Cleaner Environmental Systems 4 (2022) 100072

Contents lists available at ScienceDirect

Cleaner Environmental Systems

journal homepage: www.journals.elsevier.com/cleaner-environmental-systems

Beyond normative system boundaries in life cycle assessment: The environmental effect of income redistribution

Denise T.L. Almeida [a,b,*], Bo P. Weidema [c], Antoine Godin [d]

[a] Centre Scientifique et Technique du Bâtiment, France
[b] Arts et Métiers, I2M Bordeaux and Institut de Chambéry, France
[c] Aalborg University, Danish Centre for Environmental Assessment, Denmark
[d] Agence Française de Développement and Centre de Recherche en Economie et Gestion de Paris Nord, France

ARTICLE INFO

Keywords:
Income redistribution
Consequential LCA
Stock-flow consistency
Second-order effects
Rebound effects

ABSTRACT

The current practice for assessing the environmental life cycle impacts of a product system is limited to the activities that respond directly to a change in demand. The revenue resulting from this change in demand is then used to pay for primary factors, such as wages and taxes, while the redistribution of that money is left outside the system boundaries. The aim of this paper is to address this limitation by providing a method in which the second order effects, i.e., the effects of re-spending that money, are included. For that, an income distribution model based on a simplified stock-flow consistent framework was developed. The method is applied in a closed economy consisting of six industries, banks and three household income groups. The dynamics of the income redistribution effects are studied throughout the rounds of (re)distribution, showing that the perturbation has a permanent effect on the economy, from environmental and social perspectives, and major changes occur in the first period of distribution. In addition, the paper also provides insights on the next steps for developing a full-scale model and discussions on the relationship between income distribution and productivity growth.

1. Introduction

The system that is analysed in a Life Cycle Assessment (LCA) is defined as a product system, consisting of interlinked unit processes that models the life cycle (the production, use and final disposal) of a product. According to ISO 14040, "Ideally, the product system should be modelled in such a manner that inputs and outputs at its boundary are elementary flows" (ISO 14040, Clause 5.2.3). "Elementary flow" is the ISO 14040 term for a flow "drawn from the environment without previous human transformation" or "released into the environment without subsequent human transformation" (ISO 14040, clause 3.12), thus establishing the traditional division between the economy and the environment. While the usefulness and ontological relevance of this division has been challenged (Weidema et al., 2018), it is still common practice to limit the analysis of the economy to the suppliers that will change their production capacity in response to an accumulated change in demand for the product. These suppliers are identified by tracing each required product input backwards through the chain of activities. The cost for one (purchasing) activity is a revenue for the supplying activity. For each activity, a part of the revenue leaks out as payments to employees and entrepreneurs, taxes, and resource rents (together known as "primary factors" or "value added"). In a closed steady-state system, all the original revenue must eventually leave the system as payments to primary factors, which are not traced further upstream, thus providing a clear delimitation of the activities included in the system.

The activities included in the product system are thus limited to those that react to the change in revenue, corresponding to the first-order effects of the original spending, while keeping overall spending constant ("*ceteris paribus*" assumption). Implicitly, when comparing products with different prices, a product system will include first-order price rebound effect, while excluding second-order effects, such as changes in consumption patterns that may result from the redistribution of the initial spending on the population groups that receive the primary factor income, or second order effects of stimulating specific activities, such as education, research, and technological development (Weidema et al., 2015).

While this delimitation to first-order effects provides an unambiguous delimitation of the product systems, it is nevertheless arbitrary and thus an inherently normative delimitation. The reluctance to include second-order effects in LCA may come from the intuition that this could lead to

---

* Corresponding author. 24 Rue Joseph Fourier 38400, Saint-Martin-d'Hères, France.
E-mail address: denise.almeida@cstb.fr (D.T.L. Almeida).

https://doi.org/10.1016/j.cesys.2022.100072
Received 8 November 2021; Received in revised form 24 January 2022; Accepted 28 January 2022

an infinite expansion of the system to include all consequences of all activities 'till the end of the World' (Weidema et al., 2015). However, in this article we show that it is possible to provide a better justified and equally unambiguous system boundary for LCA by going beyond this traditional normative delimitation and include also second-order effects.

Expressed in very simple terms, we show that the intuition of an 'infinite expansion of the system' is unwarranted, because only a part of the redistributed spending in each round of redistribution will involve changes in consumption patterns, so that over a number of iterations, the effects will converge to a finite result.

2. Previous suggestions on how to include second-order effects

Several examples of including rebound effects in environmental assessments are available in the literature (Börjesson Rivera et al., 2014; Font Vivanco and van der Voet, 2014; Horner et al., 2016; Pohl et al., 2019). However, the definitions and classifications of these effects are not consensual. The most commonly found taxonomies follow Hilty et al. (2006), decomposing rebound effects into "first-", "second-" and "third-order" effects; Berkhout et al. (2000), which used the terms "direct", "indirect", "structural" and "behavioural" effects; or Greening et al. (2000), which define "direct", "indirect", "economy-wide" and "transformational" effects.

Here, we use the term "first-order effects" for the activities that occur as a result of a specific spending (consumption decision) until it has leaked from these activities in the form of payments to primary factors (wages, production taxes, entrepreneurial income, and rents). This includes activities that occur as rebound effects of consumer price differences since these activities also occur as a result of the specific consumption decision.

First-order effects are fairly well-described in the literature, for example, the use of consumer-oriented approaches such as applying Engel curves (Font Vivanco et al., 2015), marginal propensities to spend (Alfredsson, 2004), marginal income changes affecting the consumption patterns (Thiesen et al., 2008) or the use of industry-oriented approaches, such as the use of marginal production cost (Kätelhön et al., 2015).

We define here the term "second-order effects" as the effects of a specific spending decision on income redistribution, consumption patterns, and productivity growth. These effects occur after the original spending has been received by the primary factor agents (laborers, government or recipients of tax redistributions, entrepreneurs, or rentiers), i.e., as a result of re-spending the original expenditure in subsequent spending loops.

Income redistribution is the mechanism that describes how the money received by primary factor agents is ultimately redistributed among agents involved in all economic sectors and income classes. To understand this mechanism, information about savings, investments, and profits is needed. In addition, as productivity is affected by investments, income redistribution has an important effect on productivity growth, as well as the parameters and equations that are used to quantify consumer behaviour, such as propensities to save and consume, consumption patterns, and consumption and production functions.

Productivity growth occurs when innovation takes place within a firm (microeconomic phenomena) and, as the innovation is adopted by other firms, it has consequences for other economic activities (macroeconomic consequences). Numerous sophisticated economic models studying these effects, from different economic schools (neoclassical to heterodox) can be found in the literature (for reviews, see Blecker and Stefford, 2019 and Kemp-Benedict, 2017).

Within the field of environmental assessments, particularly in life cycle assessments, productivity growth has been studied by integrating agent-based models (ABM) and learning curves or power law relationships. In addition, we also found examples of including income redistribution effects by using computable equilibrium models, which are also able to consider productivity growth effects.

Learning curves and power law relationships show how cumulative production experience and average costs are associated, allowing the consideration of scale (Argote and Epple, 1990; Bergesen and Suh, 2016). Being simple and intuitive tools, these two are not intrinsically associated with investments and other monetary relationships between different economic sectors, but they could be integrated in economic models. Examples of using learning curves to assess productivity growth can be found in Bergesen and Suh (2016) and Sandén and Karlström (2007).

In ABMs, the behaviour of individuals, including their propensity to adopt a change, and their production/consumption preferences, can be modelled and simulated (Gaffard and Napoletano, 2012) to assess productivity growth. Even though these models could, in theory, also cover consumer-spending issues and deal with investments and income redistribution, we do not know of any examples of this. Examples of coupling ABM with LCA to analyse productivity growth are Navarrete Gutiérrez et al. (2017) and Walzberg et al. (2018).

Computable equilibrium models, partial (CPE) or general (CGE) are able to cover productivity growth through the price equilibrium equations indexing each firm by its productivity, considering the respective (expected) growth rate. Some examples of coupling a CPE or CGE with LCA are Dandres et al. (2012), Earles et al. (2013), Nguyen et al. (2013), Vázquez-Rowe et al. (2014) and Whitefoot et al. (2011).

Income redistribution may be assessed by CPE and/or CGE through the multiplier effects, resulting from the perturbation of the circular flow of income within the economy by the injection of additional spending. Multiplier effects are obtained from the production and consumption linkages from the Social Accounting Matrix (SAM), also known as SAM multipliers, which trace the effects of changes in demand through changes in production, household's income, and back to final demand (Breisinger et al., 2009; Robinson, 2006; Thorbecke, 2000).

In equilibrium models, the new market equilibrium is obtained after a perturbation based on two optimisation criteria: consumer utility maximization and producer profit maximization (Yang and Heijungs, 2018). The long-term equilibrium is obtained using a system of equations that describe producer and consumer behaviour (production and utility functions), controlled by market-clearing constraints. Thus, in theory, these models might cover also consumption patterns, savings and investment for different economic sectors, however often neglecting or misrepresenting the financial flows and stocks (Berg et al., 2016; Burfisher, 2012, p.13).

Even though closely related, the income redistribution effect can be analysed separately from its possible influence on productivity growth. In this article, we limit ourselves to the effects of income redistribution, and leave the productivity (growth) puzzle to future research. Considering the limitations of CGE models when it comes to the representation of the financial system, we propose the use of Stock Flow Consistent (SFC) models to analyse the second-order effects of a change in the economy. SFC models explicitly take into account the income redistribution and can provide a consistent accounting framework for describing the effects of an economic shock.

3. A simple model of income redistribution

To exemplify the income redistribution in a very simplified stock-flow consistent framework, consider a closed economy consisting of banks and six producing industries: agriculture, mining activities, non-metal production, metal production, energy, and services. In Table 1, the six first numerical columns and rows presents the inter-industry monetary flows (here called matrix A), with capital goods endogenized.

In this economy, the households are disaggregated into three income groups: low, medium, and high-skilled, each receiving an industry-specific share of the value-added and having a specific consumption pattern. We assume that the only asset that households accumulate is deposits. On the other hand, we assume that firms are indebted towards banks (to finance production and/or to finance investment).

Households receive their wages and other labour income from industries, they spend a part of their income buying consumption goods,

Table 1
Social Accounting Matrix, initial situation (million US$, year).

	Agriculture	Mining	Nonmetal products	Metal products	Energy	Services	Banks	Households Low-skilled	Households Medium-skilled	Households High-skilled	Total outputs
Agriculture	4784	2536	32851	5520	1010	2490	4931	1084	11312	9597	76115
Mining	183	18223	2629	14714	703	55	2517	446	4148	4609	48226
Nonmetal products	400	128	15813	625	69	2480	11693	3701	25961	35070	95940
Metal products	130	2234	568	25842	411	5386	9750	1173	15764	31663	92920
Energy	338	1706	886	791	16886	809	3147	902	7063	7398	39925
Services	1787	6107	12477	10034	8839	12918	33104	2043	61125	111292	259727
Banks	1924	1219	2425	2349	1009	6565		566	15497	38751	70306
Households Low-skilled	4660	643	1698	330	220	2290	74				9915
Households Medium-skilled	28625	10126	14428	13218	6489	66417	1567				139303
Households High-skilled	33284	5304	12165	19497	4289	160317	3523				234856
Total flows	76115	48226	95940	92920	39925	259727	70306	9915	140870	238379	

and the remaining part is placed as deposits in banks. In counterpart, the banks pay interest on the deposits made in the previous period. The industries receive loans from banks and pay interest on loans to them. Fig. 1 summarises the transactions between the three sectors in this simplified model.

In this example, the initial financial stock represents the wealth of each household group. Concerning the industries' initial worth, we assume that they do not hold money balances so that they entirely borrow from banks the money needed to finance their new capital expenditures. For simplicity, we assume that all investment is financed via credit. Furthermore, we assume, again for simplicity, that banks hold only loans and finance themselves only via deposits. Therefore, neither the firms nor the banks have any net worth and that both type of agents distribute all profits they might make. We further assume the price level to be constant, implying that there is no asset revaluation taking place.

The income redistribution after a perturbation can be calculated as follows. The perturbation vector f represents the increase in consumption of one (or more) industry products, which is compensated by the decrease in consumption of the products of other industries. The sum of all elements in f must be zero to respect the budget constraints of the consumers, thus accounting also for any rebound effects (see the example below).

The industries provide and consume products from each other, therefore, a perturbation affecting one industry will also impact all the other industries that are linked to its activities throughout its life cycle.

Firstly, the technical coefficients matrix ($\tilde{Z}$) must be defined. It contains the ratio of inputs from the industry "i" to the industry "j" (z_{ij}) in relation to the total outputs of industry "j" (x_j) and it is obtained by Equation (1). Total outputs here do not include the interest paid by each industry to the banks, thus it represents the total outputs of the input-output table (Table A1) in Appendix A.

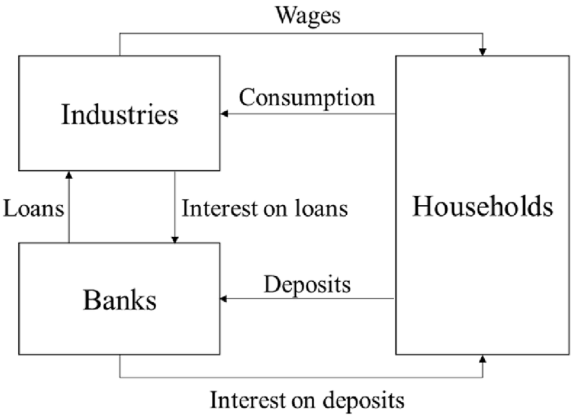

Fig. 1. Transactions between the included sectors.

$$\tilde{Z}=\frac{a_{ij}}{x_j} \tag{Equation 1}$$

A marginal change in final demand will affect the direct and indirect input requirements, obtained by Leontief's inverse $L=(I-\tilde{Z})^{-1}$. Therefore, the changes in the total outputs vector (x'), also known as the scaling factors, is calculated by Equation (2).

$$x'=(I-\tilde{Z})^{-1}f \tag{Equation 2}$$

These changes in total industries' outputs affect the amount of money received by the industries' employees, keeping the same proportions between income groups within each industry as before the shock. This can be understood either as a proportional change in the number of workers in the affected industries, or as proportional changes in wages.

This impact is algebraically computed by multiplying the normalized gross value-added coefficients matrix ($\tilde{B}$), where $\tilde{b}_j = \frac{b_j}{xj}$, by the changes in total outputs vector (x'), as presented in Equation (3).

$$G=\tilde{B}x' \tag{Equation 3}$$

Matrix G represents the changes in primary factor income, i.e., the labour income received by households working in industry "j", after any tax redistribution of income, in the three 'Households' rows.

The next step consists in the re-spending of this money, i.e., households change their consumption according to their income change. In reality, households save a part of their additional income and another part is spent on consumption goods. For the sake of simplification, we consider here that a household's consumption is only a function of labour income, while their property income is entirely reinvested. In this simple example, we considered that low-skilled households save 5%, medium-skilled save 10% and high-skilled workers save 15% of their respective labour income (i.e., vector 's' = 0.05, 0.10, 0.15). Therefore, their change in final consumption (C) can be calculated by Equation (4), which multiplies the normalized final demand C matrix ($\tilde{C}$), where $\tilde{c}_{ij} = \frac{c_{ij}}{\sum_{j=1}^{6} c_{ij}}$, by the H matrix, which represents the disposable income of households ($H_i = G_i.s_i$).

$$C=\tilde{C}.H \tag{Equation 4}$$

And, for the subsequent rounds, the new perturbation vector is computed as follows:

$$F^{r+1}=\tilde{C}H^r$$

The current change in income affects the consumption of households in the next distribution round. This induced consumption includes the shifts in consumption between industries due to the different spending patterns of the three income groups. Here a 'distribution period' includes the changes in the compensation of employees resulting from perturbation and the induced consumption resulting from the changes in income.

To illustrate this calculation framework, suppose a shift in spending of US$1750 million from the energy sector to the non-metal sector. This could occur, for example, when the households buy insulation materials (increase their spending with non-metal industry products) and save energy (decrease their spending on energy industry products). The calculations presented in this paper are provided in the Supplementary Material.

The perturbation will firstly have an effect on the life cycle of energy and non-metal products (represented by the scaling factors), as presented in Table 2.

After the perturbation, agriculture, mining, and non-metal industries have positive scaling factors, and the other three industries reduce their total output. As previously explained, these changes have consequences in the value-added of all industries and thus will affect the wages and salaries of households (represented by the matrix G and presented in Table 3), which affect their consumption, i.e., their demand for industries' products (Table 4), and thus the total output of the industries in a second round. These effects, here called second-order effects, occur as a result of re-spending the money originally received and the propagation round by round.

Households' income is partly labour income, partly property income. This latter is here obtained from the deposits held multiplied by the interest rate on deposits (here 0.25%), reflecting economic growth. In this simple model, all income groups have increasing real income over time in the *status quo* situation.

Here we are interested in the net impacts, i.e., that associated with the perturbation. For this reason, Table 3 presents the annual income of each household group before perturbation and the *net* changes to this (here matrix G), i.e., without the part of their property income that would change independently of the perturbation.

In the first period of distribution, low-skilled households receive more money than they would have received in a *status quo* situation, increasing their income by US$ 61.4 million, while medium and high-skilled households have a decrease in their income by US$ 29.2 and US$ 27.8 million, respectively.

The increase in low-skilled households' income caused by the shock occurs because the industries that have an increase in their output in the first period (Table 2) are also the industries that contribute the most to the income of the low-skilled households (see Fig. 2: agriculture with 56%, mining 12%, and non-metal products with 16%).

On the other hand, the relative decrease in income for medium- and high-skilled groups is mainly explained by the decrease in income from the energy industry itself and from the services consumed by the energy industry. Medium-skilled households are more impacted than high-skilled households because they are the most vulnerable income group to any change in the energy industry's revenue (Fig. 2).

Table 2
Changes in total output of industries in the first five periods of monetary distribution (million US$).

Industry	Before perturbation	Distribution				
		1st	2nd	3rd	4th	5th
Agriculture	76115	705	2	1.1	0.8	0.6
Mining	48226	2	1	0.7	0.5	0.4
Nonmetal products	95940	2114	2	1.4	1.1	0.8
Metal products	92920	−38	2	1.4	1.0	0.8
Energy	39925	−3048	1	0.6	0.4	0.3
Services	259727	−434	5	3.8	2.9	2.2
Total	***612853***	***−700***	***12***	***8.9***	***6.8***	***5.1***

Table 3
Labour income received by households before perturbation and the changes in the first five distribution periods (million US$, year).

Household group	Before perturbation	Distribution				
		1st	2nd	3rd	4th	5th
Wages. Low-skilled	9841	61.4	0.2	0.1	0.1	0.1
Wages. Medium-skilled	139303	−29.2	2.8	2.1	1.6	1.2
Wages. High-skilled	234856	−27.8	4.6	3.5	2.7	2.0
Total	***384000***	***4.4***	***7.6***	***5.7***	***4.3***	***3.3***

Table 4
Changes in final demand in the subsequent periods after an initial perturbation (million US$, year).

Industry	Perturbation	Distribution				
		1st	2nd	3rd	4th	5th
Agriculture	0	3.3	0.4	0.3	0.2	0.2
Mining	0	1.4	0.2	0.1	0.1	0.1
Nonmetal products	1750	13.5	1.3	1.0	0.7	0.6
Metal products	0	0.3	1.0	0.7	0.5	0.4
Energy	−1750	3.3	0.3	0.2	0.2	0.1
Services	0	−13.2	3.4	2.6	2.0	1.5
Total	***0.0***	***8.4***	***6.6***	***5.0***	***3.8***	***2.9***

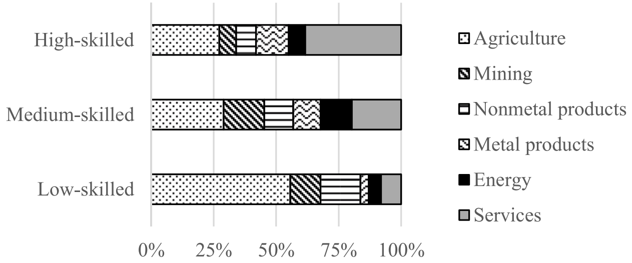

Fig. 2. Income share from each productive industry for each household type.

One may notice that the second period presents an increase in total wages, and from the third period onwards it is reduced and tends to be zero again (Table 3). This happens because the perturbation is a shift in expenditure from one industry to another, so that at the beginning of the first period there is no change in total final demand (see Table 4). However, the induced change in consumption that occurs at the end of the first period is no longer zero (because households save money at different intensity) and thus the total changes in the compensation of employees are also increasing and remain growing over the subsequent periods. Since it is an impulse shock, i.e., the exogenous perturbation occurs only in the beginning, the effects behave as an impulse as well, slowly dying out over time.

As previously mentioned, the changes in the income of households

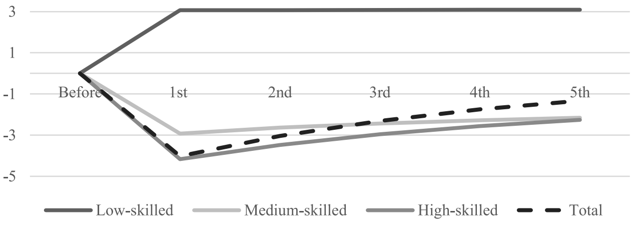

Fig. 3. Low-skilled, medium-skilled and high-skilled households' net changes in wealth (mi US$).

also affect their wealth. Fig. 3 presents the net changes in the wealth of households due to the perturbation.

The perturbation reduces the wealth of medium and high skilled households (and also the whole economy) in the first distribution period, although all three groups become richer with time. The perturbation transfers money from medium and high-skilled to low-skilled households. These latter invest less money than medium and high-skilled, therefore the total economic growth, which in this model relies exclusively on investment, is lower than it would be without the perturbation.

To ensure stock-flow consistency, all transactions are accounted for in a transactions-flow matrix (TFM). In this accounting framework, each flow has an origin (with a negative sign) in a sector and a destination (with a positive sign), therefore the sum in each column and each row is zero. Table 5 presents the net changes in the TFM to analyse how each institutional unit was impacted by the perturbation.

In this example, households save less money than they would have saved without the perturbation. At the same time, some industries (Agriculture, Mining and Nonmetal products) see their expenses (intermediate consumption and wage payments) reducing more than their income while the other industries see their income increase more than their expense. Therefore, all industries take fewer loans than they would have taken in a status-quo situation (negative values in the current account of liabilities for all industries). These changes in liabilities due to the perturbation have a permanent effect on the economy. Fig. 4 shows the net changes in industries' liabilities in the first five periods of distribution. They oscillate considerably in the first four periods and then they stabilize.

When assessing the income redistribution, it is important to assess the impact on equality (the social profile). This because earning additional money does not affect all persons equally, i.e., an additional unit of income has more utility for a lower-income person than for a higher-income one. Equity-weights can be applied to reflect the marginal change in utility for each income group, using the elasticity of the marginal utility (ρ), as presented in equation (5).

$$VA_{w,i} = VA_i \times \left(\frac{Average\ income}{income\ of\ group\ i}\right)^{\rho} \qquad \text{(Equation 5)}$$

In this equation, the $VA_{w,i}$ corresponds to the equity-weighted income, for the income group "i", being low-skilled, medium-skilled, and high-skilled. The elasticity of the marginal utility (ρ) is obtained empirically from surveys based on individual happiness and life satisfaction vis-à-vis the household income. We use here the value provided by Layard et al. (2008), $\rho = 1.24$, with a 95% confidence interval of 1.14–1.35. We assumed, arbitrarily, for this exercise an average annual income of US$ 6085 per household, being the average annual income by our income groups as follows: US$ 2500 for low-skilled, US$ 5000 for medium-skilled, and US$ 7500 for high-skilled.

The net results of the weighted total income before perturbation and the weighted changes in monetary distribution periods are presented in Table 6.

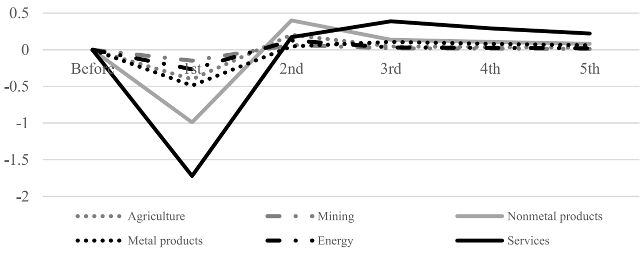

Fig. 4. Change in loans by industry (mi US$).

Table 6
Net equity-weighted income of households before perturbation and changes in distribution periods (million US$, year).

Household	Before perturbation	Distribution				
		1st	2nd	3rd	4th	5th
Low-skilled	29651	185	1	0	0	0
Medium-skilled	177696	−37	4	3	2	2
High-skilled	181203	−21	4	3	2	2
Total	*388549*	*126*	*8*	*6*	*4*	*3*

The income redistribution effect on low-skilled households is even more pronounced when equity-weighted, as would be expected. The distribution of US$61 million from medium-skilled and high-skilled to low-skilled causes, on one hand, a decrease in economic growth, on the other hand, increases the total societal utility.

The sum of the three weighted changes corresponds to the net redistribution of utility associated with the perturbation, which, expectedly, drops each round until a new steady state is reached. The positive sign of the balance indicates a beneficial redistribution effect, i.e., the perturbation in this example causes a monetary distribution where low-skilled gain more utility, while high-skilled households lose.

The equity-weighted change in net wealth can be calculated from the equity-weighted income. Fig. 5 presents the calculations of the changes in the net wealth associated with the perturbation.

The impact on net wealth is even more accentuated for low- and

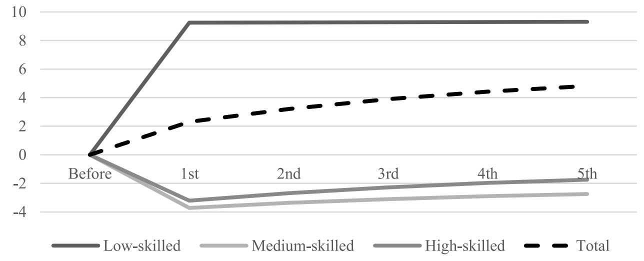

Fig. 5. Changes in equity-weighted net wealth (mi US$).

Table 5
Net changes in transactions-flow matrix in first distribution period.

	Households			Non-financial corporations						Financial corporations	Σ
	Low-skilled	Medium-skilled	High-skilled	Agriculture	Mining	Nonmetal products	Metal products	Energy	Services	Banks	
Wages	61	−29	−28	−633	−1	−639	14	861	393		***0***
Consumption	−58	26	24	3	1	1763	0	−1747	−13		***0***
Intermediate consumption				630	−1	−1123	−14	886	−378		***0***
Interests											***0***
Change in deposits	−3	3	4							−4.0	***0***
Change in loans				−0.4	−0.1	−1.0	−0.5	−0.3	−1.7	4.0	***0***
Σ	***0***	***0***	***0***	***0***	***0***	***0***	***0***	***0***	***0***	***0***	

medium-skilled households, while the changes in the net wealth of high-skilled households are less negative, than without equity-weighting, showing that high-skilled households are less vulnerable to income perturbations and recover faster than medium-skilled households. With equity-weighting, we observe that total economy net wealth increases with the perturbation, contrary to what is observed without equity-weighting in Fig. 3.

4. Including environmental effects in the model

The previous results only consider the impacts on value-added and final demand. In this section, we include an environmental externality, which is represented, for the sake of simplification, by the carbon dioxide emissions (CO_2) from industrial activities. The values arbitrarily considered for the sake of this example are presented in Table 7.

The coefficients obtained from these values are then included as a row in the matrix $\tilde{B}$. Thus, applying the same calculation framework presented in the previous section, analogously to the calculations conducted to assess the changes in primary factor income caused by the perturbation in the distribution periods, we can now obtain changes in emissions, round-by-round, as presented in Table 8.

The economic perturbation causes a reduction in CO_2 emissions during the first distribution period (representing around 2% of total annual emissions), followed by slight increases in the subsequent distribution periods that tend to zero with time. Fig. 6 presents the changes in emissions of each industry.

The reduction in demand for energy products right after the perturbation, as discussed in the previous section, is the main reason for the decrease in emissions observed in the first period. The increase in emissions from agriculture and non-metal products is significantly lower than the decrease in emissions from the energy industry, resulting in a net decrease in emissions. The other industries remain practically constant in terms of CO_2 emissions.

These results show that the income redistribution also implies a *permanent* effect on cumulative CO_2 emissions. In this example, only CO_2 emissions were considered, but this would also apply to other substances or impact categories.

5. Data sources and data availability for a full-scale model

The goal of this article is to show that it is possible to include second-order effects in life cycle assessments, without expanding infinitely the system boundaries. In the example provided here, some important and significant simplifications were made. First, the economy is only composed of six industrial sectors and the banks, value-added here is equivalent to the income of households and final demand is simplified to final consumption. Nowadays, numerous social accounting matrices and multi-regional input-output tables (MRIO), such as Exiobase, are available for the whole economy at different levels of resolution, i.e., including also other elements of value-added, such as taxes, subsidies, and operating surplus; intermediary consumption for an important number of industries; more detailed information on final demand, such as gross fixed capital formation and change in inventories; imports and exports. Our model can equally well be applied to such more detailed data sources, better representing economic interactions to identify and describe how each economic sector is impacted by an economic shock. For example, when including government accounts, the tax redistribution can be accounted for in the dynamics of the economy, which is particularly relevant for assessing the social impacts.

Table 8
Carbon dioxide emissions before perturbation and the changes in distribution and redistribution periods (million tons of CO_2).

	Before perturbation	Distribution				
		1st	2nd	3rd	4th	5th
Total CO_2 emissions	2000	−40.6	0.041	0.029	0.022	0.017

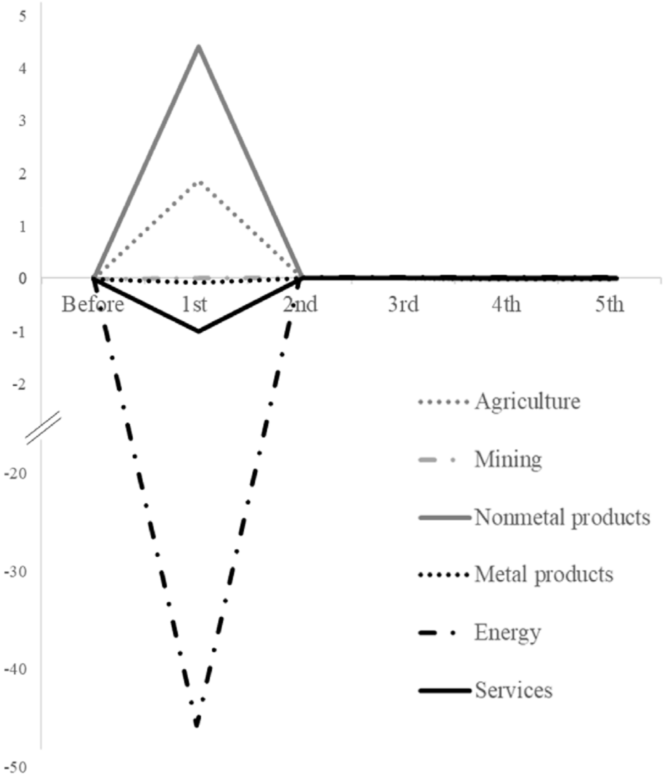

Fig. 6. Carbon dioxide emissions changes in distribution periods, by industry (million tons of CO_2).

In the example presented in this article, only carbon dioxide emissions were calculated. Multi-regional input-output tables, such as Exiobase, also present air pollution and other greenhouse gas emissions, energy and water use, land occupation, and other relevant environmental indicators. The integration of data from an MRIO will allow performing a complete environmental assessment.

In addition, in this article, households are disaggregated into three levels of income. A potential improvement is to associate to each income group more precise parameters to describe their consumption behaviour, e.g., the inclusion of more realistic propensities to consume out of wealth and out of income. Moreover, households could also be divided into workers, managers and supervisors and executives (closer to stockholders/capitalists), since they have different relationships with firms' production and, as a result, different ways of compensation. In addition, MRIOs such as Exiobase provide more information on social profile of the employees of each industry, which opens the field for improving the social life cycle assessment as demonstrated in Weidema (2018, 2020).

In our example, the initial net wealth is estimated from the net income

Table 7
Carbon dioxide emission intensities by industry.

	Agriculture	Mining	Nonmetal products	Metal products	Energy	Services
CO_2 emissions (t/USD)	0.0027	0.0043	0.0021	0.0022	0.0154	0.0024

of households and all saved money is invested in industries proportionally to their outputs. More realistic data on stocks and investment are available in the databases of different organisations, such as the Organisation for Economic Co-operation and Development (OECD), the International Monetary Fund (IMF), central banks, and others. The integration of these databases into the model will help to identify the sectors that are impacted, and who is at risk, from a perturbation. These databases also provide statistical data for interest rates, which will allow obtaining more realistic modelling of economic growth.

6. Final discussions

The results presented in the previous sections show that impulse shocks have a permanent effect, i.e., implies a new steady state. We show that the major changes occur in the first distribution period, and that, regardless of the simplifications done in this example, the inclusion of (at least) this first period in environmental and social assessments is feasible and would be helpful for decision support. These simplifications can be addressed by reproducing the framework presented in this paper to other scenarios and also including other sectors in an open economy.

Profit (of firms and banks) and level of prices should also be included to represent more realistically the economy. For this matter, and also for allowing a better representation of consumption behaviour, an agent-based model would be helpful.

Another topic that should be investigated in future research is investment. In this simple model, for the sake of simplification, the change in the balance sheet of non-financial corporations (reduction in their liabilities) means reducing their borrowing, while these savings could be used for different purposes, such as investing in fixed capital, distributing profits, etc. It would be important to include an investment function in the model to simulate the effects of investing the saved money.

One may notice that even though the focus of this simple model is to quantify the effects of income redistribution, productivity is also partially studied, since capital accumulation, wages, savings, and investments in firms are interrelated. Since income (re)distribution is an important factor for assessing productivity growth (Blecker and Setterfield, 2019), a full-scale model would allow a better understanding of productivity growth with more accurate results on how industries increase their productivity depending on the changes in investment (and by type of investment).

With regard to the inclusion of other life cycle phases in the proposed model, while domestic waste is taken into account through the consumption of waste treatment, use phase emissions, other than the exogenous energy savings, were not included for the sake of simplification. This has limited consequences for our specific example (use phase of insulating materials presents negligible emissions), however, as a general practice, it is recommended to endogenise consumption activities and emissions in the input-output model.

Finally, the simple model presented in this paper is applied to a case study where the exogenous shock is a shift in final demand (to respect the household's budget constraint), and thus the second-order effects are offset by the net-zero change in final demand. For exogenous shocks represented by an extra demand (for example, injection of extra money from public policies), the relative importance of second-order effects would be more evident.

7. Conclusions

This article shows that it is possible to include the effects of income redistribution in the LCA methodology within a stock-flow consistent framework. The inclusion of financial aspects is needed to represent the realistic situation where saved money is invested in industries and it has environmental and social consequences. We show that the income redistribution effects have a permanent effect on the economy as well as on the cumulated CO_2 emissions.

We applied this novel method on a shift in consumption from energy to non-metal products industry, which could occur, for example, when households expend their money on insulation goods and would save energy. The results present an income redistribution from higher income groups to the low-income group, which has a lower savings rate than other groups and, as a result, decrease the net wealth of the whole economy. However, total marginal utility is increased, and accumulated carbon dioxide emissions are decreased.

Regardless of the simplifications made in the example, the results show the importance of including the environmental burdens and benefits resulting from income redistribution, at least in the first distribution period, as well as the contribution to marginal utility in social life cycle assessments.

Finally, we point out possible ways to improve the framework presented in this article. For example, the use of more comprehensive input-output tables, i.e., multi-regional input-output tables, with more substances and resources and more detailed information concerning the industries' inputs are needed to make real conclusions about the sustainability impacts of products and services. The inclusion of government is also needed, to provide a better picture of the change in financial flows and stocks, as well as environmental and social impacts.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cesys.2022.100072.

Appendix A

The changes in primary factors are obtained proportionally to the changes in industries' outputs through the Leontief's inverse as in classic Input-Output analysis. Therefore, the coefficients matrices are calculated by using total outputs from Table A1.

Table A.1
Input-Output Table

	AGRICULTURE	MINING	NONMETAL PRODUCTS	METAL PRODUCTS	ENERGY	SERVICES	FINAL CONSUMPTION	TOTAL OUTPUTS
AGRICULTURE	4784	2536	32851	5520	1010	2490	25000	74191
MINING	183	18223	2629	14714	703	55	10500	47007
NONMETAL PRODUCTS	400	128	15813	625	69	2480	74000	93515

(continued on next column)

Table A.1 (*continued*)

	AGRICULTURE	MINING	NONMETAL PRODUCTS	METAL PRODUCTS	ENERGY	SERVICES	FINAL CONSUMPTION	TOTAL OUTPUTS
METAL PRODUCTS	130	2234	568	25842	411	5386	56000	90571
ENERGY	338	1706	886	791	16886	809	17500	38916
SERVICES	1787	6107	12477	10034	8839	12918	201000	253162
VALUE-ADDED, LOW-SKILLED	4660	643	1698	330	220	2290		
VALUE-ADDED, MEDIUM-SKILLED	28625	10126	14428	13218	6489	66417		
VALUE-ADDED, HIGH-SKILLED	33284	5304	12165	19497	4289	160317		
VA SUMMED	66569	16073	28291	33045	10998	229024	384000	
TOTAL INPUTS	74191	47007	93515	90571	38916	253162		597362

It is important to highlight that transactions with banks are not obtained from Leontief's inverse like the other transactions. Rather, the interest paid by industries to banks (Int_L) and from banks to households (Int_D) in the current round (r) are calculated by multiplying the interests rates (i_L and i_D) respectively to changes in loans (L) and deposits (D) from previous period (r-1), as described in Equation (A.1) and A.2.

$$Int_L{}^r = L^{r-1} \cdot i_L \qquad \text{(Equation A1)}$$

$$Int_D{}^r = D^{r-1} \cdot i_D \qquad \text{(Equation A2)}$$

The changes in stocks (loans and deposits) are obtained from the transactions-flow matrix computed in the end of each period. Loans taken from industry 'j' are the difference between its uses and resources and deposits made by household 'k' is the difference between its resources and uses, as presented in Equation (A.3) and A.4.

$$L^r{}_j = \sum_k W_{k,j}{}^r + Int_{Lj}{}^r - \sum_k C_{j,k}{}^r - \, IC_j{}^r, \; j = 1, \ldots, 6\,;\, k = 1, 2, 3 \qquad \text{(Equation A3)}$$

Where "IC_j" represents the net intermediate consumption of industry 'j', "k" represents each income group of households, "$W_{k,j}$" represents the wages payed from industry 'j' to income group 'k'.

$$D^r{}_k = \sum_k W_{k,j}{}^r + \, Int_{Dk}{}^r - C_k{}^r \qquad \text{(Equation A4)}$$

References

Alfredsson, E.C., 2004. "Green" consumption - no solution for climate change. Energy 29, 513–524. https://doi.org/10.1016/j.energy.2003.10.013.

Argote, L., Epple, D., 1990. Learning curves in manufacturing. Science 247, 920–924 (80-.).

Berg, M.B., Hartley, B., Richters, O., 2016. Stock-flow consistent input output models as a bridge between post-keynesian and ecological economics. In: FMM Conference.

Bergesen, J.D., Suh, S., 2016. A framework for technological learning in the supply chain: a case study on CdTe photovoltaics. Appl. Energy 169, 721–728. https://doi.org/10.1016/j.apenergy.2016.02.013.

Berkhout, P.H.G., Muskens, J.C., Velthuijsen, J.W., 2000. Defining the rebound effect. Energy Pol. 28, 425–432.

Blecker, R.A., Setterfield, M., 2019. Heterodox Macroeconomics: Models of Demand, Distribution and Growth. Edward Elgar Publishing, Cheltenham, UK.

Börjesson Rivera, M., Håkansson, C., Svenfelt, Å., Finnveden, G., 2014. Including second order effects in environmental assessments of ICT. Environ. Model. Software 56, 105–115. https://doi.org/10.1016/j.envsoft.2014.02.005.

Breisinger, C., Thomas, M., Thurlow, J., 2009. Social Accounting Matrices and Multiplier Analysis: an Introduction with Exercises. International Food Policy Reasearch Institute, Washington DC. https://doi.org/10.2499/9780896297838fsp5Library.

Burfisher, M.E., 2012. Introduction to Computable General Equilibrium Models, Introduction to Computable General Equilibrium Models. https://doi.org/10.1017/cbo9780511975004.002.

Dandres, T., Gaudreault, C., Tirado-Seco, P., Samson, R., 2012. Macroanalysis of the economic and environmental impacts of a 2005-2025 European Union bioenergy policy using the GTAP model and life cycle assessment. Renew. Sustain. Energy Rev. 16, 1180–1192. https://doi.org/10.1016/j.rser.2011.11.003.

Earles, J.M., Halog, A., Ince, P., Skog, K., 2013. Integrated economic equilibrium and life cycle assessment modeling for policy-based consequential LCA. J. Ind. Ecol. 17, 375–384. https://doi.org/10.1111/j.1530-9290.2012.00540.x.

Font Vivanco, D., Kemp, R., Van Der Voet, E., 2015. The relativity of eco-innovation: environmental rebound effects from past transport innovations in Europe. J. Clean. Prod. 101, 71–85. https://doi.org/10.1016/j.jclepro.2015.04.019.

Font Vivanco, D., van der Voet, E., 2014. The rebound effect through industrial ecology's eyes: a review of LCA-based studies. Int. J. Life Cycle Assess. 19, 1933–1947. https://doi.org/10.1007/s11367-014-0802-6.

Gaffard, Jean-Luc, Napoletano, Mauro, 2012. Introduction. Improving the Toolbox: New Advances in Agent-Based and Computational Models. Agent-Based Models and Economic Policy. Presses de Sciences Po.

Greening, L.A., Greene, D.L., Difiglio, C., 2000. Energy efficiency and consumption - the rebound effect - a survey. Energy Pol. 28, 389–401. https://doi.org/10.1016/S0301-4215(00)00021-5.

Hilty, L.M., Arnfalk, P., Erdmann, L., Goodman, J., Lehmann, M., Wäger, P.A., 2006. The relevance of information and communication technologies for environmental sustainability - a prospective simulation study. Environ. Model. Software 21, 1618–1629. https://doi.org/10.1016/j.envsoft.2006.05.007.

Horner, N.C., Shehabi, A., Azevedo, I.L., 2016. Known unknowns: indirect energy effects of information and communication technology. Environ. Res. Lett. 11. https://doi.org/10.1088/1748-9326/11/10/103001.

Kätelhön, A., Von Der Assen, N., Suh, S., Jung, J., Bardow, A., 2015. Industry-cost-curve approach for modeling the environmental impact of introducing new technologies in life cycle assessment. Environ. Sci. Technol. 49, 7543–7551. https://doi.org/10.1021/es5056512.

Kemp-Benedict, E., 2017. Cost share-induced technological change and Kaldor's stylized facts. Metroeconomica 70, 2–23. https://doi.org/10.1111/meca.12223.

Layard, R., Nickell, S., Mayraz, G., 2008. The marginal utility of income. J. Publ. Econ. 92, 1846–1857. https://doi.org/10.1016/j.jpubeco.2008.01.007.

Navarrete Gutiérrez, T., Rege, S., Marvuglia, A., Benetto, E., 2017. Sustainable Farming Behaviours: an Agent Based Modelling and LCA Perspective. Springer Int. Publ. Switz.

Nguyen, T.T.H., Corson, M.S., Doreau, M., Eugène, M., Van Der Werf, H.M.G., 2013. Consequential LCA of switching from maize silage-based to grass-based dairy systems. Int. J. Life Cycle Assess. 18, 1470–1484. https://doi.org/10.1007/s11367-013-0605-1.

Pohl, J., Hilty, L.M., Finkbeiner, M., 2019. How LCA contributes to the environmental assessment of higher order effects of ICT application: a review of different approaches. J. Clean. Prod. 219, 698–712. https://doi.org/10.1016/j.jclepro.2019.02.018.

Robinson, S., 2006. Macro models and multipliers: Leontief, stone, keynes, and CGEModels. In: Poverty, Inequality and Development: Essays in Honor of Erik Thorbecke. Springer Science, New York, pp. 205–232. https://doi.org/10.1007/0-387-29748-0.

Sandén, B.A., Karlström, M., 2007. Positive and negative feedback in consequential life-cycle assessment. J. Clean. Prod. 15, 1469–1481. https://doi.org/10.1016/j.jclepro.2006.03.005.

Thiesen, J., Christensen, T.S., Kristensen, T.G., Andersen, R.D., Brunoe, B., Gregersen, T.K., Thrane, M., Weidema, B.P., 2008. Rebound effects of price differences. Int. J. Life Cycle Assess. 13, 104–114. https://doi.org/10.1065/lca2006.12.297.

Thorbecke, E., 2000. The use of social accounting matrices in modeling. In: 26th General Conference of the International Association for Research in Income and Wealth. Cracow, Poland.

Vázquez-Rowe, I., Marvuglia, A., Rege, S., Benetto, E., 2014. Applying consequential LCA to support energy policy: land use change effects of bioenergy production. Sci. Total Environ. 472, 78–89. https://doi.org/10.1016/j.scitotenv.2013.10.097.

Walzberg, J., Dandres, T., Samson, R., Merveille, N., Cheriet, M., 2018. An agent-based model to evaluate smart homes sustainability potential. IEEE Int. Symp. Pers. Indoor Mob. Radio Commun. PIMRC 2017-Octob 1–7. https://doi.org/10.1109/PIMRC.2017.8292682.

Weidema, B.P., 2020. Towards a Taxonomy for Social Impact Pathway Indicators 11–23. https://doi.org/10.1007/978-3-030-01508-4_2.

Weidema, B.P., 2018. The social footprint—a practical approach to comprehensive and consistent social LCA. Int. J. Life Cycle Assess. 23, 700–709. https://doi.org/10.1007/s11367-016-1172-z.

Weidema, B.P., Grbeš, A., Brandão, M., 2015. The implicit boundary conditions of attributional and consequential LCA. Present. to ISIE Conf.

Weidema, B.P., Schmidt, J., Fantke, P., Pauliuk, S., 2018. On the boundary between economy and environment in life cycle assessment. Int. J. Life Cycle Assess. 23, 1839–1846. https://doi.org/10.1007/s11367-017-1398-4.

Whitefoot, K.S., Grimes-Casey, H.G., Girata, C.E., Morrow, W.R., Winebrake, J.J., Keoleian, G.A., Skerlos, S.J., 2011. Consequential life cycle assessment with market-driven design: development and demonstration. J. Ind. Ecol. 15, 726–742. https://doi.org/10.1111/j.1530-9290.2011.00367.x.

Yang, Y., Heijungs, R., 2018. On the use of different models for consequential life cycle assessment. Int. J. Life Cycle Assess. 23, 751–758. https://doi.org/10.1007/s11367-017-1337-4.