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Obstacles and Solutions to Integrating LCC and LCA

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Abstract: Nowadays, organizations and their decision-makers are expected, and frequently legally obliged, to make commercially sound strategic investments enhancing shareholder value, but also to reckon on their environmental impacts to a degree that substantially exceeds tangible economic incentives to do so. This brings particular challenges whenever the decision process must resort to conclusive and properly documented decision criteria. Accordingly, this paper looks at two fundamental methods, conceptually developed and applied to determine the full economic impacts of decisions, Life Cycle Cost analysis (LCC), and the full environmental impacts of decisions, Life Cycle Assessment (LCA) and at the different possible ways to improve their compatibility and mutual coherence. The key findings of the study indicate that it is meaningful and viable to strive for a partial integration of these methods in a mathematical model in order to analyse the potential for industrial symbiosis in the secondary production and use of alternative construction materials.

Keywords: Life Cycle Assessment; Life Cycle Cost analysis; industrial symbiosis, investment policies; environmental impacts; capital budgeting

JEL Classification: M21; Q51; C52

1. Introduction

Life Cycle Assessment (LCA) and Life Cycle Cost analysis (LCC) have become household terms with businesses, their stakeholders and regulators. However, despite the similarity in their designations and abbreviations, LCA and LCC feature major methodological differences, making them effectively incompatible. These differences arise from the fact that LCA and LCC were originally each designed to provide answers to fundamentally different questions.

LCA aims to assess the relative environmental performance of alternative product systems designed to provide the same function. This is being assessed as holistically as possible, ideally considering all important causally-connected processes, as well as all important resource and consumption flows, regardless of whether or not they eventually impact anyone (Hauschild et al., 2018; Pacañot, 2022).

LCC analysis, in contrast to this, compares the cost-effectiveness of alternative investments or business decisions from the perspective of an economic decision maker such as a manufacturer or a consumer (Flanagan & Jewell, 2005; Dhillon, 2010; Kara, 2019).

These conceptual differences notwithstanding, any decision maker using LCA must also eventually take the economic consequences of into account. However, these are not within the scope of existing LCA methodology, nor are they properly addressed by existing LCA tools. This has limited the influence and relevance of LCA for decision-making, and left largely unresolved the important relationships and trade-offs between the economic and life cycle environmental performance in decision making (Beaver, 2004; Curkovic & Sroufe, 2006; Helu et al., 2011; Tickner et al., 2019).

A particular domain of policy interest, where this problem arises and its solution may bring substantial benefits, involves industrial symbiosis. By definition, industrial symbiosis represents the physical exchange of materials, energy, water and by-products by industrial entities that are traditionally considered separate. Such exchange can lead to significant reductions in the consumption of primary raw materials and production of waste, while also increasing aggregate profitability and competitiveness through decreased resource costs (Jacobsen, 2006; Neves et al., 2019).

The research presented in this paper starts with a comprehensive insight into the conceptual and methodological differences between LCA and LCC, followed by an annotated summary of available or attempted approaches to their integration. The ultimate aim is to design and develop an extended LCC model, complementary to a LCA model, currently being developed to evaluate the industry-wide symbiotic potential in the construction industry, namely demolition waste, and coal combustion products in the Czech Republic (Paulů et al., 2022). Conclusions will be made on the potential for further research and its results, which will ultimately comprise a mathematical model of an economic system.

2. Theoretical Part

The differences in the purpose of LCA and LCC, respectively, have in due course resulted in major differences in their scope and method, as in Table 1.

Table 1. The main differences between LCA and LCC (adapted from Norris (2000))

Tool / Method	LCA	LCC
Purpose	Building employer brand and prestige, comparing relative environmental performance of alternative product systems for meeting the same end-use function, all from a broad perspective of the society.	Determine cost-effectiveness of alternative investments and business decisions, from the perspective of an economic decision maker such as a manufacturing firm or a consumer.
Activities considered as part of Life Cycle	All processes causally related to the physical life cycle of the product, including its complete supply chain, its use and the supply processes to use, as well as its life termination.	Activities resulting in direct costs or benefits to the decision maker during the economic life of the investment.
Flows being considered	Resources, pollutants and inter-process flows of materials and energy.	Cost and benefit money flows with a direct impacting on the decision maker.
Units for measuring flows	Mainly mass and energy, sometimes also volume or other physical units.	Monetary units (EUR, USD, CZK, ...)
Time scope and treatment	Normally, the timing of processes and their release, and that of consumption flows is ignored. In some cases, impact assessment looks at a time window of impacts (such as a 100-year time horizon for assessing global warming potential), but proper discounting is not used.	Timing is essential in assessment. Present valuing (discounting) of costs and benefits' present value (i.e., discounting) is considered. Analysis is made over a time horizon and any costs or benefits beyond that scope are typically being ignored.

The major issues involved can be demonstrated using a rudimentary example of a desktop PC purchase.

To start with, the life cycles considered by the two methods are different. The time horizon in a LCC analysis comprises the economic life of the investment, at the end of which it is hypothetically expected to be sold at its salvage value. Such a time horizon can actually be shorter than even the use phase in LCA, which in such a case might consider equipment repairs, upgrades or second-hand use.

Also, the process scope of the LCC analysis involves only the processes imposing direct economic costs or benefits upon the decision maker. It thus accounts for the prices of inputs to the investment's economic life, such as the desktop’s purchase price, some replacement batteries and the electricity cost, subtracting the salvage value from the life cycle costs. In common with an LCA, costs which are expected to be equal between alternatives (such as software, customer support and peripherals) are normally ignored for the comparison.

For the LCA, on the other hand, all the processes which are causally affected by the life cycles of the alternatives need to be included (only neglecting those which are expected to be identical in the comparison, as in the LCC analysis, as already noted). Accordingly, this would then include the manufacturing of the computer and its components, fuel and electricity delivery to the manufacturers’ whole supply chain, electricity consumption of the PC user, as well as the computer’s end of life impacts (e. g. those of its recycling or landfilling). An actual LCA may thus easily involve hundreds of process inputs (Silva et al., 2019).

Incidentally, even in its obvious complexity, the LCA scope does not include all environment-related decision-making aspects. For instance, LCA methodology does not strictly require considering the restrictions of environmental laws and regulations, but in the real world these aspects are very important and do need to be dealt with. Subjectivity, assumptions and value judgments also get involved, in the determination of system boundaries, choice of data sources, selection of environmental damage types, of calculation methods, etc. (Pacañot, 2022).

3. Methodology

As shown in the previous section, the two methods feature substantial differences in their flow scopes. The LCC analysis includes only the cost flows; however, these cost flows need not be proportional to, or even be dependent on the physical flows considered in LCA. On the other hand, LCC analysis strictly considers the timing of the cost flows, while LCA neglects this aspect. The LCC analysis, in contrast to LCA, may involve risks involved in the cost assessment, and perhaps the means of their mitigation. This can be summarized as follows (Norris, 2000).

Aspects of the LCA life cycle which are absent from LCC analysis:

- Physical flows having no direct cost impacts on the decision maker;
- Inflows and outflows of any processes outside the LCC-specific life cycle.

Aspects of the LCC analysis which are absent from LCA:

- Cash flows related to product or process change-related investments;

- Cost and revenue flows not proportional to, or even completely independent of the physical flows modelled in LCA;
- The timing of cash flows and their discounting (present valuation);
- Cost- and benefit-related risks and their mitigation.

Properly integrating meaningful economic analysis into LCA thus necessitates an approach far more sophisticated than just treating economic cost as just another physical flow or as another property of physical flows, using e. g. standard LCA software (Su et al., 2020). It needs to add a time dimension, the ability to introduce and account for variables featuring no causal dependence upon inventory flows, as well as the ability to create and involve probabilistic scenarios involving risks. It also must be recognized that LCA methodology is not perfectly standardized, and may thus provide different outcomes in different applications (Silva et al., 2019).

Accordingly, of the two generally possible approaches, extending LCA with economic considerations or extending LCC analysis with environmental considerations, the first option seems less attractive and will only be briefly summarized in the following paragraphs.

3.1. LCECA

In the past, there have been some attempts to start from the traditional LCA framework, adding cost flows and treating them just like physical flows. Nevertheless, such a mindset (that could be called LCA + Partial LCC) did not really augment LCA with capabilities useful in an LCC analysis sense, since it treated costs in ways which were in conflict with the fundamentals of LCC analysis (Norris, 2000). Accordingly, decision making using this approach did not really take into account proper economic criteria.

A relatively well-considered attempt involved Life Cycle Environmental Cost Analysis (LCECA), introduced by Senthil et al. (2003) and aimed at interpreting the outcomes of an LCA in terms of environmental costs. Their model involved a life cycle environmental cost model to estimate and correlate the effects of these costs in all the life cycle stages of the analyzed product. This resulted in newly developed categories of eco-costs which included costs of effluent treatment/control/disposal, environmental management systems, eco-taxes, rehabilitation, energy and savings of recycling and reuse strategies. The LCECA mathematical model then determined quantitative functions relating the total cost of products and the various eco-costs. Finally, the eco-costs of available investment alternatives investment were compared to the computational LCECA model, allowing some conclusions. In a sense, LCECA converges towards the LCC-based eco-cost approach (see also 4.4).

3.2. EIO-LCA

In contrast to the other methods reviewed in this study, this one is not based on calculation, but rather on macroeconomic equilibrium theory. The method's concept stems from the Economic Input-Output Analysis (EIO) by Leontief (1970). Accordingly, it applies equilibrium assumptions to demonstrate the interdependence between production departments within a closed economic system, and then derives a theoretical performance in its input-output relationships. The linear equation showing the distribution of the industrial production in the whole economic system is then used to find the commensurate yield dependencies (Lave et al., 1995).

EIO-LCA has been applied as an input-output assessment tool of LCA and was developed from the economic values of 519 different commodities published by the U.S. Department of Commerce, aggregating this into the information about economic transactions, resource requirements and the environmental impacts of particular products or services. EIO-LCA thus helps assess relevant contexts of products or services, such as mineral extraction, manufacturing, transportation, etc. (Lave & Kleissl, 2010). Combining EIO with LCA does make some sense, because while they may seem similar in formulation style and calculation methods, they also feature major differences: The EIO approach focuses on the energy metabolism from the socio-economic activities related to input-output, while the LCA approach focuses on the energy metabolism, toxicity, human health and other aspects of the whole life cycle. EIO-LCA thus combines the properties of both methods in an attempt to analyze energy metabolism in all parts of the production chain. Even though the method is quite advanced, with readily available software (Hendrickson et al., 1998), it is still principally LCA-based, however, lacking essential LCC features.

4. Results

We now summarize several possible and previously used approaches to completing LCC with environmental aspects (4.1 - 4.5). The final paragraph (4.6) looks at optimization.

4.1. TCAce

Historically, the attempts to integrate LCC with environmental considerations have been called Total Cost Assessment (Curkovic & Sroufe, 2007) and initially developed in the early 1990's by the Tellus Institute for the U.S. Environmental Protection Agency and the New Jersey Department of Environmental Protection. TCAceIntegrate was the result of a collaborative project by ten multinational companies and the American Institute of Chemical Engineers' Center for Waste Reduction Technologies (Beaver, 2004). The complete analytical process can be summarized as in Figure 1.

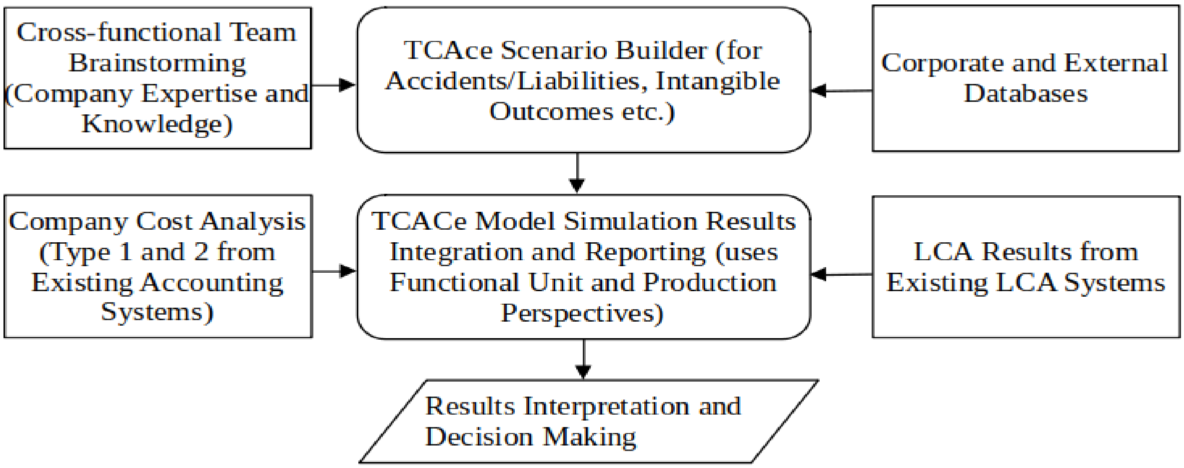

Figure 1. The TCAce process (adapted from Norris (2000) and Beaver (2004))

This schematic representation indicates the method's strong reliance on scenario and Monte Carlo simulation methods.

The TCAce method applies five cost types as summarized in Table 2. Types 1 through 4 comprise internal costs borne by the company; these costs would be included in a comprehensive LCC evaluation of investment alternatives, although traditional LCC analyses typically capture only Type 1 (direct) and some Type 2 (indirect) costs.

Table 2. Cost type breakdown (adapted from Norris (2000))

Cost Type	Description
#1: Direct	Direct costs of capital investment, labour, energy, raw material and waste disposal. May include both recurring and non-recurring costs. Includes both capital and O&M costs.
#2: Indirect	Indirect costs not allocated to the product or process (i.e., overhead). May include both recurring and non-recurring costs. Includes both capital and O&M costs.
#3: Contingent	Contingent costs such as fines and penalties, costs of forced clean-up, personal injury liabilities, and property damage liabilities.
#4: Intangible	Costs that are difficult to measure, including consumer acceptance, customer loyalty, worker morale, union relations, worker wellness, corporate image, community relations.
#5: External	Costs borne by parties other than the company (for instance, society).

The specific design of TCAce enables users to extend the relevant cost scope to include cost types 4 and 5 that are not tangible, applying quantitative methods, consistent with the firms' existing approaches to LCC analyses of Type 1 and 2 costs.

The consistency with existing corporate accounting conventions may include approaches to capital depreciation, treatment of taxes, discounting, and the time horizon of LCC evaluations. Users can also import the results of conventional LCC analyses of Type 1 and 2 costs into TCAce from their existing financial accounting software or databases. In principle, TCAce also provides users with the option of estimating Type 5 costs, which are borne by parties other than the decision-making company, its suppliers or customers. These Type 5 costs may bear a direct relevance to the Life Cycle Inventory data imported by the user into TCAce from their LCA software. Nevertheless, if they are included in the analysis, Type 5 costs must still be recorded separately from internal costs, as they do not directly impact the cost-effectiveness of a decision.

4.2. Weighting Financial LCC with Environmental LCC

The paper by Reich (2005) examined the possibilities and limitations of connecting economic information to a life cycle assessment (LCA) in the process of analysing municipal waste management systems. The author proposed a terminology and methodology for the economic assessment of municipal waste management systems, and tested it in a case study. A distinction was made between a financial life cycle costing (effectively LCC, used in parallel with an LCA) and an environmental LCC that was used as a subsequent weighting tool.

In the case study, the LCC analysis comprised all the costs incurred by the extended waste management system, applied as if the LCA system was a single economic actor. In the environmental LCC, three different weighting methods were used to monetize environmental effects such as emissions and resource use. Notably, both LCC analyses used the same unit of account, and they were therefore perfectly additive, suitable for use as a welfare-economic tool. This step-by-step aggregation resulted in a transparent and reproducible analytical method.

However, in the particular case, despite the methodology seemingly facilitating the analysis, it was established that major problems remained, due to the fact that municipal waste management diverged from standard economic systems in significant aspects.

4.3. Integrating Contingent Valuation

Bovea and Vidal (2004) proposed a model, which took an interesting approach to calibrating the value of environmental improvements, based on demand. It used an innovative combination of three methodologies: the Life Cycle Assessment (LCA) methodology to determine the environmental requirements, Life Cycle Cost analysis (LCC) to examine the internal and external costs of the product, and Contingent Valuation (CV) to quantify the customer’s value in terms of their willingness-to-pay (WTP) for a product that incorporates certain environmental improvements. This shows that the product value can be increased with the use of a design that simultaneously reduces the environmental impact and external costs, while allowing a manufacturer to pursue a profit-maximization strategy.

4.4. Eco-cost

Use of the LCC analytical framework, while adding some elements of LCA, such as physical flows from the manufacturer and perhaps first-tier suppliers generally lacks important LCA attributes, and therefore fails to identify decisions that minimize total environmental burdens over the full life cycle (Norris, 2000). One possible course of addressing this involves eco-cost, as in Dejaco et al. (2020), who applied it to residential building technologies. An interesting conclusion was that while the carbon tax (as used in Austria) had a 5% impact on total life-cycle costs of a building, and thus had little impact on decision-making, using the full eco-cost (quantified via the IPCC estimate of 135 €/tCO_2 equivalent) increased the impact to 20%, becoming highly relevant.

4.5. Circular Economy Application

Recent research has advanced the integration concept into the objectives of transitioning from the linear economy to a Circular Economy (CE). Namely, Alejandrino et al. (2022) suggested the integration of an existing environmental life cycle assessment of organizations (O-LCA) and a proposed life cycle costing of organizations (O-LCC) to identify and select possible CE improvements for industrial firms. The concept is shown in Figure 2.

After an initial diagnosis, ten CE improvements were selected and applied in eight alternative scenarios. The application showed that although all the alternative scenarios were beneficial from the CE perspective, considering the environmental and economic effects gave routinely different outcomes.

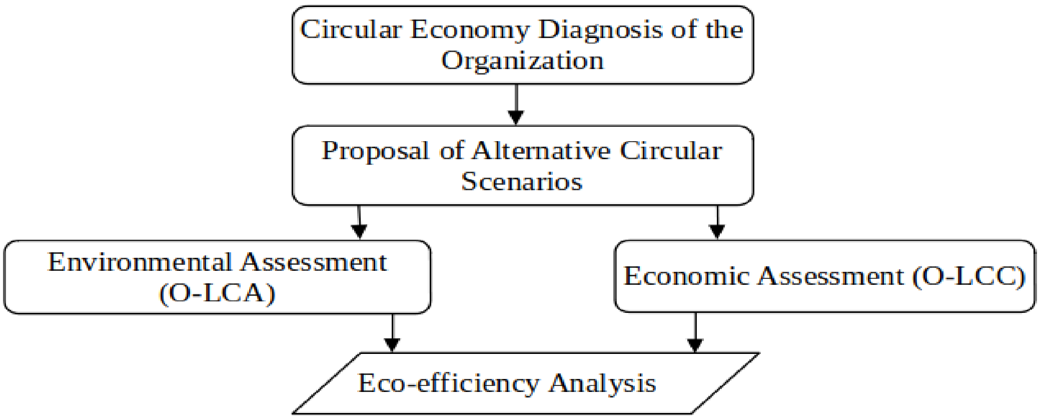

Figure 2. Integrating O-LCA and O-LCC to assess Circular Economy (Alejandrino et al. (2022))

4.6. The Optimization Problem

The relationship among economic and environmental aspects in integrated evaluation is often not in balance. This means that optimization is as important to consider as integration. Because of the nature of the decision-making process in the LCC and LCA context, the optimization problem will inevitably become multi-objective. Many studies have been carried out on multi-objective optimization and numerous potentially relevant optimization models can be found in literature. We start with the ones considering more general, but potentially related factors, such as quality and reliability, followed by those specifically considering environmental factors.

In the first category, Wright et al. (2002) developed a multi-objective optimization model to optimize HVAC (heating and cooling installation) system design and control parameters with two design objectives: to minimize the operating cost for the design days and, at the same time, to minimize thermal discomfort. Frangopol et al. (2001) focused on LCC analysis combined with civil construction reliability, which was further developed by Okasha and Frangopol (2009) using genetic algorithms to optimize in the domain of structural construction system problems considering system reliability, redundancy and the life cycle cost. Brown and Salcedo (2003) proposed the application of multiple-objective genetic optimization to a naval ship design problem, where the critical objective attributes taken into account were mission effectiveness and cost.

More closely related to LCA, due to their involvement of physical units (mass, energy), were the study of Fragiadakis et al. (2006), where the material weight and life cycle cost were the two objectives optimized by an Evolution Strategies Algorithm, and that of Hamelin and Zmeaureanu (2012), who performed an optimization of a family house envelope, using two objective functions, the life cycle primary energy use and life cycle cost.

Early adopters of multi-objective optimization involving LCA were Azapagic and Clift (1999), who used a three-objective system optimization in LCA as a means of identifying and evaluating the best possible options for environmental management of the product system. Their method offered the decision-maker a choice between two alternatives, Best Practicable Environmental Option (BPEO) and Best Available Technique Not Entailing Excessive Cost (BATNEEC), the second of which considered costs, albeit in a subordinate role.

Verbeeck and Hens (2007) performed a life cycle optimization for extremely low energy dwellings aiming at reducing financial costs and environmental impact over the life cycle. The environmental impact was evaluated through a life cycle inventory of the whole building, whereas costs were evaluated through a cost-benefit analysis. The multi-objective optimization problem was addressed by combining genetic algorithms and the Pareto concept. The results included a discussion of the trade-off curves of primary energy consumption and net present value, an analysis of the embodied energy, and a study of the impact of economic parameters, such as price developments exceeding inflation and discount rate.

More recently, Ostermeyer et al. (2013) proposed a multidimensional Pareto optimization methodology using LCC and LCA in the context of building refurbishment.

5. Discussion and Conclusions

It is clearly seen that numerous researchers have encountered the need to integrate the results of LCA and LCC analysis. Therein, two distinct possible objectives may be observed: One, primarily focused on perceived societal needs, which gave rise to approaches essentially based on LCA, i.e., the environmental aspects, such as LCECA and EIO-LCA, but also to some of the multi-objective optimization proposals. These methods' outputs may well be attractive for policy makers, as tools for the identification and, perhaps, promotion of broad policy objectives, but can hardly be considered as useful decision-making tools on the micro level in a market economy, fundamentally driven by economic incentives (in contrast to a directive-driven economy). It then remains to be seen what is available in terms of extending LCC analysis to include LCA considerations.

In the current project, focusing on industrial symbiosis, the design develops in three consecutive stages. First, separate LCA and LCC models have been created in a way that tightly coordinates the structure of inputs (these include a comprehensive dataset on relevant producers, products and their relevant parameters, including geographical locations), and with common partial objectives (such as identifying environmentally and economically break-even transport distances for material substitution).

LCC and LCA results will now be compared using several case studies of technologically viable and tested industrial symbiosis (one current case involves fly ash produced by coal combustion that can have several secondary uses in construction, besides landfilling), in order to establish whether, under circumstances, they can bring broadly compatible results. This stage will include sensitivity analyses to external developments in inputs, but also to potential policy actions, such as new or increased charges at different nodes of the system, subsidies to intermediate processing etc.

This will, in the ultimate stage, facilitate the creation of a single comprehensive model of industrial symbiosis, using LCC as well as LCA inputs, whose LCC component will be using real or transfer pricing in each of its nodes. Its intended use will be to guide the actions of company decision-makers, as well as to simulate the anticipated response of industry to policy actions. Research-wise, the model will also contribute to a better, empirically tested understanding of the integration potential of LCA and LCC analyses.

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