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1 Introduction

The circular economy package was adopted in the EU in an attempt to boost competitiveness and generate sustainable growth (EC 2015c; EC 2015a; EC 2015b). This ambitious strategy is built on adopting a holistic approach by enhancing the production cycle and stimulating Europe's transition from a take-make-dispose model into a circular model. The UK has a unique economic structure, waste treatment capacities, and waste generation characteristics. This means that the UK faces unique challenges in shifting to a circular economy.

The UK government has recently released responses to the EU circular economy package, listing barriers to adoption (DEFRA 2015b; Environmental Audit Committee 2014; DEFRA 2015a). These include regulatory, financial, information, and systemic barriers. Many of these barriers can be assisted through greater quantification of the UKs waste flows.

A consensus exists on the vital role of waste and resource management in achieving a transition from a linear model to a circular one where the value of materials and resources are maintained in the supply chain. However, in order to do so, effective strategies and plans can only be designed and implemented based on a sound understanding of the issue. In order to address the above barriers and move towards this circular model, the UK must have greater quantification of waste flows, and better identification of existing disposal options. This will allow greater understanding of the current status and ultimately allow the introduction of effective management strategies.

Quantification of waste arisings in the supply chain represents a compelling challenge in our globalized and modern world; the supply chain of products is inter-connected and fragmented across different industrial sectors. Waste systematically emerges throughout the supply chain as a result of economic activities and trades (Kurz 2006; Beamon 1999; Parfitt et al. 2010). An example of this is a study conducted by the UK Waste and Resource Action Programme (WRAP 2013) examined food and drink waste arising in the supply chain. This study estimated that 13 Mt of waste is generated in the food and drink supply chain, 85% more than waste arisings in the post consumption stage.

Within the industrial ecological toolkit there are many modelling methods that enable the tracing of waste generation and resource flows within the (circular) economy. Two similar methods are Input-Output (IO) and Material Flow Analysis (Nakamura et al. 2007). In this study we suggest the use of waste IO analysis (WIOA) to quantify the economic and waste impacts in the UK (Nakamura & Kondo 2009).

IO analysis is an accounting procedure that was principally formulated by Leontief in the 1930s (Leontief 1936), to trace financial transactions and understand the interactions between industrial sectors, producers and consumers within an economy. The IO methodology has been previously used to couple financial information with physical waste data and to link waste arisings to economic activity, examples include: the regional WIO table of Wales (Jensen et al.

2011); the Dutch NAMEA (Haan & Keuning 1996); the German physical IO table (Stahmer et al. 1998); the WIO table for Japan (S. Nakamura & Kondo 2002; Tsukui et al. 2015); Australia (Reynolds et al. 2014; Fry et al. 2015), Taiwan (Liao et al. 2015) and France (Beylot et al. 2016).

This study introduces the first part of ongoing research: the development of a national UK WIO table. Linking 34 waste types to 21 UK industrial sectors, this paper introduces the first version of the UK WIO table that enables the quantification of waste arisings throughout the supply chain. The proposed WIO table is expected to be further developed and disaggregated to help identify current disposal options. Upon the completion of the project, the UK WIO table would provide a wider understanding of the issue and, consequently, assist in the economic and waste flow modeling of tailored interventions to tackle this issue and promote waste prevention and circular economy strategies.

2 Methodology

Data Sources

The WIO table was synthesized using data from two primary sources: financial data from the 2010 UK Input Output Analytical Tables (IOATs) (ONS 2014), and waste data from the Environment Data Waste Centre (Eurostat 2011). The 2010 IOATs is the latest published table showing the composition of uses and resources across institutional sectors and the inter-dependence of industries within the UK national economy. Compiled in accordance to UK's Standard Industrial Classification 2007 (SIC 2007) for industries, the detailed version of the 2010 IOATs have 114 industrial sectors. However, due to the unavailability of high-resolution waste arisings data, these industrial sectors were aggregated into 21 categories (Table 1). For this introductory model is one waste treatment sector (#38), the activity level of this waste treatment sector is dependent upon the amount of waste treated. Aggregated categories were chosen to be compatible with other datasets used in this work. The WIO model introduced here is a single region model with a domestic technology assumption (i.e. the impact of import and export flows on waste arisings are not considered).

Waste generation data for the year 2010 was categorized into 34 waste types complying with the EWC-Stat (Eurostat 2010; Eurostat 2011). “Services” sector was disaggregated into 6 sub-sectors in accordance with DEFRA’s survey of commercial and industrial waste arisings 2010 (DEFRA 2011). All sectors were labelled based on the statistical classification of economic activities in the European community- NACE Rev. 2 (Eurostat 2008).

For the purpose of this study, we investigate the impact of direct and indirect waste arisings for each industrial sector using a hypothetical scenario: a final demand investment of £1 million.

Table 1 Classification of industries.

No.	SIC 2007	Sector	No.	SIC 2007	Sector
1	[1-3]	Agriculture, forestry and fishing	12	[31-33]	Manufacture of furniture; jewellery, musical instruments, toys; repair and installation of machinery and equipment
2	[5-9]	Mining and quarrying	13	[35]	Electricity, gas, steam and air conditioning supply
3	[10-12]	Manufacture of food products; beverages and tobacco products	14	[36-37,39]	Water collection, treatment and supply; sewerage; remediation activities and other waste management services
4	[13-15]	Manufacture of textiles and related products	15	[38]	Waste collection, treatment and disposal activities; materials recovery
5	[16]	Manufacture of wood and and related products	16	[41-43]	Construction
6	[17-18]	Manufacture of paper and paper products; printing and reproduction of recorded media	17	[45-47]	Retail and Wholesale
7	[19]	Manufacture of coke and refined petroleum products	18	[55-56]	Hotels & Catering
8	[20-22]	Manufacture of chemical, pharmaceutical, rubber and plastic products	19	[84, 86-88]	Public Administration and social work
9	[23]	Manufacture of other non-metallic mineral products	20	[85]	Education
10	[24-25]	Manufacture of basic metals and fabricated metal products, except machinery and equipment	21	[49-53]	Transport and storage
11	[26-30]	Manufacture of computer, electronic and optical products, electrical equipment, motor vehicles and other transport equipment	22	[58-82, 90-96]	Other services

IO methodology

This WIO table's mathematical structure is based on the principles of the IOA (Miller & Blair 2009). In order to link economic activities with waste arisings, we use the original extended model to define a matrix of environmental outputs – waste generation in this study (Hendrickson et al. 1998). In our study, total, direct and indirect waste arisings in the supply chain can be calculated using Eq.(1), Eq.(2) and Eq.(3), respectively. However, as per the WIO construction of Nakamura and Kondo (2002, 2009), the waste treatment sector was excluded from the calculation of multipliers (A and L). Data sources used in the model are available in the supplementary file (see Table 2). To validate our results the multipliers were also calculated using a WSUT framework (Lenzen and Reynolds 2014).

$V = LY$ Eq.(1)

$L_{total} = W(I - A)^{-1}$ Eq.(2)

$L_{direct} = W(I + A)$ Eq.(3)

$L_{indirect} = W[(I - A)^{-1} - (I + A)]$ Eq.(4)

Where,

V is a vector listing the waste arisings (tonnes) generated as a result of final demand (Y).

Y is a vector representing the final demand (£ million).

L represents waste arisings associated with the supply chain.

W is a coefficient matrix that represents waste arisings at each stage per monetary unit of output.

$(I-A)^{-1}$ Leontief inverse coefficient matrix which is based on the 2010 UK Input Output Analytical table compiled in this work.

Table 2 List of tables available in the supplementary file.

Table no.	Data	Description
A(1)	The 2010 UK IOATs	The 2010 Input-Output Analytical Table aggregated into 21 industrial sectors.
A(2)	Final demand table	Consists of final consumption expenditure, cross capital formation, and exports of goods and services.
A(3)	Waste arisings table	Waste quantities generated in 2010
A(4)	Waste arisings multipliers table	Waste quantities generated for each £1 million from final demand
A(5)	Leontiff's inverse $(I\text{-}A)^{-1}$	A square matrix describes the relationship between total consumption and final demand
A(6)	Waste arisings associated with the whole supply chain (L)	Represents waste arisings associated with the supply chain.
A(7)	Waste arisings as a result of a final demand of £1 in each sector	Quantities of waste arisings (tonne) in the supply chain based on a final demand of £1 milliom in each industrial sector. 7a total, 7b direct supply chain and 7c waste generation rates per £1m of final demand for each industrial sector.

Direct vs. indirect waste arisings

The power of the WIO methodology applied in this study is the ability to capture both direct and indirect waste arisings across the supply chain. Direct waste arisings are associated with suppliers who directly supply the industry under investigation while indirect suppliers are those that do not directly supply the industry but are suppliers to the suppliers of the industry, referred to as indirect suppliers of first level, second level …etc. Figure 1 illustrates the relationship discussed above and provides an example to elaborate the relationship between total, direct and indirect waste arisings.

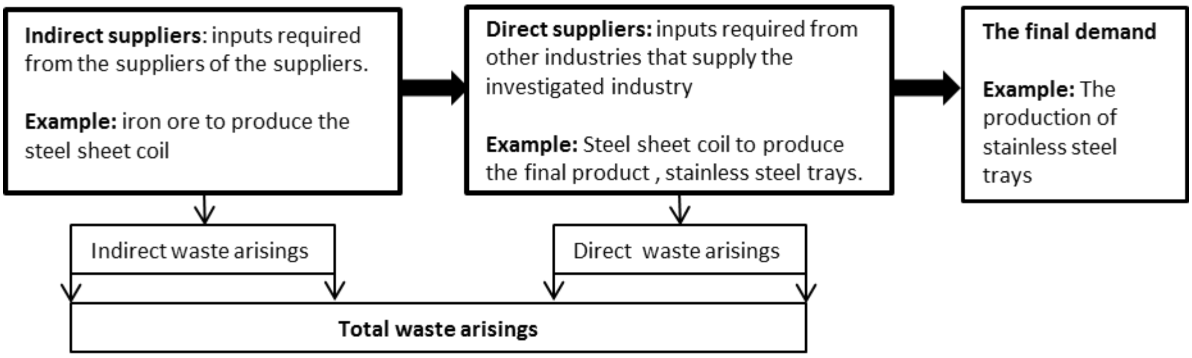

Figure 1 Direct and indirect suppliers and total waste arisings.

3 Results and discussion

Results show that the construction sector has the highest waste generation rate (742 tonne) followed by the mining and quarrying industry (694 tonne). Detailed results of waste arisings quantities and the type of waste for all 21 industrial sectors are available in the supplementary file, Table A(7). Figure 2(a) aggregates waste generation rates per £1m of final demand for each industrial sector.

In regards to waste arisings in the direct and indirect supply chain, Figure 2 (b) shows large variations in the contribution of indirect waste arisings across industrial sectors; it ranges from 13% in the mining and quarrying industry to 48% in the manufacturing of electronics. Results quantitatively confirm that sectors with a long supply chain (i.e., manufacturing and services sectors) have higher indirect waste generation rates compared to industrial primary sectors (e.g., mining and quarrying) and sectors with a shorter supply chain (e.g., construction).

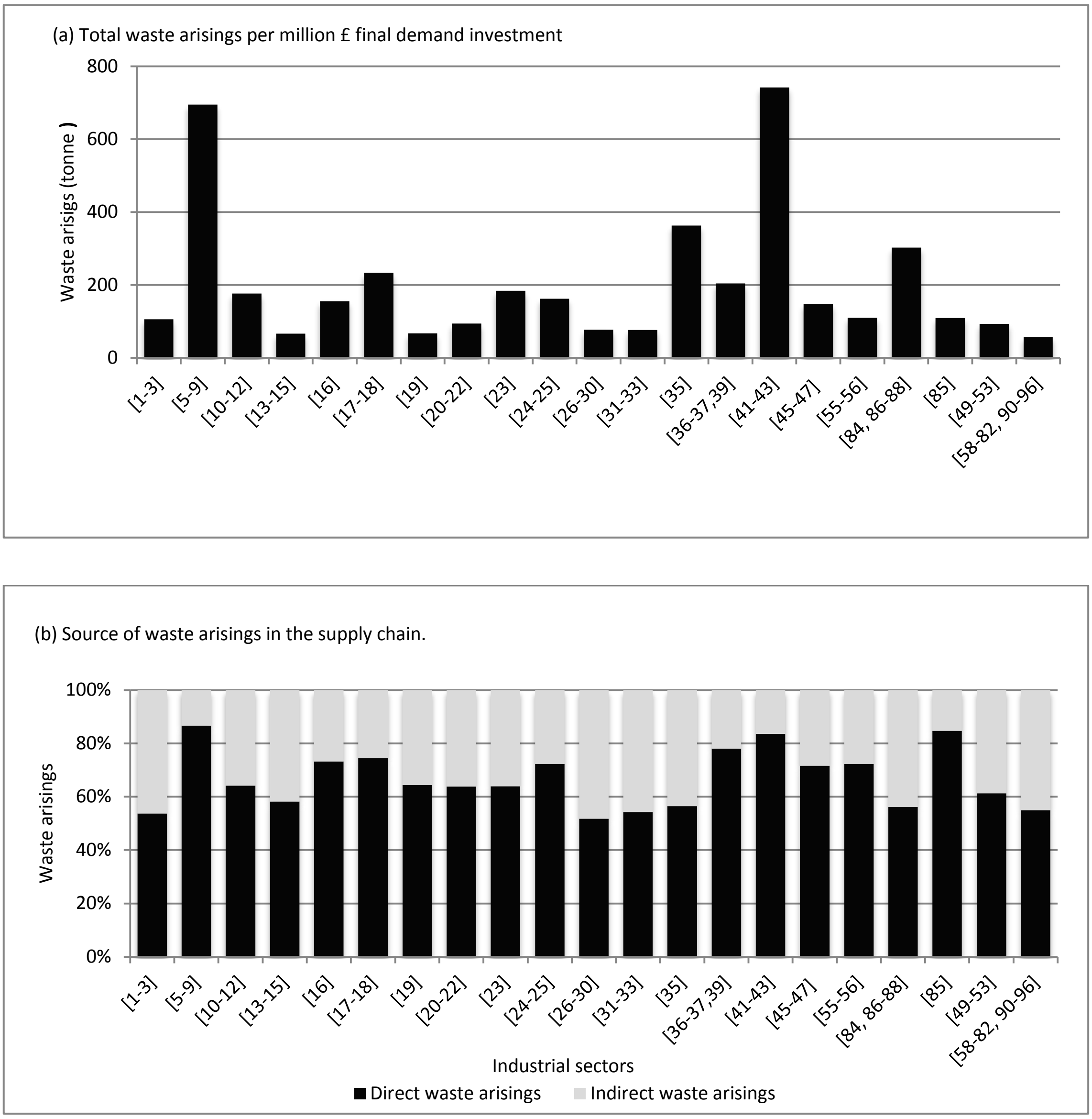

Figure 2 Total waste arisings per million £ of final demand investment (a) and its source (b) throughout the UK supply chain.

In order to demonstrate the power of the WIO table, we also investigate types of waste generated in both the direct and indirect supply chain of the agricultural sector (Figure 3). In the direct supply chain, Chemical wastes, generated due to the production and use of fertilizer and other chemical-based products, are attributed to more than 14% of direct waste arisings. Plastic and paper and cardboard waste, representing packaging waste, are accountable for 12% and 4.5% respectively. Figure 3(a) shows waste categories with generation rates that are greater than 5%. On the other side, waste from construction and demolition activities and mineral waste contribute 17% and 15% each to indirect waste arisings associated with the agricultural sector (Figure 3(b)). Other waste categories with significant generation (i.e., >5%) rates include soil and combustion waste.

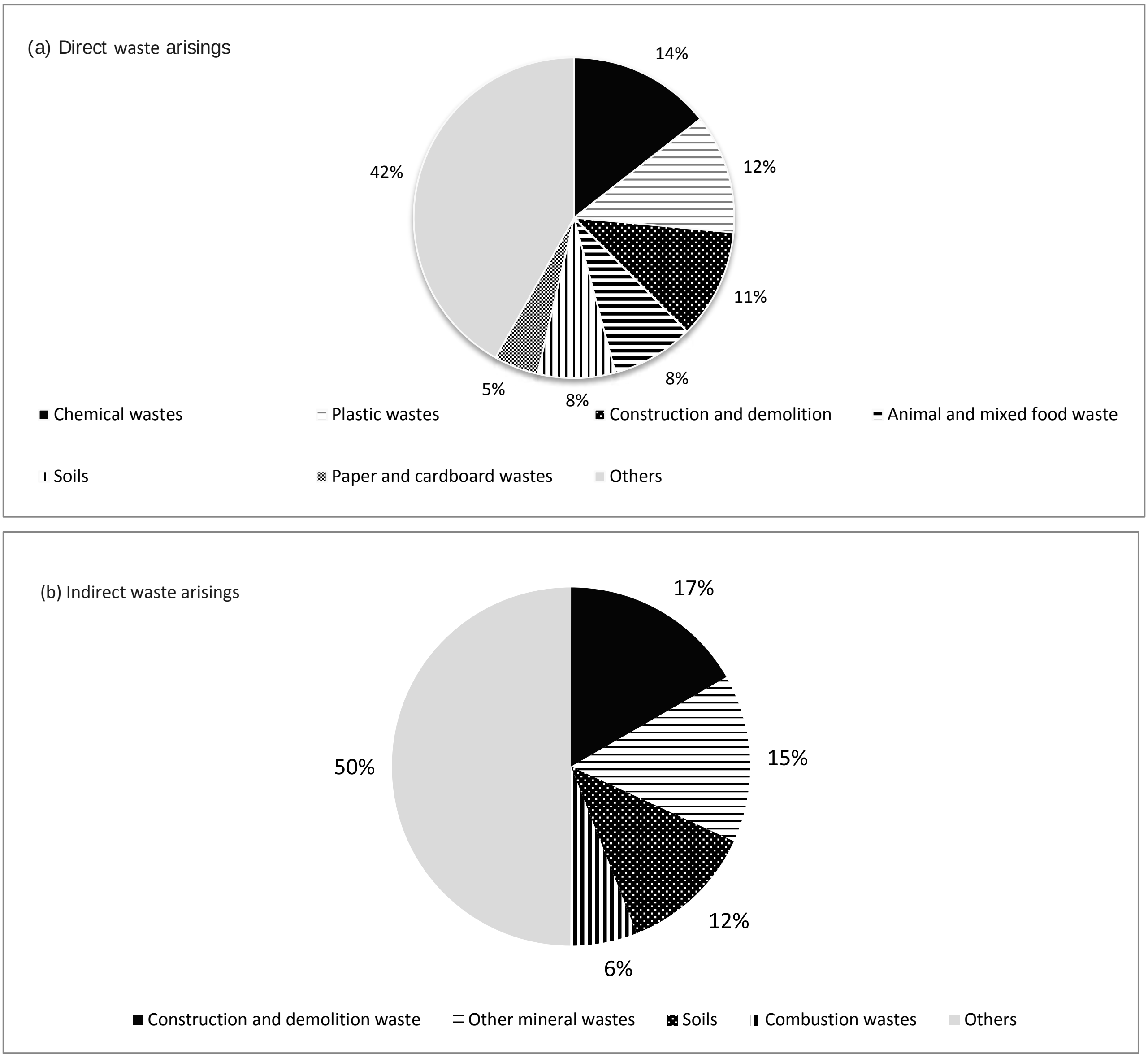

Figure 3 Types of waste arisings in both direct (a) and indirect (b) supply chain of the agricultural sector. Other mineral wastes is a Eurostat waste-category including the following waste streams: asbestos, blasting wastes and other mineral waste originate from mining, quarrying and the treatment of minerals, manufacture of construction materials and casting processes Eurostat (2010).

4 Conclusions

The aim of this paper was to introduce the first version of the UK WIO table that could be used to investigate waste arisings in the supply chain. The power of the current version of the WIO table is its ability to capture waste generation in the direct and indirect supply chains. Results have shown how sectors with a long supply chain (i.e. manufacturing and services sectors) tend to have higher indirect waste generation rates compared to industrial primary sectors (e.g, mining and quarrying) and sectors with a shorter supply chain (e.g, construction). The WIO table has also enabled the disaggregation of waste generation data into different waste categories.

Waste policy is often developed for specific waste streams or for specific economic sectors. The development of current waste policies seldom takes into account the effects of changing demand and production processes of one economic sector upon waste generation in another. This level of planning is required if a circular economy is to become a reality. The quantification provided in this paper is the first step towards more comprehensive waste policy. The UK WIO allows for the examination of waste generation hotspots, and the quantification of changes to final demand.

Several limitations to the first version of the WIO table need to be acknowledged. First, the current version doesn't provide any additional information about the final status of waste generated and its disposal option, whether recycled or landfilled. This major limitation is expected to be addressed in the second version of the WIO table to reflect recycling activities in the model in the same way as previous literature (Nakamura & Kondo 2002; Lenzen & Reynolds 2014; Nakamura & Kondo 2009). Second, the model is based on a top-down, economy-wide approach aggregating the whole economy into only 21 industrial sectors.

Although it would produce accurate and correct data in the sectorial level, it cannot distinguish sufficiently product groups of individual companies.

Notwithstanding these limitations, the introduction of the first version of the WIO table represents a step towards a better understanding of the flow of the waste. Specifically, this current UK WIO has allowed quantification of both direct and indirect waste flows for the UK economy. This work is expected to be followed up by disaggregating the waste sector into various industries, thus unlocking the “blackbox” representation of the waste sector. Consequently, this would lead to a better understanding of waste and resource flows in the supply chain.

5 Associated content

Supplementary data to this article can be found on-line.

6 Declaration of conflicting interests

The authors declare that there is no conflict of interest.

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