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NOTE

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Life cycle assessments (LCAs) are used to evaluate the environmental impacts attributable to products and processes. For construction projects, LCAs can be used to assess the pollution associated with the manufacture of building materials for the construction process. Despite the reliability of traditional LCA data, many upstream processes are excluded, which adversely affects overall reliability. Input–output analysis is systemically complete, but is subject to inherent errors when applied to the LCA of specific products. Analysis of an input–output LCA model provides a basis for more informed decision making regarding processes which can be ignored during the collection of traditional LCA data. This paper proposes a hybrid LCA method for construction in which national input–output data fill those 'gaps' not accounted for by traditional LCA data. Regardless of the level of detail at which data are collected, LCAs can now be performed at similar overall levels of framework completeness.

Keywords: Life cycle assessment, input–output analysis, hybrid LCA, construction

Introduction

The procurement of construction projects has a significant impact on the environment. Consideration of the extent to which construction impacts the environment is becoming a topical issue for construction researchers as natural resources are being depleted, fossil fuels emit damaging pollutants, and rainforests are being destroyed (Finch, 1992). The initial impact of a building on the environment results from the energy and other products consumed in its construction. Thereafter, the building continues to affect the environment directly and indirectly throughout its operation, maintenance, refurbishment and final demolition.

The use of energy for producing materials and operating buildings, be it directly or indirectly, contributes to air pollution (Suzuki and Oka, 1998). In Australia, the construction and operation of buildings account for 30–40% of the nation's energy use and energy related greenhouse gas emissions (Treloar, 1996). Thus, it is clear that environmental impact associated with buildings is as much an issue as financial cost in their construction and use (Ofori, 1992).

Numerous techniques for assessing the environmental impacts are available, all of which have their advantages and disadvantages (Cole *et al.*, 1993). Life cycle assessment (LCA) is considered to be the only legitimate basis on which to compare the environmental impacts of alternative building materials, components and services (Cole, 1998). Upstream processes are traced laboriously upstream by gathering case specific data.

Due to the diverse and complex nature of construction projects, however, generally the use of LCA is too cumbersome for considering the impact of design decisions on the environment. Even for comparatively simple products, LCAs tend to be systemically incomplete. A non-traditional approach to

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LCA involves the use of input–output data to account for upstream processes (eg, Lave *et al.*, 1995). The economically based input–output data are considerably less reliable than case specific LCA data. The input–output analysis framework is nonetheless systemically complete (Treloar, 1997).

Input–output analysis has been used to derive LCA data, particularly embodied energy related data, for basic materials and for construction sectors (e.g. Treloar, 1996; Suzuki and Oka, 1998). No methods have been identified in the LCA literature which integrate traditional and input–output LCA data within the input–output model. The purpose of this paper, therefore, is to propose a hybrid LCA method, based on the input–output model, that specifically addresses the issues of completeness and reliability.

Life cycle assessment

LCAs attempt to quantify the environmental 'loadings' and 'impacts' associated with a process. The term 'loadings' refers to quantifiable activities that have environmental effects. Environmental loadings include various emissions to air, water and land (Fossdal and Edvardsen, 1995).

Environmental loadings are calculated for each life cycle phase of a product. Figure 1 represents the upstream and downstream components of a building's life cycle, based around the construction process. 'Upstream' refers to the manufacture of goods and services used in the construction process, while 'downstream' refers to the operation, maintenance and demolition of the building, leading eventually to demolition. The term 'impacts' refers to actual effects resulting from environmental loadings, such as species loss in a stream ecosystem caused by the introduction of heavy metals, whereas an environmental loading would be the release of heavy metals into a stream. All environmental loadings are quantifiable, but many environmental impacts are assessable only in qualitative terms.

Häkkinen (1994) states that there are four steps required to undertake an LCA: 1, goal definition (i.e., the life cycle phases to be considered); 2, inventory analysis (quantifying direct and indirect inputs to each life cycle phase); 3, environmental assessment (classification and valuation); and 4, interpretation (including identification of improvement strategies). Clearly step 1 and the second part of step 3 (i.e. valuation) require value judgements. It has been stated that inventory analysis (step 2) and classification (step 3) are carried out on the basis of verifiable facts wherever possible (Häkkinen, 1994). In the selection of items to include in the inventory, intuition plays a role because the final composition of the inventory is not known beforehand. Therefore it is difficult to prioritize data collection because there is no basis for identifying items which can be excluded.

Current LCA databases are unsuitable for construction projects inasmuch as they comprise mainly basic materials. Many other processes would still be neglected (Treloar, 1997). Time spent quantifying a small item may be better spent providing more detail for a larger item. Similarly, it may be more important to know the cement content and source for the concrete rather than the number and composition of internal doors. There is no method available, however, for prioritizing the collection of LCA data, and many types of process are routinely excluded.

Simplified LCAs use generic data for a wide scope of processes in the life cycle of the product (Jensen *et al.*, 1997). Standard models can be used for commonly utilized systems, such as transport and energy supply. Most LCA software can be categorized as simplified LCAs because they use standard models for most items. Such software apparently focuses on the most important items, but the prioritization of these is based on intuition from previous conventional or simplified LCAs. Since even conventional LCAs can be systemically incomplete, intuitive assessment based on them could be invalid.

Häkkinen (1994) asserts that LCAs provide a basis for developing a system with lower impact on the environment. The authors do not agree with Häkkinen's assertion because competing systems may be assessed with frameworks of such widely differing completeness that comparisons may be invalid. This problem is exacerbated in simplified LCAs, even those using detailed databases of basic materials.

LCAs of complete buildings generally are classifiable as simplified LCAs, because standard data sets for basic materials tend to be used (Fossdal and Edvardsen, 1995). The costs of obtaining an appropriate level of detail are spread for mass-manufactured products. Consequently, conventional LCAs are more viable for mass-manufactured products than for more complex, one-off products such as construction projects.

Simplified LCAs use generic data (qualitative and/or quantitative), or standard sets of data for basic materials, transportation or energy production (Jensen *et al.*, 1997). The difference between simplified and conventional LCAs is not clear cut, but rather a continuum comprising different levels of detail. Generally it is acknowledged that simplified LCAs represent a decrease in framework completeness (Jensen *et al.*, 1997). For construction and other complex products, another LCA method is required that is comprehensive in framework but that also is able to be applied rapidly.

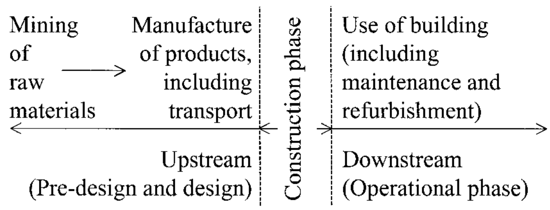

Figure 1 Phases of a building's life cycle, showing upstream and downstream phases

Input–output analysis as a basis for LCA

Input–output analysis is a technique developed in the field of economics for the purpose of rapidly assessing flow-on effects in national systems (e.g. Piertroforte and Bon, 1995). It has since been applied to environmental systems and energy analysis (e.g. Suzuki and Oka, 1998). Input–output data summarize economic transactions between sectors of an economy. One input–output coefficient may give the national average amount of cement used to make concrete. Another may give the national average amount of gas used in the manufacture of bricks nationally. A matrix of coefficients is constructed, which allows inputs to a sector to be traced upstream, through multiple transactions. A mathematical process called 'matrix inversion' is used to complete the framework systemically, so that all possible transactions between sectors of the economy are included (Treloar, 1997). Transaction pathways of infinite length are accounted for theoretically (Lave *et al.*, 1995).

Input–output analysis has been used for LCAs (e.g. for the US economy by Lave *et al.*, 1995). In this approach, the sector of the national economy that produces the product under consideration is analysed in terms of the transactions between it and other sectors of the economy. National average LCA environmental loading and impact data are associated with each sector of the economy. Such data may not be available in all countries, potentially limiting the wider application of this method.

The errors inherent in the use of economic input–output data were not acknowledged by Lave *et al.* (1995). Generally input–output data are much less reliable than traditional LCA data (Treloar, 1997). Furthermore, the input–output model is a 'black box', due to the matrix inversion process. Important components of the model cannot be identified readily.

Also there are several other types of exclusions in LCAs, as shown in the analysis of an input–output model developed by Treloar (1997) for embodied energy analysis: (i) inputs of small items (e.g. fixings and adhesives, also identified by Häkkinen, 1994); (ii) ancillary activities associated with the process, such as administration; (iii) inputs of services, such as banking and insurance; (iv) further processing of basic materials into complex products; and (v) non-feedstock energy used to make fuels. These types of exclusion are acceptable only if it can be shown that they are relatively insignificant. This would be impossible for items that have never been quantified before in an LCA. Supporting this point, Lave *et al.*, (1995) stated that not even the inventory phase of LCA is able to be supported scientifically. Generally, only the inputs thought to be important are included. Some small inputs may be rejected because they were found to be unimportant in previous studies. It is more likely, however, that most are simply ignored.

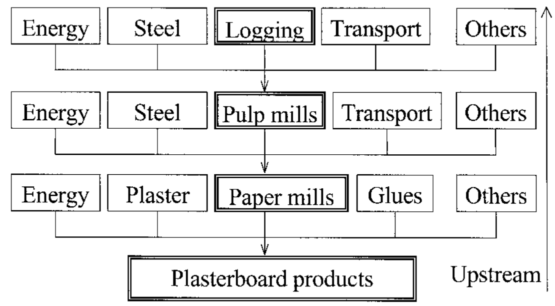

Figure 2 Direct and indirect suppliers to plasterboard product manufacturers.
The items with double borders indicate processes typically included in a traditional LCA, within the partially represented framework of an input–output LCA (after Lave *et al.*, 1995)

The most complex component of the LCA of a building is the manufacture of products for the construction process, incorporating 'pathways' of transactions leading upstream to raw materials. A pathway may comprise the extraction, refinement and transformation of a raw material into a complex product. The framework of a typical LCA in the context of the input–output model is demonstrated with an example of plasterboard products (Figure 2). Normally, only a fraction of the inputs to a process are considered in a conventional LCA (e.g. the single pathway in Figure 2 comprising 'logging' into 'pulp mills' into 'paper mill' into 'plasterboard products'). This pathway conceals a vast array of processes which normally are represented in an input–output model (Lave *et al.*, 1995).

A construction project comprises both basic materials and more complex building products, as shown in Figure 3. A building comprises many complex products, and it may not be viable to analyse each to the same level of detail using conventional LCA methodology. Consequently, many smaller inputs are ignored, and many simplifying assumptions are made.

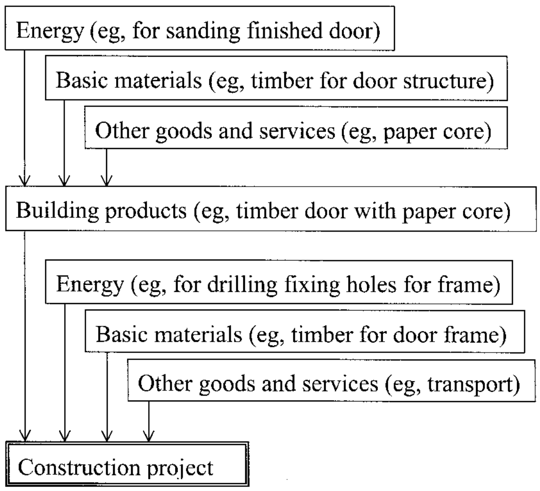

Figure 3 Basic materials and building products used in a construction project

This incompleteness may be differential, possibly invalidating comparisons between competing materials, products and systems.

A proposed hybrid LCA method

Input–output LCA methods may be suitable for analysis of national production of basic materials, where case specific data are unavailable due to industrial confidentiality. Input–output LCA methods are generally unsuitable for individual buildings because of errors inherent to input–output analysis and the complexity of construction projects. Therefore, a hybrid LCA method is proposed for complex products such as construction projects, which integrates the comprehensive input–output model with more reliable LCA data.

The proposed hybrid LCA method, comprises the following steps: 1, derive an input–output LCA model; 2, extract the most important pathways for the construction sector; 3, derive case specific LCA data for the building and its components; and 4, substitute the case specific LCA data into the input–output model. Step 1 was described in the previous section, and step 3 was described earlier in the paper. For step 2, the most important 'pathways' from the inverse input–output model can be extracted using an algorithm developed by Treloar (1997). Important pathways for construction may be rainforest timbers used in structural framing, or cement and steel used in reinforced concrete. In step 4, input–output data for the unimportant pathways are retained in the model, by deducting the initial values of the modified pathways from the total. The modified pathway values are then integrated with the retained portions of the input–output model. Thus, the framework of the proposed hybrid LCA method will be as comprehensive as the initial input–output model. Yet, due to the deductive approach, the unimportant pathways remain summed, and the complexity of that part of the model for which no traditional LCA data are derived conveniently remains as a 'black box'.

The integration of traditional LCA data will have improved the reliability of those modified components of the input–output model. Only a fraction more time needs to be spent integrating conventional LCA data into the input–output model than normally would be spent in a conventional LCA. More reliable results may be able to be obtained by targeting traditional LCA data collection methods to those pathways deemed important in the input–output LCA model, rather than just collecting data on an otherwise uninformed basis. Economic input–output data may not be as reliable as traditional LCA data, and thus should be used only for small or usually neglected items.

Conclusion

There is a need for effective techniques to assess the impact of construction on the environment. The authors argue that existing techniques such as LCA do not account adequately for upstream processes. Thus, there is a need for a more comprehensive LCA method, so that the direct and indirect environmental impacts of design and engineering decisions can be assessed. This paper acknowledges previous input–output LCA methods, but suggests that a hybrid LCA method is more appropriate. National average input–output data should be used to fill in those gaps not accounted for by traditional LCA data. By adopting this approach, more reliable comparisons of construction products and systems can be undertaken with reduced time or cost requirements compared with conventional LCAs. Currently the authors are developing the proposed hybrid LCA method by: (a) investigating the best available input–output LCA models; and (b) application of the proposed hybrid LCA method described in this paper to different building types and other non-building products.

The proposed hybrid LCA method will enable informed decision making with regard to the collection of case specific LCA data. The proposed hybrid LCA method will enable potentially a large increase in framework completeness, and hence its overall reliability, at the cost of only a small increase in research time compared with a traditional LCA. The environmental impact of the initial and recurring construction phases for buildings will be able to be calculated in a more comprehensive manner. These can then be more reliably compared with the direct and indirect operational impacts of buildings, where such comparisons are required.

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