An innovative eco-intensity based method for assessing extended supply chain environmental sustainability

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Abstract

Organisations currently face increasing pressure from multiple stakeholders to improve their environmental performance. The majority of environmental impacts in a typical supply chain usually arise beyond the focal firm boundaries or even its direct suppliers. However, no method to assess the extended supply chain environmental performance that is designed to use real-life data currently exists.

The aim of this work is to facilitate quantitative assessment of the environmental performance of extended supply chains by introducing an innovative eco-intensity based method that relates the environmental performance of the supply chain to its economic output. The method is the first to allow assessing the environmental sustainability performance of extended supply chains based on real life data, while respecting the multiple-organisation nature and non-collaborative characteristics of the majority of real life supply chains. This is achieved through the adopted decentralised approach, materialised through a recursive mechanism to pass eco-intensity values from one tier to the next, which does not require visibility of the extended supply chain by any single member, thus enhancing the applicability of the method.

The method is demonstrated through a numerical example with secondary data for four representative supply chains with different design features, to showcase its applicability. The CO_2 emissions and water eco-intensities are calculated. The findings enable both benchmarking the eco-intensity performance of the extended supply chains and comparison of the eco-intensity indicators of the individual organisations, offering a basis to guide operational improvement and to support external reporting. The method has the potential to change the way organisations approach their environmental sustainability by facilitating understanding of the wider supply chain impact.

Keywords: eco-intensity; environmental performance; multi-tier supply chain; extended supply chain; sustainability assessment; environmental benchmarking;

1. Introduction

Climate change, global warming and depletion of scarce natural resources have emerged as central themes in the agenda of the international community due to the impacts they have both on the society and the economy (Bloemhof et al., 2015; Montoya-Torres et al., 2015). Consequently, regulatory bodies have been posing increasing pressures to organisations to limit their environmental impact (Bask et al., 2013). Companies are also facing pressure from the market due to an increased green awareness of customers that are asking for more sustainable products and services (Frota Neto et al., 2008). Finally, other stakeholders such as non-governmental organisations and local communities are also demanding increased transparency of companies' practices and adequate reporting about the environmental and social impact caused by production activities (Björklund et al., 2012; Gerbens-Leenes et al., 2003).

Pressures to include environmental concerns within management and decision making were initially targeted to single organisations, mostly focal companies, which are those companies that have a leading role within the network as they "rule or govern the supply chain, provide the direct contact to the customer, and design the product or service offered" (Seuring and Müller, 2008). However, these pressures later expanded further to include more organisations part of the supply chain for two reasons.

Firstly, competition shifted from a company-versus-company to a supply chain-versus-supply chain form (Cabral et al., 2012; Hashemi et al., 2015), leading to increased specialisation of companies and outsourcing other tasks to different companies (Santibanez-Gonzalez and Diabat, 2013). Outsourcing practices have been often linked with offshoring practices, relocating parts of the supply chain to countries with low production cost, often coupled with less strict environmental regulations and standards (Harris et al., 2011; Hutchins and Sutherland, 2008; Silvestre, 2015). Environmental challenges thus expanded outside of the boundaries of the company as well, becoming a supply chain issue that encompasses the extended upstream and downstream players (Sigala, 2008; Varsei et al., 2014).

Secondly, there is significant evidence that the majority of the environmental impacts arise outside of the focal firm boundaries, being caused by other companies in the supply chain. The contribution of the extended supply chain beyond the focal company has been estimated to contribute up to 90% of the overall impact of the supply chain (Beavis, 2015; Veleva et al., 2003; WBCSD and WRI, 2009).

Consequently, a holistic approach encompassing the wider supply chain environmental performance is needed (Fabbe-Costes et al., 2011; McIntyre et al., 1998). However, existing supply chain environmental performance assessment methods have rarely expanded beyond first tier suppliers and customers, with a large body of the literature focusing on the focal firm performance in a supply chain perspective rather than addressing multiple tiers along the supply chain (Ahi and Searcy, 2015; Tuni et al., 2018). This narrow scope overlooks the fact that a poor environmental performance of a single tier upstream in the supply chain may result in an overall environmentally unsustainable behaviour of the entire supply chain. Companies therefore need to understand not only their first-tier suppliers environmental performance but also their extended supply chain environmental profile (Genovese et al., 2013; Miemczyk et al., 2012).

This work aims to introduce an innovative quantitative method to assess the environmental performance of extended supply chains, by using eco-intensity indicators that relate the environmental performance of the supply chain to its economic output. The method first assesses the environmental sustainability performance of extended supply chains based on real life data, extending the assessment beyond direct suppliers and customers, while still respecting the multiple-organisation nature and non-collaborative characteristics of the majority of real life supply chains. In contrast to existing approaches for extended supply chains performance measurement, this work does not assume the existence of a central administration of the supply chain. On the contrary, the method requires each organisation to access only its direct suppliers and customers thanks to the decentralised approach and recursive mechanism adopted, thus not requiring visibility of the extended supply chain by any member of the supply chain.

2. Background and literature review

2.1 Performance measurement and assessment in green supply chain management

Green supply chain management (GSCM) added the environmental dimension to the traditional economic dimension of supply chain management within all processes ranging from the material sourcing and selection stage down to the end-of-life management of products (Srivastava, 2007). As a result, companies recognised the need to track their environmental performance outside their organisational boundaries adopting a supply chain perspective to achieve an accurate evaluation of their environmental footprint (Varsei et al., 2014). The urge to develop tools for monitoring GSCM performance has appeared evident not only to the academia but to the industry as well. The SCOR framework, a widely adopted framework to measure performance of supply chain processes at the organisation level, included a pilot section dedicated to environmental performance in version 11 of the model to tackle this emerging issue (APICS, 2014).

Performance measurement is described as the process of evaluating the effectiveness and/or the efficiency of an action, either qualitatively or quantitatively (Neely et al., 1995). Qualitative metrics are in use to measure the social sustainability of the supply chain (Hutchins and Sutherland, 2008), but are less common to address the environmental dimension of sustainability (Ahi and Searcy, 2015), as quantitative indicators are recognised to be more reliable and unbiased in evaluating the environmental supply chain behaviour (Tsoulfas and Pappis, 2008).

Despite recurring interest for certain environmental impacts, no agreement exists on the exact metrics to be adopted to measure the GSCM performance. Scholars developed a high number of indicators with a low degree of standardisation, which is affecting the comparability of results across different studies (Ahi and Searcy, 2015). Moreover, indicators could be divided among absolute indicators that are expressed according to a fixed measurement scale and relative indicators that relate the impact value to a reference value (Mintcheva, 2005). Absolute values are helpful to understand the overall environmental impact associated with an activity of the system under analysis; however they are prone to fluctuation as a result of changes in the produced outputs thus hiding the real changes in the environmental performance (Michelsen et al., 2006). Additionally, they lose validity when comparing different systems, such as companies or supply chains, that naturally present different features and are not strictly comparable using absolute indicators (Wiedmann et al., 2009). Adopting relative indicators is thus an option to overcome these limitations; however, multiple reference values have been adopted in the literature to obtain relative indicators.

Life cycle analysis (LCA) is a widely recognised technique to evaluate the environmental performance of products in a lifecycle perspective. LCA adopts as reference value the concept of functional unit, closely associated to the benefit given to the final user by a product. A typical example is the comparison of paper towel against electric hand dryer, both providing the benefit to dry hands of the user. However, the selection of the functional unit is based on the design stage of the LCA study and thus is heavily affected by assumptions. Additionally, LCA studies embody assumptions also in the data adopted which typically are not real life data but are collected from dedicated databases increasing the uncertainty of results and ultimately compromising even the comparability of similar studies assessing the environmental performance of the same type of products (Guldbrandsson and Bergmark, 2012; Kravanja and Čuček, 2013). Alternative reference units include the units produced (Koh et al., 2012), the weight of product output or the volume of the product output (Mintcheva, 2005). These reference units are suitable to compare physically homogenous products, but unlike the functional units are not able to benchmark alternative products providing the same benefit to the user. The economic output associated with the activities generating the environmental impact can serve as an alternative reference value to overcome these limitations, as it allows comparing both products having the same functional unit as well as physically homogenous products.

The adoption of the economic output as the reference unit for the environmental indicator leads to the concepts of eco-efficiency and eco-intensity that combine the environmental and economic dimensions of sustainability in a unique indicator, offering a relative indicator to effectively benchmark alternative products without the constraints of functional unit or physical reference values. Eco-efficiency is described as “the efficiency with which ecological resources are used to meet human needs” by the Organisation for Economic Co-Operation and Development (OECD) and is a ratio of the economic value created and the sum of environmental pressures generated by an economic activity (WBCSD, 2000). Eco-intensity reverses the ratio, being the environmental impact divided by the economic benefit generated by an economic activity (Huppes and Ishikawa, 2005; Schmidt and Schwegler, 2008).

2.2 Eco-efficiency and eco-intensity in GSCM

Despite eco-intensity being identified as more easily applicable than eco-efficiency to the supply chain context from a mathematical perspective (Schmidt and Schwegler, 2008), there are only few examples of its application in this context. Joa et al. (2014) calculated the water consumption eco-intensity of the supply network of a company, taking into account the geographical differences of supply network players. The authors adopted a recursive indicator building up on a previous contribution from Schmidt and Schwegler (2008), whose work however does not identify the environmental aspects that are required to be measured. Both pieces of work adopt a decentralised approach to assess the eco-intensity of wider supply networks, rather than supply chains, making the approaches complex and unpractical for operating organisations due to the high number of companies required to be part of the analysis, including organisations that are not sub-suppliers of the focal firm.

Eco-efficiency models are applied with an increased frequency in the GSCM literature. Eco-efficiency was adopted to support different managerial decisions, thus offering coverage of different supply chain extent. Eco-efficiency scores were adopted to rank 1st tier suppliers to provide support to the green supplier selection and evaluation problem: Tseng et al. (2013) adopted linguistic variables to include uncertainties in the evaluation of decision makers within a set of twenty eco-efficiency criteria using TODIM method, whereas the eco-efficiency score of direct suppliers from Mahdiloo et al. (2015) is based on data envelopment analysis. Other scholars focused on the supply chain configuration problem in triadic supply chains, such as Colicchia et al. (2015), who developed a bi-objective optimisation function of cost and CO_2 emissions in distribution networks. A similar problem is addressed by Wu and Barnes (2016), who adopt analytical network process to select suppliers and distribution centres based on an eco-efficiency ratio as an intermediate step to solve the green lot-sizing problem. Finally, an eco-efficient frontier is calculated for the waste electrical and electronic reverse chain by Quariguasi Frota Neto et al. (2009): the environmental indicators adopted are the cumulative energy demand and the landfilled waste, whereas the profit is used as the single economic indicator.

Other authors tried to expand the supply chain extent coverage beyond the dyadic and triadic supply chains in their application of eco-efficiency models, adopting a lifecycle perspective. Examples include Saling et al. (2002), who developed an aggregated eco-efficiency index to compare five alternative dyeing supply chains of blue jeans, and the works of Michelsen et al. (2006) and Michelsen and Fet (2010) on the furnishing sector. In both papers, LCA and life cycle costing are used to calculate the eco-efficiency of different chair models taking into account their extended supply chain. Finally, Charmondusit et al. (2014) expand the eco-efficiency concept to include the social dimension of sustainability in a socio-eco-efficiency index developed specifically for the toy industry and boosting an increased applicability for small medium enterprises (SMEs). However, despite adopting a lifecycle perspective and aiming to measure the extended supply chain eco-efficiency performance, these authors completely overlook the multi-organisation nature of the supply chain, assuming a centralised entity coordinating the different stages from raw material to the end-of-life management. This approach is in contrast with the nature of operating supply chains which are built up by interconnected autonomous entities (Mena et al., 2013). Therefore, no method to assess the eco-intensity or eco-efficiency of extended supply chains, respecting their multi-organisation nature currently exists.

2.3 Multi-tier and extended supply chains

Measuring environmental performance at the supply chain level poses a number of challenges, due to the increased complexity caused by the involvement of multiple organisations (Hassini et al., 2012; Hervani et al., 2005; Shaw et al., 2010; Yakovleva et al., 2012). Lack of trust, conflicting objectives, cultural differences, lack of standardised data and metrics and inclination towards local optimisation rather than systemic approaches were identified as the major challenges arising when multiple organisations are involved in the broader performance measurement process (Hervani et al., 2005; Taticchi et al., 2013).

The challenges identified to assess performance in the green supply chain context have been further enhanced by the recent development of the competitive environment. Globalisation led to increasing specialisation of companies that are outsourcing various processes to other organisations, thus creating more complex supply chains, which are built by an increased number of tiers (Mena et al., 2013). However, including additional tiers to the supply chains affected the visibility and traceability over the supply chain as well, as companies are less knowledgeable about their upstream activities (Acquaye et al., 2014; Michelsen and Fet, 2010). Recent surveys revealed that half of supply chain executives recognised that the visibility of their supply chain is limited to the 1st tier suppliers, thus not having a complete understanding of their upstream network (Egilmez et al., 2014; O'Rourke, 2014). A result of the lack of information about the sub-suppliers caused a number of both social and environmental scandals involving different multinational groups. Examples include Nike, whose sub-suppliers were found to employ children in their facilities, as well as other organisations, such as Unilever or Nestlé that were involved in deforestation and unsustainable forestry practices in their extended supply chain leading to corporate reputation damage and economic losses (Miemczyk et al., 2012; Vachon and Mao, 2008). Despite not being directly involved in any unsustainable practice, the focal companies were held responsible for the misconduct by consumers, as their prominent role within the supply chain was recognised (Gimenez and Tachizawa, 2012).

A number of approaches for the focal companies to deal with the sub-suppliers located beyond the 1st tier suppliers have been identified in the literature. Mena et al. (2013) distinguished between closed and open triad structures based on the existence of a direct contact between the focal company and the 2nd tier supplier, suggesting that a direct contact is necessary to influence key product characteristics. Tachizawa and Wong (2014) adopted a clear sustainability perspective in their multi-tier supply chain study and identify four potential approaches in the management of sub-suppliers by the focal organisation: "don't bother", "working with third party", "direct" or "indirect". The latest approach is also addressed in the work by Wilhelm et al. (2016) that recognise the complexity and substantial inapplicability of other approaches for the biggest part of supply chain sub-suppliers due to limited control of the focal company on them. A pivotal role is thus played by suppliers at any level of the supply chain in disseminating sustainability in their upstream supply chain, a perspective that is adopted in this work as well.

The research on multi-tier and extended supply chain sustainability however stayed mostly on a conceptual level, coherently with the recent development of the field. As Brandenburg et al. (2014) highlighted in their review on sustainable supply chain management models, quantitative work on "the extended supply chain still require considerably more attention". This work thus tries to bridge this gap and quantitatively assess the environmental performance of extended supply chains by introducing an innovative eco-intensity method based on real life data. The method is innovative as it not only addresses the extended supply chain, but it also respects the multiple-organisation nature and non-collaborative characteristics of the majority of real life supply chains as well as limiting the visibility required to direct suppliers and customers only.

3. Description of the method

Based on the gaps emerged from the literature analysis, an innovative method to assess the eco-intensity performance of extended supply chains is introduced in this section. The method consists of four methodological steps performed in cascade: definition of system boundaries, selection of environmental indicators, inclusion of economic dimension and application of recursive mechanism. A sub-section dedicated to each methodological step follows. The method provides three major outputs, as highlighted in figure 1: single company eco-intensities specific to each environmental indicator, supply chain eco-intensities specific to each environmental indicator and environmental backpack of products, which is the absolute environmental impact allocated to products for each environmental indicator. Each output of the method is associated to the corresponding equations, which are later presented in the mathematical eco-intensity based model included throughout the section.

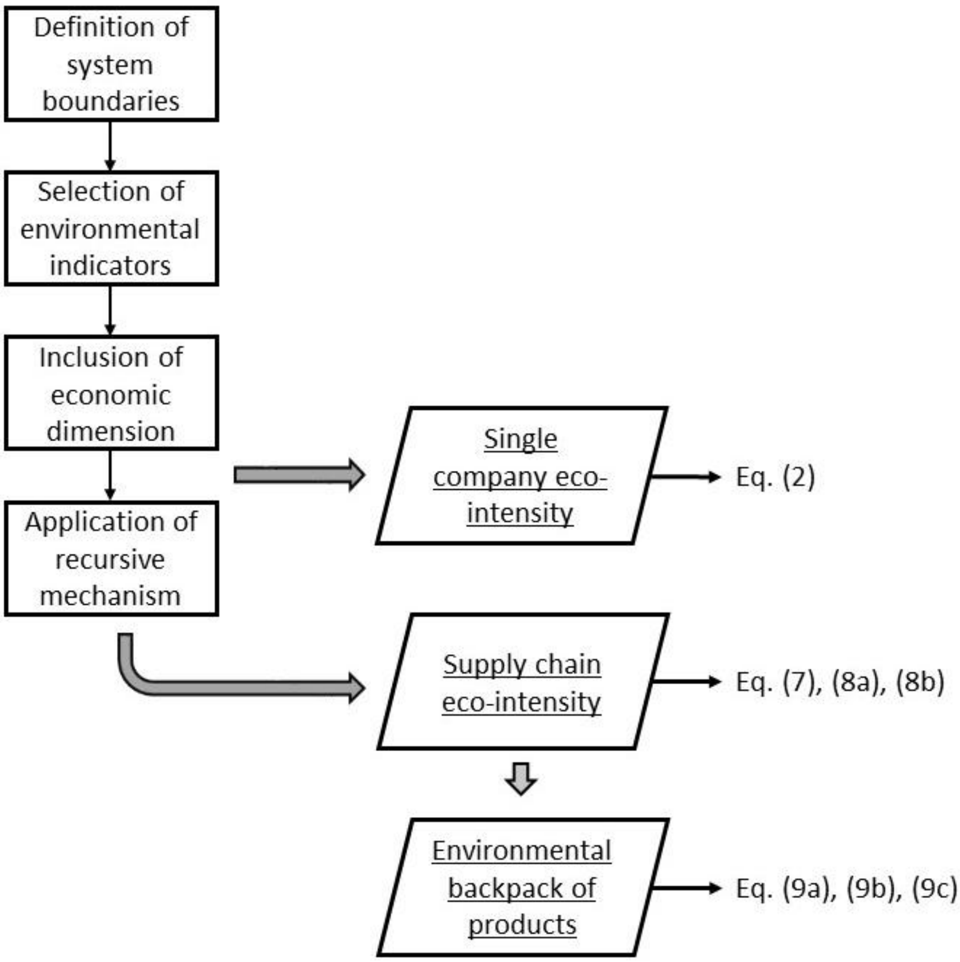

Figure 1: Methodological steps

3.1 Definition of system boundaries

The definition of the system boundaries is a necessary preliminary step to assess the performance of any system and to provide comparability of results (Wiedmann et al., 2009). The method to assess eco-intensity introduced in this section is developed for forward supply chains and adopts a cradle-to-gate approach.

Each company part of the supply chain is considered as a black box, with a certain number of environmental and economic inputs and outputs taken into account. The internal dynamics of each organisation are beyond the scope of the study and data are thus collected at the company level for each player of the supply chain.

Adopting a cradle-to-gate approach means that the usage and end-of-life management phases of product lifecycle are omitted due to the significant uncertainties in the collection of primary data for these lifecycle stages and the limited control over them by any player of the supply chain, potentially affecting the applicability of the method and its usefulness for organisational decision making (Michelsen et al., 2006). The cradle-to-gate approach defines specifically the downstream boundary of the supply chain, which is reached when the product crosses the gate between the most downstream player of the supply chain and the final customer or consumer to whom the product is sold. This player could be typically identified as a retailer or a distributor in a business-to-consumer context, whereas it could be the manufacturer in a business-to-business context. Moreover, this work assumes that the assessment is carried out only for products reaching the market as the method is not applicable if no material flows across the downstream boundary and no economic gain is generated by the supply chain within the one-year time horizon.

The remaining boundaries of the supply chain are defined according to the transformation model by Slack et al. (2009), who defines two types of resources. Transformed resources are resources that will be treated, transformed or converted during the production processes and are sourced from "product-related suppliers" (Kovács, 2008; Slack et al., 2009), whereas transforming resources are resources that facilitate the processes, including the facilities, the equipment and the machineries necessary to transform the products and involve the supporting members of the supply chain (Kovács, 2008; Slack et al., 2009).

The boundaries of the supply chain in this work are strictly defined according to the transformed resources of the transformation model. The upstream boundary is the raw material extraction stage coherently with the cradle-to-gate approach. The boundaries of the supply chains are thus including the material flow from the raw material stage down to the gate between the most downstream tier on the chain and the final user, as depicted in figure 2. The material flow moves downstream from the raw materials to the focal firm and the user and is associated to a monetary flow in the opposite direction as customers pay to receive the materials or semi-finished products from their suppliers.

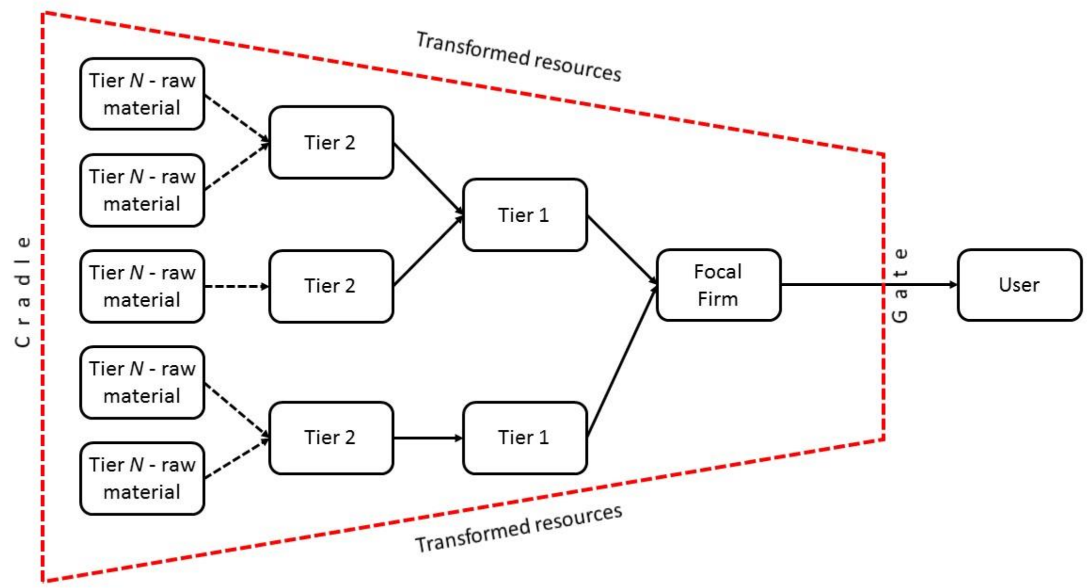

Figure 2: System boundaries

The supply chain of the transforming resources is not included within the system boundaries, as these products have already reached the usage phase and their impacts refer to a different supply chain.

3.2 Selection of environmental indicators

A balanced accounting of inputs withdrawn from the natural system and outputs environmental impacts needs to be represented in the environmental indicators selected, to reflect the limited capability of a thermodynamically closed system like planet Earth to supply resources and absorb pollution (Ayres and Kneese, 1969; Dimian et al., 2014; Kravanja and Čuček, 2013). A balanced assessment of inputs' and outputs' environmental impacts is also required in a future perspective to improve environmental sustainability performance. End-of-pipe solutions to reduce environmental outputs need to be integrated with solutions aiming to reduce the inputs to diminish the pressure on the natural capital (De Soete et al., 2013; McIntyre et al., 1998; Ritthof et al., 2002). As a result, the selected categories of environmental indicators in this work cover both environmental inputs to supply chain operations as well as environmental outputs arising from production activities of the supply chain. Environmental indicators are calculated at the company level on a yearly basis, coherently with the black box approach identified in section 3.1. Seven environmental categories identified as the most widely adopted environmental impacts tackled by performance measurement for GSCM are considered preferable to be included in the assessment (Tuni et al., 2018):

- Inputs: use of materials, water consumption, energy consumption, land occupation;
- Outputs: emissions to air, emissions to water, solid waste.

The identified impacts mirror the identified categories for inputs by Kravanja and Čuček (2013) and outputs by Brent and Visser (2005). The indicators are generally applicable to any industry, without being sector-specific and thus being relevant to determine the environmental performance of any supply chain. However, the method is flexible in its applicability and allows managers and stakeholders to introduce additional environmental indicators to address the needs of specific supply chains if required.

3.3 Inclusion of economic dimension

Comparing the environmental performance of systems through absolute environmental values is potentially misleading. Impacts “need to be expressed in relative units” to be effectively compared instead (Brent and Visser, 2005; Michelsen et al., 2006; Schaltegger et al., 2008; Wiedmann et al., 2009).

The economic dimension of sustainability is used in this work to relate the environmental performance to a single reference unit. Monetary unit was selected as the reference unit for the environmental dimension as it is applicable to any profit oriented company belonging to any industry. Alternative reference units commonly used as reference factors, such as the number of units produced, volume or weight of products are not universally applicable to any industry unlike the economic output.

The single economic indicator adopted in the model is the yearly turnover of a company, which is defined in this work as the sum of sales revenues generated by the sale of products, without considering any other source of income, as it typically appears at the top of the income statement of organisations. Turnover of the *i-th* company can be calculated through equation 1:

$$T_i = \sum_k Q_{ik} \, P_{ik} \tag{1}$$

Where k are the different products sold by company i. Each product is sold at a unitary price P_{ik} in a quantity equal to Q_{ik}.

Despite the turnover not providing a full picture of the economic performance of an organisation, this indicator suits the supply chain environment. The turnover is typically publicly available and does not pose questions about data confidentiality, especially in the case of non-collaborative supply chains, which represent the biggest share of operating supply chains (Parker and Kapuscinski, 2011; Schmidt and Schwegler, 2008). Costs or net present value, which are found as alternative economic indicators in the supply chain literature, require confidential data to be shared with other players in the chain, potentially affecting the competitive advantage of companies (Brandenburg, 2015; Caro et al., 2013).

The first output of the method is obtained at this stage. The single company eco-intensity EI_{ei} for each individual environmental indicator e outlined in section 3.2 can be calculated according to equation 2, by simply dividing the environmental performance at the company level EP_{ei} by the turnover of the company T_i. Multiple eco-intensity indicators are thus generated for each company depending on the environmental impacts considered in the analysis.

$$EI_{ei} = \frac{EP_{ei}}{T_i} \tag{2}$$

Equation 2 shows the organisation-wide eco-intensity values, which provide an indication on the performance of each company i for each specific environmental indicator e, without including any environmental impact arising in the supply chain.

3.4 Moving to the supply chain level: the recursive mechanism

The recursive mechanism enabling to move from the single company level to the supply chain level is illustrated in this section. Each organisation needs to add the environmental performance and economic output of its upstream suppliers to its internal eco-intensity to calculate the cumulative environmental impact up to that point in the supply chain. Each company thus requires to obtain relevant eco-intensity indicators upstream from its direct suppliers only, which themselves need to access their own direct suppliers to calculate their eco-intensity indicators, with the process being completed once the raw material extraction stage is reached. At the same time, each company is also passing its eco-intensity information to its customer, enabling the eco-intensity indicator to move downstream from one tier of the supply chain to the next one, until the system boundary is reached (Figure 3). The following subsections gradually build the mathematical formulation of the model developed.

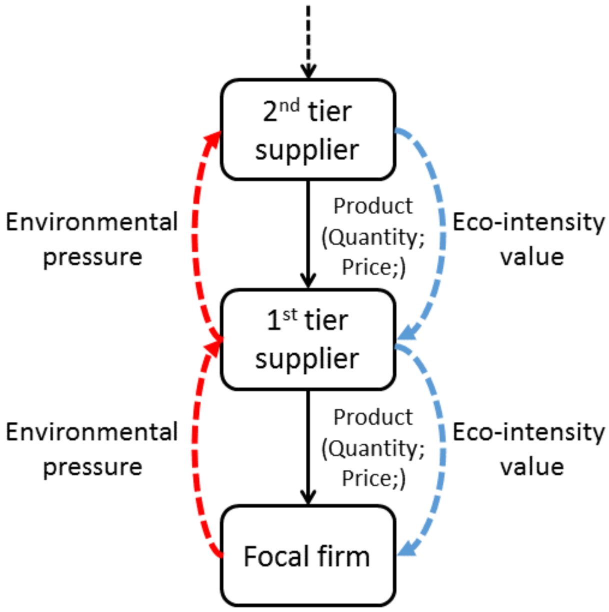

Figure 3: Recursive mechanism

3.4.1 Numerator: Environmental impact

Moving from the single company level to the supply chain level, the environmental performance needs to encompass not only the internal environmental performance of each organisation but also the environmental performance of the whole upstream supply chain up to that tier. Each company is however part of several supply chains based on its product mix, which defines the different supply chains the company belongs to.

The internal environmental performance at the company level needs to be first allocated to the various product supply chains the company is part of (Ahi and Searcy, 2014). The allocation is based, consistently with the eco-intensity concept, on the economic output generated by each product k, which is the company turnover generated by each product expressed in monetary units T_{ik}, as shown in equation 3, leading to EP_{ik}:

$$EP_{eik} = \frac{T_{ik}}{T_i} EP_{ei} \tag{3}$$

The environmental impact of the upstream supply chain needs to be then added to this value. The share of the environmental impact of suppliers that is passed on to the customers follows the same principle, being proportional to the share of turnover of supplier j generated by customer i thanks to deliveries of intermediate products n for output product k. This value can be easily calculated by the customer once the supplier communicates downstream its internal company wide eco-intensity. The eco-intensity of supplier j is multiplied by the quantity and the price of purchases of intermediate products n for output product k, leading to equation 4:

$$EP_{eik} = \frac{T_{ik}}{T_i} EP_{ei} + EI_{ej} \sum_{n} Q_{ijkn} P_{ijkn} \tag{4}$$

Where EI_{ej} is the eco-intensity of the supplier j for the environmental indicator e, Q_{ijkn} and P_{ijkn} are respectively the quantity and the price of intermediate products n shipped from supplier j to customer i for the output product k. This formulation however is valid only if supplier j is at the most upstream end of the supply chain. Otherwise, its contribution will need to include a contribution of its upstream supply tiers as well, similarly to the calculation of EP_{eik}in equation 4. Therefore, supplier j, alike its customer i, will have an eco-intensity value EI_{ejk} for each of the output products k encompassing the contribution of the upstream supply chains of all intermediate products n. This process is repeated recursively along the supply chain. Supplier j passes the product supply chain-specific eco-intensity EI_{ejk} to the next tier, therefore the equation to calculate the numerator of the eco-intensity of company i for output product k including the contribution of supplier j and its upstream supply chain environmental impact is shown in equation 5:

$$EP_{eik} = \frac{T_{ik}}{T_i} EP_{ei} + EI_{ejk} \sum_n Q_{ijkn} P_{ijkn} \tag{5}$$

If company i purchases precursor products from more than one supplier j, the environmental impact of each supplier needs to be added, leading to equation 6, which is the final formulation for the environmental numerator:

$$EP_{eik} = \frac{T_{ik}}{T_i} EP_{ei} + \sum_j (EI_{ejk} \sum_n Q_{ijkn} P_{ijkn}) \tag{6}$$

3.4.2 Economic denominator

The recursive mechanism applies to the economic denominator too. First, similarly to what happened for the environmental nominator, the economic output at the company level needs to be allocated to the product mix. Each product k generates a quota of the overall turnover T_{ik}, which is equal to the product of the quantity produced Q_{ik} times the price of a single unit P_{ik}.

Secondly, the economic benefit of the extended supply chain is not simply the sum of the turnover generated at each tier of the supply chain by the product output k and the precursor products n necessary to obtain k, but is reduced by the expenses made by each organisation to acquire the precursor products and transformed resources necessary to produce its output product.

In a dyadic chain where a single product is exchanged between supply chain partners and no supply chain exists upstream from supplier j (Figure 4), the economic output of the supply chain is the sum of the economic output from supplier j ($Q_{OUT-j} \times P_{OUT-j}$) and the economic output from customer i. The latter is given by the earnings of company i ($Q_{OUT-i} \times P_{OUT-i}$), minus the costs faced to acquire relevant supplies from supplier j ($Q_{IN-i} \times P_{IN-i}$). Moreover, this work assumes that the quantities Q_{OUT-j} and Q_{IN-i} are equal, as are P_{OUT-j} and P_{IN-i}. Thus, the expenses faced by customer i match the economic output obtained by supplier j, which can therefore be omitted. The overall economic output of the dyadic supply chain represented in figure 4 is thus equal to $T_{ik} = Q_{ik}P_{ik}$. If this mechanism is replicated along the supply chain, the ultimate economic indicator representing the economic benefit of the supply chain is eventually the turnover generated by the product at the most downstream player considered.

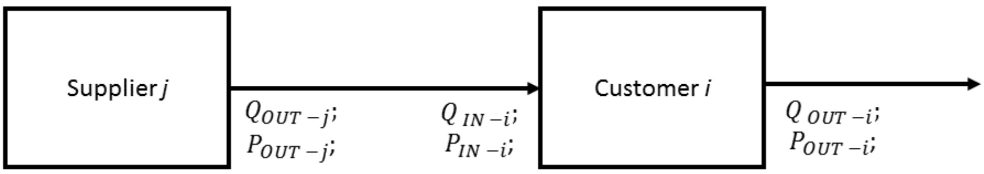

Figure 4: Economic dimension recursive mechanism

If the assumption about a single product delivered from supplier j to customer i is relaxed or multiple suppliers j are involved, the mechanism to calculate the overall economic output of the supply chain is not affected. The economic output of the supply chain still corresponds to the turnover T_{ik} generated by the most downstream company i in the supply chain thanks to product k.

3.4.3 Final formulation

Combining the recursive mechanisms illustrated in sections 3.4.1 and 3.4.2, the eco-intensity EI_{eik} of company i including its environmental impact from the supply chain of product k is thus calculated according to equation 7 for each environmental indicator e:

$$EI_{eik} = \frac{1}{T_{ik}} \left[\frac{T_{ik}}{T_i} EP_{ei} + \sum_j (EI_{ejk} \sum_n Q_{ijkn} P_{ijkn})\right] \tag{7}$$

Where T_{ik} is the turnover of company i generated by its output product k, T_i is the overall turnover of company i, EP_{ei} is the internal environmental performance of company i at the company level for the environmental indicator e, EI_{ejk} is the eco-intensity of the 1st tier supplier j for the output product k with respect to environmental indicator e including the environmental impact of its upstream product specific supply chain. Finally, Q_{ijkn} is the quantity of intermediate product n shipped from supplier j to customer i for the output product k, whereas P_{ijkn} is its price. This equation is the most practical to be adopted in an operating supply chain context, where the information about Q_{ijkn} and P_{ijkn} are available to the customer i as part of the economic transaction associated to the purchase of the precursor products or materials from supplier j. The customer i requires to obtain from each of its 1st tier suppliers j for product k only the value of EI_{ejk} to calculate the value of EI_{eik}, as all remaining data is available at the company level.

Two alternative versions of equation 7 are also presented in this work to simplify the illustration of the model in the numerical example. The summation of the n intermediate products can be substituted by the turnover of supplier j generated by deliveries to customer i for the output product k, labelled as T_{ijk}, leading to the formulation of equation 8a and 8b. In this case, the second summation of equation 7 disappears as all supplies from supplier j to customer i for the output product k are aggregated in a unique economic value.

$$EI_{eik} = \frac{1}{T_{ik}} \left(\frac{T_{ik}}{T_i} EP_{ei} + \sum_j EI_{ejk} T_{ijk} \right) \tag{8a}$$

$$EI_{eik} = \frac{1}{T_{ik}} \left(\frac{T_{ik}}{T_i} EP_{ei} + \sum_j EI_{ejk} \frac{T_{ijk}}{T_j} T_j \right) \tag{8b}$$

The simplified expression of the recursive mechanism equation can be presented either by adopting T_{ijk} or by analysing this value as a ratio of the overall turnover of supplier j as in equation 8b. The latter is adopted in the numerical example of this work.

Once the calculation of EI_{eik} is completed, the mechanism can be repeated moving downstream along the supply chain: output product k of company i becomes an intermediate product n for the next downstream stage of the supply chain and thus becomes part of the environmental backpack of the upstream supply chain for the supply chain member located right downstream along the chain. The recursive mechanism is repeated moving downstream along the supply chain until the most downstream player is reached and its internal environmental performance is included, according to the system boundaries defined in section 3.1.

Finally, the environmental backpack EBP_{eik} associated with the entire volume of every product k produced by company i can be easily calculated starting from either equation 7, 8a or 8b for each environmental indicator e. It is actually the numerator of the eco-intensity ratio, which can be expressed through any of the alternative formulation of equation 9:

$$EBP_{eik} = \frac{T_{ik}}{T_i} EP_{ei} + \sum_j (EI_{ejk} \sum_n Q_{ijkn} P_{ijkn}) \tag{9a}$$

$$EBP_{eik} = \frac{T_{ik}}{T_i} EP_{ei} + \sum_j EI_{ejk} T_{ijk} \tag{9b}$$

$$EBP_{eik} = \frac{T_{ik}}{T_i} EP_{ei} + \sum_j EI_{ejk} \frac{T_{ijk}}{T_j} T_j \tag{9c}$$

3.5 Method outputs

Once the recursive mechanism is applied until the most downstream tier of the supply chain and the environmental backpack associated to the product is calculated, all outputs of the method are available. The three outputs provide different information about the environmental performance at the single company level and at the supply chain level and can be adopted to support various managerial decisions:

- Single company eco-intensity indicators: these values indicate the eco-intensity of each organisation with respect to each specific environmental indicator e, giving indications about the internal environmental performance of each company belonging to the supply chain. The indicators can be used internally by the companies to set environmental targets, to perform longitudinal benchmarking and to support the supplier selection and evaluation processes.
- Supply chain eco-intensity indicators: these values reveal the eco-intensity of the extended supply chain of a product with respect to each specific environmental indicator e, giving

indications about the cradle-to-gate environmental performance of the supply chain. These offer a primary application to benchmark the environmental performance of products by considering their extended supply chain. Additional applications include use for external reporting of environmental performance of products as well as adoption as a reference for operational improvement towards a more sustainable supply chain behaviour. Finally, these outputs can be also used for identification of eco-intense hotspots along the supply chain, a necessary step to prioritise action (Lake et al., 2015).

- Environmental backpack of products: these values quantify the absolute environmental impact that is assigned to the produced volume of each product with respect to each specific environmental indicator, allowing to further allocate the environmental backpack on different basis for reporting purposes. For example, the CO_2 emissions per unit of product or the water consumed per kilogram of final product can be calculated.

4. Numerical example

The developed model is demonstrated through a numerical example with secondary data, in order to prove its mathematical validity and demonstrate its applicability to supply chains with different levels of complexity. A simplified version of the model is applied in this work for illustrative purposes with two environmental indicators included, covering both environmental input and environmental output categories: water consumption (m^3/year) and emissions to air (metric tonnes CO_2e/year) are the two indicators adopted. The model is applied over four different representative supply chains in an attempt to recreate the complexity of operating supply chains, which are often interconnected creating a supply network. In this example, the entire supply network is represented in figure 5.

Each box in the figure represents an organisation. The colour of the box identifies which focal firm each company is serving: blue boxes belong only to supply chains of focal firm 1 (FF1), whereas yellow boxes represent companies part of the supply chains of focal firm 2 (FF2). Finally, the yellow-blue striped boxes are those companies that are part of both FF1 and FF2 supply chains. However, each focal firm produces multiple products: FF1 is producing product 1.1 and product 1.2, whereas FF2 produces product 2.1 and product 2.2. Each product supply chain is thus associated to a specific coloured geometrical shape. The geometrical shape next to each box helps to understand to which specific product supply chain each organisation is contributing to. As an example, S1 and S2 are both serving only focal firm 1, however S1 is contributing only to the supply chain of product 1.1 (green trapezoid), whereas S2 is supplying FF1 for both supply chain of product 1.1 (green trapezoid) and 1.2 (purple rhombus). Finally, the arrows identify the links between different organisations. The value next to each arrow is the ratio of turnover of each supplier that is generated by that specific customer. As an example, 90% of the turnover of S2 is obtained thanks to deliveries to FF1: the value in Figure 5 is the overall turnover, which is broken down by product supply chains in Figures 6-9. S2 generates 50% of its turnover through supplies to FF1 for Product 1.1 (Figure 6) and 40% of its turnover thanks to deliveries to FF1 for Product 1.2 (Figure 7), summing up to 90%.

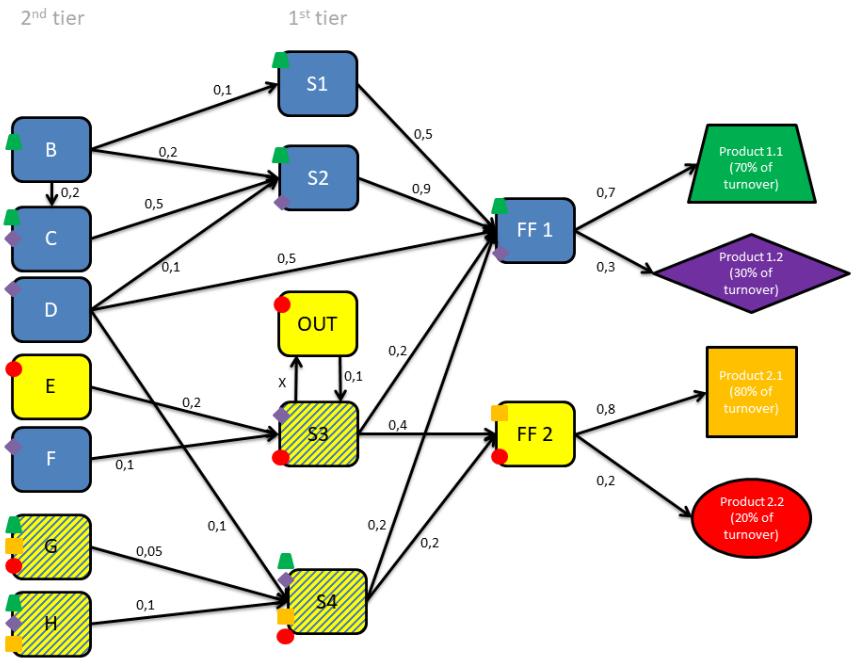

Figure 5: The entire supply network

The network illustrated in Figure 5 can be broken down in its building blocks, which are the four product supply chains, each of whom presents unique features. Supply chain of product 1.1, which is depicted in figure 6, is the only one including a 3rd tier supplier. Company B is acting both as a 2nd tier supplier, supplying S1 and S2, and as a 3rd tier supplier by delivering to company C, which is a 2nd tier supplier itself. The second supply chain, presented in figure 7 and referring to product 1.2, also includes a company belonging to two different tiers, as D is a direct supplier of Focal Firm 1 (FF1), thus being a 1st tier supplier, but acts also as a 2nd tier supplier. Company D serves both S2 and S4, that are themselves suppliers of FF1, thus making D a 2nd tier supplier. D shows an additional interesting feature, being at the origin of a divergent-convergent network: the material path exiting from D is divergent to S2 and S4, but later converges to FF1 again.

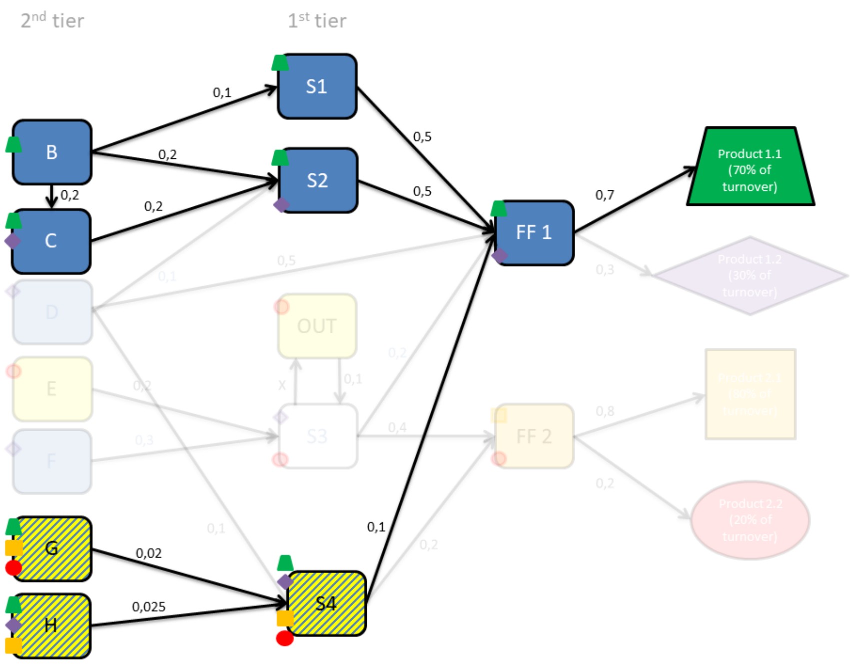

Figure 6: Supply chain of product 1.1

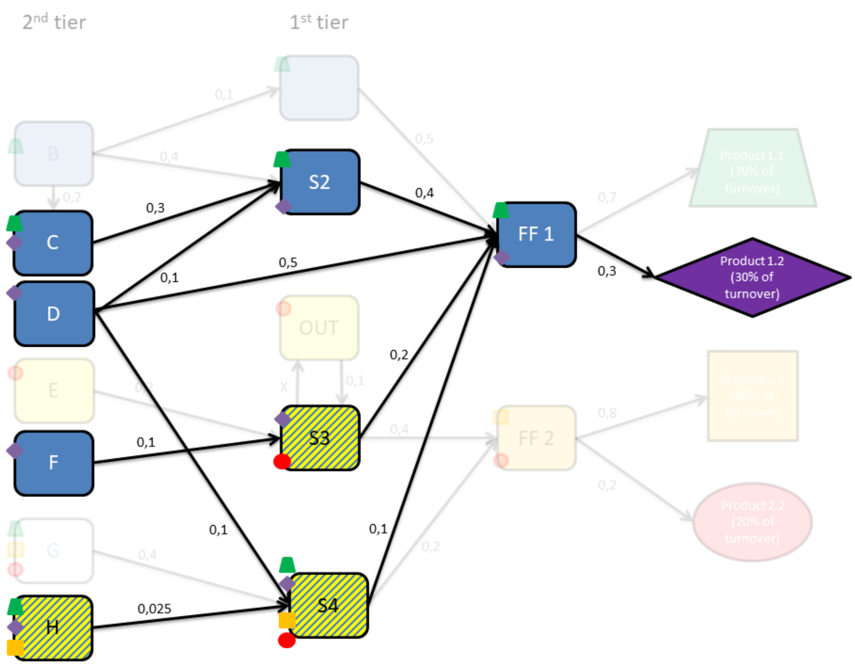

Figure 7: Supply chain of product 1.2

Supply chain of product 2.1, represented in figure 8, does not show any peculiar characteristic, featuring a simple linear supply chain. Finally, supply chain of product 2.2, pictured in figure 9, includes an outsourcing loop, as company S3 assigns certain production processes to organisation OUT. This specific case is solved by considering OUT as a normal supplier that is getting paid by S3 for the products delivered to the customer. Although the material path might include a physical shipping from S3 to OUT, there is no monetary flow connected to this link. The monetary flow is associated to the reverse link: S3 is the outsourcer and hires a third party (OUT) for certain services, therefore the monetary transaction flows from S3 to OUT. The lack of an economic transaction associated to the material path going from S3 to OUT justifies the choice of treating OUT as a supplier. Additionally, this mechanism avoids to double count the environmental impact of company S3.

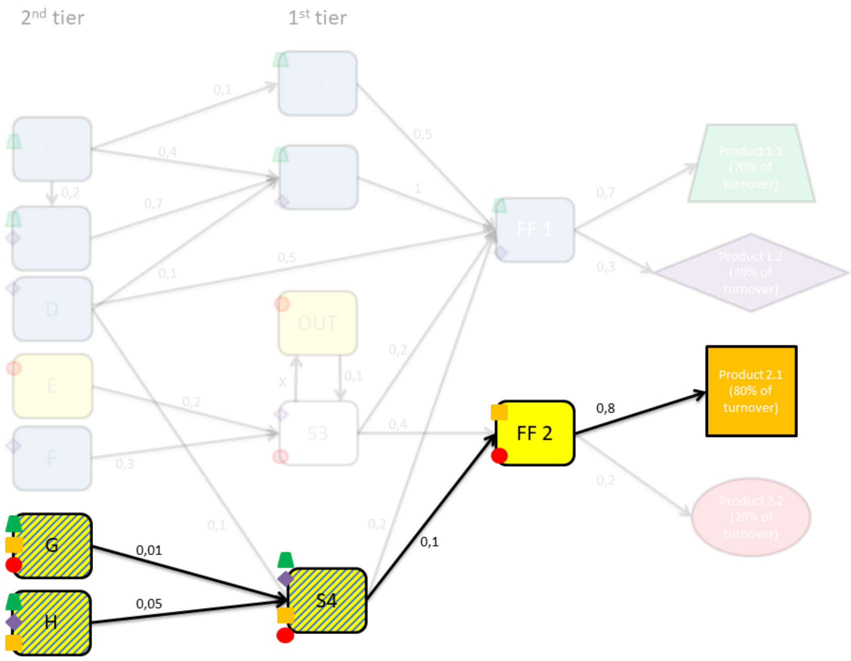

Figure 8: Supply chain of product 2.1

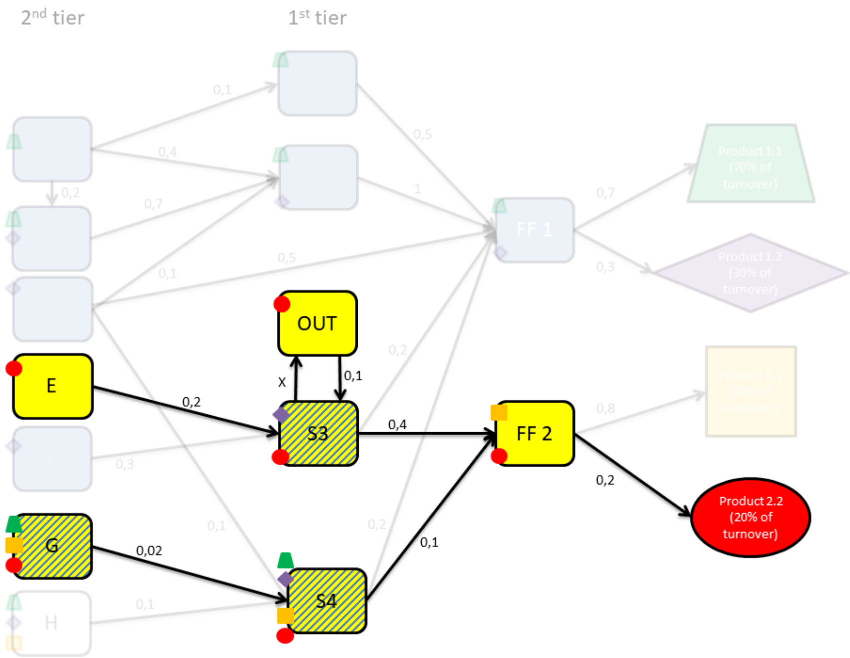

Figure 9: Supply chain of product 2.2

The model is demonstrated in a numerical example, adopting secondary data, as illustrated in Table 1. All data represent the yearly performance of the entire organisations, which belong to different sectors. Turnover ($M/year) and CO_2 emissions (metric tonnes CO2e/year) values are obtained from publicly available databases of Fortune Global 500 companies: the data of the turnover and CO_2 emissions correspond to the same real organisation, despite in different calendar years (CDP, 2013; Fortune, 2016). On the other hand, water consumption data (m^3/year) were based on a dedicated work by Joa et al. (2014) and randomly allocated to the various organisations building the representative network, thus not corresponding to the same real company. Finally, all supply chain links as well as the economic values associated to them are fictitious as real organisations, whose turnover and emissions are included in the model, may belong to different industries and business relations between them may not exist. The above assumptions do not affect the purpose of illustrating the model with a numerical example.

Tier	Company	Turnover [$M/year]	EP 1 – CO_2 emissions [metric t CO_2 e/year]	EP 2 – Water consumption [m^3/year]
2nd tier	B*	22126	53587	159000
	C	23208	1263773	365000
	D*	24861	894206	262800
	E	38143	17918	310000
	F	44294	2551626	1168000
	G	122948	83433	3985
	H	20969	213089	1482
	OUT	23065	144298	5467
1st tier	S1	29636	1075761	74795
	S2	23633	4211808	93045
	S3	36604	322000	177250
	S4	33196	40996	524000
Focal firms	FF1	482130	851495	578267
	FF2	236592	2727000	1478000

* Companies B and D belong to multiple supply chain tiers as explained in section 4, however are clustered in Table 1 according to their main tier position in the supply network.

Table 1: key figures about the companies

5. Results

The outputs of the numerical example are presented in this section, which is divided in three sub-sections. Each sub-sections is dedicated to a specific output of the model, coherently with the methodological steps identified in Figure 1.

5.1 Single company eco-intensities

An eco-intensity indicator is calculated at the company level for each environmental indicator EP_{ei}, according to equation 2, by dividing the yearly environmental performance indicator of the organisation by its yearly turnover. These indicators do not consider any environmental impact from the supply chain. In this numerical example, for illustration purposes a subset of the indicators presented in section 3.2 is adopted: the CO_2 emissions eco-intensity and the water consumption eco-intensity of all companies part of the supply network are calculated. The figures in Table 2 illustrate the internal eco-intensity performance of each organisation.

Results show a high variety in values for both eco-intensity indicators, spanning from a minimum of 0.470 tonnes CO_2e per $M for company E up to a maximum of 178.217 for S2, which is 37819% higher than the best performing organisations E. Company G is the best performing organisation in terms of water consumption eco-intensity with 0.032 m^3 per $M, whereas F is at the opposite end of the spectrum with a value of 26.369 m^3/$M. A comparison between the CO_2 emissions eco-intensity values and the water consumption eco-intensity figures is not meaningful as the ratios adopt different units of measurement at the numerator.

Company	**EI 1 – CO_2 emissions eco-intensity [metric t CO_2 e/$M]**	**EI 2 – Water consumption eco-intensity [m^3/$M]**
B	2.422	7.186
C	54.454	15.727
D	35.968	10.571
E	0.470	8.127
F	57.607	26.369
G	0.679	0.032
H	10.162	0.071
OUT	6.256	0.237
S1	36.299	2.524

S2	178.217	3.937
S3	8.797	4.842
S4	1.235	15.785
FF1	1.766	1.199
FF2	11.526	6.247

Table 2: single company eco-intensities

The results illustrated in Table 2 help to understand the validity of eco-intensity concept, demonstrating the importance of having a monetary unit of reference to effectively compare figures of companies' environmental performances. As an example, organisations S4 and FF1 have relatively similar absolute water consumption, as FF1 uses 578267 m^3 of water per year compared to 524000 m^3 of water per year of S4, showing just a 10% higher water consumption volume. However, the economic output generated by FF1 is over 14 times bigger than the economic output obtained by S4. This makes the water consumption eco-intensity comparison favourable to FF1, whose EI2 equals to 1.199 m^3/\$M compared to 15.785 m^3/\$M of company S4. Absolute indicators are effective in measuring the overall environmental impact of an organisation but are unsuitable for any comparative study, thus the benefit of using a relative indicator such as eco-intensities indicators.

5.2 Supply chain eco-intensities

An eco-intensity indicator is calculated at the supply chain level for each environmental indicator EP_{ei}, according to equation 8b, by dividing the sum of the environmental impact of the extended supply chain of each product k and the allocated contribution of the most downstream company i in the supply chain, by the turnover T_{ik} of company i generated by product k. Table 3 shows the eco-intensity performance of four product supply chains and their ranking according to CO_2 emissions eco-intensity and water consumption eco-intensity.

Supply chain of product 1.1 performs best according to both eco-intensity indicators, recording 10.461 t CO_2 e/\$M and 2.056 m^3/\$M, as illustrated in Table 3. The results show contrasting values among the other three supply chains. Considering CO_2 emissions eco-intensity, product 2.1 ranks second with 11.609 metric t CO_2 e/\$M, followed by 14.751 metric t CO_2 e/\$M of product 2.2. Finally, product 1.2 is the most CO_2 emissions eco-intense product considering the entire supply chain, accounting for 22.637 t CO_2 e/$M, which makes this product supply chain 116% more eco-intense than the best performing product 1.1.

On the other hand, the most CO_2 emissions eco-intense product 1.2 ranks second best in terms of water consumption with a value of 4.901 m^3/$M. Product 2.1 follows in the ranking with 6.524 m^3 of water consumed per $M. Finally, product 2.2 is the most water-intense product supply chain requiring 395% more water per monetary unit compared to the best performing product 1.1 when the extended supply chain is taken into account, with an overall value of 10.176 m^3/$M.

Supply chain	**EI 1 – CO_2 emissions eco-intensity [metric t CO_2 e/$M]**	**Ranking**	**EI 2 – Water consumption eco-intensity [m^3/$M]**	**Ranking**
Product 1.1	10.461	1	2.056	1
Product 1.2	22.637	4	4.901	2
Product 2.1	11.609	2	6.524	3
Product 2.2	14.751	3	10.176	4

Table 3: product supply chains eco-intensities

The results clearly show the most environmentally sustainable product being product 1.1, however do not give an overall final indication about other products due to conflicting results between the CO_2 emissions eco-intensity and the water consumption eco-intensity. An aggregation of indicators in a single eco-intensity index about performance of a product supply chain would help to come to a unique ranking of product supply chains based on their overall eco-intensity, resolving the issue of contrasting results between different indicators. However, eco-intensity indicators provide information about different environmental impacts to the decision makers, who can use it for focused interventions and operational improvement. As an example, focal firm 1, producing both products 1.1 and 1.2, can have a better understanding on which product is responsible for a high environmental impact per unit of value: they obtain clear information to tackle the supply chain members of the product 1.2 to lower the CO_2 emissions and the water consumption.

The CO_2 emissions eco-intensity scores of both products by focal firm 1 are heavily affected by the supply chain contribution due to the inclusion in the extended supply chain of some of the most CO_2 emissions eco-intense organisations (C, D, F and S2) that carry a much higher environmental backpack compared to the focal company. Within this scenario, product supply chain 1.2 is further penalised in its eco-intensity score by a low economic output at the supply chain level, leading to the bottom position in the ranking. Product supply chain 1.2 exemplifies that hotspots might be located among 1st tier suppliers, like S2, or further upstream, like F. In both cases however, the focal firm will in real life have visibility of its 1st tier suppliers only, thus not being aware of the poor performance of company F directly. The focal firm has only the ability to engage with its direct suppliers that themselves have the visibility of the 2nd tier suppliers. In the case of S2, its internal CO_2 emissions eco-intensity performance is worse than the performance of its suppliers, thus improvement efforts are to be put in place within its internal boundaries. On the other hand, S3, that is the 1st tier supplier for the branch of supply chain including company F, can realise that the hotspot is located further upstream thus passing the environmental improvement effort requirements from the focal firm onto 2nd tier supplier F. Therefore, it can be concluded that the combined comparison of the internal eco-intensity performance and the eco-intensity information provided by suppliers allows the identification of hotspots along the supply chain.

5.3 Environmental backpack of products

The environmental backpack of products can be traced back from the eco-intensity of the supply chain, as illustrated in equation 9. The environmental backpacks associated to the entire yearly produced volume of each product k, both in terms of CO_2 emissions and water consumption, are shown in Table 4. These values represent the environmental backpack that is allocated to each product based on the economic output generated, considering the extended supply chain and represent the absolute values associated to each product. Product 1.1 has the overall highest CO_2 emissions, as 70% of the environmental impact of FF1 is allocated to it on top of the environmental backpack of the upstream supply chain, however it was proved in section 5.2 that it is the best performing product in terms of CO_2 emissions eco-intensity. This demonstrates the need to use relative indicators for comparative studies.

Product	**EBP_{TOT-1} - CO_2 emissions [metric t CO_2 e/year]**	**EBP_{TOT-2} - Water consumption [m^3/year]**
Product 1.1	3530475	693724
Product 1.2	3274237	708845
Product 2.1	2197188	1234914
Product 2.2	697982	481526

Table 4: environmental backpack of products

The data illustrated in Table 4 can be thus considered an intermediate step to provide alternative environmental reporting schemes that adopt different reference units to obtain alternative relative environmental indicators to present to relevant stakeholders. Despite the advantage of eco-intensity for benchmarking purposes, alternative indicators could be more appropriate for specific reporting or external communication. As an example, the CO_2 emissions or water consumption per unit of product can be easily obtained by dividing the figures presented in Table 4 by the number of units of the final product that are produced. In this case, only the final allocation of the environmental backpack to the single unit of a product needs to be 'translated' to a different relative unit, whereas upstream methodological steps would still be based on the eco-intensity principle and the relative recursive mechanism presented.

6. Discussion

The innovative eco-intensity based method presented offers a number of advantageous features. Firstly, it is able to assess the eco-intensity of multi-tier supply chains by adopting a decentralised approach thanks to a recursive mechanism to pass the eco-intensity values from one tier of the supply chain to the next. The method has the advantage of respecting the multiple-organisation nature of supply chains considering organisations as independent entities with potential conflict of interest arising between them. The decentralised approach adopted in this work differentiates it from approaches developed in the literature so far, which largely assume the existence of a centralised superior coordination of the supply chain or a collaborative relationship between different tiers of the supply chain. The proposed method not only facilitates application in non-collaborative contexts thanks to a limited exchange of information required between different tiers of the supply chain, but it also facilitates the evaluation of the supply chain in contexts where organisations have a limited visibility and traceability of their extended supply chain.

The limited information focal companies have about their own supply chain has implications also on the level of control and influence these organisations are able to achieve throughout their supply chain. It is difficult for a company to manage directly the extended supply chain, therefore suppliers play a pivotal role to reach further upstream supply chain tiers (Wilhelm et al., 2016). This approach has been described as indirect approach in multi-tier supply chains by Tachizawa and Wong (2014). Sustainability issues are no exception to this. In this work, the capability of the supplier to involve the sub-supplier in the calculation of the supply chain environmental impact is a key aspect to the successful application of the method. The ability of a company to "measure and manage sustainability performance of a supply chain depends largely on the level of influence it has on the other partners in the chain" (Beske-Janssen et al., 2015). A developed relationship, such as a partnership, between a supplier and a customer might facilitate the participation of the supplier to the assessment and the inclusion of its upstream suppliers. On the other hand, if the relationship between the supplier and the customer is transactional, the success of pressure from each supply chain tier to its upstream supplier will depend on the relative supplier and buyer power as defined by Porter (1979). Companies are able to significantly influence their direct suppliers when they have a high relative power balance to their suppliers due to relative utility, the share of the suppliers' turnover they generate, the relative scarcity of resources that are exchanged between the two parties and the easiness of substitutability of the suppliers (Cox et al., 2007; Michelsen and Fet, 2010; Scott and Westbrook, 1991). The recursive mechanism does not adopt the traditional approach of the focal firm managing the extended supply chain, but rather the indirect approach, as the focal company is expected to manage the relationship with the direct suppliers only, relying on them to access to sub-suppliers data and to manage the dependent relationship.

Moving to the methodological aspects, the suggested environmental indicators are generic on purpose in order to be widely applicable in different sectors and to enhance the benchmarking potential of the method. The set of indicators needs to be manageable in size for practical applications, but at the same time broad in scope. The indicators indicatively should tackle both environmental inputs withdrawn from the natural capitals as well environmental outputs released to the environment, in order to achieve a holistic evaluation of the supply chain environmental performance. A sub-set of the indicators was presented in the numerical example for explanatory purposes. Moreover, additional environmental indicators can be included in eco-intensity ratios to represent industry-specific environmental impacts or particular priorities of the supply chains.

The wide applicability of the selected indicators to the majority of sectors offers the possibility to compare the eco-intensity of products taking into account their extended supply chain. The absence of a specific functional unit and of subjective assumptions in the definition of the system boundaries favours the application for external comparability of the environmental performance of the supply chain. This is particularly useful in instances where the definition of the functional unit is ambiguous. As an example, the interpretation of the environmental impact of white bread and wholemeal bread supply chains through relative indicators could be based on the environmental impact per weight of bread or per nutrient intake, with results varying as much as 300% based on the selected functional unit (USDA, 2016). The eco-intensity concept adopted in this work uses a unique reference unit, which is the economic output generated, and thus allows comparing even products not linked to the same benefit for the user, supporting more informed and sustainable decisions by customers.

Finally, the method is designed to use primary data that are already readily available in most organisations to improve applicability in real life, differentiating from methods adopting consistently secondary data from database sources such as LCA-based approaches. The method blends collection of environmental data at the company level with an assessment of the supply chain at the product level. Data collection at the company level significantly lowers the effort required by companies and is suitable for SMEs as well, which are typically lagging behind in the path towards sustainability (Yusuf et al., 2013). Data already available at companies such as documents from the purchasing department for the use of materials or utility bills for water consumption, energy consumption and waste can be used, facilitating the data collection process. Moreover, data collection at the company level aims to highlight unsustainable behaviours of any player in the chain should this happen. This aspect, along with the absence of the functional unit definition, significantly differentiates this method from the LCA methodology. Environmental impacts at the company level are allocated to products based on the economic output generated by each product, guaranteeing that all internal environmental impacts are taken into account and transparently assigned to the product mix. This allocation method avoids greenwashing, which may occur when a selected product is analysed through LCA: production processes for that specific product might prove to be environmentally friendly, but taking place in companies that are globally not environmentally sustainable. This would ultimately expose to reputational risk the focal companies against their customer, as the organisations are held responsible for their selection of the upstream suppliers as a whole rather than at a product level (Gimenez and Tachizawa, 2012).

6.1 Theoretical implications

The method introduced in this work expands the body of the literature in the emerging area of multi-tier supply chain management for sustainability. The research in this field has either focused on governance mechanisms to manage sustainability for multi-tier sustainable supply chains, such as in Mena et al., (2013), Tachizawa and Wong (2014) and Wilhelm et al. (2016) or adopted a strictly technical perspective, following the stream of research on LCA, but "without consideration of the dynamics arising from the multitiered structure and the interactions along the supply chain"(Adhitya et al., 2011). This work merges these streams of research and sets the grounds in the specific area of multi-tier GSCM performance assessment. This is realised by moving away from the more theoretical approaches of governance mechanism-focused works towards developing a practically oriented method, while at the same time respecting the multiple-organisation nature of the supply chain.

The developed method expands the number of tiers typically assessed in the GSCM literature beyond the traditional tier-1 level and obtains an effective cradle-to-gate assessment of the eco-intensity of products. The method also expands the number of environmental aspects considered in the GSCM literature for multi-tier supply chains by including multiple environmental impacts. This choice tries to balance the current tendency in the literature to decrease the spectrum of the measures adopted when the level of analysis increases beyond the dyadic supply chain (Miemczyk et al., 2012) as the focus on a single environmental performance limits an accurate evaluation of the supply chain and might provide an incomplete assessment of the overall environmental performance. The method is thus innovative as it achieves a holistic environmental performance assessment of multi-tier supply chain, by simultaneously addressing the extended supply chain in a cradle-to-gate approach while covering multiple environmental aspects, leading the way for an effective supply chain-wide environmental assessment.

6.2 Implications for practitioners

The outputs presented in this work offer a wide set of applications for organisations. The single company eco-intensity indicators measure the yearly performance of a company by considering different environmental impacts and offer an overall snapshot of the organisation-wide environmental performance, providing a balanced consideration of environmental inputs and outputs. These indicators find potential applications for external reporting in an organisational context, but can be most noticeably be adopted for longitudinal benchmarking of the environmental performance at the company level. As the data is collected on a yearly basis, single company eco-intensity indicators can be used to draw upon the historical environmental profile of an organisation. However, they have also future oriented applications, as managers can define environmental targets to be reached adopting the eco-intensity indicators as relevant KPIs.

The single company eco-intensity indicators could also find a supply chain-oriented application as part of the green supplier selection and evaluation process. The figures provide quantitative support to the procurement decisions and can be integrated in vendor ratings or other tools requiring quantitative values. The quantitative values limit the subjectivity and uncertainty introduced by supplier selection and evaluation methods based on judgements of experts or decision makers (Shokravi and Kurnia, 2014; Tsoulfas and Pappis, 2008). However, the eco-intensity values would need to be integrated with traditional green supplier selection and evaluation methods, as they do not inform decision makers about environmental practices in place at suppliers' facilities and other key requirements such as environmental management systems or certifications.

The eco-intensity indicators at the supply chain level offer several additional applications to practitioners and stakeholders. First, indicators help practitioners to understand the environmental impact of the supply chain, given the limited knowledge of managers of what happens beyond 1st tier suppliers. When the recursive mechanism is applied until the upstream end of the supply chain, it reveals precious information about each branch of the supply chain. Since pressure from green customers moves upstream along the supply chain, focal firms might press their 1st tier suppliers that are found to be environmentally unsustainable to improve the environmental performance of their supply chain branch. 1st tier suppliers however have access to additional information compared to focal firms, as they are knowledgeable about the eco-intensity performance of 2nd tier suppliers as well. Thus, 1st tier suppliers could evaluate whether the origin of the poor environmental performance of the supply chain branch is due to their internal environmental performance or their upstream supply chain. On these grounds, the method can assist them to decide whether to implement environmental actions to improve their performance or extend the pressure from green customers to their upstream business partners. The recursive mechanism allows in this way to recognise the environmental hotspots along the supply chain and to prioritise actions to improve the environmental performance.

Decision makers in the focal firm are likely to be the most interested to track the environmental performance of the supply chain as customers hold these organisation responsible for the behaviour of the extended supply chain. Focal firm managers may want to pay attention to a specific eco-intensity indicator or a subset of indicators to improve the environmental performance of the supply chain, a process that is facilitated by the level of granularity offered by the proposed method. Every industry has different features and challenges, thus posing different pressures on the natural capital: chemical industry is typically considered a water-intensive sector, therefore water consumption eco-intensity might be the most relevant indicator to tackle, whereas land occupation might be more critical in the food supply chain.

Moreover, the eco-intensity indicators show a potential application also in green marketing. The eco-intensity outputs are easy to understand by non-experts and can be adopted for external reporting of the environmental performance of products, potentially being incorporated into labelling schemes of products combined with a colour scale. The indicators are likely to be an effective way to influence the purchasing decisions in the lucrative business segment of sustainable consumers (Ormond and Goodman, 2015). The simplicity of the indicators, combined with their applicability to virtually any type of product, offer additional benefits to benchmark different products, removing the constraints to comparative studies typical of methods based on functional unit definition, as highlighted in section 2.1.

6.3 Limitations and future research directions

While the method presented in this work offers several advantages and applications, our research is not without limitations.

Some of the methodological limitations are embodied in the concept of eco-intensity. An improvement in the eco-intensity performance may be achieved by reducing the environmental impacts while maintaining the same economic output, by improving the economic output with the same environmental impact or by reducing the environmental impact and increasing the economic output simultaneously. However, improvements in the economic output might be the effect of an actual better economic performance or the effect of market forces. The use of the turnover as the economic indicator is prone to be influenced by the volatility of prices and might affect the final results (Bernardi et al., 2012).

Secondly, the allocation of environmental impacts based on the economic output risks to overestimate or underestimate the actual environmental impact associated with each product supply chain. Although the overall evaluation of the product mix of each organisation part of the supply chain is fair, products contributing to a higher share of the turnover are allocated a higher environmental backpack despite not necessarily carrying a proportional polluting contribution in terms of production processes. This is a challenge faced commonly by allocation rules for products made sharing the same processes or facilities.

Additionally, the method does not currently offer synthesised information about the overall environmental performance of the supply chain. A unique index aggregating the environmental impacts caused by the supply chain would be an additional layer of information for decision makers to compare different product supply chains, particularly in the case of eco-intensity indicators providing conflicting results. However, the introduction of a composite metric would also affect the objectivity of the method as “composite metrics are too subjective, as their results undesirably are dependent on the specific weighting system employed alongside the aggregation method used for combining the various factors involved” (Ahi and Searcy, 2014).

Finally, the black box approach adopted in this work determines which organisations are recognised as hotspots for each environmental indicator providing guidance for operational improvement but does not offer indication regarding the performance within the black box. The method aims to serve as a starting point towards operational improvement. An interesting future research direction would be to identify how organisations deploy the insights provided by the method in actual improvement plans within their organisational boundaries.

A number of challenges to the practical application of the method also exist. The numerical example of the model with secondary data demonstrated a promising applicability; however, the utilisation of the model in an operating supply chain context has still to be performed. A case study including the full set of indicators is currently underway in order to validate the model with primary data. Despite the method does not require a collaborative supply chain to be applied, a minimal information exchange between the supply chain players is still required. Certain supply chain players might be unwilling to cooperate to the assessment, while other organisations might be unsuccessful in involving their own suppliers in the application of the recursive mechanism due to unfavourable balance of power along the supply chain.

As a result, environmental data might not be available or collected for all supply chain tiers leading to an incomplete evaluation of the eco-intensity of the extended supply chain. This might be particularly the case of global supply chains, where a high number of intermediaries are involved and upstream tiers located in remote geographical areas might be difficult to be accessed (Wilhelm et al., 2016). Moreover, since each organisation is responsible for its internal self-assessment, a mechanism to verify the environmental data provided by suppliers needs to be identified in the future, potentially through an audit scheme or including a third party platform external to supply chain members.

7. Conclusion

This work aimed to quantitatively assess the environmental performance of extended supply chains by using an innovative eco-intensity based method that relates the environmental performance of the supply chain to its economic output, allowing effective multi-tier environmental sustainability assessment of the supply chain and expanding the number of tiers assessed compared to the existing GSCM literature.

The method assesses the environmental sustainability performance of extended supply chains, while respecting the non-collaborative and multiple-organisation nature of the majority of supply chains. Supply chain decisions in operating contexts are typically decentralised (Caro et al., 2013); therefore, assuming a centralised entity taking control of the full chain is not usually applicable in practice. Moreover, the increasing length and complexity of global supply chains have reduced the control of logistical issues by focal companies, decreasing the traceability of the upstream network (Hutchins and Sutherland, 2008). Subsequently, supply chain management for sustainability and environmental performance measurement systems at the supply chain level need to be suitable for non-collaborative and multi-tier supply chains. The developed model mirrors the operating conditions of existing supply chains adopting a decentralised approach, which is implemented thanks to the recursive mechanism to pass the eco-intensity values from one tier of the supply chain to the next. The limited information exchange required by the method makes it applicable to non-collaborative supply chains as well, as there is no need for a developed relationship between supply chain members. Moreover, the method enables assessment of the eco-intensity performance of extended supply chains, but has the advantage of requiring every supply chain player to access only to its direct suppliers and customers, simplifying the assessment of the supply chain. This facilitates the implementation of the method in contexts where organisations have limited visibility of their supply chain.

The model is applied to a numerical example with secondary data. Four representative product supply chains are compared according to their extended supply chain environmental performance. A subset of the proposed indicators is adopted in the numerical example, including the CO_2 emissions and water consumption eco-intensities.

Results provide a wide range of practical applications based on the different outputs of the method, as highlighted by the numerical example. Eco-intensity indicators at the company level may be internally used to determine environmental targets and to guide operational improvement. Moreover, they are potentially applicable to the supplier selection and evaluation process: organisations can compare the eco-intensities performance of suppliers at the company level to assess their 1st tier suppliers internal performance and integrate these values in their supplier selection and evaluation methods currently into practice to include an environmental perspective. Eco-intensity indicators at the supply chain level are useful to identify the environmental hotspots in the supply chain thanks to the recursive mechanism adopted and can be further used to benchmark the environmental performance of products considering their extended supply chain. The definition of clear system boundaries matching the material flow of transformed resources combined with the allocation of environmental impact based on the economic dimension of sustainability and the absence of a specific functional unit avoid assumptions that could limit the external comparability of environmental performance. The comparison of virtually any product based on the eco-intensity performance is possible, supporting more informed and sustainable decisions by customers. Eco-intensity indicators at the supply chain level are thus potentially applicable also for labelling schemes or for external reporting to communicate the environmental profile of the product supply chains to relevant stakeholders.

The method presented in this work expands the body of the literature in the growing field of multi-tier supply chain management for sustainability and more specifically in the area of multi-tier GSCM performance assessment. Its contribution lies in the extension of environmental performance assessment beyond 1st tier suppliers to effectively assess multi-tier and extended supply chains, while respecting the multiple-organisation nature and non-collaborative characteristics of the majority of real life supply chains. Moreover, the adopted decentralised approach does not require visibility of the extended supply chain by any single member, as every organisation requires access only to its direct suppliers and customers, thus enhancing the applicability of the method. Finally, the method is designed to use primarily data that are already available within organisations and has a low level of calculation complexity, therefore simplifying the process and allowing SMEs with limited resources and skills available to be part of the assessment.

Nomenclature

e	Environmental indicator
EBP	Environmental backpack
EBP_{eik}	Environmental backpack with respect to environmental indicator e of organisation i associated to its output product k
EI	Eco-intensity
EI_{ei}	Eco-intensity with respect to environmental indicator e of organisation i
EI_{eik}	Eco-intensity with respect to environmental indicator e of organisation i associated to its output product k
EI_{ej}	Eco-intensity with respect to environmental indicator e of supplier j
EI_{ejk}	Eco-intensity with respect to environmental indicator e of supplier j associated to its output product k
EP	Environmental performance
EP_{ei}	Environmental performance with respect to environmental indicator e of organisation i
EP_{eik}	Environmental performance with respect to environmental indicator e of organisation i associated to its output product k
i	Customer of each dyad for each iteration of the recursive mechanism
j	Supplier of each dyad for each iteration of the recursive mechanism

k	Products offered from an organisation i to its customer for each iteration of the recursive mechanism
n	Intermediate products purchased by organisation i from supplier j for its output product k for each iteration of the recursive mechanism
Q	Quantity
Q_{ik}	Quantity of product k sold by organisation i
Q_{ijkn}	Quantity of product n purchased by organisation i from supplier j for its output product k
P	Price
P_{ik}	Price of product k sold by organisation i
P_{ijkn}	Price of product n purchased by organisation i from supplier j for its output product k
T	Turnover
T_i	Turnover of organisation i
T_{ik}	Turnover of organisation i generated by product k
T_{ijk}	Turnover of supplier j generated by organisation i through the purchase of product k
T_j	Turnover of supplier j

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