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Economic valuation of life cycle environmental impacts of construction products - A critical analysis

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Abstract. The aim of this paper is to identify existing methods for economic valuation or monetisation of life cycle environmental impacts and to assess its applicability in the broad European context. Although environmental awareness is more and more important in several industrial sectors, including the construction sector, easy to understand data are still missing for professionals to assess and manage impacts related to the whole life cycle of a building. Life Cycle Assessment (LCA) is one of the most commonly accepted methodologies to calculate potential life cycle environmental impacts of a product or service. However, the results of such method, even when published in an Environmental Product Declaration, meant for business to business communication, are not always comparable or easily understandable by non-practitioners. Economic valuation or monetisation of LCA results is a weighting step that can make it easier for non-practitioners to use LCA results to support decision-making. From the several monetisation methods analysed, it is discussed the one that is most suitable for use when LCA results already exist. It is concluded that further work is needed to improve such weighting methods or develop a common one that can be representative at a broader geographical level (for instance, Europe-wide).

1. Introduction

Environmental degradation, such as climate change or resource scarcity, are increasing due to human activity. Population concentration in urban areas and fast urbanization are also aspects with the potential to impact society. Despite its importance in economic and social aspects (namely, accounting for 6% of the global Gross Domestic Product (GDP), providing millions of jobs, and the social service of providing housing), the construction sector is the largest global consumer of raw materials, and responsible for 25-40% of the world's total carbon emissions [1].

To enable Architecture, Engineering and Construction (AEC) professionals, decision-makers and investors throughout the EU to consider impacts related to the whole life-cycle of a building, empirical-based, reliable, transparent and comparable data are needed, based on clear indicators of the building performance [2]. Life Cycle Assessment (LCA) is a commonly accepted and well-established methodological tool. It applies life cycle thinking, quantitatively, to the environmental analysis of activities related to processes or products [3]. However, to apply the Sustainability concept to buildings based on its three pillars (environmental, social and economic), other tools must also be used. Currently, several European standards, developed by the Technical Committee (TC) 350 of the European Committee for Standardization (CEN) (TC350/CEN), are published concerning the evaluation of construction works performance in all these three pillars [4–7]. Both TC350/CEN and ISO have also



developed standards concerning the communication of environmental impacts through Environmental Product Declarations (EPD), that aim at providing AEC professionals with LCA information on construction materials [8, 9].

In what concerns LCA application within the building sector, as a strategy to reduce environmental impacts, it is often identified as complicated and time-consuming. Moreover, most of the impact assessment methods commonly used result in a set of environmental categories that are not easily understandable or interpretable [10]. This conclusion can be obtained from the analysis of the list of parameters and environmental information specified for a Type III Environmental label - EPD [9]:

- Parameters describing environmental impacts (7 impact categories);
- Parameters describing resource use (17 parameters);
- Environmental information describing output flows (4 parameters);
- Environmental information describing waste categories (3 parameters);
- Parameters describing pollutants emission from materials (3 parameters);

Taking this into account, for AEC professionals to use LCA more efficiently as a decision support tool, this information needs to be simplified, and monetisation is a solution for that. Currently, opinions diverge on the monetisation of environmental impacts, with a discussion on whether and how to value them [11]. This paper intends to identify existing monetisation approaches and methods for environmental impacts and their main pros and cons when applied to LCA results. More specifically, it intends to assess their application in the case that LCA results are available in the form of an EPD.

2. Material and Methods

The main method used for the development of this work was through a literature review.

Methods reviewed for this work include LCA and monetisation methods already developed, used and accepted by the scientific community.

3. The Life Cycle Assessment method

LCA is a structured, comprehensive and internationally standardised method (ISO 14040 series [12]). It allows the quantification of all relevant emissions, resources consumed and the related potential environmental and health impacts and resource depletion issues that are associated with any goods or services (“products”) (ISO, 2006). This is a complex and data-intensive methodology that considers the potential impacts of the whole life cycle of a product, from the extraction of resources, through production, use, and recycling, up to the disposal of remaining waste [13]. This method is an important tool applied to [12]:

- Identify “critical points” and respective opportunities to improve the environmental performance of products at several stages of their life cycle;
- Inform decision-makers in industry, government or non-governmental organizations in the search for more sustainable consumption and production (e.g. for the purpose of strategic planning, priority setting, product or process design or redesign);
- Select relevant indicators of environmental performance, including measurement techniques;
- Marketing activities (e.g. implementing an eco-labelling scheme, making an environmental claim, or producing an environmental product declaration).

LCA methodology is standardized namely by ISO 14040 concerning Environmental management - Life cycle assessment - Principles and framework [12] and by ISO 14044 concerning Environmental management - Life cycle assessment - Requirements and Guidelines [14].

ISO 14040 describes the principles and framework for LCA, including its four main stages: the goal and scope definition of the LCA study, the life cycle inventory analysis (LCI) phase, the life cycle impact assessment (LCIA) phase, and the life cycle interpretation phase.

There are cases in which the aim of an LCA can be achieved by performing only the first two phases - it corresponds to an LCI study [15]. However, a complete LCA includes the evaluation of the environmental impacts associated with these inputs and outputs of the system (LCIA) and the interpretation of the results of the inventory and evaluation phases, taking into account the objectives of

the study [14, 15]. Life cycle impact assessment is the stage of an LCA that allows understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system. ISO 14040/44 refers to several steps in the LCIA [12, 14], as described in the following paragraphs.

- Mandatory elements:
 - Selection of impact categories, category indicators and characterization models;
 - Classification: assignment of LCI results to the selected impact categories - each elementary flow from the inventory is assigned to the impact categories according to the substances' potential to contribute to different environmental problems (e.g., eutrophication, climate change); these impact categories may be endpoint (human health, resource depletion, later in the cause-effect order) or midpoint (climate change, land use; earlier in the cause-effect order);
 - Characterization: calculation of category indicator results - for each impact category several substances contribute with specific magnitudes.

To reduce all substances to a common equivalent unit, normalisation, equivalence factors or characterisation factors may be applied during this step (optional).

- Optional elements:
 - Normalization: calculating the magnitude of category indicator results relative to reference information, for instance, in reference to the average level of pollution produced by an average European citizen;
 - Grouping: sorting and possibly ranking of the impact categories;
 - Weighting: converting and possibly aggregating indicator results across impact categories using numerical factors based on value-choices;
 - Data quality analysis: better understanding the reliability of the collection of indicator results/the LCIA profile.

Thus, weighting is an optional element with two possible procedures, either to convert the indicator results or normalized results with selected weighting factors or to aggregate these converted indicator results or normalized results across impact categories. Weighting steps are based on value-choices and are not always objective [14]. This is the step that allows the monetisation of environmental impacts by attributing an economic value to the equivalent unit of the characterisation result of each impact category.

4. Monetisation approaches and existing methods

Monetisation expresses the relative importance of an impact category in monetary value. This value can be based on the costs associated with preventing or repairing damage (e.g. damage costs using market prices). Another example to monetise an impact category is to measure how people are willing to pay to prevent a given impact. These include expressed willingness (through interviews) or estimated willingness to pay through value attribution by the users or measurement of welfare losses, as well as political willingness to pay [16, 17]. These are applicable to both use and non-use values, i.e. the value that people derive from goods independently of any use, present or future, that they might make of those goods, in contrast with use values, which people derive from direct use of the good [16]. A summary of monetisation approaches is presented in Table 1.

Based on these approaches, several monetisation methods/weighting sets have been developed and are widely used for the weighting of environmental impacts resulting from LCA studies. The most relevant are listed in Table 2.

5. Discussion

The **Eco-costs** approach is a prevention-based monetisation method [18]. It translates the environmental impact into economic cost by measuring the cost of preventing a given amount of environmental burden [19]. Eco-costs provides monetary values for the following impact categories: acidification (from the LCIA method International Reference Life Cycle Data - ILCD); eutrophication and summer smog (from the LCIA method Recipe); ecotoxicity and human toxicity (from the LCIA method UseTox 2); fine dust (from the LCIA method RiskPol); and global warming (from the LCIA method of Integrated Pollution

Prevention and Control - IPPC). In addition, there is a set of eco-costs to characterize the 'midpoints' of resource depletion [18]:

- Eco-costs of abiotic depletion (metals, including rare earth, and fossil fuels);
- Eco-costs of land-use change (based on loss of biodiversity);
- Eco-costs of water (based on the midpoint Water Stress Indicator - WSI);
- Eco-costs of landfill.

Table 1. Monetary valuation approaches (adapted from [20]).

Approach	Description
Revealed willingness to pay	Market prices (damage costs: loss of production, loss of capital or added value) Revealed preference methods (productivity method and travel cost method) Hedonic pricing (combining market places of a good and the influence of environmental aspects on the user's willingness to pay)
Expressed willingness to pay	Stated preference methods (contingent valuation and choice modelling)
Imputed willingness to pay	Damage cost avoided method (e.g. restoration costs, remediation costs, defensive expenditures) Replacement cost method uses the cost of replacing an ecosystem or its services Substitute cost method uses the cost of providing substitutes for an ecosystem or its services
Political willingness to pay	Costs-to-reach-target Taxes
Avoidance costs	Estimation of the cost to limit some emissions or impacts to a chosen limit, based on a hypothetical situation and not on willingness to pay

Table 2. Identified monetisation methods and respective approach.

Method	Approach
Eco-costs	Revealed willingness to pay - Market prices (prevention prices)
Ecotax 2002	Political willingness to pay - Taxes
Ecovalue 08	Revealed willingness to pay - Market prices (added value) and imputed willingness to pay - Damage cost avoided method (defensive expenditures)
Environmental Prices	Revealed willingness to pay - Market prices (prevention prices)
Environmental Priorities Strategies in product design (EPS)	Imputed willingness to pay - Damage cost avoided method (defensive expenditures)
External costs of energy (ExternE)	Revealed willingness to pay - Market prices (added value)
LIME	Expressed willingness to pay - Stated preference methods
Social Cost of Carbon	Revealed willingness to pay - Market prices (damage costs: loss of welfare)
Stepwise 2006	Imputed willingness to pay - Damage cost avoided method (defensive expenditures)

Eco-costs refers to the environmental categories most often used in the environmental assessment of building materials and assemblies, which are compatible with the environmental information provided in EPDs [21, 22]. The marginal prevention costs at a midpoint level can be combined and expressed as “endpoints” in three groups, plus global warming as a separate group [18]:

- Eco-costs of human health = the sum of carcinogens, summer smog, and fine dust;
- Eco-costs of ecosystems = the sum of acidification, eutrophication, and ecotoxicity;
- Eco-costs of resource depletion = the sum of abiotic depletion, land-use, water, and landfill;
- Eco-costs of global warming = the sum of CO₂ and other greenhouse gases (GWP 100 table);
- Total eco-costs = the sum of human health, ecosystems, resource depletion and global warming.

Ecotax 2002 is a monetization approach based on the Swedish eco-taxes and fees on emissions and resource use. It assumes that political decisions reflect societal values of environmental impacts. This method also uses CML Baseline midpoint impact categories, which are compatible with the use of EPDs. In some cases, a tax or fee can be used directly as a weighting factor, for example, the taxation on CO₂ for global warming (CO₂ eq.). In other cases, weighting values are calculated based on existing taxes, for instance, taxes on nitrogen fertilizers are adapted to provide a weighting factor for eutrophication [23–25].

Ecovalue 08 builds on weighting factors that aggregate midpoints on a monetized endpoint impact. It is based on market valuations of resource depletion and individual Willingness To Pay (WTP) estimates for environmental quality. The characterisation method used for the midpoint impact categories is CML (Centre for Environmental Sciences - Leiden University) baseline [26]. This method is compatible with the use of EPDs as information sources for the environmental LCA results.

Environmental Prices expresses the willingness-to-pay for less environmental pollution in Euros per kilogram of pollutant [27], similarly to Eco-costs. It indicates the loss of economic welfare derived from each additional kilogram of the pollutant entering the environment and often coincides with external costs. Environmental prices distinguish on the environmental categories it values. Environmental Prices Handbook defines five endpoints [27]:

- Human health (morbidity, i.e. sickness and disease, and premature mortality);
- Ecosystem services (including agriculture);
- Buildings and materials (man-made capital);
- Resource availability;
- Wellbeing (aesthetic and ethical values).

Regarding midpoint categories, environmental prices closely follow the categories used in the ReCiPe method, add a nuisance-related category, and are not consistent with the information provided by EPDs. However, environmental prices are presented also at the pollutant level, allowing for the application of the method based on the inventory of the product/process assessed.

Environmental Priorities Strategies in product design (EPS) system [28] is one of the eldest (1991-1992) monetary valuation models developed to facilitate comparison of environmental impacts (mostly for product development). It calculates environmental costs using inventory data, characterization factors, and weighting factors (monetisation), reaching an endpoint result. The impact categories in the EPS method are identified within four areas of protection: human health, ecosystem production capacity, abiotic stock resources, and biodiversity. Damages to these safeguard subjects are monetised according to the willingness to pay (WTP) to avoid changes from the present state of the environment. Environmental aspects such as emissions of substances (e.g. CO₂, CO, NO_x, SO_x, etc.) or resources extraction (e.g. fossil fuels, minerals) are classified in each of the mentioned areas of protection. Weighting factors are defined for 15 impact categories, grouped in 4 main damage categories, as defined in the EPS 2000 method used for life cycle impact assessment, not consistent with the information provided by EPDs.

External costs of energy (ExternE) is a project funded by the European Commission, which started in 1995, intending to monetise socio-environmental damages caused by distinct energy carriers. ExternE makes a detailed and systematic assessment of the full cause-to-effect chain from burdens or emissions to environmental impacts and damages. The three safeguard subjects considered are public health, built environment, and ecosystem production capacity. Impacts are valued based on market prices or ‘willingness to pay’. The two follow-up projects of ExternE are the New Element for the Assessment of

External Costs from Energy Technologies (NewExt) and the New Energy Externalities Developments for Sustainability (NEEDS). The aim of the former was to improve the assessment of externalities and that of the latter was to evaluate costs and benefits of energy policies and of future energy systems [25]. This method is also not compatible with the use of products' EPDs as input for the monetisation.

LIME, Life-cycle Impact Assessment Method based on Endpoint Modelling, is a Japanese project that aims at developing a database to assist industries in implementing reliable LCA studies in the characterization step. LIME considers 11 impact categories: urban air pollution, hazardous chemicals, eutrophication, global warming, ecotoxicity, acidification, ozone layer depletion, photochemical oxidant creation, land use, waste, and resource consumption. The monetisation is based on a survey conducted in 2004 (in Tokyo) and in 2012 (throughout Japan) to assess the WTP of the Japanese society to avoid damage on certain safeguard subjects (for example, human health or biodiversity). With the use of logit modelling, the weighting factors to aggregate midpoint categories were calculated estimating the environmental attitudes and preferences of the Japanese public. Based on the logit model, LIME provides two types of weighting factors: a dimensionless index; and an economic valuation. Both can be used on the results of different impact assessment methods for estimating monetary values [24, 25].

Stepwise 2006 [29] is a monetization method built on the results of LCIA method Ecoindicator99 [30], which provides results as physical scores for each of the three safeguard subjects: humans, ecosystems, and resources. These damage categories are redefined [29] so that they can be measured in: Quality Adjusted Life Years (QALYs - the amount an average person is willing to pay for an additional life year) for impacts on human well-being; in Biodiversity Adjusted Hectare Years (BAHYs) for impacts on ecosystems; and in monetary units for impacts on resource productivity. To aggregate these results, a monetary value is attributed to QALY and to BAHY and an exchange rate between BAHY's and QALY's is set, measuring impacts on resource productivity. Both valuations allow environmental impacts to be expressed in monetary values [29]. Considering that the LCIA method Ecoindicator99 is an endpoint method based on panel approach, there is already a high subjectivity of the results even before the monetisation step. However, currently, the STEPWISE method uses characterisation models from IMPACT2002+ v. 2.1 and the EDIP2003 methods, that are second-generation methods, building on previous work (Ecoindicator1999 and EDIP1997, respectively) [31]. Still, the format of environmental information provided by EPDs is not compatible with this method.

The Social Cost of Carbon (SCC) is a commonly employed metric of the expected economic damages from carbon dioxide (CO₂) emissions [32, 33]. SCC represents the economic cost associated with climate damage derived from the emission of an additional tonne of carbon dioxide (tCO₂). Considering that global warming potential, measured in CO_{2eq.}, is one of the indicators provided in EPDs, this valuation method may also be compatible with this source of information. It neglects, however, other important environmental impact categories declared in these declarations.

Table 3 presents some examples of the application of the identified monetisation methods. The examples chosen were those from the most recent years and, when available, including the application of the valuation methods to the construction sector.

6. Conclusions

Taking into account the economic and environmental relevance of the construction sector, there is a growing need to provide the AEC professionals with tools that support the improvement of its sustainability, namely in the environmental dimension. LCA is an important methodology for that. However, considering the complexity, and the information and time demand, of this methodology, it is understandable that it is not the focus of these professionals. Even the results of an LCA study as presented on EPDs (most common sources of LCA results for these professionals) are usually difficult to interpret and use. The weighting of these results in the form of monetisation of environmental impacts has the advantage of providing a single indicator in an objective unit, allowing professionals to evaluate and easily compare options while being aware of the magnitude of environmental impacts in each life cycle stage (in relation to market costs of a project).

Table 3. Examples of application of the identified methods.

Method	Reference and additional methods	Objective of the use of monetisation
Eco-costs	Scheepens <i>et al</i> , 2018 [34]	A combined analysis of cost, (market) value, and eco-burden was used to compare strategies of passive (insulation focused) and active (behaviour focused) end-users, by applying the methods of eco-costs/value ratio (EVR) and eco-efficient value creation. The analyses identified the economic and environmental payback and the likelihood for potential rebound effects.
	Mano <i>et al</i> , 2017 [35]	Incorporation of costs of the environmental impacts caused by energy generation and equipment construction in the heat exchanger networks (HEN) using the eco-costs methodology. The inclusion of indirect costs (externalities) in the optimization procedure was found to significantly affect the characteristics of the minimum cost design, the operational conditions and HEN topology.
	Carreras <i>et al</i> , 2016 [36]	Eco-costs method was used to translate the environmental impact of the building envelope into monetary units. This was incorporated into the economic performance assessment, to optimise the thermal insulation of a building envelope in different climate zones.
Ecotax 2002	Du <i>et al</i> , 2018 [37] (also Ecovalue 08)	Comparison of the environmental performance of two bridge types through the whole life cycle, based on eight selected cases in Sweden, applying Ecovalue08 and Ecotax02 methods to evaluate the environmental costs of each design option.
	Nguyen <i>et al</i> , 2016 [25] (also EPS and Stepwise 2006)	Calculation of the environmental externalities of electricity from renewable (e.g. biomass) and from non-renewable sources (e.g. coal, oil, and gas), and comparing three monetization methods, the EPS 2000, the Stepwise 2006, and the Ecotax.
Ecovalue 08 (also Stepwise 2006)	Huysegoms <i>et al</i> , 2018 [24]	Application of different monetization methods of LCA study results to the assessment of the site remediation of a former gas plant. Implementing monetized LCA results in social cost-benefit analysis (CBA) allowed for a more detailed overview and valuation of the secondary environmental effects.
Environmental Prices	Huysegoms <i>et al</i> , 2019 [38]	Application of the environmental prices method to incorporate LCA in Social CBA in the comparison of remediation alternatives for a dry-cleaning facility.
ExternE	Entler <i>et al</i> , 2018 [39]	Ex-ante economic analysis of a fusion power plant in terms of the cost of electricity. It includes the external costs of energy based on the OECD statistical data and on the EU ExternE project results.
	Jochem <i>et al</i> , 2016 [40]	Comparison of the main external cost components for electric vehicles and internal combustion engine vehicles, based on the ExternE method.
LIME	Yamasaki <i>et al</i> , 2019 [41]	Incorporation of life cycle impact assessment (LCIA) into the calculation of environmental loads for administrative divisions applying monetisation method LIME-3.
Social Cost of Carbon		Investigation of the cost-effectiveness and environmental impacts of a green roof in an educational building of the University of Florida. Environmental costs were integrated using Global Warming Potential (GWP) measure to determine the social cost of carbon.

In this work, it was possible to identify several monetisation methods. However, taking into account standards for the development of EPDs, Eco-costs, Ecovalue 2008, Ecotax 2002 and Social Cost of Carbon are the most suitable ones, because they are based on CML baseline midpoint impact categories, declared in EPDs. Moreover, the first two were the methods for which case studies were found related to the construction sector. However, they do not show broad geographic representability, since they are both strongly influenced by the Swedish framework (in terms of existing taxes and of the valuation of environmental impacts).

From this work, it is possible to conclude there is a need for further development/improvement of monetisation sets or methods, in order to obtain larger consensus and representability. Considering the efforts for the democratisation of the use of LCA and the communication of its results, it would be important to develop a monetisation method that can be Europe-wide representative as well as easily applicable to the available information, for instance, EPDs or other standardised sources of LCA information. Moreover, standards and guidelines related to these communication tools could also include the option of weighting the LCA results through monetisation, providing the common user with an easier to interpret and more tangible information in what relates to the potential life cycle environmental impact of a product.

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