To cite this version :

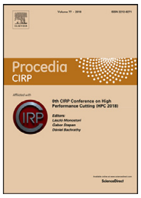
Denise T.L. ALMEIDA, Carole CHARBUILLET, Charlotte HESLOUIN, Alexandra LEBERT, Nicolas PERRY - Economic models used in consequential life cycle assessment: a literature review - Procedia CIRP - Vol. 90, p.187-191 - 2020

Procedia CIRP 90 (2020) 187–191

Contents lists available at ScienceDirect

Procedia CIRP

journal homepage: www.elsevier.com/locate/procir



Economic models used in consequential life cycle assessment: a literature review

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ARTICLE INFO

Keywords:
Consequential LCA
Consequential modelling
Non-marginal change
Economic models
Construction sector

ABSTRACT

The construction sector is a key actor for achieving the sustainable development goals, particularly from an environmental point of view, due to the significant sector's contribution to energy consumption, greenhouse gas and pollutants emissions, waste generation, resources depletion etc. Life Cycle Assessment (LCA) is a multi-criteria tool to assess environmental impacts, preventing the impact transferring from one life cycle stage to another and thus is widely used to support decision-making.

Consequential LCA (CLCA) can be particularly relevant for decisions involving non-marginal changes and may have an important role in supporting decision-makers of the construction sector by giving a wider comprehension of the environmental impacts associated with the changes caused by their decisions.

Particularly when assessing large-scale consequences, it is recommended to couple an economic model to the CLCA methodology to assess the changes in the background system. Therefore, this research aims at reviewing the CLCA works applied to the construction sector and the use of economic models in CLCA for assessing non-marginal changes. For that, the review is divided in two parts: the first reviews the CLCA works and papers in the construction sector; and the second part reviews CLCA studies that assess non-marginal changes, regardless the activity or sector.

1. Introduction

The buildings and construction sector (residential and tertiary) is a key player to attain sustainable development goals. Regarding energy consumption, the sector has the largest shares in a global perspective, responding for 36% of the global final energy consumption in 2017 (UN Environment and International Energy Agency, 2017).

Regarding greenhouse gas (GHG) emissions, the sector's contribution was around 39% of 2017's global GHG emissions (UN Environment and International Energy Agency, 2017).

The sector is also responsible for emitting important amounts of pollutants such as particulate matters (PM), polycyclic aromatic hydrocarbons (PAH), hydrofluorocarbons (HFC) and polychlorinated di-benzo-dioxins (PCDD), for example (CITEPA, 2019). In France, buildings and construction sector accounts for more than 50% of these four pollutant groups (CITEPA, 2019).

Waste generation and resource consumption are other significant activities for buildings and construction sector. In France, for example, the sector's share for waste generation is around 75% (Ministère de la Transition Ecologique et Solidaire, 2015). Concerning material resources, 40 out of 93 billion tons of resources extracted globally each year are addressed to the buildings sector and less than 10% of the construction materials come from a circular economy (Rapf, 2015).

Therefore, the sector recognizes the urgency for actions to reduce the environmental impacts (International Energy Agency and United Nations Environment Programme, 2018). From this perspective, life cycle assessment (LCA) is a recognized tool to assess environmental impacts from a life cycle viewpoint and thus is widely used to address this issue.

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https://doi.org/10.1016/j.procir.2020.01.057

A variety of LCA approaches is available in the literature. Guinée et al. (2018) provide a non-exhaustive review of the currently used LCA approaches. According to the authors, the most known and discussed in the literature are attributional and consequential LCA.

Consequential LCA (CLCA) is defined by UNEP's Global Guidance Principles for LCA Databases as 'a modeling approach that provides information on the environmental burdens that occur, directly or indirectly, as a consequence of a decision, generally represented by changes in demand' (UNEP, 2011).

Because of this direct relationship between CLCA and decision-making, this approach can play an important role in helping decision-makers of buildings and construction sector while providing a wider comprehension of the environmental impacts caused by their decisions, in particular when assessing large-scale policies.

Despite the LCA community's lack of consensus on the criteria for choosing one approach or another (Guinée et al., 2018), it seems to be a common-sense that CLCA is relevant for strategical decisions involving changes (Guiton and Benetto, 2013) or for assessing the environmental consequences of non-marginal changes (EC-JRC, 2010).

In this purpose, biofuels and agricultural sectors have leveraged the development of the CLCA methodology, mainly for assessing large-scale effects of new biofuel policies (Roos and Ahlgren, 2018). Normally, these works couple an economic model to the LCA methodology with the aim of identifying the effects in the economy caused by a non-marginal change (Yang and Heijungs, 2018). An economic model can be defined as a tool that tries to capture and represent reality using a set of variables and quantitative correlations.

There is a variety of modelling types, based on a set of assumptions and presenting its own strengths and weaknesses.

Considering the construction sector's recognized need of including an LCA perspective in decision-making, the consensual perception that the consequential approach is useful for this matter and the importance of the choice of economic models in CLCA, the goal of this research is two-folded: i) to review the CLCA works applied to the construction sector and ii) to review the use of economic models in CLCA for assessing non-marginal changes regardless the sector.

Therefore, this review is divided in two parts: firstly, we review publicly available CLCA studies in the construction sector; and, secondly, we review non-marginal CLCA studies. This latter needs to explore sectors that have a similar problematic relative to the consequential effects. Thus, studies in the domain of agriculture, biofuels, energy and mobility have been reviewed.

This paper will first discuss the size and time horizon, then look at the different economic models, before proposing a review method and some results.

2. Reviewing criteria

The greatest challenge of conducting a CLCA is to identify how the unit processes are linked and how a change made by a decision will affect them. We can cite some key elements: the size and time horizon of the change, rebound effects, choice of economic models and uncertainty. Since the choice of the economic model depends on the size and time horizon of the change, both are selected as reviewing criteria in this paper as well as the choice of the economic models.

2.1. Size and time horizon of the change

The definition of CLCA implies that the consequential assessment evaluates a change in demand or supply. Following this definition, the change may present different scales that will affect differently the market parameters and thus will need a different type of economic model, depending on the size of the market effects.

A small-scale change may be defined as the change that does not affect the overall market parameters, such as the market trend or constraints in production (Weidema et al., 2009) while large-scale, on the other hand, would affect them.

Frischknecht and Stucki (2010) proposed a quantified method for defining the scale of the change in demand as small, medium or large. They propose the following indicators:

- Annual consolidated turnover relative to the annual gross domestic product
- Monetary or physical purchase volume from relevant economic sectors relative to the annual consolidated turnover of the sectors or the annual total volume of outputs of the sectors, respectively

If the indicator is lower than 0.1% it is considered as small scale, if it is greater than 0.1% but smaller than 1% it is considered as medium scale, otherwise, it is large-scale.

The authors argue that an economic criterion might be used rather than an environmental one because the environmental consequences occur as a result of the goods and services that are affected by the change.

The general guide of the International Reference Life Cycle Data System (ILCD) provides a rule based on the annually installed capacity for considering a change as “small” or “big”. The latter occurs if the annual additional demand or supply is larger than the usual annually replaced installed capacity (EC-JRC, 2010). The guide uses the inverse of the production equipment lifetime as an example of determining annual capacity (i.e. 4% for a 25 years' lifetime). In this example, the installed capacity of producing a globally traded material “X” is considered as 10 Mt/year and, thus, an annual demand that exceeds 0.4 Mt ($0.04 \times 10 \times 10^6\ t = 400{,}000$ t) of the material X shall be assumed as large scale, as it triggers an additional capacity beyond the replacement of old plants.

Concerning time horizon, several definitions can be applied to define short, medium and long-term. Because of the ubiquitous use of these terms, it is difficult to have a consensual definition of time ranges for each horizon type.

Some references (Frischknecht and Stucki, 2010; Burfisher, 2012) argue that short-term changes affect only capacity utilization while long-term changes would also affect capital investment, for example when installing new facilities (demand increase) or deactivating installations (demand decrease). Large-scale (or non-marginal) changes will usually affect capital investment and are thus also long-term.

From an environmental viewpoint, the concept of time horizon is usually associated with the reversibility of damage. When assessing environmental risks, for example, it is based on the time recover after the damage, being short-run (months to years) or long-run (three to five years to decades) (Noy, 2016).

It is important to note that a succession of short-term changes can result in a long-term, for both perspectives (Weidema et al., 2009).

2.2. Economic models

According to Yang and Heijungs (2018), economic models can be linear or nonlinear. Linear models consider a linear relationship between the cause and effect and, thus, an increase or decrease in the cause (e.g. 10% increase in the demand of functional unit) will result in a proportional reaction on the effect (e.g. increase in 10% of the production by the marginal suppliers). It is consensus in the literature that, for small-scale (marginal) changes, linear models are appropriate for identifying the affected processes.

Nonlinear models, on the other hand, consider other factors to obtain the cause-effect correlation, for example, the cumulative effect that results in a crisis or price elasticity. These models are suitable to non-marginal changes, when the affected processes may respond differently than expected.

2.2.1. Supply and demand analysis

Supply and demand analysis are linear models, based on the law of supply and demand and consists of studying the interaction of buyers and sellers in determining the prices and quantities of transactions (Dandres, 2012). Price evolution is determined by the elasticity of supply (or demand) and simultaneously reflects the value for the buyer to purchase a marginal unit and the cost to the seller of that unit (Dandres, 2012).

Weidema et al. (2009) provided a step-wise procedure to identify the marginal suppliers within a CLCA. This method consists of following the 4 steps:

- Identifying the scale and time horizon of the change
- Identifying the limits of a market
- Identifying trends in the volume of a market
- Identifying changes in supply and demand

2.2.2. Computable general or partial equilibrium

Equilibrium models calculate the new equilibrium established after a shock in a system. These nonlinear models use the theories of neoclassical economists Léon Walras, for general equilibrium, and Alfred Marshall, for partial equilibrium, for defining the equations describing the interactions between the economic actors (Dandres, 2012, Burfisher, 2012).

Computable Partial Equilibrium Model (CPEM) differs from Computable General Equilibrium Model (CGEM) with regard to the extension of the model. While a CPEM describes economic behavior in one industry holding prices and quantities in the rest of the economy constant, CGEM describes the economic behavior of the whole economic activities (Burfisher, 2012).

2.2.3. Agent-based models (ABM)

ABM are bottom-up, nonlinear and dynamic socio-economic models that take into account the interaction between the different agents involved in the study. Agents are completely autonomous and make decisions according to a set of rules in common to all entities that are reunited as the same agent (Davis et al., 2009; Querini and Benetto, 2014; Bonabeau, 2002).

2.2.4. Stock-flow consistent models (SFC)

SFC are post-Keynesian models that use specific Social Accounting Matrix (SAM) to ensure that each payment flow comes from somewhere and goes somewhere and that every financial stock is recorded as a liability for an actor and an asset for the other so that there are no black holes in the model (Caiani et al., 2016; Godley and Lavoie, 2007; Le Héron, 2018). Traditional SFC models are nonlinear and highly aggregated, dividing the economy into institutional sectors, typically: households, banks, firms and the public sector (Caiani et al., 2016).

3. Method adopted for the literature review

This review was carried out in two parts, the first part was focused on the construction sector and the second one on CLCA studies concerning non-marginal changes.

The aim of the first part is to identify the publicly available papers and works presenting a CLCA methodology applied to the construction sector, with no restriction with regard to the size of the studied change.

The second part focused on the publications that adopt a CLCA methodology to study non-marginal changes and the economic models that are used in these assessments. As medium- and large-scale changes present usually long-term effects, the second part of this review is focused only on the economic models.

The research was conducted using Scopus and Google Scholar to search for publications (papers, works, reports) on this matter, available in English or French.

Table 1
CLCA applied to the construction sector, size of the change.

Size of the change	Number
Small-scale	22
Medium-scale	2
Large-scale	1
Total	***25***

Table 2
CLCA applied to the construction sector, time horizon.

Economic model	Number
Short-term and long-term	1
Short-term, mid-term and long-term	1
Long-term	13
No information	10
Total	***25***

4. Results

4.1. Construction sector

This review found 25 studies that adopted a CLCA approach to evaluate environmental impacts in the construction sector. This is a small sample, however, some observations may be pointed out.

The first study dates from 2007 and, from 2013 onward, it is observed an increase in the interest for CLCA by the sector, with a peak of publications in 2016. This increase in interest is associated with the launch of the Ecoinvent version 3 in 2013, which included a consequential database based on the step-wise method provided in (Weidema et al., 2009).

Among the CLCA's works, 15 publications compare the ALCA and CLCA methodologies, most of them date from 2007 to 2014, showing that the dichotomy ALCA-CLCA has become less important in recent years.

Table 1 presents the number of publications for each scale of change evaluated in the studies (small, medium and large).

The majority of works assesses small-scale changes (22 out of 25) and, of these, 8 explicitly specify the use of the Ecoinvent consequential database, corroborating the importance of an available database for conducting CLCA studies.

The only publication found by this research that can be considered as a large-scale change assesses the increase in demand of 1 million apartments by year in Europe using wood-based construction materials (Eriksson et al., 2012). The authors use an integrated approach by coupling CLCA with a partial equilibrium model.

The time horizon of the studied change is explicitly mentioned in 15 publications. The great majority considers long-term changes, which is one of the assumptions from Ecoinvent consequential database as it is the situation "by default" (Weidema et al., 2009). Table 2 summarizes the time horizons adopted by the studies considered in this review.

Two studies use more than one time horizon to analyze the difference in the conclusions when changing this parameter (Kua, 2015; Kua and Lu, 2016). The first one (Kua, 2015) assesses the replacement of sand by steel slag for concrete production in Singapore. The author considers three consequential scenarii: short-term, midterm and long-term. The difference between them is how

Table 3
CLCA applied to the construction sector, economic model.

Economic model	Number
Supply and demand analysis	17
(of which step-wise from (Weidema et al., 2009)*)*	*(12)*
CPEM	3
No information	5
Total	***25***

Table 4
CLCA applied to the construction sector, economic model.

Economic model	Number
CGEM	5
CPEM	11
CGEM and CPEM	1
ABM	6
Linear equations	3
Total	***26***

the substitution will interact with other sectors triggering or not reductions/increase in consumption or import/export of sand.

The second one (Kua and Lu, 2016) studies the replacement of tempered glass by polycarbonate in constructions in Singapore, considering two time horizons: short-term and long-term. The authors conclude that the short-term consequences and ALCA present the same results and they highlight that the long-term effects should be included in assessments for policymaking.

With regard to the use of economic models, Table 3 synthesizes the number of publications according to the type of model chosen by the study.

Twelve works state using the step-wise procedure provided by Weidema et al. (2009), which is consistent with the size of the change assessed by these studies.

Regarding the three studies that use a CPEM, two of them are the works that studied a medium-scale change (see Table 2) (Lesage et al., 2007a, 2007b; Skullestad et al., 2016). The third one studies the increase in demand for wood-based materials for a million apartments by year scenario (Eriksson et al., 2012).

4.2. Other sectors

In this current review, we analyzed 26 CLCA studies that couple an economic model to assess non-marginal changes. Table 4 presents the economic models used in the reviewed studies.

The majority of the studies presents an equilibrium model to identify market effects. Concerning general equilibrium models, they are used in five publications, including the first three reviewed in this paper (Kløverpris et al., 2008; Hedal Kløverpris et al., 2010; Dandres et al., 2011). All of them use the model Global Trade Analysis Project (GTAP), which is a model that has a considerable level of disaggregation of economic sectors and for this reason is used for studying the global effects of environmental policies (Dandres, 2012).

According to our review, the application of CGE in CLCA has decreased in the last years, even though we found a publication from 2018 using GTAP to couple input-output with macro LCA to assess biofuels in transport policies (Somé et al., 2018).

On the other hand, the use of partial equilibrium models in CLCA has increased since its first application in 2011 (Whitefoot et al., 2011). In this study, the methodology is applied to a designing decision to downsize the engine of a mid-size vehicle of 25% and conclude that the proposed methodology captures important ripple effects that could influence decision making.

Concerning ABM, this review found an increase in their use in recent years. The first one is from 2013 (Miller et al., 2013) and it studies the emerging use of switchgrass to produce biofuels in order to meet the renewable energy goals. ABM is chosen to include the landowners' behavior through three attributes: profitability, resistance to change and technology familiarity.

Some authors have coupled ABM to CLCA to study mobility systems (Querini and Benetto, 2014; Querini and Benetto, 2015; Vasconcelos et al., 2017). The choice of ABM is justified by the importance of drivers' behavior and social interactions in mobility policies.

The most recent ABM-LCA works found in this review are related to agriculture processes (Marvuglia et al., 2016; Navarrete Gutiérrez et al., 2017) and are a part of the *MUlti agent Simulation for consequential life cycle assessment of Agro-systems* project (MUSA), developed by the Luxembourg Institute of Science and Technology (LIST). The project analyzes the agricultural and economic consequences of prospective scenarios of biogas production from maize over the long-term [44].

Three works use linear relationships between supply and demand to define the market effects of a non-marginal change. The first one (Rajagopal et al., 2011) proposes a methodology for assessing indirect land-use change based on a linear condition to describe the response of supply and demand. The other two (Styles et al., 2015b, 2015a) use a tool from UK Department for Environmental, Food and Rural Affairs (DEFRA), which scales-up LCA results to evaluate large-scale changes.

5. Discussion

Some authors argue that computational equilibrium models do not represent consistently reality (Caiani et al., 2016; Godley and Lavoie, 2007; Le Héron, 2018). Being rooted in neoclassicism, equilibrium models present assumptions of perfect behavior, as, for example, rational expectations, which implies that representative agents know the "true model" of the economy and will react rationally to a shock (Caiani et al., 2016).

The limitations of equilibrium models can be also related to the way of computing the long-term equilibrium (Bonabeau, 2002; Le Héron, 2018). In neoclassic models, this latter defines the succession of short-term equilibriums and determines the growth needed to result there (Le Héron, 2018), resulting in important inconsistencies and lack of reality.

ABM presents key advantages for coupling with CLCA methodology because they are bottom-up models and allow to represent individuals directly, by their interactions with each other and the environment (Baustert and Benetto, 2017), with more realistic assumptions than equilibrium models. However, accounting inconsistencies can also be found in these models.

SFC are accounting consistent, however highly aggregated. To address the limitations from both ABM and SFC, some authors propose a coupling between ABM and SFC, the so-called AB-SFC models (Caiani et al., 2016; Nikiforos and Zezza, 2017). This research did not find any application case of AB-SFC model with CLCA.

6. Conclusion

This paper reviews twenty-five studies of CLCA in the construction sector. It was observed that the majority of them considers small-scale and long-term changes, using linear models to identify the marginal suppliers and technologies that are affected by the studied change. Only three papers may be considered as studying non-marginal changes and all the three use an equilibrium model, more precisely a CPEM.

This paper also reviews twenty-six studies of CLCA that assess non-marginal changes, using the economic model choice as a criterion. The majority of them couples a computational equilibrium model to CLCA, most of them use a CPEM.

Our review of the literature suggests some conclusions. The time horizon of the studied change is normally consistent with the chosen economic model. However, an important number of studies do not mention this parameter.

The use of nonlinear models seems necessary to identify the affected markets in an economy-wide perspective. Nowadays, the equilibrium models are the most commonly applied on CLCA studies, although they have been criticized in recent publications because of their significant limitations. These issues could be addressed by other modelling tools, such as ABM simulations, SFC models or yet AB-SFC. Indeed, we observed an increase in the use of ABM simulations in CLCA studies.

We recommend the development of tools capable of widening the boundaries of conventional life cycle assessments (to include economy-wide effects) while keeping economic consistency. Indeed, AB-SFC may be an interesting tool in this sense and further research on coupling CLCA with AB-SFC is recommended.

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