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A Framework for Estimating Regional Footprint of Companies towards Absolute Sustainability

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Abstract

Global warming and water scarcity are two endangered environmental indicators of environmental boundaries. The industrial sector is an intensive greenhouse gas (GHG) emitter and water consumer, and has a strong potential for improvement. The combination of the Planetary Boundary concept and Life Cycle Assessment offers an analytical basis for a target-driven life cycle engineering in a move towards absolute sustainability on the company level. The aim of this paper is to provide a framework for quantifying the current environmental footprints of companies throughout their value-chains with respect to the regional distribution of emissions between involved countries and companies. The framework helps companies to estimate their regional footprint, and accordingly set the goal for reducing their environmental footprints to stay within their regionally determined share of the space within the planetary boundaries. In addition, it helps companies to understand the water stress of their products throughout their value chains.

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Keywords: Life Cycle Assessment, Planetary Boundaries, Consumption-based Accounting, Production-based Accounting, Absolute sustainability.

1. Introduction

Due to industrialization and growth in human productivity and corresponding increase in consumption of natural resources, mankind is confronted with critical issues including resource depletion and environmental impacts [1]. These concerns have led to the advent of the concept; "sustainable development" that is defined as “meeting the needs of the present generation without compromising the ability of future generations to meet their own needs” [2]. Despite the importance of the social and economic aspects of human activities, their environmental aspects require careful study as well. For the purpose of reducing environmental impacts, both top-down and bottom-up concepts and approaches have been introduced. Life Cycle Engineering (LCE) is one of the bottom-up concepts that helps companies maintain their economic competitiveness while decreasing the environmental footprint of their manufacturing activities throughout all life cycle stages. Life Cycle Assessment (LCA) is one of the LCE tools that helps to quantify the environmental impacts of products and processes from cradle to grave, which includes raw material extraction to End-Of-Life. LCA has a holistic lifecycle.
viewpoint on the products and with consideration of all environmental impacts including both global and local [3, 4]. In accordance with the ISO 14044 standard for LCA [5], the impacts from the product system may be normalized against local background impacts to comprehend their magnitude [6]. The findings have led to more eco-efficient products, processes, and services relative to the past [7]. For instance, relative sustainability incorporates the environmental aspects with Product development processes (PDP) to provide decision makers supportive tools for choosing among different alternatives. Design for Environment (DfE) and Design for Sustainability (DfS) have been developed to minimize environmental impacts through product design [8]. Also, ISO 14001 [9] supports life cycle thinking with taking into consideration each stage of a product or service from cradle to grave. ISO/TR 14062 was published in 2002 [10], which includes concepts, processes and guiding practices for the integration of environmental aspects in product design.

For the purpose of LCA integration with PDP, so many studies have been done. Such as Souza and Borsato (2016) studied comparison of the environmental profile of a product with an existing one[11], Poudel et al., (2012) provided a supportive decision-making tool for designers [12], and so many other studies. Prominently, Seow et al. (2016), proposed Design for Energy Minimization (DIEM) to minimize energy consumption in the phases of conceptual design, detailed design, and production[13]. Recently, da Luz, Leila Mendes, et al., (2018), a methodological approach for integration of LCA in PDP as a supportive decision-making tool to help companies to make development processes more sustainable [8].

However, relative sustainability has not been sufficient enough to cease depletion of natural resources. Increase in consumption and population can neutralize or even overdo the improvements obtained through eco-efficiency increases [14], hence possessing sustainable technology and production are not the only factor that impacts environmental performance. Human affluence (consumption) and population are, also, factors in environmental impacts of products. Additionally, the thresholds of pressure for the planet, where serious changes can be expected as the reaction of the planet to the variables in the ecosystem, are measured by Hauschild [15]. Hence, planetary boundaries are introduced as the lower bound of the uncertainty intervals around the thresholds [7]. Relative sustainability has not been successful in keeping the environmental impacts under the planetary boundaries. In order to stay below planetary boundaries, absolute sustainability remarks that all human activities should not exceed the carrying capacities of our ecosystem. Thus, simultaneous consideration of production, population, and consumption is essential to move towards absolute sustainability. Although many researches have been done on providing tools for companies, there is a little study on proposing a framework to employ those tools for evaluating the environmental footprint of companies throughout their value-chain to stay within the planetary boundaries.

From a top-down perspective, under the United National Framework Convention of Climate Change (UNFCC) countries are committed to announcing their National Emission Inventories (NEI) to benchmark the emission reduction and move towards UNFCC goals [16]. Consumption-Based Accounting (CBA) and Production-Based Accounting (PBA) are two top-down prominent approaches for emission allocation between regions. CBA and PBA are two extreme approaches to emission allocation as CBA puts the responsibilities of exports/imports on consumer countries and PBA allocates the responsibilities of imports/exports to manufacturing countries. However, there is no consensus on which one is more constructive since import/export products add value in both consumer and manufacturing countries [17].

One of the first attempts at combining a top-down perspective on absolute sustainability with a bottom-up approach like life cycle engineering was the Lyngby Framework [18]. Also, more tools and techniques for LCE practitioners have been proposed including target-driven life cycle engineering to operationalise the concept of planetary boundaries in LCE activities of companies [7]. Most of the efforts up to now have focused on providing, concepts, indicators, and tools for companies to evaluate and optimize their product’s environmental footprints relatively (from bottom-up), without consideration of total environmental impacts, which includes human affluence and population. And from top-down approaches, the efforts have been made for the allocation of environmental footprints between regions and countries (from top-down).

1.2. Objective

The objective of this paper is to consider human affluence and population to quantify the environmental impacts of companies throughout their supply chains to stay within planetary boundaries. Also, apply CBA and PBA concepts, which are used at the economy-wide (high) level for emission allocation between economy’s parties (countries), to assign environmental footprints’ responsibilities of products to countries and companies involved in the value chain at the process (low) level. As a company’s activities throughout their supply chain provide value for involved companies as well as countries, there is no consensus on who is responsible for the environmental impacts of products and services. Therefore, the proposed framework quantifies environmental footprints of companies and divide environmental footprints of products among involved countries and companies throughout the value chain. Also, a few local and global indicators are chosen to demonstrate the proposed framework.

The remaining part of the paper proceeds as follows: in section 2 the proposed methodology is described. The framework and approaches that are applied to measure the regional environmental footprint of a company are studied in section 3 under the case study title. In section 4, the outcomes are discussed, and conclusions are drawn.

2. Methodology

The framework for estimation of the regional environmental footprint of companies is depicted in Fig.1. It supports companies to set the goals for the reduction of their environmental footprints in order to avoid exceedance of their predetermined share of that regional space, which allows the region to stay within the planetary boundaries. First, life cycle assessment is performed to evaluate the global and local environmental impacts of product portfolios based on ISO 14044. The following step is quantification of the total environmental impact of the product portfolio with volume consideration, as proposed by Kara et al (2018) [7]. In order to relate each indicator to the relevant thresholds to stay within
planetary boundaries, local and global impacts are treated
differently, and the reduction goals are set separately.

<table>
<thead>
<tr>
<th>Determination of Product Portfolio’s value chains</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw materials</td>
</tr>
<tr>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>Total Environmental Impact of product portfolios</td>
</tr>
<tr>
<td>Allocation of TEI among involved companies and countries</td>
</tr>
<tr>
<td>Global Impacts</td>
</tr>
</tbody>
</table>

Consumption-based Accounting (CBA) or Production-based Accounting (PBA)

Quantification of the company environmental footprints

Scientific based targets to stay under planetary boundaries

Set goals for companies and countries to reduce their environmental footprint for NCM

Fig. 1. Framework for estimation of regional environmental impacts of companies to stay below planetary boundaries.

2.1. Determination of product portfolios’ value chains

Determination of product portfolio value chains includes boundaries definition for product portfolios in the first phase of the framework. Also, it defines all countries and areas, which are involved in the comprised product life cycles and hence gain benefit from that company’s activities.

2.2. Total environmental impact of product portfolios

To determine the total environmental impacts (TEI) of a product portfolio, life cycle assessment based on ISO 14044 is applied for evaluation of environmental impacts (EI) in relation to the products from cradle to grave, back to the raw material extraction and down to the waste treatment, based on LCA. One of the most important reasons for choosing LCA is to reveal and avoid the shifting of burdens from one impact to another impact or from one life cycle stage to another [19]. Volume ($V_i$) consideration incorporates the human affluence and population into evaluation as human affluence and population affect the volume of production. Hence, TEI of a product (i) is calculated based on Eqn.1 [7]. Consider that we assume a product portfolio j has i = 1... N product types at the market simultaneously. Hence, the total environmental impacts of a product portfolio throughout the value-chain is calculated as given in Eqn.2.

$$\text{TEI}_i = \text{EI}_i \times V_i$$

$$\text{TEI}_j = \sum_{i=1}^{N} \text{TEI}_i$$

2.3. Allocation of total environmental impact among involved companies and countries

Environmental impacts include global and local impacts. The evaluation of global and local indicators will be discussed separately.

2.3.1. Allocation of global impacts via PBA

The developed countries (known as Annex 1 countries in the protocol) agreed to the Kyoto Protocol to reduce net emissions from their territorial ecosystems. However, PBA has led to “carbon leakage”, which is relocating carbon-intensive industries from Annex 1-countries to non-Annex 1-countries. Despite the fact that PBA has not been successful, it has a number of merits including its simplicity in calculation, availability of the required data, and its consistency with Gross Domestic Product accounting (GDP) and current methodologies of data collection [20]. From top down, the emission’s responsibility of each country is evaluated according to Eqn.3 based on PBA approach. Also, Eqn3 and relevant assumptions, which are mentioned under section 3.2, are applied for calculation of shares of involved companies and countries from the environmental impacts of a product portfolio based on PBA.

Emissions’ responsibility of a country = Domestic Production (DP) + emissions embodied in Imports (I) 

2.3.2. Allocation of global impacts via CBA

Consumption-based accounting (CBA) is the most prominent alternative for PBA. Although CBA has disadvantages such as more complex calculation and political hinders, it has advantages including better coverage of global emission with limited participants, providing more mitigation options, and promoting cleaner production. Also, Eqn.4 demonstrates the way that CBA concept is used for allocation of the environmental impact’s share of involved countries and companies

Emissions’ responsibility of a country = Domestic Production (DP) + emissions embodied in Exports (E)

2.3.3. Allocation of local impacts with consideration of normalization

For freshwater use, the impact assessment proposed by Lévová and Hauschild is adapted to depict the impact of freshwater extraction and its use [4] according to Eqn.5

$$\text{IS}=Q_{IM} \times CF_{IE}$$

Where IS is the impact score, $Q_{IM} [m^3]$ is the water consumption of the production, calculated based on Eqn.6. $Q_{IN} [m^3]$, the amount of water used for the production and categorized into subcategories including Blue water (extracted), Green water (precipitation and soil moisture), Grey water (mildly polluted), and Black water (heavily polluted). $Q_{TOT} [m^3]$ is the available water in the water body from which the water is extracted, and $Q_{OUT} [m^3]$ is water that is returned to the water body through discharge.

$$Q_{IM} = Q_{IN} - Q_{OUT} + (Q_{OUT} \times (Q_{IN}/Q_{TOT})) + Q_{DIL}$$

Eqn.6 includes changing water quality ($Q_{DIL}$) and a time delay between water extraction and discharge ($Q_{OUT} \times (Q_{IN}/Q_{TOT})$) and includes them as water volume. $Q_{IM}$ is calculated based on Eqn.7 and 8 when two geographically individual areas are involved. It may occur that
water is extracted from watershed 1 (W1) and discharged in another watershed (W2). In this case, the calculation is based on Eqn. 7 and 8 for the W1 and W2 respectively [21].

\[ Q_{W1}^{IN} = Q_{IN} \]

\[ Q_{W2}^{IN} = Q_{IN} - Q_{OUT} \]  

(7)

(8)

Noteworthy, the resulting water impact on W2 may be negative if \( Q_{OUT} \) is larger than \( Q_{IN} \).

In Eqn.5 \( CF_{IE} \) is defined as the characterization factor for the environmental impact of water usage on the ecosystem and illustrates the importance of the water extraction considering the local scarcity of freshwater. Eqn.9 shows the calculation of the characterization factor based on the ratio of water extraction and restrictions of the watershed.

\[ CF_{IE} = \left( \frac{W_{U}}{W_{R}-EWR} \right)^{\frac{WR}{2} \times EWR} \]  

(9)

Where, WU is for Water Usage, which is the current water demand of humans, which indicates water withdrawal from the natural water resource of the region or local area, where manufacturing processes are located, for production. WR is for Renewable Water Resource, which is the size or the capacity of the natural water resource, which is available. EWR is Environmental Water Requirement, which is the freshwater needs of the local freshwater ecosystems. With this expression, the freshwater use of the product system is normalized against local water availability to a better understanding of its relative magnitude and severity. After calculation of IS, if the local Impacts are treated the same as global impacts

2.4. Quantification of a company environmental footprint

The current environmental footprint of a company(A) is calculated based on Eqn.10, where we assumed the company has L product portfolios \( j = 1, \ldots, L \) and each product portfolio has N product types \( i = 1, \ldots, N \).

\[ TEI_{A,j,i} = \sum_{j}^{L} \sum_{i}^{N} TEI_{j,i} \]  

(10)

3. The case study and results

As case study company, one of the leading manufacturers of medical technology and pharmaceutical products and services is chosen, and it is assumed that the company has one product portfolio, which includes product 1 and product 2. Also, the considered volume is 3000 units. Due to confidentiality, further details of the company have not been disclosed.

3.1 Determination of product portfolios’ value chains and total environmental impact of products.

A brief description of two products and their life cycles is provided in Table 1. Life Cycle Assessment (LCA) of products was conducted from Cradle-to-grave to assess Environmental Impact (EI) of products, including the distribution transportation, usage by the prospective customers and the disposal transportation and disposal process.

Input data was obtained from the company’s data and supplemented by a literature survey. Ecoinvent 2.2 and Australian data 2007 databases were used for background processes and some foreground processes. The Life Cycle Impact Assessment was focused on climate change using the Global Warming Potential (GWP100) characterization factors from SimaPro 7.2.4, presenting environmental impact results in kg CO2eq. the environmental of one-unit product 1 and product 2 are 0.74533 and 186 kg CO2eq respectively. The volume of 3000 units of single-use product 1 and the multiple-use product 2 was considered to calculate the Total Environmental Impact (TEI) of products based on Eqn.1 and the results are depicted in table 2.

3.2 Allocation of global environmental impacts among the involved company and countries through CBA and PBA.

In order to allocate environmental impacts of products throughout their life cycles to involved companies and countries, Production-Based Accounting (PBA) and Consumption-Based Accounting (CBA) are applied to the case study based on Eqn.3 and 4. The basic assumptions are that domestic production for consumer countries is defined as the emissions related to consumption and production’s emissions, including raw material extraction, manufacturing processes, transportation of components or raw materials, and end of life, are counted as the company’s responsibility. Also, it is required to mention that imports/exports are defined as all required transportation from the factory to the consumers, which includes inbound logistics, outbound logistics, and international transportations, and consumption. Additionally, transportation between involved countries in production is counted as the company’s responsibility. Table 3 depicts the results of the allocation of the total environmental impacts of two products.

### Table 1. The descriptions of two products

<table>
<thead>
<tr>
<th>Products</th>
<th>Type of Product</th>
<th>Production location</th>
<th>Distributed from</th>
<th>Use location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product 2</td>
<td>Multiple use</td>
<td>Malaysia</td>
<td>Germany</td>
<td>Germany</td>
</tr>
<tr>
<td>Product 1</td>
<td>Single use</td>
<td>Malaysia</td>
<td>Germany</td>
<td>Germany</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Scissors Product 1</th>
<th>Product 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>EI</td>
<td>0.74533</td>
<td>186</td>
</tr>
<tr>
<td>TEI</td>
<td>2,236</td>
<td>559230</td>
</tr>
</tbody>
</table>

### Table 3. The allocation of Total Environmental Impacts of Two products

<table>
<thead>
<tr>
<th>Product Approach</th>
<th>Product 1</th>
<th>Product 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Environmental Impact (TEI) of two products (unit: kg CO2eq)</td>
<td>CBA</td>
<td>PBA</td>
</tr>
<tr>
<td>Formula</td>
<td>DP + I</td>
<td>DP + E</td>
</tr>
<tr>
<td>Company</td>
<td>2,063+0</td>
<td>2,063+0</td>
</tr>
<tr>
<td>Germany</td>
<td>0+173</td>
<td>0</td>
</tr>
<tr>
<td>Malaysia</td>
<td>0</td>
<td>0+173</td>
</tr>
<tr>
<td>Switzerland</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 4. demonstrates the Total Environmental Impacts of the product portfolio between involved countries and the company based on Eqn.2. Company’s environmental footprint equals all environmental impacts of product portfolios, based on Eqn.8.
Eqn. 5 and 7. All water impact of Product 1 happens in the production stage, so it is the company’s responsibility. The water impact of Product 2 in Malaysia originates from the consumption stage, so it is the country’s responsibility. Therefore, the water footprint of the company and Germany equal to 0.00305 and -0.00631 (m$^3$/year) respectively. Table 7 demonstrates the result of water footprint allocation based on CBA/PBA approaches.

Table 7. IS calculation

<table>
<thead>
<tr>
<th>Country</th>
<th>IS (unit: m$^3$/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany</td>
<td>-0.00631</td>
</tr>
<tr>
<td>Company</td>
<td>0.00305</td>
</tr>
<tr>
<td>Malaysia</td>
<td>0.00515</td>
</tr>
<tr>
<td>Switzerland</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 8. Water footprint allocation

<table>
<thead>
<tr>
<th>Company/Country</th>
<th>Water footprint responsibility (unit: m$^3$/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany</td>
<td>-0.00631</td>
</tr>
<tr>
<td>Company</td>
<td>0.00305</td>
</tr>
</tbody>
</table>

Table 9. TEI allocation scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Impact</th>
<th>Global Impact</th>
<th>Local Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base-line scenario</td>
<td>Consumption-related environmental impact ➔ country’s share</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Production-related environmental impact ➔ Company’s share</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alternative scenario</td>
<td>Consumption-related environmental impact ➔ country’s share</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Production-related environmental impact ➔ x value – added%$_{\text{com}}$ = company’s share</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>x value – added%$_{\text{com}}$ = country’s share</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As it is demonstrated in Fig. 2, the PBA approach shifts responsibility slightly from the consumers to the producer, relative to the CBA approach.

3.3 Allocation of local environmental impacts among the involved company and countries

Water footprint is assessed as a local environmental impact. As Eqn. 5 shows, the first step is to calculate the amount of water that is consumed through the life cycle of the two types of products, defined as includes the water input ($Q_{\text{DI}}$), the water output ($Q_{\text{DO}}$), from material extraction to end of life, and $Q_{\text{TOT}}$, which is defined as Total internal renewable water resources (IRWR). $Q_{\text{DO}}$ is not considered as there was no information about it from the LCA study. Table 6 shows the calculation of $Q_{\text{IM}}$ for the two products and $CF_{IE}$, based on Eqn. 6 and 9 (one example of the calculations of $CF_{IE}$ are provided in Table 5) [6].

Table 5. $CF_{IE}$ calculations of two products

<table>
<thead>
<tr>
<th>Country</th>
<th>WU</th>
<th>WR</th>
<th>EWR</th>
<th>$CF_{IE}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany</td>
<td>3.3E+10</td>
<td>1.5E+11</td>
<td>7.4E+10</td>
<td>0.43</td>
</tr>
</tbody>
</table>

Table 6. $Q_{\text{IM}}$ and $CF_{IE}$ calculations for involved countries

<table>
<thead>
<tr>
<th>Nation</th>
<th>$CF_{IE}$</th>
<th>$Q_{\text{IM}}$(Product 2)</th>
<th>$Q_{\text{IM}}$(Product 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany</td>
<td>0.43</td>
<td>-0.015</td>
<td>-0.017</td>
</tr>
<tr>
<td>Malaysia</td>
<td>0.039</td>
<td>0.131</td>
<td>0.13</td>
</tr>
<tr>
<td>Switzerland</td>
<td>0.075</td>
<td>-</td>
<td>0</td>
</tr>
</tbody>
</table>

As it is mentioned in section 2.3.3, it is not unexpected if $Q_{\text{IM}} < 0$, as the case study is a multi-regional case scenario and $Q_{\text{DI}}$ is assumed equal to 0. $CF_{IE}$ is calculated according to Eqn. 9 based on WU, which is the total water withdrawal, EWR, which is the Environmental Flow Requirements, and WR, which the Total renewable water resources in the region [22]. Table 7 documents the IS calculation of two products, based on Eqn. 5 and 7. All water impact of Product 1 happens in the production stage, so it is the company’s responsibility. The water impact of product 2 in Malaysia originates from the production stage, so it is the country’s responsibility. Therefore, the water footprint of the company and Germany equal to 0.00305 and -0.00631 (m$^3$/year) respectively.
4. Discussion and conclusion

Currently, life cycle engineering activities are mainly focused on relative sustainability and eco-efficiency to make products and services more efficient relative to the past. However, in order to stay within planetary boundaries and protect the functioning of the earth’s life support systems, it is required to move towards absolute sustainability and eco-effectiveness. Many tools and techniques have been introduced required to move towards absolute sustainability and eco-effectiveness. LCA provides a comprehensive evaluation of company’s environmental impacts, and allocate the responsibility of environmental impacts of products for staying under planetary boundaries. So far companies have been blamed for the products’ environmental impacts. However, companies are not the only beneficiaries, who have gained profit from the selling of products; countries are other parties that have grown their economies, the level of their residents’ welfare, and the like. Hence, the environmental footprint of products should be shared between the countries and companies involved in the product’s value chain. The aim of this study is to provide a framework with the application of top-down and bottom-up approaches to assess the current environmental impacts of companies, and allocate the environmental responsibility between actors in the value chain.

LCA provides a comprehensive evaluation of product’s environmental footprints including local and global impacts, and. Quantification of total environmental impacts (TEI) of product portfolios reflects the environmental footprints of products and also factors in consumption (human affluence) and population. CBA and PBA are two approaches for emission allocation among stakeholders. As a mitigation strategy, an alternative scenario was suggested that considered value-added percentage as a criterion to allocate regional environmental impacts to the involved countries and companies in the products’ value chains. The insight that companies will gain from the application of the proposed framework help them to set a reduction goal for themselves based on their share of environmental impact. However, one of the most important assumptions of this study is that emissions related to consumption are consumers’ responsibility and emissions related to manufacturing processes are companies’ responsibility. By running different distribution shares, we investigate the sensitivity of the actual choice which also gives us an idea about the sensitivity to how we consider the different forms of value creation – direct and indirect (higher tiers) in the allocation.

References