Supporting Information for

Assessing the End-of-Life Impacts of Buildings

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Summary of Life-cycle Assessment Techniques

There are two conceptually different approaches to LCA: process-based LCA and economic input-output analysis-based LCA (such as EIO-LCA) (*1*). The major difference between these two is that while the former looks at the processes used to make a product or generate a service, the latter includes all the monetary fluxes generated in a country's or region's economy by the production of a good or by the offer of a service.

The process-based LCA was initially developed by the Society for Environmental Toxicology and Chemistry (SETAC) and the procedures involved in this methodology were formalized by the International Organization for Standardization in their ISO 14040 series (*2, 3*). LCA is conducted in four main steps (*4*): definition of the processes that need to be analyzed (and the boundary of the analysis), data collection (inventory) for these processes (inputs and outputs), impact assessment; and interpretation of the results. Figure 1 shows a simplified example application of this LCA technique to the production of concrete.

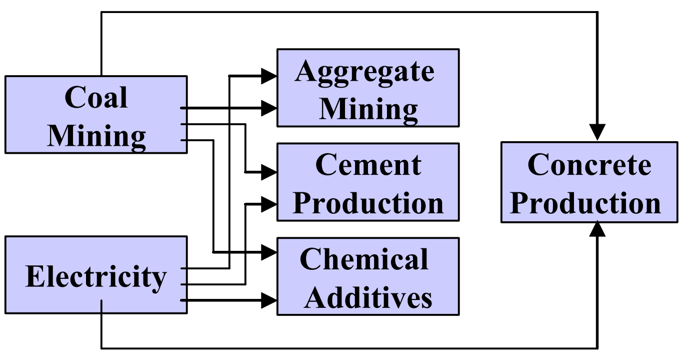

Figure 1 – Simplified process LCA of concrete production, without water (adapted from reference (*5*)).

EIO-LCA uses economic input-output tables and data on resource consumption and environmental emissions to trace out "the various economic transactions, resource requirements and environmental emissions required for a particular product or service" (*5*). It allows for capturing all the resources used and emissions caused directly and indirectly (in the supply chain) by the manufacture of a product or offer of a service.

The data used in EIO-LCA are collected from economic input-output matrixes (available from the U.S. Department of Commerce) and from publicly available databases on resource consumption and environmental emissions. An emission factor is calculated for each economic sector and then it can be combined with the economic input-output data to obtain an environmental impact caused by the acquisition of a dollar value from a specific economic sector. The eiolca.net web site allows for assessments on line (*6*).

Each of the two LCA techniques presented above has advantages and disadvantages (Table 2), and they have been thoroughly addressed by Hendrickson et al. (*5*).

	Process Models	EIO-LCA
Advantages	• Detailed process-specific analyses • Specific product comparisons • Process improvements/weak point analyses • Future product development assessments	• Economy-wide, comprehensive assessments (all direct and indirect environmental effects included) • Sensitivity analyses/scenario planning • Publicly available data, reproducible results • Future product development assessments • Information on every commodity in the economy
Disadvantages	• System boundary setting subjective • Tends to be time intensive and costly • New process design difficult • Use of proprietary data • Cannot be replicated if confidential data are used	• Some product assessments contain aggregate data • Process assessments difficult • Difficulty in linking dollar values to physical units • Economic and environmental data may reflect past practices • Imports treated as U.S. products • Difficult to apply to an open economy (with substantial non-comparable imports)

Table 2 – Advantages and disadvantages of two life-cycle assessment approaches (*5*)

Hybrid LCA promotes the joint use of these two techniques in order to take advantage of the respective positive aspects. This is done by using the comprehensiveness of EIO-LCA with regards to supply-chain emissions to overcome the trouble of performing a process-based assessment of all the processes in the supply chain, and using process-based assessment to overcome the lack of accuracy of EIO-LCA when it is too aggregate for the purposes of a detailed LCA. Bilec et al. (*8*) present an excellent review of existing hybrid models and have used this approach to assess construction processes.

Building from the two examples presented above, Figure 2 shows an example of the application of hybrid LCA to the inventory assessment of the production of ready-mixed concrete. EIO-LCA data are used to assess comprehensively the impacts associated with the production and supply chains of electricity and mining of coal. A process-level analysis that would have to consider hundreds of different processes. The assessment of the concrete production stage (at the concrete plant) can nevertheless be performed at the process level as there are a small number of processes and technologies to be considered, allowing for the process-based LCA to perform a more accurate assessment than EIO-LCA. The combined hybrid LCA is expected to give more comprehensive results than process-based LCA and EIO-LCA separately.

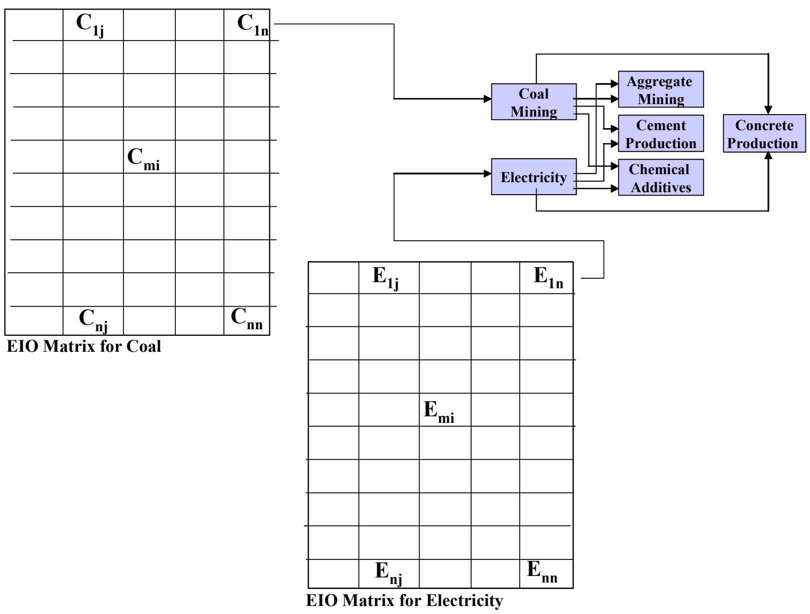

Figure 2 – Hybrid LCA of ready-mixed concrete

Brief Discussion on the Markets Mentioned in the Paper

Aggregates market

Aggregates have been traditionally used by the construction industry for a very long time and for different purposes. This legacy together with lack of at-hand substitutes makes it difficult to change construction techniques in the short term and start using substitutes. For this reason the elasticity of demand for these products should be low. In the long term, the elasticity of demand can be slightly higher because both users of these products for buildings and producers of other alternative products will be able to change their production systems. Still, the long-term elasticity of demand is expected to be low, again because of legacy issues but also because these products do not represent a significant portion of the total costs of products in which they are used. The elasticity of supply is also expected to be low in the short term because of capital, land and throughput constraints in mines, mills and plants. Although in the long-term these facilities may adapt leading to an increase in the elasticity of supply, this effect is not likely to be significant due mostly to lack of suitable land available, and regulatory and public pressure. Elasticity of demand and supply can be calculated for both crushed stone and sand and gravel for the U.S. in the period 1971-2004 from USGS data on unit prices, production and apparent consumption. Depending on the calculation method used (linear or arch), for crushed stone the values of the elasticity of demand range from 0.52 to 0.68, and elasticity of supply ranges from 0.46 to 0.64. For sand and gravel, the values of the elasticity of demand range from 0.17 to 0.34 and elasticity of supply ranges from 0.17 to 0.35. These ranges show that the elasticity of supply is very close to the elasticity of demand. Therefore, it is fair to assume that an X decrease in demand for aggregates for buildings will lead to an X/2 decrease in the amount of aggregates being produced and an increase in X/2 in the amount of aggregates going into alternative products.

Cement market

Cement is a critical product in the construction industry. Construction techniques, technology and procedures often depend on cement. This makes it very difficult for cement users to change their habits, which results in a very low short-term elasticity of demand. Though adaptation is possible, no real alternative products seem to exist for large scale use of cement (less than 3% of cement is used in products other than concrete) and low long-term elasticity of demand should also be low. The high cost of capital and capacity constraints of cement plants can result in a low short-term elasticity of supply. A larger long-term elasticity of supply will depend on the capacity of these plants to expand their production capacity. Despite this, the long-term term elasticity of supply is expected to remain fairly low. Data from the USGS allows one to calculate the elasticity of demand and supply of cement in the U.S. based on unit prices, production, and apparent consumption. For the period 1971-2004 and depending on the calculation method used (linear or arch), the values of the elasticity of demand range from 0.24 to 0.43 and elasticity of supply ranges from 0.12 to 0.25. Though these numbers are not definite, they clearly confirm that both elasticity values are low as expected. Just as with the aggregates market, it can be assumed that an X decrease in demand for cement for buildings will lead to an X/2 decrease in the amount of cement being produced and an increase in X/2 in the amount of cement going into alternative products.

Recycled concrete market

With an increasing tendency for recycling of construction materials, aggregate producers, building and road contractors are looking for additional streams of recycled/recyclable material. The main input streams in this market are crushed concrete from structural construction and reclaimed asphalt pavement.

According to the USGS, in 2005 U.S. crushed stone and sand and gravel producers recycled a total of 5.65 million tons of asphalt concrete (*9, 10*). These producers also recycled a total of 8.5 million tons of cement concrete. These numbers represent nevertheless a very small percentage of the total recycled concrete because most of the recycling is done by construction or demolition companies that are not surveyed by the USGS. They show, however, that the amounts of recycled asphalt concrete and cement concrete have similar magnitude. Given this scale similarity, and strong similarities in technologies and processes used in the recycling of these two streams of concrete, it is fair to assume that their elasticity of supply and of demand are similar. In other words, this justifies the assumption that both of these recycling streams will be equally affected by market changes. As a consequence, an increase of X in the amount of concrete recycled from buildings will result in a decrease of X/2 in the amounts of concrete recycled from other sources and an increase of X/2 in the amount of overall concrete being recycled in the market.

Data Quality Assessment

Process/Activity	Acquisition Method	Independence of data supplier	Representativeness	Temporal correlation	Geographical correlation	Further technological correlation
Cement production	2	1	2	3	2	3
Aggregate production	2	1	2	3	2	3
Alternative use for cement – concrete pipes	2	1	2	3	2	3
Competing concrete pipes products - PVC pipes	2	1	2	3	2	3
Alternative use for aggregate – base	2	1	2	3	2	2
Competing base products – recycled concrete	2	2	4	2	2	1
Alternative use for aggregate – asphalt paving mix	2	1	2	3	2	2
Complementary asphalt products – bitumen	2	1	2	3	2	5
Competing asphalt products – PCC pavement	2	1	2	3	2	3

Concrete production	2	1	2	3	2	3
Frame construction	3	2	4	3	2	3
Frame demolition	3	2	4	3	2	3
Separation	3	2	4	3	2	3
Landfilling of concrete	2	2	2	3	3	4
Waste management for other sources of "scrap" concrete	2	2	2	3	3	4
Recycling of concrete	2	2	4	2	2	1
Cement market	3	2	4	3	3	4
Aggregate market	3	2	4	3	3	4
Concrete "scrap" market	3	2	4	3	3	4

Table 3. Data quality assessment matrix (1 indicates highest, 5 lowest quality data). Based on reference (*11*).

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