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Three alternative ways to allocate the cost of the CF produced in a water supply and distribution system

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ABSTRACT

Greenhouse gas (GHG) emissions are considered to be the main cause of climate change, globally. On one hand, specific targets regarding these emissions have been already adopted in a European level. These targets include 20% reduction of GHGs and 20% reduction of energy consumption until 2020, below 1990 levels. Furthermore, EU leaders, going one step forward, have endorsed the objective of reducing Europe's GHG emissions by 80–95% compared to 1990 levels, until 2050. A number of initiatives have been adopted in order to fulfill these expectations. On the other hand, it is widely recognized that every product's supply chain consists of high energy-consuming processes. Carbon footprint (CF) is a parameter that should be integrated in the improvement of these processes' energy efficiency. In this paper, three new approaches of the CF, which produced cost allocation (end-user pays, production based, and profit based), among producers and users are being analyzed. These approaches' differences are focused to the "blame" put to each stakeholder involved, during the different phases of the "product's" life cycle. Everyone should pay a fair price to fully recover the costs related to the entire process. This could only lead to a socially just pricing policy of a product and to improvements in the performance targets of an organization.

Keywords: Carbon footprint; Full water cost recovery; Water supply chain

1. Introduction

Trying to incorporate the growing concern on global climate change impacts and carbon emissions in everyday processes, many organizations have already adopted the "CF" concept to estimate their own contribution to global climate change environmental impacts. Policy-makers have recognized the need to quantify these impacts and, on this basis, identify measures to reduce them. They have already implemented several strategies, methodologies, and tools in order to identify more stable paths to reach these targets. An urban water supply chain (WSC) also consists of several energy and water usage processes. Managing the CF across a WSC is the next step for a water utility in its effort to reduce emissions and mitigate climate change. The term of full water cost (FWC) recovery is being introduced by WFD 2000/60/EC. It is based on the polluter-pays principle, in which the FWC consists of three subcosts, namely direct (DC), environmental (EC) and resource (RC) costs. DC includes the direct cost of a water supply process and daily costs of the water utility; EC expresses the environmental impacts of construction, installation, maintenance, and operation of the WSC, increased water

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use, and the cost needed to restore the environment to its original condition; RC is the opportunity cost of alternative uses of water due to depletion of resource more than the natural rate of renewal. A WSC includes a number of activities, where large amount of energy is used. Greenhouse gas (GHG) emissions, considering all phases of a WSC life cycle, must be included in the EC. In fact, CF-related cost should be included in the EC calculation process. Natural energy, shaft energy, useful energy delivered to users, leakage energy losses, friction energy losses, and compensation energy are the types of energy involved in the water supply energy audit [1]. The current carbon emissions and their cost per water unit should be evaluated for any new infrastructure, new water/wastewater treatment facilities. This paper highlights the importance of CF reduction along a product's supply chain, introducing three different approaches of its cost allocation among the stakeholders involved. The main goal is to increase the sensitivity in developing strategies to combat climate change and act on the opportunities to reduce emissions and save money at the same time.

2. Greenhouse effect (global warming), ice melting, and sea level rise

Global warming theory (greenhouse effect) was first formulated by Fourier in 1824, fully presented by Fleming [2], where it was systematically investigated by Arrhenius in 1896, fully presented by Crawford [3]. The greenhouse effect is a natural process that maintains the earth's temperature at 15℃. Otherwise, the earth would be cold (about −18℃), not allowing either the existence or the preservation of life. Twenty five kilometer above the earth's surface, a thin layer exists consisting of GHGs and vaporized water, which allows the heat being transferred by the sun's ultraviolet radiation to reach earth's surface (Fig. 1), preventing, at the same time, the exit of the heat into space. Seventy percent of the incoming solar radiation is absorbed by the oceans (51%), the atmosphere (16%), and the clouds (3%); the remaining 30% is reflected back to space by the clouds (20%), the atmosphere (6%), and the earth's surface (4%). It must be noted that the greenhouse effect, although a natural process, is being enhanced by human activity, which causes an increase in the GHG concentration (Fig. 2). Therefore, nowadays, when someone refers to global warming, he does not imply the natural process, but its rapid acceleration due to the "pollution" of the atmosphere by human activities. Furthermore, the GHG do not cause an increase in temperature only in the areas that are emitted as they are being spread across the surface of the planet.

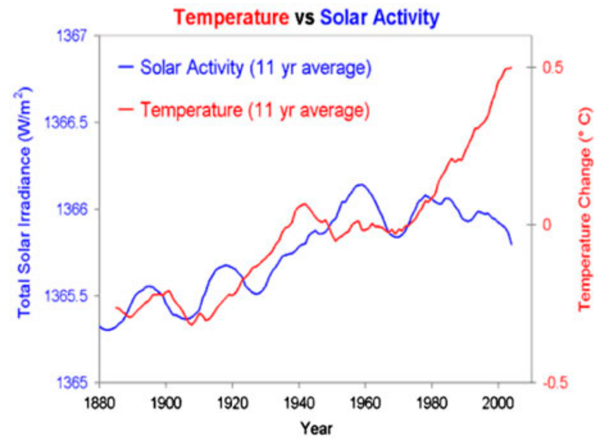


Fig. 1. Temperature and solar radiation over time [4].

In the early 1980s, the term "climate change" came to force referring to the change of earth's temperature and the upcoming impact on the environment. The process of earth's temperature increase (Fig. 3) is reflected to the commonly used term "global warming." The earth's climate has changed many times during the planet's history, including periods of glacial and periods of severe drought. Natural factors, such as volcanic eruptions, the amount of energy released by the sun, and increasing the concentration of GHGs, have affected the earth's climate. In addition, human activities initiated and mainly associated with the industrial revolution have changed the composition of the atmosphere and, therefore, have influenced the earth's climate. Regarding the latter, many human activities are to blame for. The combustion of fossil fuels for electricity needs produces millions of tons of CO_2 annually. Other factors are the use of heating and industrial fuel, transportation, waste treatment, agriculture, and livestock. According to the

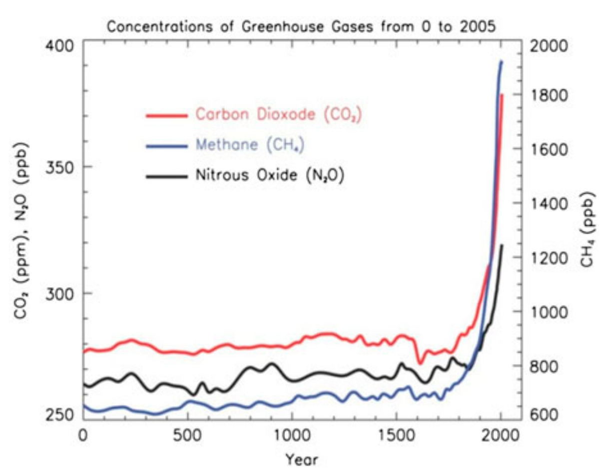


Fig. 2. GHG concentrations over time.

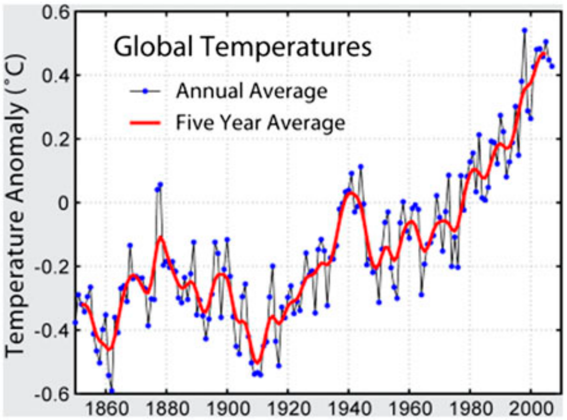


Fig. 3. The global temperature over time.

Intergovernmental Panel on Climate Change (IPCC) [4], the global temperature during the period 1906–2005 was increased by 0.74˚C, and is expected to increase by 0.2˚C per decade in the next decades (Fig. 4). Catastrophic changes in the environment will occur if global temperatures rise more than 2˚C. Such an increase corresponds to a concentration of carbon dioxide in the atmosphere of about 450 ppm. In early 2007, the concentration of carbon dioxide was 380 ppm (Fig. 4). With a growth rate averaging 2–3 ppm per year, it is estimated that the critical value of the increase in global temperature will be reached in about 20–30 years.

The main impact of global warming is the ice melting at the poles, resulting in the gradual increase in sea level around the globe. The existence of ice is particularly important to limit further warming of the planet due to their capacity to reflect about 85–90% of the incoming solar radiation, unlike the oceans and soils which reflect only 10–20%. The rise in temperature due to global warming leads to the melting of glaciers and increasing of ocean surface, thus reducing the reflected solar radiation and further increasing the temperature of the planet. Specifically, the greatest glacier of western Antarctic decreases with a rate that is 50% bigger compared with 1994. The same also stands for Greenland's ice layers. The continuous ice melting has a negative impact on the availability of drinking and irrigation water supplies, whose stocks decline more and more. The problem gets even worse during drought periods. Already half a billion people live in areas, where water is scarce. By 2050, it is estimated that 1.75 billion people will live in areas with under drinking water shortage conditions. Sea level rise results from oceans' expansion due to global warming and ice melting (Fig. 5). According to surveys, the sea level increased by 2.3 mm for the period 2005–2010, whereas today the mean annual raise is 3 mm [4]. A typical example is Greenland, where it is estimated that sea level rise due to melting glaciers will reach 10 cm by 2100. Bearing in mind the other factors causing sea levels to rise, the total increase may reach 90 cm. Another example is Philippines sea level, whose annual rise is 10 mm since 1991 [4]. The rise in sea levels threatens about one-tenth of the world's population living in coastal areas and islands, as the risk of flooding is high. Computer models predict that global temperatures are expected to rise by 2–5˚C by 2100, forcing more than 180 countries negotiate for a global treaty that will run until 2020 and will force them reduce their GHG emissions enough, to prevent global warming exceed 2˚C.

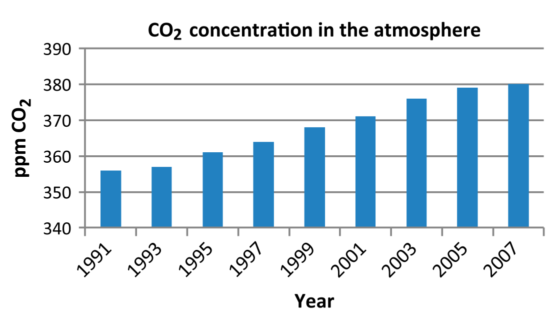


Fig. 4. CO_2 concentrations over time.

3. Integrating the carbon footprint concept in a water network

Carbon footprint (CF), in general, includes all GHG emissions from every human activity and is expressed

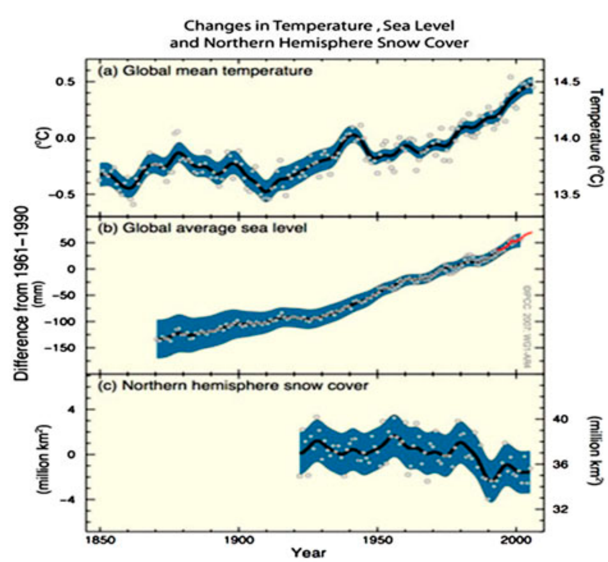


Fig. 5. Global mean temperature vs. Global average sea level vs. Northern hemisphere snow cover over the years [4].

in CO_2 equivalents. One of its basic definitions is that … "CF is a measure of the exclusive total amount of GHG emission directly and indirectly produced by an activity or is accumulated over the life stages of a product" [5]. Considering that CF can be analyzed in different scales, "the CF of a functional unit is the climate impact under a specified metric that considers all relevant emission sources, sinks, and storage in both consumption and production within the specified spatial and temporal system boundary" [6]. Other CF definitions from the literature state that CF can be calculated by "measuring the CO_2 equivalent emissions from its premises, company-owned vehicles, business travel and waste to landfill" [7] or that CF is

> a measure of CO_2 amount emitted through combustion of fossil fuels. In the case of a business organization, it is the amount of CO_2 emitted either directly or indirectly as a result of its everyday operations. It might also reflect the fossil energy represented in a product or commodity reaching market. [8]

Therefore, CF is the amount of CO_2 emitted due to a human's daily activities.

A water pipe network consists of high energy-consuming processes starting from water abstraction, up to the waste water treatment facilities. Leaks occurring along the water supply process (even more than 50% of the system input volume are also characterized by significant energy usage. Additional processes, such as desalination [9], lead to an even greater energy use. In a water network, the energy balance for a given period can be expressed using Eq. (1) [9].

$$\begin{aligned} E_{Input}(t_P) &= E_N(t_P) + E_P(t_P) \\ &= E_U(t_P) + E_L(t_P) + E_F(t_P) + \Delta E_C(t_P) \\ &= E_{Output}(t_P) + E_{Dissipated}(t_P) + \Delta E_{Compensation}(t_P) = \gamma \\ &\cdot \sum_{i=1}^{i=n_N} \left(\sum_{t_k=t_1}^{t_k=t_P} Q_{Ni}(t_k) \cdot H_{Ni}(t_k) \right) \cdot \Delta t + \gamma \\ &\cdot \sum_{i=1}^{i=n_P} \left(\sum_{t_k=t_1}^{t_k=t_P} Q_{Pi}(t_k) \cdot H_{Pi}(t_k) \right) \cdot \Delta t = \gamma \\ &\cdot \sum_{i=1}^{i=n} \left(\sum_{t_k=t_1}^{t_k=t_P} q_{ui}(t_k) \cdot H_i(t_k) \right) \cdot \Delta t + \gamma \\ &\cdot \sum_{i=1}^{i=n} \left(\sum_{t_k=t_1}^{t_k=t_P} q_{li}(t_k) \cdot H_i(t_k) \right) \cdot \Delta t + \gamma \\ &\cdot \sum_{j=1}^{j=n_l} \left(\sum_{t_k=t_1}^{t_k=t_P} q_j(t_k) \cdot \Delta h_j(t_k) \right) \cdot \Delta t + \gamma \\ &\cdot \sum_{i=1}^{i=n_C} \left(A_i \cdot (z_i^2(t_P) - z_i^2(t_1))/2 \right) \end{aligned} \quad (1)$$

where E_{Input} (t_p) is the system energy input; $E_N(t_p)$ is the natural energy supplied by external sources; $E_P(t_p)$ is the shaft energy supplied by pumps; $E_U(t_p)$ is the useful energy delivered to users; $E_L(t_p)$is the leakage energy losses; $E_F(t_p)$ is the friction energy losses; $E_C(t_p)$ is the compensation energy associated with internal system tanks; γ is the specific weight of water; $q_{ui}(t_k)$ and $q_{li}(t_k)$ are the supplied and leakage flow rate delivered in node i at time t_k; $q_{uj}(t_k)$ and $q_{lj}(t_k)$ are the supplied and leakage flow rate circulating in line j at time t_k; $H_i(t_k)$ is the piezometric head in node i at time t_k; $z_i(t_1)$ and $z_i(t_p)$ are the levels of the free surface of water of tank i at the initial and final times, respectively; Ai is section of the i tank; $H_Pi(t_k)$ is the piezometric head of the I pump at time interval t_k.

3.1. General methods to calculate the CF produced in a supply chain

The CF can be calculated according to the EU directive 2007/589/EC based on the following equation (the calculation process should be separately conducted for each activity, facility, and fuel):

$$\begin{aligned} \text{CF} &= \text{GHG (or } CO_2 \text{ equivalent) Emissions} \\ &= \text{Activity data} * \text{Emission factor} \\ &\quad * \text{Oxidation factor} \end{aligned} \quad (2)$$

where activity data—electrical energy, fossil fuels use, renewable energy use (production process); emission factor—predetermined factors from the IPCC or per government; oxidation factor—if it is not considered that part of the carbon is being oxidized.

The CF calculation process can be methodologically done following two distinct approaches [2]:

- the bottom-up approach, based on the process analysis (PA) and life-cycle assessment (LCA);
- the top-down approach based on the environmental input–output analysis, (IOA). The most representative models based on IOA approach were developed in 1985 by: (a) Leontief [10] and (b) Miller and Blair [11].

PA helps in understanding and calculating the environmental impacts of the products throughout their entire life cycle. Thus, this method is, by nature, based on a product's LCA, facing boundaries setting problems. For larger scales of application (e.g. governments, households, and industries), this method faces further problems [3]. IOA is based on economic analysis of economic activities. In conjunction with environmental data, this approach provides the possibility to evaluate the CF in an integrated manner, taking into account all the effects, defining an entire economic system boundary. However, the completeness opposes

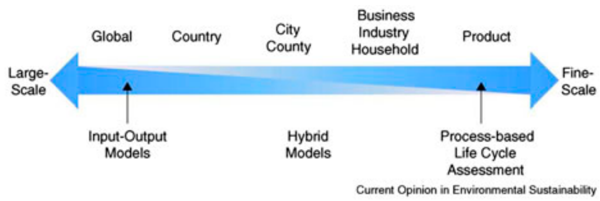


Fig. 6. CF calculation methodologies/approaches based on the scale of analysis desired.

detail. The analysis of environmental input–output is suitable to assess the CF in a microsystem where products or processes are limited, as it requires homogeneity in prices, outputs, and GHG emissions at each stage. Despite the fact that the sectors can be separated for further analysis, creating microsystems, large-scale segregation is limited. The biggest advantage of this method is that it has very little demand in time and manpower [3]. The best choice for a detailed, comprehensive, and reliable analysis is to combine both methods. Such an approach allows the detail and accuracy of bottom-up approach at low stages, while at higher stages, the requirements are covered by the model input–output. Such a combined method, incorporating the procedures in input–output tables, is the most modern method in ecological economic modeling. The choice of method depends on the purpose of research and the availability of data and resources. Specifically, we believe that the analysis of the environmental IOA is better to estimate the CF at macroeconomic and mesoeconomic systems. For example, the CF of industries, private companies, the larger production units, households, governments, an average citizen, or an average member of a particular socioeconomic group can easily be estimated using the IOA. In contrast, PA has clear advantages for the examination of microeconomic systems: a particular procedure with a single product or a relatively small group of individual products (Fig. 6).

3.2 Methods to allocate the CF produced along a supply chain

Over the past decade, researchers supported that producers were responsible for GHG emissions during a product's manufacturing process, resulting in incorrect national GHG balances, taking into consideration the international trade environment. Generally, the cost allocation of CF should meet three prerequisites: (1) involve producers and consumers too; (2) avoid double-counting of CF; and (3) include the product's full life cycle. There are three basic CF allocation approaches:

(a) the CF appointed at each stage of a supply chain is calculated based on the product's LCA and the prior stages followed. This approach satisfies only prerequisites 1 and 3, but not the 2nd;
(b) the product involved along a supply chain should take full responsibility of the CF produced. This approach satisfies only prerequisites 1 and 2, but not the 3rd;and
(c) the consumers involved along a supply chain should take full responsibility of the CF produced. This approach satisfies only prerequisites 2 and 3, but not the 1st.

The first attempt to identify the cost allocation of footprints in a supply chain was done by Szyrmer in 1992 [12], based on the total flow concept by Jeong [13,14] and Leontief's model [10]. The next effort was done by Gallego and Lenzen in 2005 [15], presenting the responsibility as a measured size and separated flows for each transaction through Leontief's model. This approach divides the responsibility of environmental impacts between all factors, in a way that reflects their contribution to the production process. Gallego and Lenzen showed that it is possible to divide impacts into mutually exclusive portions, sharing responsibilities to producers and consumers. According to this approach, the total upstream responsibility for production impacts F can be expressed as:

$$F = \sum_i F_i^{(p)} = \sum_i f_i \cdot x_i$$
$$x_k \rightarrow \begin{cases} \beta \cdot y_k \rightarrow \text{assigned to final consumers of sector } k \\ (1-\beta) \cdot y_k + (1-a) \cdot (x_k - y_k) \rightarrow \text{assigned to industry } k \\ a \cdot \sum_j a_{kj} \cdot x_j \rightarrow \text{assigned to sectors } j \text{downstream from } k \end{cases} \tag{3}$$

where f_i is the environmental impact; β is the percentage assigned to final consumers (end-users); y_i is the output of sector i to the end-users; α is the percentage assigned to the intermediate demand/user; x_i is the total output of sector i; and $\alpha_{ij} = x_{ij}/x_{j,}$ x_j: the flow from sector i to sector j.

Rodrigues et al. in 2006 [16] took an important step using the expression of an environmental indicator for cost allocation of footprints, based on IOA: When an environmental problem involves several agents, different environmental indicators can be chosen. The quantitative contribution of each agent to the environmental problem is an indicator of "environmental responsibility." This indicator must possess properties that most agents are likely to accept. Apart from a normalization condition, that indicator must be: (1) additive, implying that the responsibility of a set of agents is the sum of the responsibilities of each agent; (2) account for indirect effects under economic causality, implying that the agent that benefits economically from an environmental damage is responsible for it; (3) monotonic in direct environmental pressure, implying that the responsibility of a given agent cannot decrease if its actions lead to an overall worsening of the environmental problem; (4) symmetric in production and consumption, meaning that if the contribution of an agent's consumption and production behavior is interchanged, that agent's responsibility cannot change. Rodrigues et al. [16] stated that environmental responsibility is the average between the environmental pressure generated to produce the final demand and the primary inputs of an agent:

$$U_k = \frac{V_{k0} + V'_{0k}}{2} \quad V_{k0} = \sum_{i \in S_k} u_{i0} \quad V'_{0K} = \sum_{j \in S_k} u'_{0j} \qquad (4)$$
$$u_{ij} = m_i \cdot z_{ij} \quad u'_{ij} = m'_i \cdot z_{ij}$$

where m_i and m_j are the upstream environmental intensity of sector i and the downstream of sector j; z_{ij} is the economic flow of sector I to sector j; and z_j is the total inflow or outflow of sector j.

4. The suggested new approaches for CF cost allocation

"CF is the total set of GHG emissions caused by an organization, event, product or a person" [1], according to one of the latest CF definitions. Another definition is "the total amount of GHG emissions inside a supply chain or a product life cycle" [17]. Every phase of a supply chain should be examined separately, in order to be able to evaluate GHG emissions. The total CF produced in a product's life cycle results from the CF produced in each of this cycle's phases. Four core phases exist in a "typical product's" supply chain (Fig. 7). CF is produced (raw materials use, production, distribution, and sales), till the product reaches the end user. In sub-phases like raw materials transportation, storage of end products is embodied in the raw materials use and production phases, respectively. $CFi_{IMPORTED}$ is the CF transferred to process (i) from the previous one $(i-1)$; CFi PRODUCED is the CF produced during a process (i), in order for the product to be developed or for the provision of services; and $CFi_{EXPORTED}$ is the CF that is being extracted to the

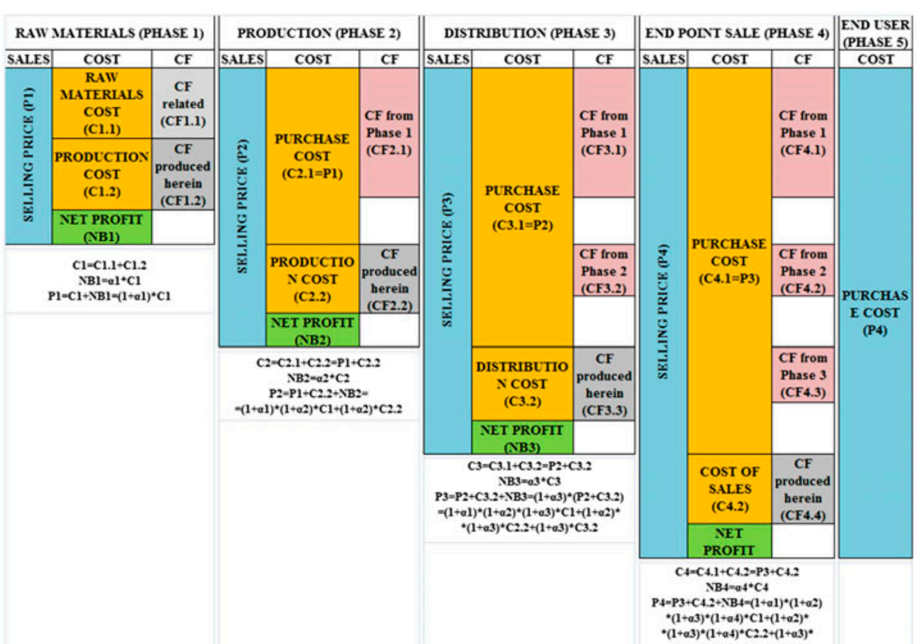


Fig. 7. CF in a product life cycle.

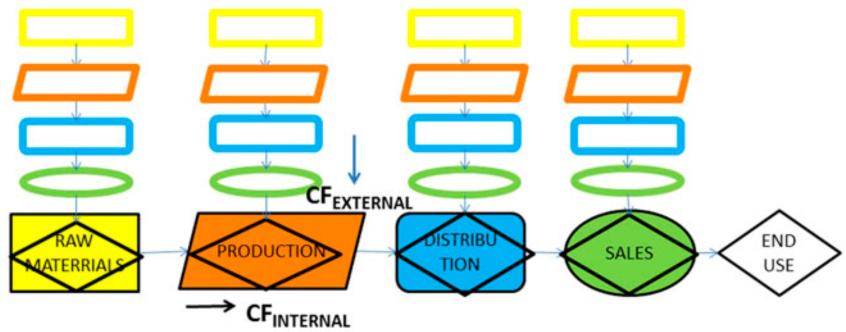


Fig. 8. Analysis of the evaluation in two different dimensions.

next one ($i+1$), by selling the product. This CF is being transferred to the next stage considered as CF IMPORTED of the present phase. CFp = CF that is being "paid and is equal" in each production phase. CFs = CF that is being "sold" and should be transferred to the next phase. Additionally, ΣCFp = ΣCF. In order to properly include all investment/operation activities in the evaluation exercise, two different dimensions in a product supply chain are taken into consideration (Fig. 8). The "horizontal" one includes CF internal, whereas in the vertical one, every phase of the "horizontal" chain ends in a CF external. CF external is added to CF internal (CFi Produced in each phase). Their sum is the amount of CF that is being allocated. A percentage of this amount is being allocated inside the present phase (CF_{Paid}), and the rest is being "transferred" to the next phase (CF_{Sold}). In a WSC, the above phases could be named: raw water abstraction, raw water treatment/freshwater production/quality preservation, water supply/distribution, water sale/outlet, and water use (Fig. 8).

Each of these phases is a part of the WSC, the fact that the "product" is the water aimed to be supplied to the customer of the water utility, while, at the same time, each phase is the final phase (end use) of a supply chain, where the "product" is the phase itself. For example, the distribution phase is considered the 3rd phase of the WSC and at the same time is the 5th (last) of another supply chain, where the "product" is the network itself.

4.1. Product's end-user pays approach

In this approach, the demand for the final product is the only variable to be blamed for the CF produced. Each phase in the supply chain is charged only with the part of the CF produced during the "product developing process" occurring in this phase, multiplied by the profit made to the price increase, due to the product-developing process in this phase (Eq. (5)). This means that CF allocation in each phase is based on the net profit divided into the difference between the selling price and the purchase price (CFp = (CF produced herein) * (net profit/(selling price − purchase price)). The remaining CF cost in each phase is being "pushed" to the next one (CFs = CF produced herein − CFp). This approach punishes the unjustified high demand of the product, but it does not punish CF overproduction due to inappropriate product-developing processes applied

4.2. CF production-based approach

Both the demand for the final product and its developing practices applied are to be blamed for the CF produced. Each phase is charged with the CF internally produced, multiplied by the profit made to the price increase due to the developing process applied, and the CF transferred from a previous phase, multiplied by the profit rate (CFp = (CF produced herein) * (net profit/(selling price − purchase price)) + (CF transferred) * (net profit/selling price))) (Eq. (6)). Although it punishes CF overproduction due to non-appropriate product-developing processes applied, it does not punish the unjustified high demand (waste) of the product. As already stated, the CF not charged in one phase is being transferred to the next one.

4.3. Profit-based approach

Here, both the initial demand for the final product and its developing practices applied are to be blamed for the CF produced. Each phase is charged with the sum of the internally CF produced and the CF transferred from a previous phase, multiplied by the profit made in the phase to the total profit made along the entire supply chain (CFp = (CF produced herein + CF transferred) * (net profit/total net profit)). The remaining CF cost in each phase is being "pushed" to the next one (CFs = (CF produced herein + CF transferred − CFp)) (Eq. (7)). This approach punishes both the CF overproduction due to inappropriate product-developing processes applied and the "excessive profit making" in each. CF not charged in one phase is transferred to the next one. The main idea is that all the CF "involved" in each phase is being allocated based on the rate of the net benefit of each phase compared to the total net benefit made throughout the supply chain.

where i are the phases; αi is the net profit in each phase; and C is the in-phase cost.

5. Comparing the results

To compare the alternative approaches proposed, a hypothetical case of a supply chain was formed (Table 1). The analysis of the results revealed a number of similarities and differences (Table 2). In the 2nd

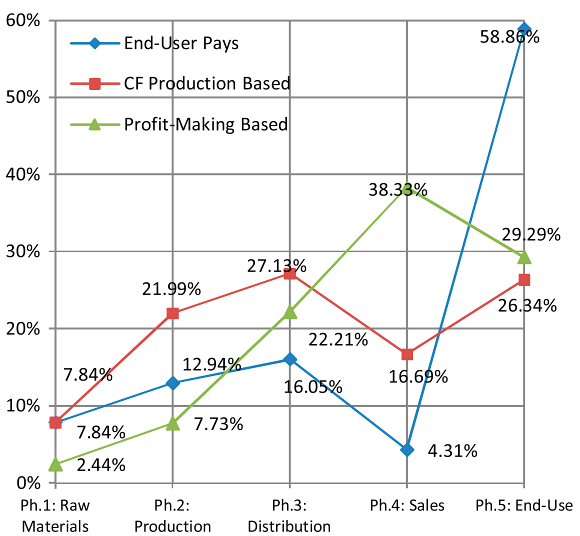
$$
\begin{aligned}
CF_i^P &= CFi,i\cdot\frac{\alpha i\cdot Ci,2+\alpha i\cdot\sum_{j=1}^{i-1}\left[\prod_{z=j}^{i-1}(1+\alpha z)\cdot Cj,2\right]}{(1+\alpha i)\cdot Ci,2+ai\cdot\sum_{j=1}^{i-1}\left[\prod_{z=j}^{i-1}(1+\alpha z)\cdot Cj,2\right]}\\
CF_i^S &= CFi,i\cdot\frac{Ci,2}{(1+\alpha i)\cdot Ci,2+ai\cdot\sum_{j=1}^{i-1}\left[\prod_{z=j}^{i-1}(1+\alpha z)\cdot Cj,2\right]}\\
CF_{use} &= \sum_{i=1}^{4}CFi^S=\sum_{i=1}^{4}CFi,i\cdot\frac{Ci,2}{(1+\alpha i)\cdot Ci,2+ai\cdot\sum_{j=1}^{i-1}\left[\prod_{z=j}^{i-1}(1+\alpha z)\cdot Cj,2\right]}
\end{aligned}
\tag{5}
$$

$$
\begin{aligned}
CF_i^P &= \sum_{j=1}^{i-1}CFj,j\cdot\frac{Cj,2}{(1+\alpha j)\cdot Cj,2+aj\cdot\sum_{z=1}^{j-1}\left[\prod_{k=z}^{j-1}(1+\alpha k)\cdot Cz,2\right]}\\
&\quad\cdot\prod_{n=j+1}^{i}\left(\frac{an}{an+1}\right)+CFi,i\cdot\frac{\alpha i\cdot Ci,2+\alpha i\cdot\sum_{z=1}^{j-1}\left[\prod_{k=z}^{j-1}(1+\alpha k)\cdot Cz,2\right]}{(1+\alpha i)\cdot Ci,2+ai\cdot\sum_{z=1}^{i-1}\left[\prod_{k=z}^{i-1}(1+\alpha k)\cdot Cz,2\right]}\\
CF_i^S &= \sum_{j=1}^{i}CFj,j\cdot\frac{Cj,2}{(1+\alpha j)\cdot Cj,2+aj\cdot\sum_{z=1}^{j-1}\left[\prod_{k=z}^{j-1}(1+\alpha k)\cdot Cz,2\right]}\cdot\prod_{n=j+1}^{i}\left(\frac{1}{an+1}\right)\\
CF_{use} &= CF_4^S
\end{aligned}
\tag{6}
$$

$$
\begin{aligned}
CF_i^P &= \sum_{j=1}^{i}CFj,j\cdot\frac{\left[\prod_{z=j}^{i-1}\left[\sum_{k=1}^{4}\left[\alpha k\cdot Ck,2+\alpha k\cdot\sum_{n=1}^{k-1}\left[\prod_{m=n}^{k-1}(1+\alpha m)\cdot Cn,2\right]\right]-\left[\alpha z\cdot Cz,2+\alpha z\cdot\sum_{k=1}^{z-1}\left[\prod_{n=k}^{z-1}(1+\alpha n)\cdot Ck,2\right]\right]\right]\right]}{\left[\sum_{z=1}^{4}\left[\sum_{k=z}^{4}\left[ak\cdot\prod_{n=z}^{k-1}(1+an)\right]\right]\cdot Cz,2\right]^{i+1-j}}\\
&\quad\cdot\left[\alpha i\cdot Ci,2+\alpha i\cdot\sum_{k=1}^{i-1}\left[\prod_{n=k}^{i-1}(1+\alpha n)\cdot Ck,2\right]\right]CF_i^S\\
&= \sum_{j=1}^{i}CFj,j\cdot\frac{\prod_{z=j}^{i}\left[\sum_{k=1}^{4}\left[\alpha k\cdot Ck,2+\alpha k\cdot\sum_{n=1}^{k-1}\left[\prod_{m=n}^{k-1}(1+\alpha m)\cdot Cn,2\right]\right]-\alpha z\cdot Cz,2+\alpha z\cdot\sum_{k=1}^{z-1}\left[\prod_{n=k}^{z-1}(1+\alpha n)\cdot Ck,2\right]\right]}{\left[\sum_{z=1}^{4}\left[\sum_{k=z}^{4}\left[ak\cdot\prod_{n=z}^{k-1}(1+an)\right]\right]\right]^{i+1-j}}\\
CF_{use} &= CF_4^S
\end{aligned}
\tag{7}
$$

Table 1
Assumptions and results for the three new approaches

	End user pays	CF prod. based	Profit based		End user pays	CF prod. based	Profit based
Assumptions				*Results*			
C1.1	5.00	5.00	5.00	P1	12.00	12.00	12.00
C1.2	5.00	5.00	5.00	NB1	2.00	2.00	2.00
CF1.1	17.00	17.00	17.00	(RM) $CF_{present}$	24.00	24.00	24.00
CF1.2	7.00	7.00	7.00	CF_1^P	4.00	4.00	1.25
Raw materials profit	20%	20%	20%	CF_1^S	20.00	20.00	22.75
C2.2	3.00	3.00	3.00	% CF_1^P	7.84%	7.84%	2.44%
CF2.2	11.00	11.00	11.00	% CF_1^S	39.22%	39.22%	44.62%
Production profit	30%	30%	30%	P2	19.50	19.50	19.50
C3.2	6.00	6.00	6.00	C2.1	12.00	12.00	12.00
Distribution profit	40%	40%	40%	NB2	4.50	4.50	4.50
C4.2	8.00	8.00	8.00	CF2.1	20.00	20.00	22.75
CF4.4	3.00	3.00	3.00	(M) $CF_{present}$	35.00	35.00	35.00
Sales profit	50%	50%	50%	CF_2^P	6.60	11.22	3.94
				CF_2^S	4.40	19.78	29.81
				% CF_2^P	12.94%	21.99%	7.73%
				% CF_2^S	8.63%	38.79%	58.46%
				P3	35.70	35.70	35.70
				C3.1	19.50	19.50	19.50
				CF3.1+CF3.2	24.40	19.78	29.81
				CF3.3	13.00	13.00	13.00
				NB3	10.20	10.20	10.20
				(D) $CF_{present}$	48.00	48.00	48.00
				CF_3^P	8.19	13.84	11.33
				CF_3^S	4.81	18.95	31.49
				% CF_3^P	16.05%	27.13%	22.21%
				% CF_3^S	9.44%	37.15%	61.74%
				P4	65.55	65.55	65.55
				C4.1	35.70	35.70	35.70
				CF4.1+CF4.2+CF4.3	29.21	18.95	31.49
				NB4	21.90	21.85	21.85
				(S) $CF_{present}$	51.00	51.00	51.00
				CF_4^P	2.20	8.51	19.55
				CF_4^S	0.80	13.44	14.94
				% CF_4^P	4.31%	16.69%	38.33%
				% CF_4^S	58.86%	26.34%	29.29%
				P5	65.55	65.55	65.55
				(FU) $CF_{present}$	51.00	51.00	51.00



and 3rd, the end user is charged with almost similar CF volumes. In the 2nd, the burden is higher for the distribution phase, while in the 3rd, it is higher for the sales that have a relatively higher profit rate. In the 1st, the unjustified high demand is being punished, while in the other two, the end user and the production processes are co-responsible for the CF produced. The failure to reduce the CF produced, and the excessive profit making, is punished in the 2nd and the 3rd approach, respectively. Alternatively, each phase can be charged with the difference between the real CF internally produced and the minimum technically feasible (unavoidable) CF according to standards.

Comparing the three alternative approaches with the predominant ones, several differences were highlighted (Fig. 9). Based on the fundamental methodol-

Table 2
Basic similarities and differences of the three alternative approaches

Approach		Product's end-user pays	CF production-based	Profit-based
Principle		CF is produced due to product's demand	CF is produced due to product's demand and due to production processes	CF is produced due to product's demand and is being allocated due to its profit
Disadvantage		Not allocated to production, it is over allocated to the end user	Not allocated to production, due to high demand	
Subprinciples	1	Allocated due to profit % in every phase		Allocated due to profit % in every phase/total profit of all phases
	2	In every phase only the CF internally produced is allocated	In every phase the total CF (transferred and produced) is allocated	
	3	Allocation percentage = profit of every phase/end price due to production		Allocation percentage = profit of every phase/total profit of all phases
	4	CF not allocated in a phase is transferred to the end user	CF that is not allocated in each phase is transferred to the next one	
	5	End user is responsible for CF production	End user and producer are both responsible for the production of CF	
	6	Weakness of CF production reduction of every phase is the one not to be blamed		Excessive profit making in any phase is blamed
	7	High demand is the one to be blamed		
	8	In every phase the percentage allocated includes the real CF produced and the minimal technically unavoidable CF		

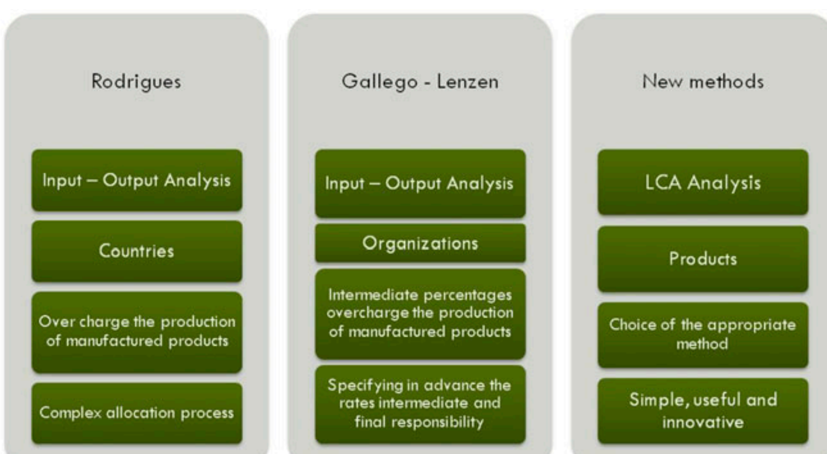


Fig. 9. The three new approaches compared with those of Gallego and Lenzen and Rodrigues.

ogy applied, both Gallego and Lenzen and Rodrigues et al. approaches follow the environmental IOA using the models of Leontief or Miller and Blair, respectively. On the contrary, the three alternative approaches follow the product's LCA. As already mentioned, the scale of application is ruled by the methodology followed (Fig. 7). Thus, Rodrigues et al. approach is more suitable for large-scale systems (e.g. countries, regions, and cities), while Gallego and Lenzen's is suitable for responsibility allocation between cities or companies/organizations. On the other hand, the three new approaches can be also used to allocate the responsibility for even a product or a service.

Regarding the complexity of the application process, several difficulties arise as far as the predominant approaches are concerned. Gallego and Lenzen approach handicap has to do with the fact that the responsibility rates between the intermediate and the final use should be predetermined. If a balanced allocation of the responsibility rate is chosen, then the first sector in the queue is being overcharged in case it produces the biggest environmental stresses. Regarding the environmental indicator suggested by Rodrigues et al. approach, apart from being extremely difficult to calculate, it overcharges the production of goods (although being exported) with several environmental stresses, while it benefits countries importing industrialized products. On the contrary, three new approaches are simple and easy to comprehend and apply. Using the most appropriate among the three, a socially just allocation of the CF produced along a product's supply chain, among its producers and users, can be achieved [18]. They can also be used in special conditions (e.g. when excessive profit-making is identified as a threat to the social character of a product or service [14]).

6. Conclusions

In this paper, the concept of three alternative new approaches (end-user pays, production based, and profit based), regarding CF's cost allocation produced along a "product's supply chain," is briefly demonstrated. The analysis of the concept of three alternative approaches for the CF produced cost allocation among the producers and the users along a supply chain is the basic objective. The decision-maker should have the ability to choose what he considers "a socially fair solution." Till now, research has been focused on defining the CF produced volume and cost. It is also equally important to define who is going to pay for this cost. A more detailed analysis of the "supply chain" in order to include additional phases of CF production (regarding the specific "product"), such as its reuse/recycling, should be imposed. These aspects must be taken into account in policy recommendation, incorporating environmental, and economical and social impacts in a national/regional/local level. The adoption of the most appropriate approach depends on the policy-makers' strategy and could lead decision-makers to targeting direct and also indirect impacts.

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