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Sustainable supply chain management and the transition towards a circular economy: Evidence and some applications ☆

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ABSTRACT

In the last decades, green and sustainable supply chain management practices have been developed, trying to integrate environmental concerns into organisations by reducing unintended negative consequences on the environment of production and consumption processes. In parallel to this, the circular economy discourse has been propagated in the industrial ecology literature and practice. Circular economy pushes the frontiers of environmental sustainability by emphasising the idea of transforming products in such a way that there are workable relationships between ecological systems and economic growth. Therefore, circular economy is not just concerned with the reduction of the use of the environment as a sink for residuals but rather with the creation of self-sustaining production systems in which materials are used over and over again.

Through two case studies from different process industries (chemical and food), this paper compares the performances of traditional and circular production systems across a range of indicators. Direct, indirect and total lifecycle emissions, waste recovered, virgin resources use, as well as carbon maps (which provide a holistic visibility of the entire supply chain) are presented. The paper asserts that an integration of circular economy principles within sustainable supply chain management can provide clear advantages from an environmental point view. Emerging supply chain management challenges and market dynamics are also highlighted and discussed.

1. Introduction

Circular economy [49] represents a theoretical concept which aims at creating an industrial system that is restorative by intention [75,69]; in recent times, business have become more aware about such concept, seeing it as a mechanism that can be used to create competitive advantage [25]. As such, the paper seeks to address the implications of these practices in a supply chain context from environmental, market, policy and societal points of view.

The recent embracing of new business models that encourage design for re-use and improve materials recovery represents a departure from historic production and consumption systems. In fact, classical economic theory posits that disproportionate production and consumption patterns represent a natural or desirable outcome since they drive the creation of wealth resulting from economic activity (including the flow and use of raw materials and resources) and trade of goods and services [73]. However, it has also been established that economic and production systems cannot be separated from the environment, with contemporary ecological economic theory emphasising the increasing impacts of human activities on the natural environment [16,40]. This phenomenon has led to the crossing of certain biophysical thresholds [63]. As a result, the emphasis on sustainability, a concept which is now integrated in most disciplines since the publication of the Brundtland Report by the World Commission on Environment and Development [13], has become even more important in the present time.

The increasing influence of sustainability in supply chain management and operations practices can also be attributed to the fact that, in addition to increased demands of strong economic performance, organizations are now held responsible for the environmental and social performance by major stakeholders [92,86]. As such, sustainability has forced the redefinition of the operations function [19]. Additionally, sustainable supply chain management has become a strategic process enabling firms to create competitive advantage [72]. This assertion is backed by Porter's [58] hypothesis, which states that the conflict between environmental sustainability and economic competitiveness is a false dichotomy based on a narrow view of the sources of prosperity and a static view of competition.

Within this context, in the last decades, sustainable supply chain management theories have been emerging (*inter alia:* [87,69,66]). These frameworks are underpinned primarily by product lifecycle

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influences and operational influences [65]. Savaskan et al. [67] suggest that the requirement to take a holistic view of the whole product supply chain is a fundamental step for establishing greener and more sustainable production systems [35], based on re-using and re-manufacturing materials [94]. These systems could also lead to the creation of new competitive business models [42]. Such models could be based on the paradigm of *cradle-to-cradle*, encouraging the use of raw materials known as technical and biological nutrients, which do not have a negative impact on the environment, have an entirely beneficial impact upon ecological systems and return to the ecosystem without treatments [12].

Interestingly, the concepts of green and sustainable supply chain management have been developed in parallel (although there are some fundamental differences in principles) to the circular economy discourse, which has been propagated in the industrial ecology literature and practice for a long time [46,24]. In fact, sustainable supply chain management seeks to integrate environmental concerns into organisations by minimizing materials' flows or by reducing unintended negative consequences of production and consumption processes [75,76,66,21]. On the other hand, as described by McDonough et al. [50], circular economy pushes the frontiers of environmental sustainability by emphasising the idea of transforming products in such a way that there are workable relationships between ecological systems and economic growth (Francas and Minner, 2007). This is achieved by creating a paradigm shift in the redesign of material flows based on long-term economic growth and innovation [12]. It is implied that circular economy is not just concerned with the reduction of the use of the environment as a sink for residuals [8] or with the delay of cradle-to-grave material flows (as sustainable supply chain management suggests) but rather with the creation of metabolisms that allow for methods of production that are self-sustaining, true to nature and in which materials are used over and over again [49].

Finding ways to align sustainable supply chain strategies to circular economy principles has therefore become important if the boundaries of environmental sustainability are to be pushed. Additionally, circular economy is primarily concerned with material flows in economic systems [54,47] through a paradigm shift in production philosophy; this therefore leaves other important issues such as understanding environmental impacts (such as the ones related to energy usage and carbon emissions) and the implications of such impacts unresolved. Consequently, the main research questions which would be addressed in this paper are:

- How can sustainable supply chain management be enhanced by aligning it to the circular economy concept?
- What are the environmental implications of circular production systems in terms of carbon emissions, resource use and waste recovered when compared to a traditional linear production paradigm?
- What are the potential market dynamics, policy and societal implications that could arise by the implementation of circular production systems? What kind of challenges do they pose?

To answer to these questions, based on the theoretical constructs of circular economy, two case studies (based on product supply chains from different process industries) are analysed. The findings would be used to provide insight to the analysis and discussions. Chosen case studies are concerned with food (specifically, the waste cooking oil supply chain) and chemical (ferrous sulphate supply chain) industries. Greenhouse gas emissions (in the following, simply referred to as *carbon emissions*) were selected as the main environmental impact indicator because of their prominence in contemporary literature and as a result of easy access to data.

Food and chemical supply chains were chosen for this study because (apart from the fact that they are two very different process industries) both supply chains have been known to have significant consequences on the environment. Additionally, according to Beamon [10] limited research has been carried out on the food processing sector mainly because of the complexity of the supply chain, hence leaving important issues involving waste, re-use of resources, greenhouse gas (GHG) emissions unaddressed [32]. Regarding the chemical industry supply chain the OECD [55] reports that despite it being one of the most regulated of all industries, there is a potential for a negative impact at every stage of its lifecycle. This situation is exacerbated by the increase use of chemicals in major economic development sectors [82].

To address these issues, the paper is structured as follows: in Section 2, a literature review is conducted on the principles of circular economy, on frameworks for evaluating the environmental performance of supply chains and on supply chain configurations. In Section 3, methodological notes and generalities about the case studies are presented. Section 4 addresses the key findings, analysis and discussions of the study leading to the concluding remarks reported in Section 5.

2. Theoretical backgrounds

2.1. The circular economy paradigm

Environmental economics is concerned with identifying and solving problems related to damage and pollution associated with the flow of residuals [30,8]. In this context, the principles underlining circular economy suggest that, by assuming the planet as a closed system, the amount of resources depleted in a period is equal to the amount of waste generated in the same period. This principle is thus subject to the Laws of Thermodynamics [84,62], although in practice this is not the case because Daly [18] reiterates that the circular flow of exchange (which consist of the physical flow of matter and energy) is ultimately linear and unidirectional beginning with low entropy resources from the environment and ending with the pollution of the environment with high entropy waste. Despite these limitations, due to basic physical laws, the paradigm of circular economy seeks to continually sustain the circulation of resources and energy within a closed system (the planet) thus reducing the need for new raw material inputs into production systems. The principles of circular economy thus reveal an idealistic ambition of pushing the boundary of sustainable supply chain management practices. Such practices, indeed, are ultimately concerned with the reduction (or the delay) of unintended negative impacts on the environment due to cradle-to-grave material flow [59]. Thanks to initiatives such as The Circular Economy 100 [25], a number of companies have embraced these concepts also as a mechanism for collective problem solving. The circular economy paradigm has then provided a framework by means of which businesses operating within the same supply network (and beyond) can engage with sustainability activities, enabling best practices to be adopted.

In this context, the concept of *Reverse Supply Chain Management* has been developed [32,44] as an adaptation of circular economy principles to supply chain management. Indeed, a reverse supply chain includes activities dealing with product design, operations and end-of-life management in order to maximize value creation over the entire lifecycle through value recovery of after-use products either by the original product manufacturer or by a third party.

Reverse supply chains are either open-loop or closed-loop. Basically, open-loop supply chains involve materials recovered by parties other than the original producers who are capable of reusing these materials or products. On the other hand, closed-loop supply chains deal with the practice of taking back products from customers and returning them to the original manufacturer for the recovery of added value by reusing the whole product or part of it [32]. Because of the benefits of reverse supply chains, it is unsurprising that manufacturing

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industries have been placing, recently, a lot more emphasis on achieving sustainable production by shifting from end-of-pipe solutions to a focus on whole lifecycle assessments and integrated environmental strategies and management systems (OECD, 2009).

Early contributors to the design of circular supply chains include Thierry et al. [80], who designed an *integrated supply chain model* in which product returns from the end-user undergo a recovery operation (such as re-use, repair, remanufacture or recycling); hence products are integrated back into the '*forward*' supply chain.

Despite its idealistic principles, the concept of circular economy has still implications of environmental externalities. This is because external effects always occur as a result of transactions between different entities [57], represented, in this case, by the flow of materials and resources between different production systems or different stages of a same production system. Methodologies that can be used to evaluate the environmental implications of such production systems are generally based on the principles of lifecycle assessment (LCA).

2.2. Frameworks for environmental assessment of product supply chains

Lifecycle assessment (LCA) is a widely applied methodology in the context of environmental analysis to support cleaner production [91] and greener supply chains [1]. UNEP [82] have also reported that such methodology can be utilized to assess resource use throughout the lifecycle of a product, indicating precisely where inefficiencies exist, and for analysing environmental impacts taking into account the whole amount of goods and services needed to manufacture and deliver that particular product (Luo et al., 2009). The LCA framework for a product, process or activity/operation can bring together the impacts of collaborative supply chain partners arising from extraction and processing of raw materials; manufacturing, transport and distribution; re-use, maintenance recycling and final disposal. LCA is therefore a holistic approach which brings environmental impacts into one consistent framework, wherever and whenever these impacts have occurred or will occur [39]. Adopting LCA provides useful advantages in supply chain management practice [7]. Indeed, production paths associated with high energy and resource usage, pollution and emission of greenhouse gases (here synthetically defined as *carbon hot-spots*) can be identified and appropriate intervention strategies devised and implemented in order to address them.

Two basic LCA modelling techniques can be used to examine the environmental impact of a supply chain production system, namely the process (*bottom-up*) models or the macro-economic environmental (*top-down*) models [41].

2.2.1. Bottom-up models: Process lifecycle assessment methodology

Traditional (or process) LCA methodology is highly defined by ISO standards (International Standard Organisation, 1998), working by creating a system boundary dictated by the aims of the study and accounting for individual impacts assessments (for instance, *carbon-equivalent emissions*, as used in this paper) within the system (Refer to Fig. 1 for a schematic representation of a typical process LCA system). This methodology has been described as incomplete, primarily because it is not possible to account for the theoretically infinite number of inputs of very complex product supply chains into the LCA system (Crawford, 2008; Rowley et al., 2009). However, because of the specificity of individual inputs within the defined LCA system boundary, the environmental impacts of those inputs can be more accurately determined (Lenzen and Crawford, 2009). Extending this methodology to address its limitations in terms of a restricted LCA system boundary, but leveraging on its advantage in increasing the accuracy is therefore crucial when setting up environmental assessment models of product supply chains [4].

2.2.2. Top-down models: Environmental input–output methodology

Environmental Input–Output (EIO) is a LCA methodology that uses country and/or regional input–output trade data coupled with sector-level emissions to calculate environmental impacts, yielding an all-encompassing result within an extended system boundary (Berners-Lee et al., 2011; [2]). However, it has the drawback of being less specific due to aggregation of a range of products or services in one sector (Mongelli et al., 2005) and the assumptions of proportionality and homogeneity [3].

The EIO framework is a macro-economic model based on a generic top-down model of the economy (Wiedmann et al., 2007), thus simulating the whole supply chain at an economy-wide level, along with its sectorial changes and production and consumption patterns [9]. The whole economy can therefore be described as an aggregation of different sectors as shown below in the EIO framework (Fig. 2). In the manufacturing of a product, any resource input used directly or indirectly at any tier of the supply chain can be traced to one of these economic sectors. As such, the EIO framework provides a complete system boundary for the environmental assessment of the product supply chain ([88]; Majeau-Bettez et al., 2011). Thus, the EIO offers a global (or multi-regional) supply chain perspective to the environmental analysis, by extending the system boundary in such a way to account for the very large number of supply chain inputs.

2.2.3. Integrating bottom-up and top-down models: Hybrid LCA methodology

The combination of process (bottom-up) and macro-economic (top-down) approaches can offer a third methodology (the so-called hybrid methodology) that integrates the process and environmental input–output methodology into a more consistent and robust framework based on a whole lifecycle assessment principle. This is because the hybrid methodology integrates the advantages of both process LCA and environmental input–output methodologies while overcoming their respective limitations. Indeed, process LCA is complemented with EIO LCA which is used to estimate missing indirect inputs not included in the original system boundary (Lenzen and Dey, 2000; [88]). The integration of the two basic approaches leads to the development of a more robust methodology; that is the Hybrid LCA. In the Hybrid LCA approach used in this paper, we adopt a multi-regional input–output (MRIO) framework in which EIO is interconnected with the matrix representation of the

Fig. 1. Schematic representation of a typical process LCA system.

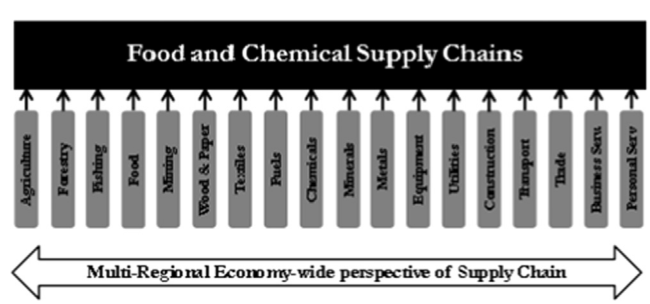

Fig. 2. Whole economy representation based on an EIO framework.

physical process LCA system. As a result, in the upstream and downstream inputs into the LCA system, where there are no or better process LCA data available, EIO estimates are used [78]. A detailed explanation of the Hybrid LCA methodology is provided in Acquaye et al. [4] and Wiedmann et al. [90].

It is an established fact that the Hybrid LCA methodology has been well promoted. However, because of the inherent complexity of product supply chains (as a result of the globalized nature of product, process and service inputs), hybrid LCA must be developed not just using country specific IO models, but a multi-regional IO framework. Additionally, the results should be presented in such a way that they have direct benefit and relevance to supply chain management practices. This paper therefore seeks to use these methodological constructs to answer the posed research questions.

3. Research methodologies and applications

3.1. General input–output model

An input–output (IO) model records the flows of resources (products and services) from each industrial sector considered as a producer to each of the other sectors considered as consumers [53]. An IO model is therefore a matrix representation of all the economic (production and consumption) activities taking place within a country, region or multi-region.

The general input–output methodology has been well documented in literature [79,29]. In the general IO notation, it can be shown that:

$$\underline{x} = (\boldsymbol{I} - \boldsymbol{A})^{-1} \cdot \underline{y}$$

In this equation, $\boldsymbol{A} = [a_{ij}]$ describes all the product requirements (i) needed by industry (j) to produce a unit monetary output. It is called the technical coefficient matrix because it describes the technology of a given industry which is characterised by the mix of supply chain inputs (including raw materials, machinery, energy, goods, transport, services, etc.) required to produce a unit output [9]. The vector $\underline{x}$ represents the total output in a given sector. It is equal to the sum of those products consumed by other industries and those consumed by the final demand $\underline{y} \cdot (\boldsymbol{I} - \boldsymbol{A})^{-1}$ is referred to as the Leontief Inverse matrix and $(\boldsymbol{I} - \boldsymbol{A})^{-1} \cdot \underline{y}$ describes the total (direct and indirect) requirements needed to produce the output, $\underline{x}$ for a given final demand $\underline{y}$ [53].

Hence, in terms of supply chain visibility [85], the supply chain of a given product can be set up in such a way that not only direct inputs are captured, but also, irrespective of the origin of these inputs (domestic or imported), indirect ones can be considered in the analysis.

This is a result of the extended system boundary of the IO framework [3,48,90]. As a result, a whole lifecycle perspective, which is a key principle of sustainable supply chain management, is adopted [14].

3.1.1. Multi-regional input–output (MRIO) hybrid LCA model

The MRIO model used in environmental input–output analysis is usually presented as a 2-region model (see for instance McGregor et al. [51] who used a two-region MRIO model to enumerate CO_2 emissions embodied in interregional trade flows between Scotland and the rest of the UK). In this paper, the Supply and Use format within a two-region (UK and the Rest of the World—in the following referred to as ROW) IO framework is adopted (see Fig. 3 for an exemplification). As reported by EUROSTAT [28], the advantages of Supply and Use tables as an integral part of the national accounts lies in the fact that they have a stronger level of detail which ensures a higher degree of homogeneity of the individual product and therefore better possibilities for determining categories of uses and consequently the environmental impacts. Additionally, it enables to perform a split between emissions associated with supply chain inputs as a result of UK production and ROW production. The methodology, developed within the integrated Hybrid LCA framework, [78] is presented below. The following Eq. (1) represents the general expression of the model (see also [6]):

$$\text{Total Emissions Impact} = \begin{bmatrix} \boldsymbol{E_p} & 0 \\ 0 & \boldsymbol{E_{io}} \end{bmatrix} \begin{bmatrix} \boldsymbol{A_p} & -\boldsymbol{D} \\ -\boldsymbol{U} & (\boldsymbol{I} - \boldsymbol{A_{io}}) \end{bmatrix}^{-1} \begin{bmatrix} \underline{y} \\ 0 \end{bmatrix} \qquad (1)$$

where $\boldsymbol{A_p}$ provides the square matrix representation of process inventory (dimension: s × s); $\boldsymbol{A_{io}}$ represents the MRIO technology coefficient matrix (dimension: m × m); $\boldsymbol{I}$ represents an identity matrix (dimension: m × m); $\boldsymbol{U}$ provides the matrix representation of upstream cut-offs to the process system (dimension: m × s); $\boldsymbol{D}$ reproduces the matrix of downstream cut-offs to the process system (dimension: s × m); $\boldsymbol{E_p}$ represents the process inventory environmental extension matrix. CO_2-eq emissions are diagonalised (dimension: s × s); $\boldsymbol{E_{io}}$ represents the MRIO environmental extension matrix. CO_2-eq emissions are diagonalised (dimension: m × m); $\left[\underline{y}/0\right]$ represents the functional unit column matrix with dimension $(s+m,\ 1)$ or where all entries are 0 except y.

Following on this, (A_{io}) is presented in the Supply and Use format as shown below:

In a matrix representation, this becomes

$$\boldsymbol{A_{io}} = \begin{bmatrix} 0 & \boldsymbol{A_{(UK)U}} & 0 & 0 \\ \boldsymbol{A_{(UK)s}} & 0 & \boldsymbol{A_{(UK)EXP}} & 0 \\ 0 & 0 & 0 & \boldsymbol{A_{(ROW)U}} \\ \boldsymbol{A_{(UK)IMP}} & 0 & \boldsymbol{A_{imp}} & 0 \end{bmatrix}$$

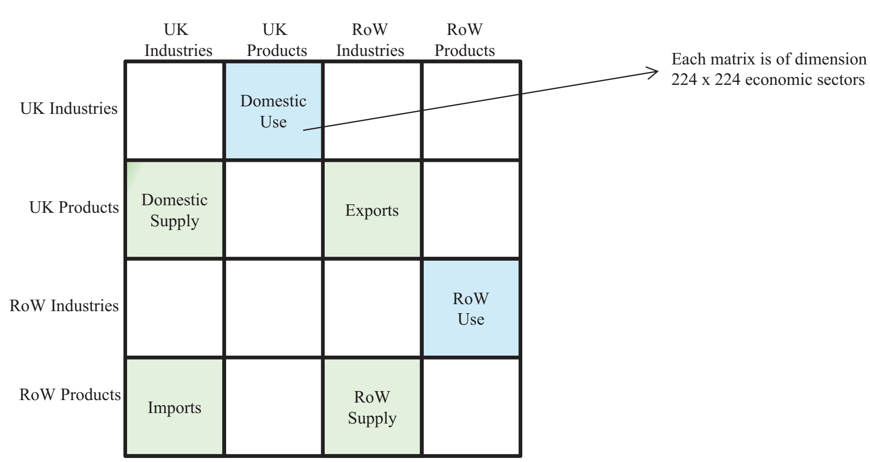

Fig. 3. Supply and use input–output framework.

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where A_{io} becomes the 2-region MRIO technical coefficient matrix. This includes the respective technical coefficient matrices for UK Domestic Use, $\boldsymbol{A}_{(UK)U}$, UK Domestic Supply, $\boldsymbol{A}_{(UK)s}$, UK Export to ROW, $\boldsymbol{A}_{(UK)EXP}$, ROW Use, $\boldsymbol{A}_{(ROW)U}$, UK Imports from ROW, $\boldsymbol{A}_{(UK)IMP}$ and ROW Supply to ROW, $\boldsymbol{A}_{(ROW)s}$. All of the individual $\boldsymbol{A}$ matrices are of dimensions 224×224; hence, A_{io} and $\boldsymbol{I}$ (the Identity Matrix) are therefore of dimension 896×896.

The Technical Coefficient Matrix for UK Imports from ROW, $\boldsymbol{A}_{(UK)IMP}$, for example, is defined as:

$$\boldsymbol{A}_{(UK)IMP} = \left[\frac{q_{ij}^{(ROW,UK)}}{x_j} \right]$$

where $q_{ij}^{(ROW,UK)}$ represents elements of UK Imports input–output table from the ROW region indicating the input of product (i) from ROW into the industry (j) of the UK, while x_j represents the total output of UK industry, (j).

Referring back to Eq. (1), A_p can be described as a matrix representation of the Process LCA framework. For n different types of supply chain inputs into the Process LCA system, $\boldsymbol{A_p}$ would be of dimension $(n+1)\times(n+1)$; where there are n supply chain product inputs and 1 main product output. Let q_n represents the quantity of supply chain inputs used for any given input, n and $k_{r,c}$ the elements of $\boldsymbol{A_p}$ so that $\boldsymbol{A_p} = [k_{r,c}]$ where r (rows) represents inputs and c (columns) processes of those inputs in the Process LCA system. A simplified way of formulating mathematically the Process LCA system is presented below:

$$\boldsymbol{A_p} = [k_{r,c}] = \begin{cases} k_{r,c.} = q_r \quad \text{if } r = c \text{ and } (r \neq n+1, c \neq n+1 \\ k_{n+1,n+1} = 1 \\ k_{r,n+1} = -q_r \quad \forall r \text{ except for } r = n+1 \\ k_{r,c} = 0 \quad if\ r \neq c \end{cases}$$

3.1.2. Environmentally extended MRIO hybrid model

The Input–Output analysis component of the hybrid model can be extended to an Environmental Input–Output (EIO) lifecycle assessment (LCA) to generate results which can be used in the assessment of product supply chain emissions.

Given that $\underline{x} = (\boldsymbol{I}-\boldsymbol{A})^{-1} \cdot \underline{y}$ defines the total (direct and indirect) requirements needed to produce an output x for a given final demand, y; the EIO LCA can therefore be defined in a generalised form as:

$$\underline{E} = \boldsymbol{E}_{io} \cdot \underline{x} = \boldsymbol{E}_{io} \cdot (\boldsymbol{I}-\boldsymbol{A})^{-1} \cdot \underline{y}$$

where $\boldsymbol{E}_{io}$ is the direct emissions intensity (kg CO_2-eq/£) of the IO industries and $\boldsymbol{E}_{io} \cdot (\boldsymbol{I}-\boldsymbol{A})^{-1}$ the total (direct and indirect) emissions intensities (kg CO_2-eq/£).

By extension, the matrix $\boldsymbol{E}_{io}$ expressed in terms of the MRIO Supply and Use structure becomes:

$$\boldsymbol{E}_{io} = \begin{bmatrix} \widehat{\boldsymbol{E}}_{UK} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \widehat{\boldsymbol{E}}_{ROW} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} \end{bmatrix}$$

where $\widehat{\boldsymbol{E}}_{UK}$ and $\widehat{\boldsymbol{E}}_{ROW}$ are respectively the diagonalised direct emissions intensity (sector emissions in kg CO_2-eq per total output in £) of each industrial sector in the UK and the ROW.

Similarly, the environmental extended component for the process LCA system $\boldsymbol{E}_p$ in the hybrid model (refer to Eq. (1)) is defined as a diagonalized matrix of the respective environmental values e_n of each input n into of the process LCA system obtained by multiplying product input quantities q_n and emissions intensities $e_{(int)_n}$.

$$\boldsymbol{E}_p = [\hat{e}_n]$$

where $\forall$ n into the process lCA system.

$$e_n = q_n \cdot e_{(int)_n}$$

As described earlier, $\underline{y}$ represents the final demand; in this instance, the output of the LCA system. This final demand matrix is represented as a column matrix.

The generic matrix dimension or size of $\underline{y}$has already being established to be (s+m, 1). However, specific to this study, this dimension equals $((n+1+896), 1)$, where n is the number of supply chain product inputs for the process LCA system and 896 the dimension of the MRIO matrix. Since $\underline{y}$ is a column matrix, let $f_{(d,1)}$ be the elements of $\underline{y}$ such that d represents the row elements of the single column (represented as 1).

Hence:

$$\underline{y} = [f_{d,1}]; \text{ where } f_{d,1} = 1 \text{ if } d = n+1 \text{ and } 0, \ \forall \text{ other } d$$

The environmentally extended MRIO model (with each part of the model described in Section 3.1) is the methodological basis used to calculate the product supply chain emissions. Input–output data and sectorial environmental extensions used in this paper are based on a disaggregation of UK input–output tables which is structured in the form of the two region Multi Regional Input–Output framework as presented in Wiedmann et al. [89] (see also [90,5]).

3.2. Applications: Case studies

In this paper, case studies from the chemical (ferrous sulphate supply chain) and food (specifically, the waste cooking oil supply chain) industries will be illustrated, in order to evaluate the performance of different supply chain configurations. Circular supply chains, that assume a broader perspective of the entire production system (in order to include post-production stewardship) will be compared to linear production systems, just concerned with the production of a specific product [45]. The first case study, dealing with the comparison of chemicals in the water industry, is based primarily on empirical data (collected from the focal company and its suppliers), which is complemented with secondary data sources. The second case study, concerned with the production of biodiesel from cooking oils, is however solely based on secondary data sources.

3.2.1. Case study I—Chemical supply chain (ferrous sulphate)

Delivering quality drinking water and returning clean wastewater to the environment represent energy intensive activities that have environmental implications in terms of carbon emissions on the environment. A good portion of the environmental impact is related, in this context, to the use of chemical compounds in the water supply and management process.

Among the main chemicals used in the water treatment processes, the following ones can be mentioned: Ferric Chloride and Ferrous Sulphate which are alternate ferric salts; and Sodium Hydroxide and Calcium Hydroxide which are alternate alkaline reagents used for acid neutralization. For the purposes of this paper, the case study will analyse Ferrous Sulphate and the Ferric Chloride supply chains which can both be used as coagulant. Data for the chemical supply chains have been obtained from actual company sources from the UK and are complemented with secondary data from Ecoinvent [23].

In order to analyse the carbon emissions implications of a circular production process involving the production of Ferrous Sulphate, which can be produced by using a by-product (the acidic waste) of titanium dioxide as raw material, its supply chain is compared to the Ferric Chloride supply chain which is produced from a mainly linear production system. For details of the process data used in this case study, refer to the Appendix (sub-section Supplementary data I).

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3.2.2. Case study II—Food supply chain (waste cooking oil)

The second case study assesses the carbon emissions implications of two different supply chain configurations using cooking oil for the production of biodiesel: a traditional (*linear* or *forward*) supply chain based on a linear production system where virgin cooking oil is utilized in the production of a secondary product (biodiesel) and a circular (*open-loop*) supply chain configuration based on the recovery of value from waste cooking oil used in the production of biodiesel (Refer to Fig. 4). Data for these processes were sourced from Ecoinvent [23] with details presented in the Appendix (sub-section Supplementary data II).

4. Results and discussions

4.1. Case study results

Based on the methodological framework of the Environmentally Extended MRIO Hybrid Model presented in Section 3.1.2, the carbon emissions implications of the implementation of a circular supply chain were examined for both the chemical (ferrous sulphate) and the food (waste cooking oil) supply chains. This involved a calculation of the comparative change in lifecycle carbon emissions of the whole supply chain. Tables 1–5 provide an overview of the breakdown of the results. These are used to construct synthetic supply chain carbon maps (refer to Figs. 6, 7, 9 and 10). Within the carbon maps, process categories highlighted as hot-spots provide an indication of the relative high carbon emission paths in the supply chain. These maps provide a visualisation technique of illustrating supply chains in order to support decision-making. The following thresholds for emissions ranking are adopted: Very High (shown in Red, it indicates inputs with emissions greater than 10% of the total lifecycle emissions); High (orange, 5–10%); Medium (yellow, 1–5%); Low (green, less than 1%).

Coherently to the use of the Hybrid LCA, the study also calculates and assesses the indirect carbon emissions impacts which consist of inputs from the wider economy, not captured through process inputs. These are indicated on carbon maps as indirect inputs, representing an aggregation of 18 sectors, namely: agriculture, forestry, fishing, mining, food, textiles, wood and paper, fuels, chemicals, minerals, metals, equipment, utilities, construction, trade, transport and communication, business services, personal services.

An analysis of the two case studies is presented in the following sub-sections.

4.1.1. Results: Chemical supply chain

The results compare the carbon emissions implications of using Ferrous Sulphate produced from a by-product (acidic waste) of the production process of titanium dioxide, seen as the implementation of a circular open-loop supply chain, compared to the use of Ferric Chloride which is produced from a mainly linear production system. Results are presented in Tables 1 and 2, reporting the complete breakdown of emissions across supply chain inputs; Figs. 6 and 7 also illustrate category-aggregated carbon maps for the two supply chains.

Based on the methodology presented in Section 3, the total Ferric Chloride emissions (0.9932 kg CO_2-eq/kg) were determined to be more than three times higher than the Ferrous sulphate (0.3282 kg CO_2-eq/kg). Comparative levels of direct and indirect emissions are presented in Fig. 5. As observed above, the difference in emissions between the two salts is significant; moreover, because the Ferrous Sulphate is manufactured from acidic waste (a by-product of titanium dioxide production or, alternatively, from steel production) emissions that would have generated for the neutralization of the acidic waste and its disposal are also avoided. According to data retrieved from Ecoinvent [23], the emissions generated by the disposal of 1 kg residue from TiO_2 production to landfill equals 0.3289 kg CO_2-eq/kg. As seen from Fig. 5, the total emission of producing 1 kg of Ferrous Sulphate is practically the same as that the emissions of disposing 1 kg of residue from Titanium Dioxide. The use of Ferrous Sulphate produced by this circular process is not only generating less emission than the linear production system of Ferric Chloride supply chain, but also preventing the occurrence of emissions generated by the disposal of waste.

The breakdown of CO_2-eq emissions for the circular configuration (Ferrous Sulphate) is presented in Table 1; the carbon map in illustrated in Fig. 6. It can be observed that electricity is the main "hotspot" since it is the main input used in the purification of the by-product (acidic waste). It contributes to 35.94% of the total emissions, followed by the operations of the chemical plant (15.07%) and outbound road transport (12.10%). Direct and indirect inputs account, respectively, for 73.28% and 26.72% of the total emissions. In the case of the Ferric Chloride (see Table 2 and Fig. 7), the main hot-spot is represented by the mercury-cell production process of chlorine (a very electricity-intensive process). This contributes towards 54.00% of the emissions, followed by the chemical plant (12.45%), chlorine production through membrane-cell process (9.84%) and road transport from supplier (8.45%). It was also determined that direct inputs (process emissions) and upstream indirect emissions account, respectively, for 89.71% and 10.29% of the total emissions.

4.1.2. Results: Food supply chain

For a food supply chain, achieving circularity allows meeting two important requirements. First, circular supply chains divert end-of-life products from being considered waste and hence discarded; also, the secondary resources that result from the reprocessing of these end-of-life products replace primary resources in forward supply chains [37]. As a result, in addition to the carbon emission implications of the supply chain, virgin resources used and potential waste recovered have been also examined from a lifecycle assessment perspective.

A comparison between a linear supply chain based on a production system where virgin cooking oil is utilized in the production of a

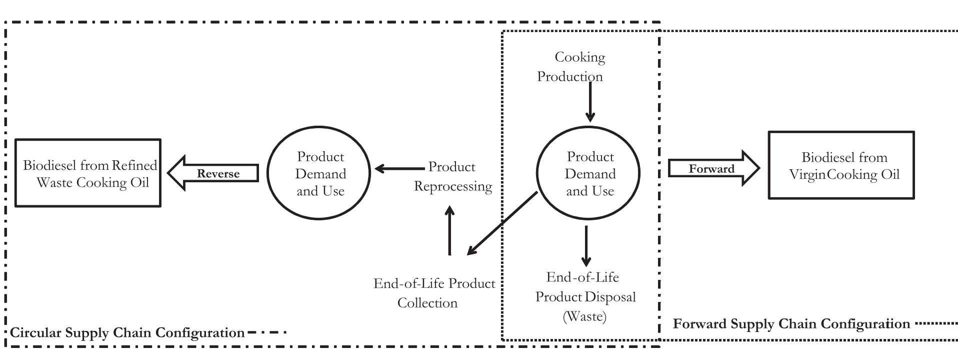

Fig. 4. Linear and circular cooking oil supply chain configurations in biodiesel production.

Table 1
Supply chain emissions breakdown for ferrous sulphate.

Input	Category	Quantity	Unit	Emissions intensity (kg CO_2-eq/unit)	Emissions (kg CO_2-eq)	Emissions (%)
Electricity, medium voltage, at grid	Utilities	0.2220	kW h	0.5314	0.1180	35.94
Chemical plant, organics	Organic Chemicals	0.0000	Unit	123,660,000.0000	0.0495	15.07
Transport, lorry 3.5–20 t, fleet average, outbound	Transport	0.1420	t km	0.2798	0.0397	12.10
Chemicals	Indirect	N/A	N/A	N/A	0.0289	8.81
Transport, lorry 3.5—20 t, fleet average, inbound	Transport	0.1000	t km	0.2798	0.0280	8.52
Utilities	Indirect	N/A	N/A	N/A	0.0227	6.91
Transport and Communication	Indirect	N/A	N/A	N/A	0.0151	4.60
Mining	Indirect	N/A	N/A	N/A	0.0105	3.20
Transport, transoceanic freight ship	Transport	0.5000	t km	0.0108	0.0054	1.64
Fuels	Indirect	N/A	N/A	N/A	0.0033	1.00
Metals	Indirect	N/A	N/A	N/A	0.0020	0.60
Minerals	Indirect	N/A	N/A	N/A	0.0020	0.60
Agriculture	Indirect	N/A	N/A	N/A	0.0016	0.50
Business services	Indirect	N/A	N/A	N/A	0.0007	0.20
Trade	Indirect	N/A	N/A	N/A	0.0003	0.10
Equipment	Indirect	N/A	N/A	N/A	0.0003	0.10
Wood and paper	Indirect	N/A	N/A	N/A	0.0003	0.10
Personal Services	Indirect	N/A	N/A	N/A	0.0000	0.00
Construction	Indirect	N/A	N/A	N/A	0.0000	0.00
Textiles	Indirect	N/A	N/A	N/A	0.0000	0.00
Food	Indirect	N/A	N/A	N/A	0.0000	0.00
Fishing	Indirect	N/A	N/A	N/A	0.0000	0.00
Forestry	Indirect	N/A	N/A	N/A	0.0000	0.00
				Total emissions (kg CO_2-eq/kg)	0.3282	100.00

Table 2
Supply chain carbon emissions breakdown for ferric chloride.

Input	Category	Quantity	Unit	Emissions intensity (kg CO_2-eq/unit)	Emissions (kg CO_2-eq)	Emissions (%)
Chlorine, gaseous, mercury cell	Inorganic Chemicals	0.4920	kg	1.0900	0.5363	54.00
Chemical plant, organics	Organic Chemicals	0.0000	unit	123,660,000.0000	0.1237	12.45
Chlorine, gaseous, membrane cell	Inorganic Chemicals	0.1060	kg	0.9220	0.0977	9.84
Transport, lorry 3.5–20 t, fleet average (from supplier)	Transport	0.3000	t km	0.2798	0.0839	8.45
Chemicals (indirect)	Indirect	N/A	N/A	N/A	0.0309	3.11
Utilities (indirect)	Indirect	N/A	N/A	N/A	0.0248	2.50
Hydrochloric acid, 30% in H_2O	Inorganic Chemicals	0.0220	kg	0.8530	0.0188	1.89
Transport and communication (indirect)	Indirect	N/A	N/A	N/A	0.0173	1.74
Iron scrap	Metals	0.3280	kg	0.0420	0.0138	1.39
Mining (indirect)	Indirect	N/A	N/A	N/A	0.0116	1.17
Transport, lorry 3.5–20 t, fleet average	Transport	0.0220	t km	0.2800	0.0062	0.62
Business services (indirect)	Indirect	N/A	N/A	N/A	0.0060	0.60
Transport, transoceanic freight ship	Transport	0.3930	t km	0.0108	0.0042	0.43
Fuels (indirect)	Indirect	N/A	N/A	N/A	0.0037	0.37
Disposal, sludge from $FeCl_3$ production, 30% water, to underground deposit	Waste Management	0.0060	t km	0.6040	0.0036	0.36
Electricity, medium voltage, at grid	Utilities	0.0186	kW h	0.1310	0.0024	0.25
Minerals (indirect)	Indirect	N/A	N/A	N/A	0.0024	0.24
Metals (indirect)	Indirect	N/A	N/A	N/A	0.0023	0.23
Agriculture (indirect)	Indirect	N/A	N/A	N/A	0.0017	0.17
Trade (indirect)	Indirect	N/A	N/A	N/A	0.0005	0.05
Wood and paper (indirect)	Indirect	N/A	N/A	N/A	0.0004	0.04
Tap water, at user	Utilities	1.2300	kg	0.0003	0.0004	0.04
Equipment (indirect)	Indirect	N/A	N/A	N/A	0.0003	0.03
Food (indirect)	Indirect	N/A	N/A	N/A	0.0001	0.01
Construction (indirect)	Indirect	N/A	N/A	N/A	0.0001	0.01
Textiles (indirect)	Indirect	N/A	N/A	N/A	0.0001	0.01
Forestry (indirect)	Indirect	N/A	N/A	N/A	0.0000	0.00
Fishing (indirect)	Indirect	N/A	N/A	N/A	0.0000	0.00
Personal services (indirect)	Indirect	N/A	N/A	N/A	0.0000	0.00
				Total emissions [kg CO_2-eq]/kg]	0.9932	

final product (biodiesel) and a circular supply chain configuration based on the recovery of value from waste cooking oil for the production of the same final product is presented in Table 3. The complete breakdown of the supply chain analysis is reported in Tables 4 and 5. A synthetic breakdown of the emissions (between direct and indirect ones) is presented in Fig. 8, with aggregated carbon maps shown in Figs. 9 and 10.

It can be observed from Fig. 8 that the circular supply chain (which consists of the collection and reprocessing of waste cooking oil and its use in the production of biodiesel) reports a total lifecycle emissions

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Table 3
Summary of results for environmental indicators for biodiesel linear and circular supply chains.

Environmental indicator		Units	Linear supply chain	Circular supply chain
Carbon emissions	Total emissions	kg CO_2-eq/kg	1.2737	0.7602
	Identified	% of kg CO_2-eq/kg	Virgin Veg. Oil (68.31%)	Vegetable oil (37.05%)
	Hot-spots (top five listed)		Upstream mining (7.38%)	Upstream mining (11.25%)
			Methanol (6.59%)	Methanol (10.40%)
			Heat, gas, > 100 kW (4.03%)	Heat, gas, > 100 kW (7.57%)
			Upstream utilities (3.13%)	Upstream utilities (4.92%)
Resource: virgin resource used		kg	0.964	0
Waste: recovered waste		kg	0	0.895

Table 4
Circular supply chain emissions breakdown for biodiesel production from waste cooking oil.

Input	Category	Quantity	Unit	Emissions intensity (kg CO_2-eq/unit)	Emissions (kg CO_2-eq)	Emissions (%)
Vegetable oil, from waste cooking oil	Biomass/fuels	0.8950	kg	0.4140	0.3705	37.05
Mining	Indirect	N/A	N/A	N/A	0.0855	11.25
Methanol	Biomass/fuels	0.0989	kg	0.7998	0.0791	10.40
Heat, gas, furnace > 100 kW	Utilities	0.8040	MJ	0.0716	0.0576	7.57
Utilities	Indirect	N/A	N/A	N/A	0.0374	4.92
Agriculture	Indirect	N/A	N/A	N/A	0.0275	3.62
Electricity, medium voltage, at grid	Utilities	0.0368	kW h	0.5314	0.0196	2.57
Potassium hydroxide	Inorganic chemicals	0.0099	kW h	1.9059	0.0188	2.48
Chemicals	Indirect	N/A	N/A	N/A	0.0176	2.31
Transport and communication	Indirect	N/A	N/A	N/A	0.0115	1.51
Food	Indirect	N/A	N/A	N/A	0.0107	1.41
Phosphoric acid, 85% in H_2O	Inorganic chemicals	0.0040	M3	1.4201	0.0057	0.75
Metals	Indirect	N/A	N/A	N/A	0.0046	0.60
Minerals	Indirect	N/A	N/A	N/A	0.0046	0.60
Fuels	Indirect	N/A	N/A	N/A	0.0031	0.40
Business services	Indirect	N/A	N/A	N/A	0.0015	0.20
Transport, freight, rail	Transport	0.0677	t km	0.0207	0.0014	0.18
Transport, lorry > 16 t, fleet average	Transport	0.0103	t km	0.1336	0.0014	0.18
Trade	Indirect	N/A	N/A	N/A	0.0008	0.10
Equipment	Indirect	N/A	N/A	N/A	0.0008	0.10
Wood and paper	Indirect	N/A	N/A	N/A	0.0008	0.10
Tap water, at user	Utilities	0.0238	kg	0.0003	0.0000	0.00
Waste management	Waste management	0.0001	m^3	0.0149	0.0000	0.00
Personal services	Indirect	N/A	N/A	N/A	0.0000	0.00
Construction	Indirect	N/A	N/A	N/A	0.0000	0.00
Textiles	Indirect	N/A	N/A	N/A	0.0000	0.00
Fishing	Indirect	N/A	N/A	N/A	0.0000	0.00
Forestry	Indirect	N/A	N/A	N/A	0.0000	0.00
				Total emissions [kg CO_2-eq]/kg]	0.7602	

value of 0.7602 kg CO_2-eq/kg of biodiesel. On the other hand, the linear supply chain has a total lifecycle emissions value of 1.2737 kg CO_2-eq/kg of biodiesel. It can clearly be observed that the there is an environmental gain of 0.5135 kg CO_2-eq/kg of biodiesel in terms of avoided emissions produced when the circular supply chain is benchmarked against the linear alternative.

In managing product-level supply chain impacts, focal firms can implement low carbon interventions and measures that can directly reduce the impacts of inputs classed as direct supply chain inputs. On the other hand, although the focal firm may not be able to directly address the indirect impacts associated with the product supply chain, it can be able to: (i) gain a better understanding of the overall emissions profile of activities; (ii) identify emissions reduction opportunities; (iii) track performance and engage suppliers through closer supply chain collaborations. The direct supply chain impacts for the linear and circular supply chains represents the biggest potential for emissions reduction since it constitutes the bigger proportion of the total lifecycle supply chain emissions (83.51% and 72.87%, respectively). From a pure environmental sustainability perspective, a focal firm can understand that in the circular supply chain of waste cooking oil, where value in the form of refined vegetable oil is recovered (Table 4), the biggest potential to reduce the carbon emissions potential directly from their perspective lies on intervention options targeted at:

- the use of refined vegetable oil (0.3705 kg CO_2-eq/kg or 37.05%);
- upstream mining: 0.0855 kg CO_2-eq/kg or 11.5% (from activities related to extraction of raw materials for energy production, minerals for fertilizer, etc.);
- use of methanol in the biodiesel esterification process (0.0791 kg CO_2-eq/kg or 10.40%);
- use of industrial gas furnaces (> 100 kW) for heat production: 0.0716 kg CO_2-eq/kg or 7.57%;
- upstream utilities: 0.0374 kg CO_2-eq/kg or 4.92% (from agricultural activities related to the raw materials used in the production of the vegetable oil);
- upstream agriculture: 0.0275 kg CO_2-eq/kg or 3.62% (from agricultural activities related to the raw materials used in the production of the vegetable oil).

On the other hand, the carbon hot-spots analysis for the linear supply chain (Table 5) shows that the use of virgin vegetable oil (0.8701 kg CO_2-eq/kg or 68.31%), upstream mining (0.0940 kg

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Table 5
Linear supply chain emissions breakdown for biodiesel production from non-waste cooking oil.

Input	Category	Quantity	Unit	Emissions intensity (kg CO_2-eq/unit)	Emissions (kg CO_2-eq)	Emissions (%)
Soybean oil	Biomass/fuels	0.9460	kg	0.9198	0.8701	68.31
Mining	Indirect	N/A	N/A	N/A	0.0940	7.38
Methanol, at regional storage	Biomass/fuels	0.1050	kg	0.7998	0.0840	6.59
Heat, gas, furnace > 100 kW	Utilities	0.7170	MJ	0.0716	0.0513	4.03
Utilities	Indirect	N/A	N/A	N/A	0.0399	3.13
Agriculture	Indirect	N/A	N/A	N/A	0.0296	2.33
Electricity, medium voltage, at grid	Utilities	0.0389	kW h	0.5314	0.0207	1.62
Chemicals	Indirect	N/A	N/A	N/A	0.0155	1.21
Phosphoric acid, 85% in H_2O	Inorganic chemicals	0.0105	kg	1.4201	0.0149	1.17
Heat, hard coal furnace 1–10 MW	Utilities	0.0960	MJ	0.1313	0.0126	0.99
Transport and communication	Indirect	N/A	N/A	N/A	0.0116	0.91
Metals	Indirect	N/A	N/A	N/A	0.0052	0.40
Minerals	Indirect	N/A	N/A	N/A	0.0052	0.40
Fuels	Indirect	N/A	N/A	N/A	0.0039	0.30
Hydrochloric acid, 30% in H_2O	Inorganic chemicals	0.0042	MJ	0.8529	0.0036	0.28
Heat, light fuel oil, furnace 1 MW	Utilities	0.0374	MJ	0.0910	0.0034	0.27
Transport, lorry > 16 t, fleet average	Transport	0.0120	t km	0.1336	0.0016	0.13
Transport, freight, rail	Transport	0.0716	t km	0.0207	0.0015	0.12
Business services	Indirect	N/A	N/A	N/A	0.0013	0.10
Trade	Indirect	N/A	N/A	N/A	0.0013	0.10
Equipment	Indirect	N/A	N/A	N/A	0.0013	0.10
Wood and paper	Indirect	N/A	N/A	N/A	0.0013	0.10
Tap water	Utilities	0.0252	kW h	0.0003	0.0000	0.00
Waste management	Waste management	0.0001	m^3	0.0149	0.0000	0.00
Personal services	Indirect	N/A	N/A	N/A	0.0000	0.00
Construction	Indirect	N/A	N/A	N/A	0.0000	0.00
Textiles	Indirect	N/A	N/A	N/A	0.0000	0.00
Food	Indirect	N/A	N/A	N/A	0.0000	0.00
Fishing	Indirect	N/A	N/A	N/A	0.0000	0.00
Forestry	Indirect	N/A	N/A	N/A	0.0000	0.00
				Total emissions [kg CO_2-eq]/kg]	1.2737	100.00

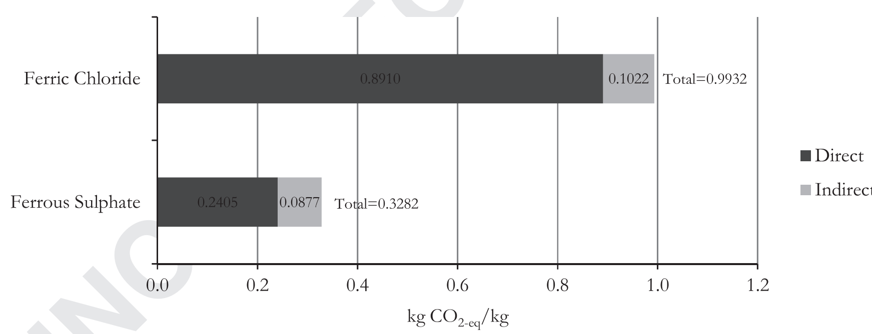
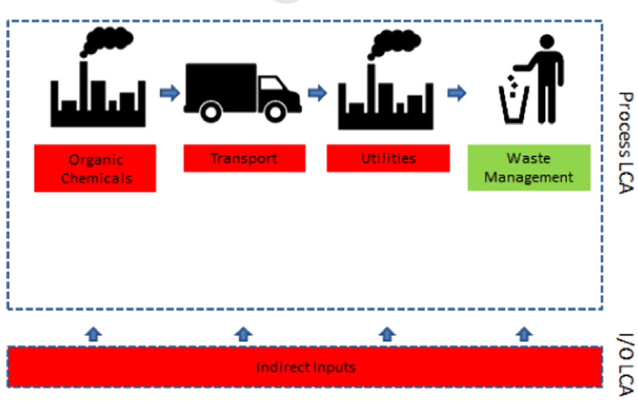


Fig. 5. Comparative levels of emissions by ferrous sulphate and ferric chloride supply chains.



Q6 **Fig. 6.** Supply chain carbon map for ferrous sulphate. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

CO_2-eq/kg or 7.38%), use of methanol (0.0840 kg CO_2-eq/kg or 6.59%), use of industrial gas furnace (> 100 kW) (0.0513 kg CO_2-eq/kg or 4.03%), upstream utilities (0.0399 kg CO_2-eq/kg or 3.13%) and upstream agriculture (0.0296 kg CO_2-eq/kg or 2.33%) are the top-ranking hotspots.

Interestingly, for both the linear and circular supply chains, with the exception of the vegetable oil (virgin resource for the forward supply chain: 0.8701 kg CO_2-eq/kg; refined resource recovered from waste for the reverse one: 0.3705 kg CO_2-eq/kg), the other identified hot-spots are very similar in terms of their carbon emissions impacts. This goes to reaffirm the environmental benefits deriving from the implementation of circular supply chain strategies to recover value from waste and re-use it where applicable in the production of secondary products.

Circular supply chains provide the benefit of diverting used products from being discarded as waste through the recovery of value and reused in the production of secondary products. The benefit of these is clearly noticed in the summary of results presented in Table 3. For every kg of biodiesel that is produced, the forward supply chain which is based on the principles of a linear production paradigm uses 0.964 kg of virgin cooking oil. This is in contradiction to the circular supply chain, which uses 0.895 kg of refined cooking oil recovered from waste cooking oil

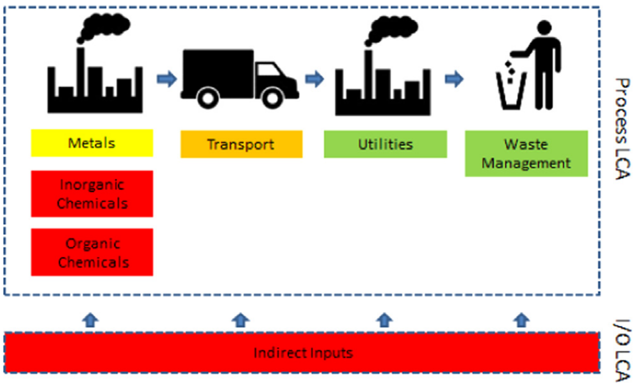


Fig. 7. Supply chain carbon map for ferric chloride. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

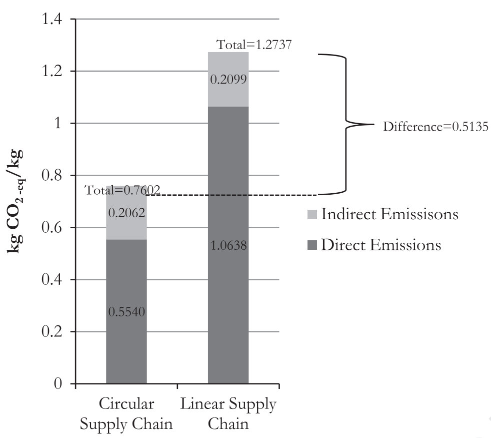


Fig. 8. Total (including direct and indirect) carbon emissions breakdown of the supply chains.

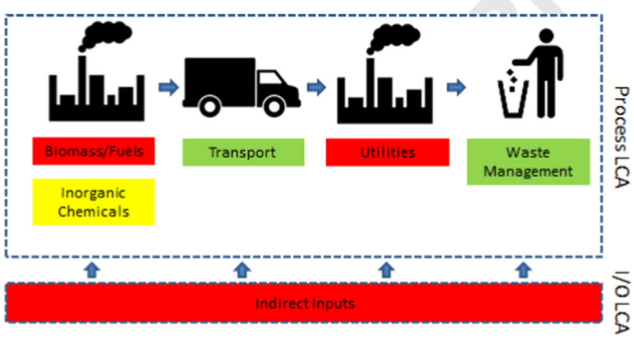


Fig. 9. Circular configuration carbon map of biodiesel production from waste cooking oil. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

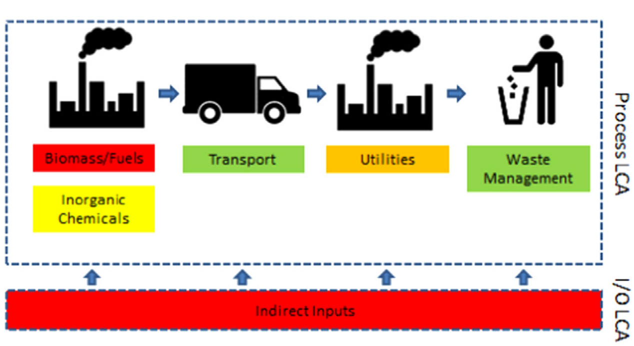


Fig. 10. Circular configuration carbon map of biodiesel production from non-waste cooking oil. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

which otherwise may have illegally ended up in the environment or in waste disposal sites. A crucial supply chain implication of the linear production paradigm is the creation of a direct competition between the supply chains of food for human consumption and food as a feedstock for bioenergy production. When the 0.964 kg of virgin cooking oil used for biodiesel production are scaled up, the risk posed to the food supply chain becomes clearer. For instance, the US Department for Agriculture [83] reports that about 15% of 2010/2011 global soy oil production was used for biodiesel production. This direct competition between food and bioenergy may also result in higher prices for food [15], land use issues [60] and food security [68], thus threatening the sustainability of food supply chains. Implementing circular supply chains for biodiesel production represents also a way to address this challenge, preserving virgin resources.

4.2. Implications to sustainable supply chain management

The principles of circular economy assume that the raw materials used in production systems must be both technical and biological. These raw materials should not have a negative impact on the environment and should be regenerative, hence returning to the ecosystem without treatments required to rebuild the natural capital. In essence, there is no degeneration and environmental impact of materials within a production system which operates in a restorative cycle.

Since the concept of circular economy is subject to the universal laws of thermodynamics, there would still be a degeneration of the raw materials in a production system over time. This is due to the fact that the circular flows of exchanges are coupled with the physical flows of matter-energy, which are not circular [77]. Hence, resource flows are ultimately linear and unidirectional, beginning with the depletion of low entropy resources from the environment and ending with the pollution of the environment with high entropy waste [18]. Nevertheless, the implications of circular economy can be aligned to sustainable supply chain management, by noticing that, although supply chains cannot be theoretically circular, the underlining principle of using the higher entropy waste as substitute for lower entropy virgin materials could form a pivotal underlining principle for greener production systems. This holds true as argued by Beinhocker [11], who suggested that in order to have a sustainable economy where damage to the environment is reduced, overall entropy of our earth system must be reduced. As such, the circular economy concept can describe a framework in which businesses operating within the same supply chain and beyond can engage with sustainability activities to create shared value.

4.3. Implications to market dynamics

The transition towards a sustainable economy is a challenging process, as a wide spectrum of constraints emerges. The case studies reported above have shown that some obvious environmental advantages can be achieved by utilizing circular rather than linear supply chains. However, the economic viability of the circular supply chains may be questionable, as mechanisms to enact them may be very fragile.

As regards the case study from the chemical supply chain, it has been shown that total emissions related to the linear supply chain (0.99 kg CO_2-eq/kg) are more than three times higher than emissions for the reverse one (0.3285 kg CO_2-eq/kg), and that advantages can be achieved in terms of diversion of waste from landfill and virgin resources preservation. However, it has to be considered that, as mentioned above, manufacturing of Ferrous Sulphate relies on the acidic waste from the production of Titanium Dioxide (TiO_2) by the sulphate method. In 2009 the production of TiO_2 by the sulphate

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process stopped in the UK; therefore, the metal slag used in the circular supply chain is imported from overseas [33]. This has a detrimental impact in the cost and production of the ferrous sulphate. Data shows that the price of Ferrous Sulphate has increased by 80% in the last 5 years and that the annual production capacity in UK has declined by 15%. Demand is expected to outstrip its offer in the next years [33]. Price and the supply of Ferrous Sulphate could represent a problem in the future, making the circular alternative less attractive than the linear one (based on Ferric Chloride) in terms of economic convenience.

In the case of the biodiesel production, availability of used cooking oil to be recycled is not a problem, due to abundant and widespread supply. However, manufacturing costs may make some issues arise: indeed, currently, in the UK, biodiesel costs around 75 p/l to produce compared with petrodiesel at 52 p/l [74]. If biodiesel is made from 100% verified renewable sources (like used cooking oil), it is eligible for government support (24 p/l); this puts the biodiesel production at a 1 p advantage to petrodiesel. The risk here is the longevity of the government support regime, together with the cost of the used cooking oil, currently reported to be between 25 and 60 p/l depending on the quality [74]. Margins are fairly tight for the producers; collectors (who operate on a very fragmented market) may operate at even tighter margins.

Therefore, both the analysed cases highlight that, while environmental benefits may be obvious, the implementation of circular supply chains may be challenging from an economic point of view. Thus, bottom-up initiatives at a supply chain level might need to be incentivized through some form of top-down governmental support (such as in the case of the biodiesel supply chain).

4.4. Policy and societal implications

In terms of the policy implications, as a result of the increasing need to address unsustainable patterns of resource consumption and waste production, national governments in the European Union [27] and China [34], along with international agencies [56] are beginning to recognise the need to adopt production systems inspired by the circular economy concept. A direct implication of this change on society would be a gradual shift from an economy based on the sale of goods to an economy based on the sale of performance [26]. For businesses, a rethink of the value chain cycles and a whole system design approach would play significant role in operational practices.

These positive implications of circular economy concepts to policy strengthen the overall green agenda. Indeed, an example of the increasing alignment of circular economy concepts and sustainable supply chain management practices is provided by the fact that the United Nations Environment Programme (UNEP) [81] reported that the Chinese implementation of the circular economy initiative is undertaken within a Sustainable Consumption and Production program. Such a programme strives to meet resource consumption and waste challenges through cleaner production, industrial ecology and life-cycle management; all fundamental principles of sustainable supply chain management ([65,93]; Acquaye and Yamoah et al., 2014).

4.5. A systems approach for the transition towards a more sustainable economy

The transition towards a sustainable economy is a challenging process, as a wide spectrum of constraints, including political, cultural, human, economic structures and technological limitations emerge. This transition can be viewed from two extreme perspectives; a top-down approach and a bottom-up one (refer to Fig. 11). This paper has presented a bottom-up view to the initiation of environmental sustainability, starting from the product-level (Type IV System perspective) and stimulating impacts across higher-level systems. This follows Sikdar [70] identification of four types of sustainable systems of which System Type IV (products) is a subset of System Type III (Businesses) which in turn is a sub-set of System Type II (Regions/Cities). An aggregation of regions and cities then forms System Type I (The Earth). This approach offers opportunities to develop sustainable business models benefiting from environmental assessments at a much disaggregated level of analysis (product-level systems). The framework provides a first step in decision support, thereby enabling businesses to choose appropriate and specific green business models in any low carbon transition plan. These green business models may include radical and systemic eco-innovations [20], product-service systems [64], industrial symbiosis [22], cradle-to-cradle systems [12].

Compared to top-down models where international and national policies are expected to diffuse down to companies and their operations and supply chains, the bottom-up approach works on the principle that, informed by environmental assessments, sustainable solutions at the product level can be aggregated across businesses in order to improve their sustainability and, ultimately, at the one of the wider economic systems. Top-down policies should therefore be also aimed at enhancing bottom-up initiatives.

Some of the practical challenges that such a framework would face are concerned with the implementation of the output of the analysis and the scaling up of solutions across a wider context. These are respectively indicated in the framework diagram (Fig. 11) as Impact Boundary and the Transfer and Aggregation of Solutions/Policies. In particular, the bottom-up approach illustrated in this study could also be adopted by policy-makers and other relevant stakeholders in regional context as a tool to identify and encourage greening and decarbonisation opportunities to be promoted through appropriate schemes and programmes. Indeed, by identifying synergies between supply chains, relevant bodies (such as Central Government Departments, Local Authorities and Chambers of Commerce) could encourage the use of by-products (derived by some product supply chains) as raw materials to be re-processed in further supply chains, favouring the transition towards a more sustainable economy by reducing virgin resources usage, carbon emissions and waste production; such bodies could encourage this transition by improving the economic convenience of these options.

Optimizing materials and energy flows among facilities within specific regions or industrial ecosystems is a basic industrial ecology strategy. In this context, external stakeholders (such as local and central governments, governmental agencies, industrial bodies) could play a “facilitator” role, by helping the matching of virgin resources demand and equivalent by-products supply, by developing integrated approaches to eco-industrial development. Examples of these approaches include the establishment of appropriate eco-industrial parks for resource recovery and tax exemption policies for companies involved in reverse supply chain activities (see, for instance: [61,38]). This, as argued by Mathews and Tan [47] would provide the required top-down support to complement bottom-up initiatives.

5. Conclusions

In the last decades, green and sustainable supply chain management practices have emerged, trying to integrate environmental concerns into organisations by reducing unintended negative consequences of production and consumption processes.

In parallel to this, the circular economy discourse has been propagated in the industrial ecology literature and practice. Circular economy pushes the frontiers of environmental sustainability by emphasising the idea of transforming products in such a way that there are workable relationships between ecological systems and economic growth. Therefore, circular economy is not just concerned with the reduction of the use of the environment as a sink for

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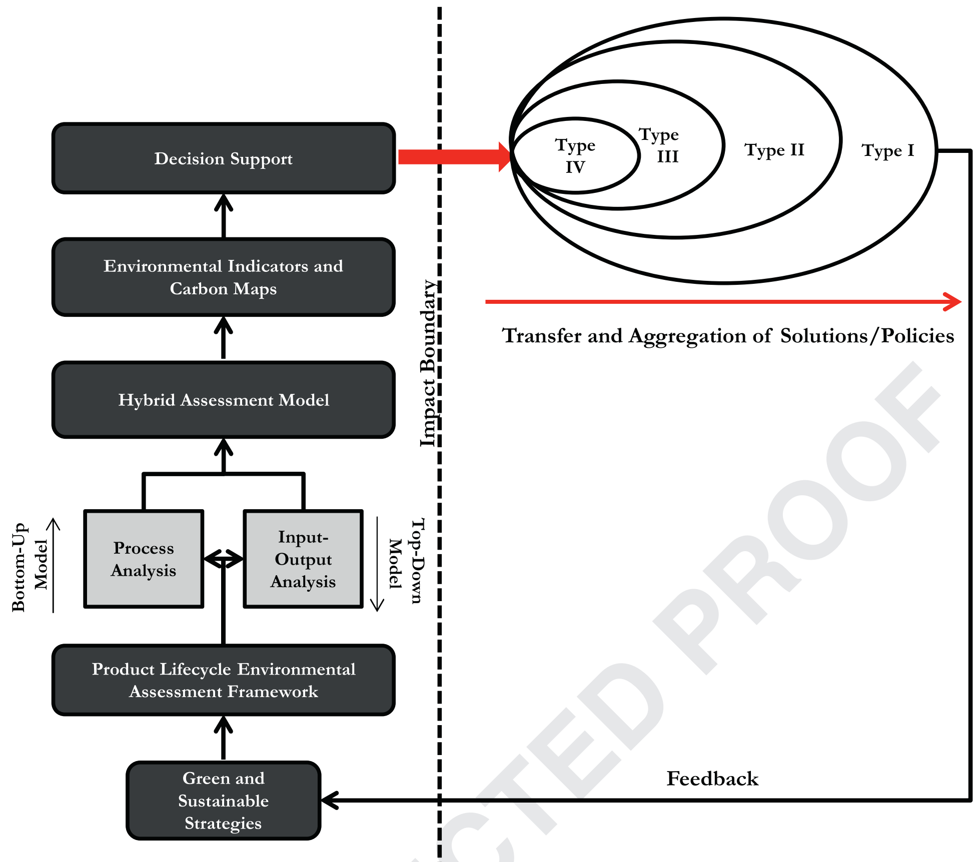

Fig. 11. Bottom-up sustainable pathway framework. The types of system perspective to sustainability: Type I (earth); Type II (regions/cities); Type III (businesses); Type IV (sustainable technologies or product level); adapted from Sikdar [70].

residuals, but rather with the creation of self-sustaining production systems in which materials are used over and over again.

Within this context, the main objective of the paper has been the verification of a potential enhancement of sustainable supply chain management practices by aligning them to circular economy concepts. By using a case-based approach (adopting examples from the chemical and food industries) the study has investigated the environmental implications related to the implementation of circular production systems, providing a comparison with traditional linear production alternatives.

The analysis was formulated using a Hybrid LCA methodology, combining both process LCA and the environmentally extended multi-regional input–output (MRIO) hybrid model. This led to the calculation and analysis of direct, indirect and total lifecycle emissions, of resource used and recovered waste. Also, supply chain carbon maps were derived, providing a holistic visibility of the supply chain.

The paper has asserted that integrating the core principles of circular economy within green supply chain management can provide clear advantages from an environmental point of view. However, the implementation of circular supply chains may be challenging from an economic point of view. Thus, bottom-up initiatives at a supply chain level might need to be incentivized through some form of top-down governmental support (such as in the case of the biodiese l supply chain). For this reason, the paper also discussed a theoretical base for the potential implementation of environmental sustainability measures inspired by circular economy concepts, starting from the product-level of the value chain. As such, it is envisaged that the paper would strengthen the knowledge-base of green supply chain management practice.

Further researches will be addressed to widen the empirical evidence, by developing further case studies related to the assessment of circular production systems. From a methodological point of view, more relevant environmental indicators could be considered in order to perform the comparison between linear and circular systems. Also, attention will be devoted to the cited economic implications, in many cases representing the main challenge for the implementation of circular economy initiatives.

Uncited references Q2

[17,31,43,71,36,52].

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.omega.2015.05.015.

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