓: considered in the reviewed model; x: not considered; x*: only considered for a WIO-MFA model.

4.2.1. *The unit of intersectoral flows in the economy*

The completeness of the representation of flows and the units used to represent transactions in the economy need attention when performing waste management analysis.

Almost 75% of IO models used in the reviewed case studies measured the intersectoral flows of products in **monetary units**. The reviewed WEIO models such as (Beylot et al., 2017; Choi et al., 2011; Reynolds et al., 2016a) and WIO models such as (Beylot et al., 2015; Nakamura and Kondo, 2002a; Tsukui et al., 2015) have measured product flows in monetary units, but have recorded waste in physical units (see Table 1 A, B and Fig. 4 A, B). This enabled them to assess the economic impacts of waste management policies, in addition to the waste intensity per monetary unit or the environmental impacts of waste treatment processes. As an example, Reynolds et al. (2016b) used a WEIO to estimate the economic value loss of New Zealand's food waste in addition to the tonnage of waste generation.

However, we join the consensus that measuring intersectoral flows of products only in monetary units can be considered as a major limitation for the analysis of waste management strategies, because of the disconnection between the monetary values of intersectoral flows and the physical transactions of flows in the economy (Aguilar-Hernandez et al., 2018; McCarthy et al., 2018; Stahmer, 2000; Weisz and Duchin, 2006). The physical flows (of resources, products and waste) provide important information, for instance, the quantity of resources used (i.e. resource intensity), materials or products to produce a commodity (i.e. the/material/product intensity) and the quantity of waste generated (i.e. the waste intensity per physical unit).

The reviewed PIO models have completely expressed all flows in **physical units** (see Table 1 C and Fig. 4 C). One could think a PIO model is more suited than WEIO and WIO models in capturing the physical aspects of waste management issues, i.e. representing the physical transactions of resources and materials flows. However, the basic PIO models neglect sectors which have non-physical outputs as it is typically the case in the service-based sectors. This general limitation of conventional PIO models is also confirmed by the reviewed case studies. For instance, in their case study on paper recycling, Liang et al. (2012) stated that the uncertainties in analyzed environmental impacts came from the exclusion of services that cannot be expressed in physical units in their PIO model. Indeed, neglecting impacts of service sectors can lead to an underestimation of environmental impacts (Liang et al., 2012). This is why, Yang et al. (2010) suggest to include the monetary flows that are uncaptured in their current PIO model to perform a more comprehensive analysis.

The development of a of a **mixed-unit** or **hybrid unit** framework in a HIO model is part of the path toward completeness in representing interactions of flows in the economy and the environment. For instance, Merciai and Schmidt (2017) and Schmidt et al. (2010) have developed a HIO model that is three-unit multiregional SUTs accounted in mass, energy and monetary units, appended with environmental extensions including waste accounts. This can be seen as an additional advantage of HIO model compared to WEIO, WIO and PIO model, to the extent that such a HIO model tackles the limitations (mentioned earlier) of each of these models. We believe with (Aguilar-Hernandez et al., 2018; Merciai and Schmidt, 2017; Tisserant et al., 2017; Wood et al., 2015) that, covering as many transactions of flows as possible in the economy and the environment can increase the comprehensiveness of the waste management analysis and can be of particular importance when assessing the environmental and economic impacts of waste treatment options, in a context of circular economy. Yet, none of these IO models allows completely describing each flows in terms of any of its units of measurement.

4.2.2. Modelling waste in input-output models

Different approaches have been developed in IO models for the representation of waste flows, waste generation and waste treatment. This occurrence of different approaches can be partly explained with differences in the definition of waste, more precisely the distinction of waste from by-products. In the following, we first give a theoretical definition of waste and by-products and then put these definitions in the context of waste management analysis. Second, based on the definition of waste in the context of waste management analysis, we analyze how waste generation and treatment have been modelled in the reviewed IO models.

Fig. 3 illustrates how *waste* and *by-products* can be distinguished on a theoretical basis, starting with the total physical *output*[3] of an economic activity which consists of *products* and *waste*.

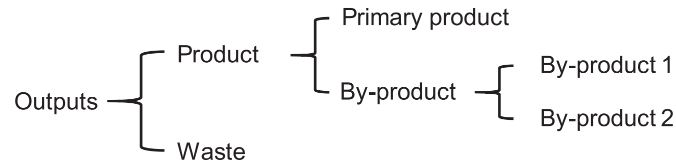

Fig. 3. Definition of waste from Nakamura and Kondo (2009).

A product can be a *primary product* or *by*-product. The *primary product* of a sector is the main or determining product of that sector (for example, paper products from the paper industry). *By-products* are "substances or objects resulting from a production process not primarily aimed at producing such substances or objects "(EC, 2008). In other words, *by-products* are technically related to the production of that sector, but not typically the economic driver of the sector. Nakamura and Kondo (2009) distinguish two types of *by-products*. *By-product 1* is the primary product of another sector (e.g. electricity from waste incineration plants). *By-product 2* is not the primary product of any other sector. There is no producing sector where it is primarily produced (e.g. fly ash from waste incineration plants).

In the Waste framework directive, *waste* is defined as '*any substance or object which the holder discards or intends or is required to discard*' (EC, 2008). 'Discard' in this definition includes any operations necessary for its reuse, recovery, and recycling (in addition to disposal or final treatment operations). However, when a *waste* is sent to recycling, it can be seen as a *by-product 2*, since a recycled *waste* is not the primary product of another sector, and there is no producing sector where it is primarily produced.

To instantiate, on the one hand, following the Waste framework directive, fly ash can be seen as a *waste* because it is a residue of waste incineration plants that is intended to be discarded (e.g. landfill). On the other hand, fly ash can be seen as a *by-product 2* when it is used as input to the cement industry, with fly ash not being the primary product of another sector and not being primarily produced by another sector. The perception of fly ash as *waste* or *by-product 2* may depend on the market/economic conditions. Hence, the limit between *waste* and *by-product 2* is not clear enough and this makes the definition of waste 'ambiguous' in a general context.

For waste management analyses that are performed with IO models, we observe that all the reviewed case studies account for **waste generation** in a similar way but used different **definitions of waste**. As shown in Fig. 4, in all models, waste generation is accounted as a positive flow from sectors and final demand to waste markets. However, this waste flows may represent *by-products 2* and *waste* which is the case in for example (Nakamura and Kondo, 2002a) and (Merciai and Schmidt, 2017) or only *waste*, such as Zeller et al. (2019) and Ruiz-Peñalver et al. (2019). We have found that this is not due to a conceptual difference of IO models, but it is due to the different aims of the studies and different types of data used. And, here we emphasize on the difference between the way of accounting the generation of waste and of modelling the generation of waste (for the latter see section 4.2.3).

Regarding the **treatment of waste**, we have observed that only the WIO, PIO and HIO models can represent the physical link between waste generation and treatment (Fig. 4). The effective linking of physical waste flows to waste treatment sectors was made possible in WIO models by the so-called waste allocation matrix ***S***, as previously presented (Nakamura and Kondo, 2002a). In the WIO model, ***S*** accounts for the proportion of waste types used by each waste treatment sector. The concept of this allocation matrix is

[3] Emissions are also part of the output, but is excluded for the sake of analytical convenience.

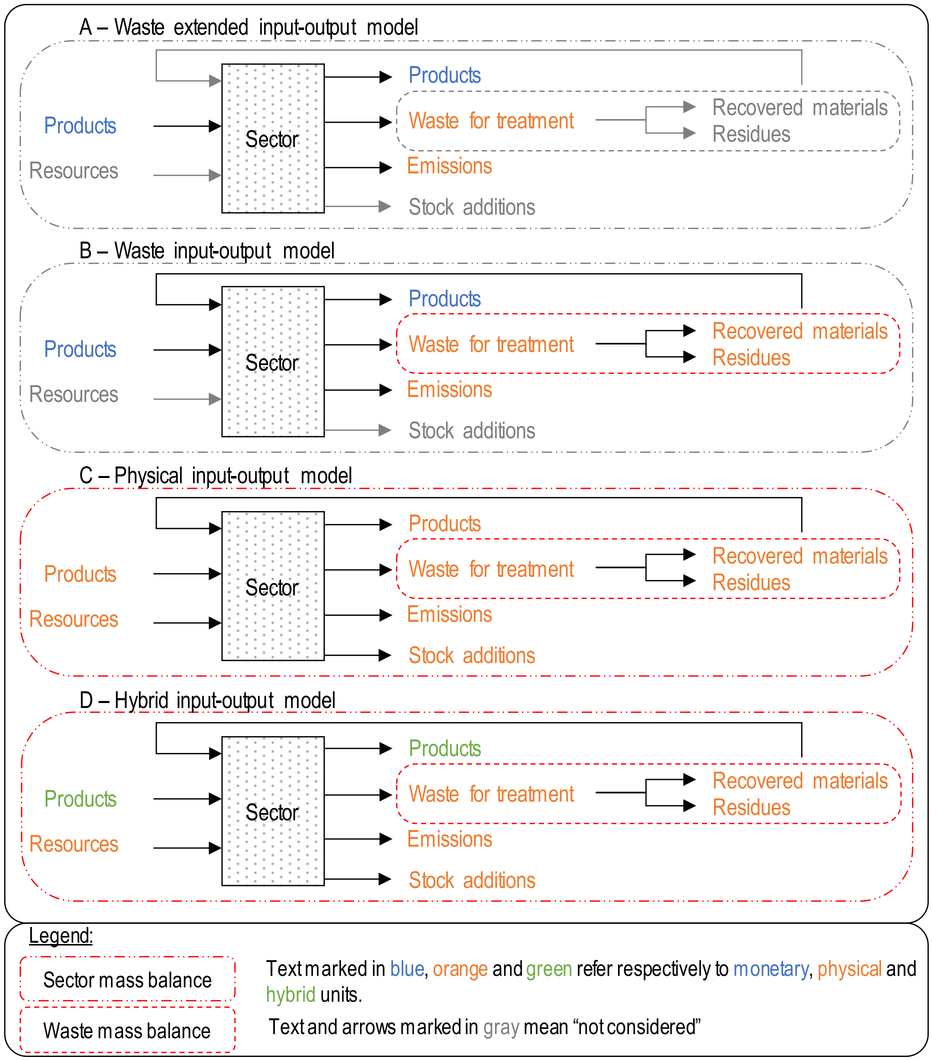

Fig. 4. Representation of unit of flows, waste modelling and mass balance in the reviewed IO models.

otherwise known as the residuals distribution matrix ***J***. Schmidt et al. (2010) developed a HIO model, in which ***J*** plays the same role in a HIO model as ***S*** does in a WIO model. ***S*** and ***J*** reflect the waste treatment situation in a given area. They have been built from waste treatment statistics or based on assumptions when data is lacking. A similar approach to attribute waste types to waste treatment sectors was applied in case studies based on the PIO model without giving a specific name to the relation between waste types and waste treatment types. The PIO case studies have often focused on a specific sector (e.g. tire industry) with one specific waste type (e.g. scrap tire) such as Yang et al. (2010).

Furthermore, we have observed that the **inputs of secondary materials** into sectors have been treated differently in the reviewed models. The handling of secondary materials is an important feature of models, because it determines whether circularity assessment can be conducted. 'Closing the loops' of supply chains is one of the main principles in circular economy (Ghisellini et al., 2016) and models that allow the complete assessment of loops (from products, to waste, to secondary materials, to new products) have an additional functionality for waste management analyses.

In the original WIO model such as in (Lin and Nakamura, 2018; Nakamura and Kondo, 2002a, 2002b; 2006a; Nakamura et al., 2008), and the WIO-MFA model such as in (Nakamura et al., 2008; Ohno et al., 2015), **secondary materials** are modelled as negative entries to productive sectors and recycling is not represented as a waste treatment sector. **Secondary inputs** to sector can also be modelled as positive entries in the waste extension part of the model where recycling is represented as a distinct waste treatment sector. This is done in WSU models such as (Lenzen and Reynolds, 2014; Reynolds et al., 2014). It is noteworthy that the difference between the two approaches is not necessarily conceptual, but is driven by data availability and the ambition of respective authors to provide a substantial illustration of their models. The reason of excluding recycling from waste treatment sectors in the original WIO and WIO-MFA models is that the allocation to sectors using **secondary materials** could not be exogenously parameterized in advance, since the demand for secondary products, such as metal scrap or waste paper depends on endogenous economic conditions (Nakamura and Kondo, 2009). Furthermore, the focus when including recycling as a distinct waste treatment sector in WSU models resides in providing a workable numerical example for illustration sakes, but not on analyzing the inputs of secondary products to sectors (Lenzen and Reynolds, 2014).

In the reviewed WSU models such as (Beylot et al., 2015; Lenzen and Reynolds, 2014; Reynolds et al., 2014; Zeller et al., 2019), recycling is considered as an intermediate activity (pretreatment) to transform waste into a secondary material. What is modelled is the amount of waste sent to recycling and the amount of produced recycled material (that could be used in the productive sectors), but not the input of recycled materials in a specific productive sector (e.g. plastic production). Hence, modelling the **inputs of secondary materials** to productive sectors using a WSU model remains a step forwards toward an even better illustration of such model.

Besides, in the original WIO models reviewed, the **inputs of secondary materials** to sectors is in physical unit per monetary unit, since secondary materials are in physical units and intersectoral flows are in monetary units. This precludes for instance the possibility to analyze the contribution of secondary materials to the physical inputs to sectors. The WIO-MFA (Nakamura et al., 2007) was developed to tackle such issues. WIO-MFA model enables to estimate the material composition of products by tracing the fate of materials along the supply chain upwards, from basic materials towards final products across different stages of fabrication and consumption (Nakamura et al., 2007). Here, the secondary materials are mostly directly modelled as inputs to sector without a representation of recycling sectors. Such a model has been mostly applied for a specific waste type (e.g. metal scrap) and sector, such as the steel producing or the automobile sector.

In the reviewed PIO and HIO models, the modelling of **inputs of secondary materials** goes beyond the representation of recycling in waste treatment sectors, and further considers the use of secondary materials as inputs to sectors. In PIO models (such as (Liang et al., 2012)) and HIO model (such as (Merciai and Schmidt, 2017; Schmidt et al., 2010), **secondary materials** are integrated in the transactions of flows between sectors and modelled as positive inputs to sectors. The distinction between primary inputs and secondary inputs is explicitly represented. Accordingly, the reviewed PIO and HIO models have been able to model the **inputs of secondary products** to sectors (see Fig. 4).

One limitation common to most studies is that modeling the inputs of secondary materials to sectors overlooks the **qualitative aspects of materials**. In reality, the quality of secondary materials does not necessarily equal the one of primary materials. This is due to the impurities in the materials and the fact that fibers get shorter during the recovery and recycling processes. For instance, Nakamura et al. (2012) argued that mixing different metal scraps from end-of-life (EoL) products during recycling results in metal scrap, that no longer equal the primary materials in terms of quality. Therefore, the recycling process requires dilution of the secondary material by adding high purity materials. Acknowledging these aspects, the authors used a WIO-MFA model to quantify the quality and dilution losses associated with recycling ferrous materials from end-of-life vehicles. Likewise, such issues, quality aspects of input of recovered metal scraps to sectors, have also been addressed for instance by Ohno et al. (2014), Ohno et al. (2015), Pauliuk et al. (2017), Nakamura et al. (2017), Ohno et al. (2017),Nakamura and Yamasue, 2010), etc.

In summary, we can conclude that the **modelling of the secondary materials as inputs** to sectors with WIO models is a criteria to distinguish the original WIO, WIO-MFA and WSU models. However, this difference between the three models and approaches is not conceptual, but derived from practical considerations (data availability, illustration sakes). WIO-MFA, PIO and HIO with physical intersectoral flows have consistently (with regard to the physical connection) integrated the use of secondary materials as input to sectors. And, the quality of secondary inputs has been only considered with WIO-MFA models.

4.2.3. The relation with mass balance principle

In order to analyze the mass balance principle in the reviewed articles, we distinguish the mass balance at product, sector and waste level. The product balance describes that for any product the sum of production and export must equal the sum of use and import (SEEA, 2014). The sector balance ensures that for any sector, the input (of product, resources and recovered material) must equal the output (of products, waste, stock additions and emissions) (SEEA, 2014). The waste balance ensures that the waste for treatment equals the recovered materials plus residues to be disposed (Nakamura and Kondo, 2002a). Here, we focus on the last two mass balance types which directly involve waste.

WEIO and WIO (WIO-MFA excluded) models describe intersectoral flows in monetary units and parts of the interactions from economy to nature in physical units. Thus, they do not consist of all components necessary for a mass balance at sector level (see Fig. 4 A, B). However, they have all components for the waste balance, since the link between the waste for treatment and the recovered materials and residues is ensured within the waste allocation matrix (see Fig. 4 B). Evidently, PIO and HIO models are able to completely satisfy the sector and waste balance, because they represent in physical units the production of intermediate and final goods together with the generation of emissions and wastes during their production and consumption activities (see Fig. 4 B).

However, one reviewed study (Merciai and Schmidt, 2017) has illustrated the application of the mass balance principle (including the mass balance at sector level) within a HIO model at multiregional level, when considering only physical units. This application (as shown in Fig. 4 D) allows to quantify i) the waste generation as the result of the input material that does not end up as a new product, nor emission. This theoretical potential waste is useful, because it allows to provide information that was not available in waste statistics and support the interpretation of waste statistics. For instance, if the potential waste is higher than waste statistics, there may be unregistered waste or stock formation; if else, the in-use stock may have been depleted. It also allows to measure ii) the material circularity as the part of waste generated that end up in a new product (see (Merciai and Schmidt, 2016, p41 and 48)).

The WIO-MFA that is an analytical MFA model incorporated in a physical WIO is also fully consistent with the mass balance principle. The application is similar to the one of the PIO as in Fig. 4 C. It includes in its core part, in place of a monetary intersectoral flow matrix, a matrix with the physical composition of products. The mass balance principle has been applied in WIO-MFA model to trace a specific material input (metal) through supply chains such as the one of car production in Japan (e.g. (Nakamura et al., 2011, 2014; Pauliuk et al., 2017)).

All the reviewed models are data intensive and we discuss (in section 4.3.6) how the lack of comprehensive and detailed physical data on products, materials and waste flows hampers each of the analyzed functionality of the IO models. Next to a more effective monitoring and collection of physical IO and waste data, efforts should also be directed towards the development of methods to consistently and endogenously estimate data. Acknowledging the advantage of WIO-MFA, PIO and HIO models to implement a mass balance of sectors, we see and promote a consistent mass balance application as a valuable solution to overcome the unavailability or inconsistency of waste data. This has been demonstrated once by Merciai and Schmidt (2017) where the implementation of a mass balance procedure of industrial processes within a HIO model has contributed to estimate the actual amount of waste generated.

In summary, important aspects of waste management in a CE context (e.g. quantifying the waste generation from economic activities and final demand, measuring the material circularity, tracing and analyzing the fate of specific input of materials throughout the supply chain, waste data gap filling, etc.) are consistently analyzed with IO models when the mass balance principle is integrated. WIO-MFA, PIO and HIO models are conceptually able to satisfy that principle. While several applications exist with WIO-MFA models specifically for metal materials, one application exists with HIO model.

4.3. Analysis of the functionalities of the input-output models for waste analyses

4.3.1. Waste generation accounting

There is a consensus that a detailed and comprehensive accounting of waste generation forms a quantitative basis for designing adequate waste management policies (Duchin, 1990; Huang et al., 1994; Nakamura, 1999; Barata, 2002; Tisserant et al., 2017; Ruiz-Peñalver et al., 2019).

We have categorized the waste accounting in the case studies into **two** main types: territorial waste accounting and waste footprint accounting (see Table 4). The former strictly follows the production-based calculation, i.e. waste generated by a sector and final demand, as a result of production activities of that sector and consumption by final demand respectively. The latter refers to a consumption-based calculation, that considers the effects of direct and indirect inputs requirements of sectors to satisfy the final demand plus waste generated by final demand itself (Nakamura and Kondo, 2009).

Fig. 5 shows the number of publications per IO model that have performed a certain type of waste accounting. The majority (around 75%) of case studies have applied the **waste footprint accounting.** The latter was mainly applied with WEIO and WIO models, the WEIO model being the most represented. While the HIO model has been used to account for waste generation with **territorial waste accounting**, none of the reviewed studies used the PIO model for a waste generation accounting.

For the **territorial waste accounting**, we have observed that the integration of statistical waste data was performed differently in WEIO and WIO models (with monetary intersectoral flows) compared to HIO models (for the physical intersectoral flows).

In WEIO (such as (Reynolds et al., 2016a)) and WIO models (such as (Zeller et al., 2019), the integration of waste is performed by allocating the total waste generated across economic sectors. In most cases, the total gross output per sector is used as allocation key. Also, the employment rate per sector or the amount of inputs of production per intermediate sector can be used, as in Reynolds et al. (2014). This procedure assumes that each sector produces waste relatively to its economic size, or to its employment capacity. In HIO models (such as Merciai and Schmidt (2017)), the waste generation is calculated based on a complete mass balance approach, when the physical unit is chosen. Therein, the underlying principle is that waste generation is the sum of the parts of inputs of products, resources and secondary products that are not embodied in the final products and that do not end up as emissions.

The **waste footprint accounting** such as in Ruiz-Peñalver et al. (2019) integrates the statistical waste data in an IO framework and allocates waste according to aforementioned indicators (such as the total gross output per sector). Subsequently this type measures the waste generation applying the consumption-based calculation. Some waste footprint were calculated at country level such as by Beylot et al. (2016); Jensen et al. (2013); Liao et al. (2015). In such

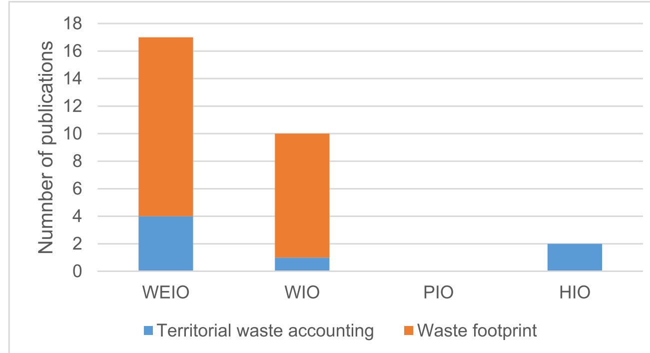

Fig. 5. Analysis of waste accounting types per model. (This figure shows 29 publications of the 78 reviewed studies in which a waste generation accounting has been performed).

studies, to account for the waste embodied in the trade, the authors assume that the production technology of abroad is similar to the domestic one, due to data lack. However, such assumption can lead to an underestimation of the national waste footprint, especially if there is a considerable part of imports. For example, Fry et al. (2015) estimated that such assumption has led to an underestimation of the Australian waste footprint by approximately 2.7% representing 1.5 million tons of waste. However, performing the waste footprint at global scale using a MRIO model can allow tackling such limitation, it was done by Tisserant et al. (2017) who have calculated the global waste footprint considering the country-specific technology.

We have found that the disparities in applying waste accounting methods to the reviewed IO models, has nothing to do with the conceptual differences of models. Indeed, all the models are able to apply both waste accounting calculations, but depending on the data availability and the aim of the study not all types have been applied.

We have furthermore observed that the calculated waste footprints has often led to higher amounts of waste generated compared to the amounts reported by official statistics (i.e. territory-based accounts). For instance, it was more than twice the amount reported in official statistics for Spain (Ruiz-Peñalver et al., 2019) and more than six times for Guangdong province (China) (Guan et al., 2019). That occurs because the waste footprint calculation includes the waste generated both directly by sectors and final users and indirectly throughout the supply chain (during the intermediate consumption, trade, etc.). To instantiate, Ruiz-Peñalver et al. (2019) have noted that for some sectors such as manufacture of computer, electronic and optical products, electrical equipment, motor vehicles, the high participation of indirect suppliers caused the generation of more than three quarters of total waste. For the HIO model, namely in (Merciai and Schmidt, 2017; Schmidt et al., 2010), the main differences between the available waste statistics and the results of the mass balance procedure are related to differences in the scope of waste statistics across countries and uncertainties of product lifetimes to estimate postconsumer waste flows. Moreover, uncertainties can be introduced when accounting for waste generation. We present and discuss

Table 4
Description of waste accounting types in reviewed case studies.

Territorial waste accounting	Waste footprint accounting
• Integration of statistical waste data in an IO framework • No indirect effects of input requirements • Production-based or territory-based accounting: considering waste directly generated by sectors and households	• Integration of statistical waste data in an IO framework • Direct and indirect effects of input requirements • Consumption-based accounting: considering the waste generated directly by sectors and households but also generated throughout the whole supply chain

these uncertainties in section 4.3.6.

Regarding their use in **circular economy policies**, the waste accounting methods indicates a clear advantage as a waste data monitoring instrument, compared to official statistical waste databases. Indeed, WEIO, WIO, PIO or HIO models, can close data gaps and increase the level of detail in the waste data, for example by providing the waste generated per type and per sector, which is originally not present in official waste statistics. Hence, waste footprints can allow policy makers to identify hotspots of waste generation. For instance, knowing which sectors generate the most waste can help to design strategies on waste prevention and reduction at source (Guan et al., 2019). Furthermore, the waste footprint helps in understanding the waste issues in a circular economy context from a consumption-based perspective, i.e. the relation between the trade and circular economy. As demonstrated by Tisserant et al. (2017), waste embodied in trade increases faster than waste generated domestically, as per capita income rises and waste footprints appear better correlated with personal affluence than the territorial accounts. Thus, decision-makers should consider both perspectives when designing waste or circular economy policies.

Waste footprints also contribute to design circular economy strategies. For example, the territorial waste accounting performed by Zeller et al. (2019) has contributed in empirically identifying the waste flows with the most promising circular economy valorization potential for cities such as Brussels. Furthermore, calculated waste footprints can also help in estimating the potential for increased recycling and recovery, as instantiated by Tisserant et al. (2017) noting that almost 0.8 Gt of the 1.5 Gt of landfilled waste can potentially be recycled.

4.3.2. Purpose of the input-output modelling and types of analyses

Fig. 6 shows for the four types of IO models the number of reviewed publications performing a **diagnosis or scenario analysis**. A **diagnosis** refers to an analysis of the current state of waste management. It can include an identification of hotspots in the waste management chain. To instantiate, Reutter et al. (2017) have identified the environmental and economic hotspots in the Australian food waste management; Beylot et al. (2015) have identified the environmental impacts of waste management systems in the French waste policies; and Liao et al. (2015) have identified the driving forces affecting the waste generation in Taiwan. A diagnosis refers also to analyses of material use within an economy such as (Ohno et al., 2016) and Jiang et al. (2017), respectively for the intersectoral flows of eight metals types in the USA and a petrochemical compound Bisphenol A in the Chinese Economy. Our analysis showed that all models are well-suited for a diagnosis: 60% of them are used as a diagnosis instrument. As shown in Fig. 6, more case studies based on WEIO and WIO models have been used to perform a diagnosis compared to the PIO and HIO.

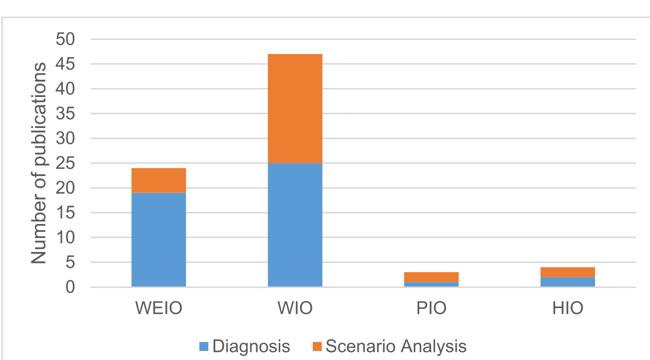

Fig. 6. Analysis of the purpose of models.

Although a **scenario analysis** is less used than a **diagnosis** (40% of overall reviewed models applied scenario analysis), scenario analyses applied to waste management remains an interesting topic and is mainly applied by WEIO and WIO models as shown in Fig. 6. Scenario analyses have been applied to assess the environmental and economic impacts due to changes in waste treatment policies (for instance (Ferrão et al., 2014; Kondo and Nakamura, 2004)) or due to changes in the household consumption (for instance (Takase et al., 2005)).

Table 5 shows the main types of analyses that were conducted in the frame of a diagnosis and a scenario analysis, namely focusing on: waste generation, EoL management including material recycling, extending lifetime, etc., as well as environmental and economic assessments. Further details on them are provided in the Supplementary Information. From Table 5, WEIO and WIO models have been mostly applied to diagnose a waste management situation, but WEIO models have been less widely applied to analyze multiple scenarios of waste management respectively. The most dominating type of diagnosis pertains to waste generation analyses, while scenario analyses have been mainly applied to EoL management. Environmental and economic analyses are less widely applied, but we notice considerable scenario analyses of environmental impacts of EoL management.

Furthermore, we notice a considerable reduction of studies when it comes to the combination of different analyses. We have found that the most recurrent combination of analyses is the environmental assessment of EoL management, with more scenario analyses than diagnosis and mainly carried out by WIO models.

While no reviewed studies combined the four analyses, we notice few studies that have carried out the diagnosis of i) waste generation and environmental assessment of EoL treatments (e.g. (Schmidt et al., 2010)) and ii) the environmental and economic assessments of the EoL treatments (e.g.(Nakamura and Kondo, 2006b)), iii) the environmental and economic assessments of waste generation (e.g. (Reutter et al., 2017)).

Indeed, combining different types of analysis allows capturing trade-offs between the different results of these analyses and thus increasing the comprehensiveness of the analysis and deepening it. With this section, we would like to highlight that although valuable studies have been performed, there are still some empirical needs to tackle, precisely related to the combination of different types of analysis of waste management in the context of circular economy.

4.3.3. Geographical scale

Fig. 7 shows the number of publications of reviewed models that were applied at different geographical scales: single- and multi-region models at subnational and national scales. Fig. 7 shows that 75% of models were applied for a country (single-region at national level), and 12% for a region (single-region at subnational level). Multi-region models at national and subnational scales are less represented (around 8% and 6% respectively).

Furthermore, Fig. 7 also shows disparities in the geographical coverage of models. WIO models have been applied at all different geographical scales. WEIO models are also well represented for applications at single-region scales but were not applied as multi-region at national scale. PIO and HIO models have not yet been applied for multiple regions at subnational scale.

Indeed, it is important to consider inter-regional and national scales when analyzing (1) the interdependences between sectors and regions for waste footprint calculations, (2) analyzing the environmental impacts of waste management strategies and in (3)

Table 5
Types of analysis for diagnosis and scenario analysis.

I: Diagnosis. I: scenario analysis	WEIO	WIO	PIO	HIO
Waste generation analysis (A)	IIIIIIIIIIIIIIIIII I	IIIIIIIIIIIIIIIIII II		I I
End-of-Life analysis (B)	III III	IIIIIIIIIIII IIIIIIIIIIIIIIIII	 II	II II
Environmental analysis (C)	IIIIII III	IIIIII IIIIIIIIIIIII	 II	II II
Economic analysis (D)	IIII II	IIIIII III		
(A) + (B)	II	IIIII		I I
(A) + (C)	IIIIII	IIII I		I I
(A) + (D)	III	IIII		
(B) + (C)	I II	III IIIIIIIII	 II	II II
(B) + (D)	I I	II II		
(A) + (B) + (C)	I	I		I I
(A) + (B) + (D)				
(A) + (C) + (D)	III	II		
(B) + (C) + (D)		II		
(A) + (B) + (C) + (D)				

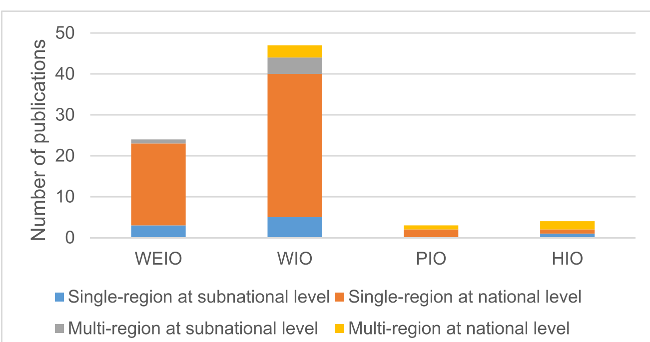

Fig. 7. Analysis of geographical coverage of models.

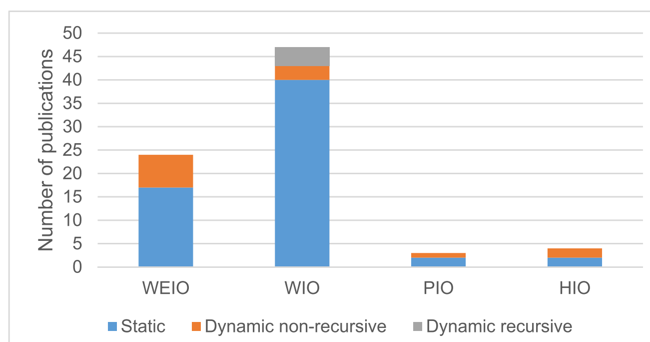

Fig. 8. Analysis of temporal coverage of models.

designing waste management policies (3). To illustrate (1), when measuring the waste footprint of Japanese cities, Tsukui et al. (2015) found that the difference in industrial waste generation is mainly attributable to differences in the economic structure of Tokyo and Kyoto. (2) The authors have quantitatively demonstrated that Tokyo depends, both directly and indirectly, on other regions for waste transportation and waste treatment and hence contributes in additional environmental impacts created in the other regions. (3) The authors suggested for waste policies design, that Tokyo should take more responsibility for the additional environmental loads created in other regions. Furthermore, Fry et al. (2015) have estimated the waste footprints of Australian regions and have found that differences in waste footprints can be explained by the variation of mean weekly household income between regions. They also found that smaller and less populated regions have a higher proportion of their waste footprint attributed to other regions. This is why, with this review, we join the others and stress that there is need to go further in the geographical resolution of models. And this is mostly a function of data constraints (see discussion Section 4.3.6).

4.3.4. Temporal dimension

Fig. 8 shows the number of publications of reviewed IO models pertaining to the temporal dimension in the analysis, namely: static, dynamic non-recursive and dynamic recursive.

Fig. 8 shows that for all the models, the static application dominates. Whilst almost 78% of models are applied in a static context, only 5% refer to a dynamic recursive application. The main underlying reason for such a slow uptake of dynamic perspective is that the reviewed IO models in their original form are static models and do not explain the dynamic process in which durable products become EoL products and are transformed into residues and/or recycled.

Fig. 8 also shows that among all the reviewed models, the WIO model is the unique model that has been applied in a dynamic recursive perspective. And, the dynamic non-recursive application is more commonly approached by all the models. However, we observed that the main limitation in the dynamic non-recursive modelling in waste generation and management is the consideration of constant coefficients of waste generation over the years, due to lack of time series data.

The consideration of dynamic recursive in analyzing waste management with IO models is important because it will allow to consistently explore the dynamics of waste generationand recycling, namely explaining the dynamic process in which durable products become end-of-life products and are transformed into residues and/or recycled (Nakamura and Kondo, 2018). Implementing dynamic recursive in IO model for waste analyses have contributed to increase the understanding of the use of materials over time and the implications of extending the lifetime of products. For instance, it has contributed to trace the fate of materials (mostly metals) over time and across products (such as automobile) in recycling, considering losses and the quality of scrap, resulting in that closing metal supply chains is often hampered by losses and product lifetimes (Nakamura et al., 2014, 2017; Pauliuk et al., 2017). In the same vein, Kagawa et al. (2015), using predictive method with a WIO model have forecasted the demand for replacement purchases of vehicles, the induced iron scrap obtained from these EoL vehicles (the secondary material supply) and the amount of secondary material necessary to satisfy the final demand.

However, integrating dynamic aspects in such models comes at the expense of additional requirements for the data, such as a time series of the final demand for durable products together with their material composition and the lifetime distribution (Nakamura and Kondo, 2018). Currently, such limitations are often coped with some assumptions, such as in Kagawa et al. (2015) where steady-state conditions are assumed for the passenger car stock, or Pauliuk et al. (2017) where a fixed technology is assumed over time. While these requirements may appear rather challenging, the application of dynamics in waste management analyses with IO models is still at its embryonic stage. Time series of environmental extended multiregional IOTs that are emerging such as (Stadler et al., 2018), can foster the integration of dynamics in waste analyses with IO models.

Furthermore, integrating dynamics in waste generation and management can help in designing resource policy and circular economy strategies. For instance, the developed framework of dynamic WIO (Nakamura and Kondo, 2018) provides a consistent framework in which multiple circular economy indicators, recycling rate, energy intensity, energy efficiency can be quantified simultaneously. Moreover, the consideration of the supply-demand balance of secondary materials that would enable such a dynamic IO model, would provide the essential inputs to waste policies design (Nakamura and Kondo, 2018; Pauliuk et al., 2017).

4.3.5. Coupling input-output models for waste analyses with other methods

Fig. 9 shows how the reviewed models have been coupled with other methods. It clearly appears that all the models have been combined with other methods. Table 6 provides more elements highlighting which methods have been coupled with which IO models.

When analyzing the intensity of model coupling, we found that some case studies present a low-level coupling or a soft link between models. This means that the output of a model (namely the reviewed IO models) is used as inputs or parameter to the other models (Beaussier et al., 2019). We have found that, the low-level couplings between IO models and other models can be explained by the different nature of the other models, the latter originating mostly from distinct disciplines, for instance from econometric modelling, as in (Beylot et al., 2017). In that latter case, the results of the waste footprint are inputs to that econometric model, including other economic and physical parameters and constraints. Furthermore, WIO models have been coupled to a linear programming (LP) procedure such as in (Kondo and Nakamura, 2005) where the results of the results of ecoefficiency analysis of waste management strategies and in Lin (2011) where the results of the environmental loads of waste water treament option (in the latter) have been integrated in a LP procedure. The finality was to explore and help taking the optimal waste treatment option respectively.

We also found case studies that present high-level coupling or the use of an integrated method (see Table 6). For example, IO models coupled with life cycle assessment, life cycle costing and material flow analysis. The high-level couplings occurs if other models have a similar structure of inventory (representing all the inputs and outputs from a life cycle perspective) and are all part of the Industrial Ecology models (Pauliuk et al., 2015).

4.3.6. Resolution of waste treatment sectors and waste types

We present the results on the resolution of sectors with emphasis on waste treatment sectors and waste types. In general, for all the reviewed models, we observed that 41% cover less than 50 products and sectors of the economy whereas 37% cover more than 100 products and sectors (see Supplementary Information). The highest sector resolution shows a 619 × 519 product-by-sector table. Such a table was developed in the form of WIO-MFA by disaggregating certain products and sectors, namely iron and steel products and the automobile sector (Nakamura et al., 2012; Ohno et al., 2014, 2015). In general, we noticed that WIO models show a higher sector resolution than the other models, in contrast to the PIO models that have the lowest sector resolution.

In addition to the overall sector resolution, we pay particular attention to the resolution of the waste treatment sector. We have found that almost 60% of models contain less than 5 waste treatment sectors and around 30% contain more than 10 waste treatment sectors. Incineration (with and without energy recovery), recycling and landfill are the most represented waste treatment sectors (see Supplementary Information). Even though the highest resolution shows 34 waste treatment sectors among the 200 products and sectors in the form of a HIO model (Merciai and Schmidt, 2017), WIO models generally presented a higher resolution of waste treatment sectors than the others. However, no specific sector related to reuse activities have been found.

Besides the resolution of the waste treatment sector, the number of waste type considered in also of interest. It appeared that 45% of models include less than 10 waste types, and 45% include between 10 and 50 waste types. The highest number of waste types analyzed was 358 in total including 190 types of general industrial waste and 168 types of hazardous industrial waste. This high amount of industrial waste was considered in a WIO-based study investigating the potential waste and materials exchanges to foster industrial symbiosis (Chen and Ma, 2015). Moreover, the waste account of the WSUTs of Australia indicating 61 categories of food waste generated by the 344 sectors and households (Reynolds et al., 2015).

However, the deficiency in waste treatment sector and waste type resolutions, as a common issue to all reviewed models is narrowly linked to the availability of waste data. To avoid such deficiency, a reasonable approach could be to disaggregate products and sectors in more detailed categories. However,

Fig. 9. Analysis of the couplings of IO models with other models.

Table 6
Cross-analysis between IO models and coupling with other methods.

Methods	WEIO	WIO	PIO	HIO
Structural Decomposition Analysis (SDA)	II			
Ecological Network Analysis		I		
Life cycle analysis (LCA)		III		II
New Econometric Model of Evaluation by Sectorial Interdependency and Supply (NEMESIS model)	I			
Linear programming (LP)		IIIII		
Material flow analysis (MFA)		IIIIIIIIIII	I	
Substance flow analysis (SFA)		I		
Life cycle costing (LCC)		II		
Engineering model		I		
Product lifetime analysis		I		

disaggregating sectors in such models presents a challenge by itself because sectoral data may not be available at the required level of detail and in parallel related data on waste types and waste treatment sectors need to be available. For instance, a limit for the analysis of recycled products in the IO framework is that waste treatment is one aggregated sector, which is labelled “Waste collection, treatment and disposal services” (Teh et al., 2018). Recycling sectors and their accompanying products are also not captured in detail and are sometimes represented as part of the main waste sector (Choi et al., 2011). The unavailability of high-resolution waste generation data by sector, caused the aggregation of the Spanish IOT from 63 sectors to 27 to quantify the waste generation (Ruiz-Peñalver et al., 2019).

In most countries and especially regions (subnational level), there is a lack of harmonized waste data and waste data at sufficiently disaggregated level. The lack of waste data is an issue common to all IO models for waste analysis and waste data constitutes the core element in constructing any WEIO, WIO, PIO and HIO models for waste analysis. In general, waste data are published by the official waste statistics offices at EU, national or subnational levels, federal, state or local governments, or industries. The datasets are often not directly comparable because the coverage, classification system, and level of aggregation varies between them. This is the case for example in Australia and in Brussels, where WSUTs have been consequently constructed based on the compilations of different waste data sources since no single published data source exists that contains enough information to build such a model (Fry et al., 2015; Zeller et al., 2018). All these shortcomings cause intense data treatment and alignments in an IO structure, and preclude the development of comprehensive and detailed IO models for waste analyses.

Besides, waste data sources contain uncertainty arising from sampling, measurement and reporting errors. Some data are derived (e.g. cubic meter to ton), others are estimated (e.g. weight deduced from a ton per capita indicator). The data quality also varies with region, reporting entity, and waste producer (for instance, household waste data are generally better quality than industry waste data). Some errors can also occur when datasets with different classification systems are merged. The confrontation between different waste data sources generates uncertainty. Also, the confrontation of bottom-up data (compiled waste data) and top-down data (IO data) for data alignment and disaggregation also introduces uncertainty. We have observed that such uncertainties have not been analyzed in none of the reviewed case studies insofar as IO data and waste data were statistically obtained and not derived from a mechanism highlighting their particular uncertainty.

An alternative solution to deal with the unavailability of data is to use of proxy data for the disaggregation. In their study Fry et al. (2015) have disaggregated the source data:1 national region to 8 subnational regions; 8 sectors to 19 sectors, using a technique for an arbitrary level of disaggregation (Lenzen, 2011) and proxy information. In this case, the lack of comprehensive data has not hampered the increase of sector resolution, because the reason why disaggregation is encourages is that it the aggregation bias that occurs when heterogeneous sectors (or regions) with very different environmental impact intensities are grouped together (Lenzen, 2011).

Moreover, we see and promote the integration of engineering models within IO models (such as in (Nakamura and Kondo, 2002a)) as another alternative solution to a data mining procedure with a lower use of a priori information. Indeed, in that iteration, the linear IO model estimates, under a certain waste treatment scenario, the initial emissions and waste. The latter are then translated into parameters in the engineering model that considers the non-linearity of waste treatments in terms of requirements and emissions under different waste characteristics. The adjusted requirements and emissions are then used to update the technological behavior of waste treatment sectors in the IO model that recalculates the emissions and waste generated. And the iteration carries on until the models converge toward a consensus in the data representation of the waste treatments that is consistent with the scenario in the IO model and coherent with the technology in the engineering model (Nakamura and Kondo, 2002a).

5. Discussion and outlook

In this section we focus on the contributions of this review to the discussion about improving IO application on waste management strategies in a context of circular economy.

First, the results from the bibliometric analysis have confirmed that WIO models are the most spread and widely applied. Although they are older than WIO model, PIO and HIO models for waste analysis develop at a slower pace. Indeed, the popularity of the WIO model can be attributed to the availability of monetary IO data and waste statistics at a certain level of detail, plus its recognized analytical framework. The same does not seem to apply to PIO and HIO models. Hence, acknowledging efforts achieved toward the expansion of these latter models, physical IO data are still scarce and there is still no standardized analytical framework so far. This gives room to further research in that direction.

Second, the results from the analysis of model characteristics have revealed that the HIO, followed by PIO models incorporate several properties advantageous for the analysis of waste management strategies. The main property we emphasize on here is related to the respect of the mass balance principle (see section 4.2.3).

We found that the respect of waste mass balance is present in most reviewed studies. The analysis of the waste balance starts at the stage where the waste is already generated and uses the data gathered on waste treatment (or more precise waste generated/ collected dedicated for treatment) to make a waste supply-use balance. However, integrating the mass balance at higher scales, especially at sector level, enables to consistently capture the waste generation and material circularity mechanisms, which is not possible with the waste mass balance. The wide and valuable application of WIO-MFA models (e.g. (Nakamura et al., 2007, 2014; Ohno et al., 2014, 2015; Pauliuk et al., 2017) has mostly contributed to increase the understanding of material circularity mechanisms in tracing the fate of EoL materials to sectors, considering the efficiency of processes, the quality of scrap and the dimension of time. Yet, despite these works plus the one of Merciai and Schmidt (2017), the underlying mechanisms of waste generation with IO models remain poorly understood; and the integrating the mass balance principle can contribute in that sense. Therefore, with this review, we also aim to foster increasing attention of researchers that respecting the mass balance principle at several levels is a crucial property that IO models should hold for a consistent analysis of waste management strategies in a circular economy context.

Third, the analysis of functionalities of IO models that have been analyzed through case studies has revealed that all their abilities and features have nothing to do with a conceptual difference. Indeed, there is no cause-effect link between the conceptual characteristics and the functionalities of IO models, since all models are able to include all these functionalities. However, the use of functionalities of a model depends on the data availability, the technical knowledge of the practitioner and the aim of the study. With this analysis of functionalities, we identified some ‘empirical novelties’ in the IO literature relevant for waste management analysis that can nourish the pool of case studies: the development of a single- or multi-region at subnational level especially with HIO and PIO models to capture regional variations of waste related issues; an analysis of trade-offs between waste footprint and other environmental footprints; a diagnosis or scenario analysis that consistently analyze waste generation and EoL management as well as the related environmental and economic impacts, and so on.

We also see research potentials in more couplings, not only to pursue addressing the issues related to the static nature of IO models for which tremendous works has been carried out, but also to address the linearity issues in IO models. In this regard, all IO models remain linear to the extent that the characteristics of waste flows allocated to each of the treatment methods are fixed. However, a change in these characteristics may affect the coefficients of the model and break the linearity. An integration of an engineering model within a WIO model by Nakamura and Kondo (2002a) has demonstrated the non-linear nature of waste treatment in the WIO model. The integration lies upon an iteration between the representation of a certain waste sector in a WIO model and in an engineering model, to describe the non-linear behaviour of treatment processess under alternative waste composition. Such integration has been operated once by Nakamura and Kondo (2002a) and since then, to the knowledge of the authors, no endeavour has been made to exploit this potential. Therefore, with this review, we also aim to raise the attention of researchers to this research possibilty.

In the reviewed studies, recycling of materials is most widely analyzed option of material circularity. In practice, direct reuse of products or reuse after preparation for reuse is also part of waste management strategies. Yet, we found that very few reviewed study or IO model has approached this topic. For instance, Merciai and Schmidt (2017) have separately introduced the direct reuse of bottles as one economic activity. However, in the current reviewed models, preparation for reuse activities may be grouped with the sector that includes waste collection, disposal, and material recovery facilities and remanufacturing. In any case, these reuse activities are aggregated with conventional sectors. Hence, disaggregating these activities from conventional sectors would allow assessing consistently impacts of reuse activities. Such disaggregation procedure represents not only a methodological challenge, but is also constrained by the availability of data, especially in physical units. We acknowledge the previous work of Ferrer and Ayres (2000) who developed a methodology for disaggregating monetary IOTs to incorporate remanufacturing sectors as competitors of existing manufacturing sectors in France, to assess the economic changes in the demand for labor and inputs requirements. Future efforts in that direction especially using the reviewed IO models should follow, giving paths to further research.

Lastly, we have seen that WEIO, WIO, PIO and HIO models describe the transactions with different units, HIO model being the most complete (in terms of unit). However, the evident limitation common to these models is that the system is never completely described in terms of any of its units of measurement (Majeau-Bettez et al., 2016; Stahmer, 2000). For instance, services described in monetary unit cannot be used to check the mass balance; or products accounted in mass cannot be involved in a cost analysis of a waste management strategy. Multi-unit or multilayered SUTs (ML SUTs) thus contribute in providing a more complete representation of transactions. The development of such tables has been first (to the knowledge of the authors) carried out by Stahmer (2000) covering three unit: mass, monetary and time. And recently a tremendous endeavor has also led to the development of EXIOBASE, which can be considered as a ML SUTs inventoried in mass, monetary and energy units, at multi-regional level (Merciai and Schmidt, 2017; Stadler et al., 2018).

Yet, no analysis of waste management strategies in a context of circular economy has been conducted using this type of model, i.e. considering the three layers together. Although, using such a model would allow an even more comprehensive analytical scope than the reviewed ones, such as performing simultaneously and consistently economic and environmental analyses. However, applying such a model for waste management analysis remains a methodological and analytical challenge and may require high computational features given its complexity. With this review, we thus also aim to contribute in fostering raising attention related to these aspects and promote the use of ML SUTs for waste management analysis in the context of circular economy.

6. Conclusion

We have reviewed 78 studies that have used IO models for waste management analyses. We have categorized all IO models into four types (waste extended IO (WEIO), waste IO (WIO), physical IO (PIO) and hybrid IO (HIO)). We have then defined of each model within a waste analysis framework, and carried out a bibliometric analysis. Our comparative analysis was twofold. Firstly, to compare the models conceptually, we have analyzed and discussed three characteristics of the models – the units of intersectoral flows, the modelling of waste and the relation with mass balance principle. Secondly, we have analyzed and discussed six criteria pertaining to the functionalities of the models, – the waste generation accounting, the purpose of the modelling, the geographical scale, the temporal dimension, the coupling of the IO models with other methods and the level of details of waste treatment sectors and waste types.

Our findings are fourfold

First, there is increasing interest in assessing waste management policies with IO models. Subsequently, while WIO models are most spread and widely applied, followed by WEIO models, PIO and HIO models for waste analysis develop at a slower pace. This exemplifies – for the specific field of waste management analysis – and corroborates with what have been commonly mentioned in the literature that: the physical and hybrid representations of the economy are still lacking (Altimiras-Martin, 2014; Giljum and

Hubacek, 2009; Kytzia, 2009; Minx et al., 2009; Tisserant et al., 2017).

Second, the analysis of characteristics of each IO model has revealed the conceptual similarities and differences between models. The monetary nature of intersectoral flows of reviewed WEIO and WIO models limits their abilities to consistently analyze the waste generation and circularity mechanisms. While the reviewed PIO models excel in capturing the physical metabolism of the economy, they fail in representing non-material output of service-based sectors. The reviewed HIO models tackles the limitations of the WEIO, WIO and PIO models with its mixed-unit framework. Yet, a limitation common to all these models lies in the difficulty to completely describe flows in terms of any of its unit of measurement. Thus, a multilayered IO model is indispensable and should be fostered, since no waste related analysis has been conducted with such model so far. Furthermore, the respect of the mass balance of industrial processes is the one of the major property that PIO and HIO models should hold for a consistent analysis of waste management strategies.

Third, the analysis of functionalities of IO models that have been analyzed through case studies has revealed that there is no cause-effect link between the conceptual characteristics and the functionalities of IO models, since all models are able to include all these functionalities. However, the use of functionalities of a model depends on the data availability, the technical knowledge of the practitioner and the aim of the study. With this analysis of functionalities, we have also contributed to identify some empirical needs and novelties which can pave the way for several future research.

Fourth, the main limitation common to all models is data related. Future efforts should be oriented toward a more effective monitoring and collection of physical IO data and waste data. A common framework for compiling waste statistics from economic activities on a global scale, e.g., similar to what is already available on the EU scale but considering a more disaggregated level regarding waste-generating economic activities and waste treatment sectors, would significantly improve the reliability of WEIO, WIO, PIO and HIO models. Further applications of the PIO and HIO models are highly fostered, in other to capture the complete physical metabolism of economies, not only from a waste management scope, but also including resources and material management. More efforts should also be directed toward the development of methods to consistently and endogenously estimate waste data, when it becomes the limiting factor.

Indeed, the development of multi-regional IO databases, including extensions to waste generation, as well as time series, at national level such as the EXIOBASE database (Merciai and Schmidt, 2017; Stadler et al., 2018), but also at subnational level, appears promising. Beside, initiatives such as the one of the Industrial Ecology Virtual Laboratory (IELab) in Australia, encouraging researchers to pool data and share competences in data alignment and reconciliation from many different data sources, sounds also promising (Lenzen and Reynolds, 2014).

Such efforts on (i) increasing the availability of data and (ii) developing methods to estimate missing data, align and reconciliate different data sources can highly tackle limitations related to the low resolution of models, and foster the integration of dynamics in waste analyses with IO models.

It is noteworthy that our methodology may show some limits, in the sense that the choice of characteristics and features was based on what the authors esteem were of relevance for this review that focuses on assessing waste management policies at economy-wide level. This review can be improved by for instance performing a quantitative and objective ranking of IO models in respect to a larger pool of criteria.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References

Aguilar-Hernandez, G.A., Sigüenza-Sanchez, C.P., Donati, F., Rodrigues, J.F.D., Tukker, A., 2018. Assessing circularity interventions: a review of EEIOA-based studies. J. Econ. Struct. 7, 14.
Altimiras-Martin, A., 2014. Analysing the structure of the economy using physical input–output tables. Econ. Syst. Res. 26, 463–485.
Barata, E.J.G., 2002. Solid Waste Generation and Management in Portugal: - an Environmental Input-Output Modelling Approach a, p. 25 (Tunisia).
Beaussier, T., Caurla, S., Bellon-Maurel, V., Loiseau, E., 2019. Coupling economic models and environmental assessment methods to support regional policies: a critical review. J. Clean. Prod. 216, 408–421.
Beylot, A., Vaxelaire, S., Villeneuve, J., 2015. Reducing gaseous emissions and resource consumption embodied in French final demand: how much can waste policies contribute? J. Ind. Ecol. 20, 905–916.
Beylot, A., Boitier, B., Lancesseur, N., Villeneuve, J., 2016. A consumption approach to wastes from economic activities. Waste Manag. 49, 505–515.
Beylot, A., Boitier, B., Lancesseur, N., Villeneuve, J., 2017. The waste footprint of French households in 2020: a comparison of scenarios of consumption growth using input-output analysis. J. Ind. Ecol. 22, 356–368.
Chen, P.-C., Ma, H., 2015. Using an industrial waste account to facilitate national level industrial symbioses by uncovering the waste exchange potential. J. Ind. Ecol. 19, 950–962.
Choi, T., Jackson, R.W., Green Leigh, N., Jensen, C.D., 2011. A baseline input–output model with environmental accounts (IOEA) applied to E-waste recycling. Int. Reg. Sci. Rev. 34, 3–33.
Dietzenbacher, E., Giljum, S., Hubacek, K., Suh, S., 2009. Physical input-output analysis and disposals to nature. In: Suh, S. (Ed.), Handbook of Input-Output Economics in Industrial Ecology. Springer Netherlands, Dordrecht, pp. 123–137.
Duchin, F., 1990. The conversion of biological materials and wastes to useful products. Struct. Chang. Econ. Dyn. 1, 243–261.
EC, 2008. Directive 2008/104/EC of the European parliament and of the council of 19 november 2008 on waste and repealing certain directives (text with EEA relevance). In: Core EU Legislation. Macmillan Education UK, London, pp. 426–429.
EC, 2015. (European Comission) Closing the Loop - an EU Action Plan for the Circular Economy. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions.
Ferrão, P., Ribeiro, P., Rodrigues, J., Marques, A., Preto, M., Amaral, M., Domingos, T., Lopes, A., Costa, e I., 2014. Environmental, economic and social costs and benefits of a packaging waste management system: a Portuguese case study. Resour. Conserv. Recycl. 85, 67–78.
Ferrer, G., Ayres, R.U., 2000. The impact of remanufacturing in the economy. Ecol. Econ. 32, 413–429.
Fry, J., Lenzen, M., Giurco, D., Pauliuk, S., 2015. An Australian multi-regional waste supply-use framework. J. Ind. Ecol. 20, 1295–1305.
Ghisellini, P., Cialani, C., Ulgiati, S., 2016. A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. J. Clean. Prod. 114, 11–32.
Giljum, S., Hubacek, K., 2009. Conceptual foundations and applications of physical input-output tables. In: Handbook of Input-Output Economics in Industrial Ecology. Springer, Dordrecht, pp. 61–75.
Guan, Y., Huang, G., Liu, L., Huang, C.Z., Zhai, M., 2019. Ecological network analysis for an industrial solid waste metabolism system. Environ. Pollut. 244, 279–287.
Hoekstra, R., van den Bergh, J.C.J.M., 2006. Constructing physical input–output tables for environmental modeling and accounting: framework and illustrations. Ecol. Econ. 59, 375–393.
Huang, G.H., Anderson, W.P., Baetz, B.W., 1994. Environmental input-output analysis

and its application to regional solid-waste management planning. J. Environ. Manag. 42, 63–79.
Jensen, C.D., Mcintyre, S., Munday, M., Turner, K., 2013. Responsibility for regional waste generation: a single-region extended input–output analysis for wales. Reg. Stud. 47, 913–933.
Jiang, D., Chen, W.-Q., Liu, W., Chertow, M., 2017. Inter-sectoral Bisphenol A (BPA) flows in the 2012 Chinese economy. Environ. Sci. Technol. 51, 8654–8662.
Kagawa, S., Inamura, H., Moriguchi, Y., 2004. A simple multi-regional input–output account for waste analysis. Econ. Syst. Res. 16, 1–20.
Kagawa, S., Nakamura, S., Kondo, Y., Matsubae, K., Nagasaka, T., 2015. Forecasting replacement demand of durable goods and the induced secondary material flows: a case study of automobiles. J. Ind. Ecol. 19, 10–19.
Kaza, S., Yao, L., Bhada-Tata, P., Van Woerden, F., 2018. WHAT A WASTE 2.0 A Global Snapshot of Solid Waste Management to 2050. World Bank Group.
Kneese, A.V., Ayres, R.U., d'Arge, R.C., 1970. Economics and the Environment: A Material Balance Approach. Johns Hopkins University Press, Baltimore, MD.
Kondo, Y., Nakamura, S., 2004. Evaluating alternative life-cycle strategies for electrical appliances by the waste input-output model. Int. J. Life Cycle Assess. 9, 236.
Kondo, Y., Nakamura, S., 2005. Waste input–output linear programming model with its application to eco-efficiency analysis. Econ. Syst. Res. 17, 393–408.
Kytzia, S., 2009. An input-output framework to enhance consistency in hybrid modeling. In: Suh, S. (Ed.), Handbook of Input-Output Economics in Industrial Ecology. Springer Netherlands, Dordrecht, pp. 99–121.
Lenzen, M., 2011. Aggregation versus disaggregation in input–output analysis of the environment. Econ. Syst. Res. 23, 73–89.
Lenzen, M., Reynolds, C.J., 2014. A supply-use approach to waste input-output analysis. J. Ind. Ecol. 18, 212–226.
Leontief, W., 1970. Environmental repercussions and the economic structure: an input-output approach. Rev. Econ. Stat. 52, 262.
Leontief, W.W., 1936. Quantitative input and output relations in the economic systems of the United States. Rev. Econ. Stat. 18, 105–125.
Liang, S., Zhang, T., Xu, Y., 2012. Comparisons of four categories of waste recycling in China's paper industry based on physical input–output life-cycle assessment model. Waste Manag. 32, 603–612.
Liao, M., Chen, P., Ma, H., Nakamura, S., 2015. Identification of the driving force of waste generation using a high-resolution waste input–output table. J. Clean. Prod. 94, 294–303.
Lin, C., 2011. Identifying lowest-emission choices and environmental pareto frontiers for wastewater treatment wastewater treatment input-output model based linear programming. J. Ind. Ecol. 15, 367–380.
Lin, C., Nakamura, S., 2018. Approaches to solving China's marine plastic pollution and CO2 emission problems. Econ. Syst. Res. 0, 1–15.
Majeau-Bettez, G., Wood, R., Hertwich, E.G., Strømman, A.H., 2016. When do allocations and constructs respect material, energy, financial, and production balances in LCA and EEIO? J. Ind. Ecol. 20, 67–84.
McCarthy, A., Dellink, R., Bibas, R., 2018. The Macroeconomics of the Circular Economy Transition: A Critical Review of Modelling Approaches.
Merciai, S., Schmidt, J., 2016. Physical/hybrid Supply and Use Tables - Methodological Report.
Merciai, S., Schmidt, J., 2017. Methodology for the construction of global multi-regional hybrid supply and use tables for the EXIOBASE v3 database. J. Ind. Ecol. 22, 516–531.
Miller, R.E., Blair, P.D., 2009. Input-Output Analysis: Foundations and Extensions. Cambridge University Press.
Minx, J.C., Wiedmann, T., Wood, R., Peters, G.P., Lenzen, M., Owen, A., Scott, K., Barrett, J., Hubacek, K., Baiocchi, G., et al., 2009. Input–output analysis and carbon footprinting: an overview of applications. Econ. Syst. Res. 21, 187–216.
Nakamura, S., 1999. Input-output analysis of waste cycles. Proc. First Int. Symp. Environ. Conscious Des. Inverse Manuf. 475–480.
Nakamura, S., Kondo, Y., 2002a. Input-output analysis of waste management. J. Ind. Ecol. 6, 39–63.
Nakamura, S., Kondo, Y., 2002b. Recycling, landfill consumption, and CO2 emission: analysis by waste input–output model. J. Mater. Cycles Waste Manag. 4, 2–11.
Nakamura, S., Kondo, Y., 2006a. A waste input–output life-cycle cost analysis of the recycling of end-of-life electrical home appliances. Ecol. Econ. 57, 494–506.
Nakamura, S., Kondo, Y., 2006b. Hybrid LCC of appliances with different energy efficiency (10 pp). Int. J. Life Cycle Assess. 11, 305–314.
Nakamura, S., Kondo, Y., 2009. Waste Input-Output Analysis: Concepts and Application to Industrial Ecology. Springer Science & Business Media.
Nakamura, S., Kondo, Y., 2018. Toward an integrated model of the circular economy: dynamic waste input–output. Resour. Conserv. Recycl. 139, 326–332.
Nakamura, S., Yamasue, E., 2010. Hybrid LCA of a design for disassembly technology: active disassembling fasteners of hydrogen storage alloys for home appliances. Environ. Sci. Technol. 44, 4402–4408.
Nakamura, S., Nakajima, K., Kondo, Y., Nagasaka, T., 2007. The waste input-output approach to materials flow analysis. J. Ind. Ecol. 11, 50–63.
Nakamura, S., Murakami, S., Nakajima, K., Nagasaka, T., 2008. Hybrid Input–Output approach to metal production and its application to the introduction of lead-free solders. Environ. Sci. Technol. 42, 3843–3848.
Nakamura, S., Kondo, Y., Matsubae, K., Nakajima, K., Nagasaka, T., 2011. UPIOM: a new tool of MFA and its application to the flow of iron and steel associated with car production. Environ. Sci. Technol. 45, 1114–1120.
Nakamura, S., Kondo, Y., Matsubae, K., Nakajima, K., Tasaki, T., Nagasaka, T., 2012. Quality- and dilution losses in the recycling of ferrous materials from end-of-life passenger cars: input-output analysis under explicit consideration of scrap quality. Environ. Sci. Technol. 46, 9266–9273.
Nakamura, S., Kondo, Y., Kagawa, S., Matsubae, K., Nakajima, K., Nagasaka, T., 2014. MaTrace: tracing the fate of materials over time and across products in open-loop recycling. Environ. Sci. Technol. 48, 7207–7214.
Nakamura, S., Kondo, Y., Nakajima, K., Ohno, H., Pauliuk, S., 2017. Quantifying recycling and losses of Cr and Ni in steel throughout multiple life cycles using MaTrace-alloy. Environ. Sci. Technol. 51, 9469–9476.
Ohno, H., Matsubae, K., Nakajima, K., Nakamura, S., Nagasaka, T., 2014. Unintentional flow of alloying elements in steel during recycling of end-of-life vehicles. J. Ind. Ecol. 18, 242–253.
Ohno, H., Matsubae, K., Nakajima, K., Kondo, Y., Nakamura, S., Nagasaka, T., 2015. Toward the efficient recycling of alloying elements from end of life vehicle steel scrap. Resour. Conserv. Recycl. 100, 11–20.
Ohno, H., Nuss, P., Chen, W.-Q., Graedel, T.E., 2016. Deriving the metal and alloy networks of modern technology. Environ. Sci. Technol. 50, 4082–4090.
Ohno, H., Matsubae, K., Nakajima, K., Kondo, Y., Nakamura, S., Fukushima, Y., Nagasaka, T., 2017. Optimal recycling of steel scrap and alloying elements: input-output based linear programming method with its application to end-of-life vehicles in Japan. Environ. Sci. Technol. 51, 13086–13094.
Pauliuk, S., Majeau-Bettez, G., Müller, D.B., 2015. A general system structure and accounting framework for socioeconomic metabolism. J. Ind. Ecol. 19, 728–741.
Pauliuk, S., Kondo, Y., Nakamura, S., Nakajima, K., 2017. Regional distribution and losses of end-of-life steel throughout multiple product life cycles—insights from the global multiregional MaTrace model. Resour. Conserv. Recycl. 116, 84–93.
Reutter, B., Lant, P., Reynolds, C., Lane, J., 2017. Food waste consequences: environmentally extended input-output as a framework for analysis. J. Clean. Prod. 153, 506–514.
Reynolds, C., Geschke, A., Piantadosi, J., Boland, J., 2016a. Estimating industrial solid waste and municipal solid waste data at high resolution using economic accounts: an input–output approach with Australian case study. J. Mater. Cycles Waste Manag. 18, 677–686.
Reynolds, C., Mirosa, M., Clothier, B., Reynolds, C.J., Mirosa, M., Clothier, B., 2016b. New Zealand's food waste: estimating the tonnes, value, calories and resources wasted. Agriculture 6, 9.
Reynolds, C.J., Piantadosi, J., Boland, J., 2014. A waste supply-use analysis of Australian waste flows. J. Econ. Struct. 3, 5.
Reynolds, C.J., Piantadosi, J., Boland, J., 2015. Rescuing food from the organics waste stream to feed the food insecure: an economic and environmental assessment of Australian food rescue operations using environmentally extended waste input-output analysis. Sustainability 7, 4707–4726.
Ruiz-Peñalver, S.M., Rodríguez, M., Camacho, J.A., 2019. A waste generation input output analysis: the case of Spain. J. Clean. Prod. 210, 1475–1482.
Schmidt, J.H., Weidema, B.P., Suh, S., 2010. Documentation of the Final Model Used for the Scenario Analyses.
SEEA, 2014. United Nations, European Union, Food and Agriculture Organization of the United Nations, International Monetary Fund Organisation for Economic Co-operation and Development. The World Bank. System of Environmental-Economic Accounting 2012 Central Framework.
Stadler, K., Wood, R., Bulavskaya, T., Södersten, C.-J., Simas, M., Schmidt, S., Usubiaga, A., Acosta-Fernández, J., Kuenen, J., Bruckner, M., et al., 2018. EXIOBASE 3: developing a time series of detailed environmentally extended multi-regional input-output tables. J. Ind. Ecol. 22, 502–515.
Stahmer, C., 2000. The Magic Triangle of Input-Output Tables. Macerata, Italy.
Suh, S., 2004. Functions, commodities and environmental impacts in an ecological–economic model. Ecol. Econ. 48, 451–467.
Takase, K., Kondo, Y., Washizu, A., 2005. An analysis of sustainable consumption by the waste input-output model. J. Ind. Ecol. 9, 201–219.
Teh, S.H., Wiedmann, T., Moore, S., 2018. Mixed-unit hybrid life cycle assessment applied to the recycling of construction materials. J. Econ. Struct. 7.
Tisserant, A., Pauliuk, S., Merciai, S., Schmidt, J., Fry, J., Wood, R., Tukker, A., 2017. Solid waste and the circular economy: a global analysis of waste treatment and waste footprints. J. Ind. Ecol. 21, 628–640.
Tsukui, M., Kagawa, S., Kondo, Y., 2015. Measuring the waste footprint of cities in Japan: an interregional waste input–output analysis. J. Econ. Struct. 4, 18.
United Nations, 1993. Handbook of National Accounting. Integrated Environmental and Economic Accounting, New York.
United Nations, 2014. System of Environmental-Economic Accounting 2012 Central Framework. New York.
Weisz, H., Duchin, F., 2006. Physical and monetary input–output analysis: what makes the difference? Ecol. Econ. 57, 534–541.
Wood, R., Stadler, K., Bulavskaya, T., Lutter, S., Giljum, S., De Koning, A., Kuenen, J., Schütz, H., Acosta-Fernández, J., Usubiaga, A., et al., 2015. Global sustainability accounting—developing EXIOBASE for multi-regional footprint analysis. Sustainability 7, 138–163.
Yang, N., Chen, D., Hu, S., Li, Y., Jin, Y., 2010. Evaluation of the tire industry of China based on physical input–output analysis. J. Ind. Ecol. 14, 457–466.
Zeller, V., Towa, E., Degrez, M., Achten, W.M.J., 2018. Integration of waste supply and use data into regional footprints: case study on the generation and use of waste from consumption and production activities in Brussels. Procedia CIRP 69, 100–105.
Zeller, V., Towa, E., Degrez, M., Achten, W.M.J., 2019. Urban waste flows and their potential for a circular economy model at city-region level. Waste Manag. 83, 83–94.