USING HYBRID EIO-LCA TO ASSESS ENVIRONMENTAL IMPACTS ASSOCIATED WITH MANUFACTURING WOOD-CEMENT COMPOSITES

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ABSTRACT

Conducting a life cycle assessment on hybrid materials has always been a challenge. However, Environmental Input-Output Life Cycle Assessment has been proposed by economists as a different approach, accounting for all economic transactions between sectors of the economy thereby eliminating system boundaries by taking an aggregate view of the entire national economy. This study offers a simple demonstration of how to use the input-output hybrid modeling tool to assess resource requirements and pollutant releases for production of a wood-cement composite.

KEYWORDS:

EIO-LCA, hybrid product, wood-cement composites, greenhouse gas emissions

INTRODUCTION

Life cycle assessment (LCA) is widely considered an important decision-making tool in building products processing, contributing to the overall environmental evaluation in the building construction sector.

The sustainability of the cement component in wood-cement composites (WCC) is unknown and therefore, it may be difficult for WCC to compete with conventional wood-based panels in a *cradle-to-grave* carbon-balance calculation. However, it was well documented that manufacturing wood-only products generate less fossil carbon emission than manufacturing equivalent of metal or concrete products (Sathre and O'Connor, 2010). Acquisition and processing of raw materials, as part of any manufacturing process, is mainly responsible for the production energy consumption and emission of noxious gasses. Avoiding cement process emissions is often mentioned as key benefit in favour of wood products over concrete products because of the impacts of greenhouse gases (GHG).

LCA can be done via environmental or social assessment, but it is the environmental life cycle assessment (ELCA) technique that is used to estimate the environmental impacts associated with all stages of building products and can be used for WCC as well. There are two standards (ISO 14040 (2006) and ISO 14044 (2006)) used in ELCA which describe the required and the recommended phases of conducting an assessment, including defining the scope of the analysis, the inventory, assessment and interpretation of the process/product.

ELCA is a process-type technique which assesses in detail resource requirements and pollutant releases for the main production (manufacturing) processes. Adjacent contributions from second-order production activities and suppliers are usually included in ELCA evaluation as well. However, upstream production stages are often not included in the analysis because the process would become extremely time consuming (Treloar et al., 2000). For example, financial, insurance, consulting and real estate related activities are ignored by the energy balances (Hendrickson et al., 2006). Therefore, choosing the system boundary is essential. Lenzen (2006) calculated errors caused by the truncation of the production system boundary, by the omission of resource requirements or pollutant releases of higher-order upstream stages of production. Truncation errors above 50% for most of the process analysis, including first-order inputs, were determined. As the process evaluation included production stages at higher orders the truncation errors decreased accordingly.

The field of economics has proposed an input-output approach of the life cycle assessment accounting for all the economic transactions between economic sectors. This has been described as the Environmental Input-Output Life Cycle Assessment (EIO-LCA) and it uses average data on a national scale, associated with each sector of the economy. This approach brings a different kind of research strategy, eliminating system boundaries by taking an aggregate view of the entire national economy (Lave et al., 1995). From the initial purchase, through the entire supply chain, EIO-LCA accounts for every inter-sectoral transactions as direct and indirect economic contributions required by the final demand of a particular product or process.

ENVIRONMENTAL INPUT-OUTPUT LIFE CYCLE ASSESSMENT

EIO-LCA is based on the input-output economic method developed by Wassily Leontief (Leontief, 1966) and applied by many economists afterwards (Miller and Blair, 2009). The basic approach of the method is to quantify the interdependence between individual sectors within an economic system. National economies are most common systems, but smaller entities (such as regions, provinces or metropolitan areas) and larger structures (such as the international economic system) can benefit from the use of the theory as well. The transactions between individual sectors are expressed through linear equations made of so called *input coefficients.* Each coefficient describes the magnitude of the interdependence between any two sectors. These coefficients are produced empirically and aggregated in statistical input-output tables which are generated by the economic authorities in many countries.

The framework for developing the input-output tables, that can be used to calculate the changes in the flow of goods and transactions between sectors following a change in final demand for one or more sectors, is presented in Table 1, in a simplified form. We assumed an economic system comprised of only two product sectors: Wood and Cement. A third sector, as a mandatory component of any economic system, is labour and it was included as the Household sector. For clarity, these inter-sectoral flows were converted into monetary transactions which simulated the basic movement of goods between the three sectors.

Table 1. Monetary transactions between sectors (all values represent $)

into: / from:	**Wood**	**Cement**	**Household (demand)**	**Total output (T-O)**
Wood	10	5	40	55
Cement	20	15	50	85
Household (labour/salaries)	30	50	10	90
Total Input (T-I)	60	70	100	230

It was assumed that there was a demand (D_1) for consumption of wood products in amount of $40. In addition, the Wood sector itself required wood products (worth of $10) generated within the sector, for example, these could be seeds for forest regeneration, lumber used during logging operations or for building various constructions at the mill sites, or wood used as fuel in lumber dry kilns. The Cement sector also purchased products from the Wood sector, such as lumber for buildings and wood as fuel used in lime calcination kilns. Assuming the value of the goods absorbed by the Cement sector from the Wood sector was $5, that means the total output from the Wood sector was $55 including the consumer demand plus the transaction values within the Wood sector and between Wood and Cement sectors.

Similarly, there was a $50 demand ($D_2$) for cement from the Household sector, plus a $20 transaction from the Cement sector to the Wood sector, say, for road and mill concrete building construction and a $15 transaction within the Cement sector to fulfil the cement needs of this sector itself. Total output for the Cement sector was $85.

The labour required by each sector is shown in the third row. Basically, this represents the salaries paid in each sector, $30 for the labour put into the Wood sector and $50 for the labour put in the Cement sector. In the Household sector column, $10 represents other direct transactions (D_3) within households, separate from Wood or Cement purchasing. Total output for the Household sector was $90.

Table 2. Calculation of the input coefficients

into: / from:	Wood	Cement	Household (demand)	Total output (T-O)
Wood	a_{11} = 10/55 = 0.182	a_{12} = 5/85 = 0.059	$D_1 = 40$	55
Cement	a_{21} = 20/55 = 0.364	a_{22} = 15/85 = 0.176	$D_2 = 50$	85
Household (labour/salaries)	a_{31} = 30/55 = 0.545	a_{32} = 50/85 = 0.588	$D_3 = 10$	90
Total Input (T-I)	60	70	100	230

The input coefficients, characteristic of each sector, were calculated as the ratio between input values and the total output for that particular sector (Table 2). For the two sectors, Wood and Cement, those were further converted into a matrix of input coefficients (Equation 1).

$$\begin{bmatrix} \mathbf{a}_{11} & \mathbf{a}_{12} \\ \mathbf{a}_{21} & \mathbf{a}_{22} \end{bmatrix} = \begin{bmatrix} \mathbf{0.182} & \mathbf{0.059} \\ \mathbf{0.364} & \mathbf{0.176} \end{bmatrix} \tag{1}$$

This matrix of input coefficients is the foundation for all calculations resulting from any change in demand for either sector. For the purpose of this demonstration, we assumed a change in demand for wood products (d_1) from \$40 to \$80, while the new demand for cement (d_2) remained unchanged at \$50 (Equation 2).

$$\begin{bmatrix} \mathbf{d}_1 \\ \mathbf{d}_2 \end{bmatrix} = \begin{bmatrix} \mathbf{80} \\ \mathbf{50} \end{bmatrix} \tag{2}$$

New demand for wood products generated a direct effect not only within the Wood sector but also between Wood and Cement sectors and eventually, between Cement and Wood sectors and within the Cement sector as well. So new total outputs for the two sectors (Equation 3 and Equation 4), as result of the direct effect of the new demand, became:

$$\text{T-O Wood}_1 = d_1 + [\mathbf{a}_{11} \quad \mathbf{a}_{12}] \times \begin{bmatrix} \mathbf{d}_1 \\ \mathbf{d}_2 \end{bmatrix} = 80 + 17.51 = 97.51 \tag{3}$$

$$\text{T-O Cement}_1 = d_2 + [\mathbf{a}_{21} \quad \mathbf{a}_{22}] \times \begin{bmatrix} \mathbf{d}_1 \\ \mathbf{d}_2 \end{bmatrix} = 50 + 37.92 = 87.92 \tag{4}$$

However, this new increase in sectoral demand (Equation 5) required even more production from both sectors.

$$\begin{bmatrix} \mathbf{d}_{11} \\ \mathbf{d}_{22} \end{bmatrix} = \begin{bmatrix} \mathbf{17.51} \\ \mathbf{37.92} \end{bmatrix} \tag{5}$$

In other words, second-tier effects were generated by a new change in sectoral demand (\$17.51 from Wood sector and \$37.92 from Cement sector) because of the direct effects of the initial Household demand change. The new total outputs, after the second-tier effects, were:

$$\text{T-O Wood}_2 = \text{T-O Wood}_1 + [\mathbf{a}_{11} \quad \mathbf{a}_{12}] \times \begin{bmatrix} \mathbf{d}_{11} \\ \mathbf{d}_{22} \end{bmatrix} = 97.51 + 5.42 = 102.93 \tag{6}$$

$$\text{T-O Cement}_2 = \text{T-O Cement}_1 + [\mathbf{a}_{21} \quad \mathbf{a}_{22}] \times \begin{bmatrix} \mathbf{d}_{11} \\ \mathbf{d}_{22} \end{bmatrix} = 87.92 + 13.05 = 100.97 \tag{7}$$

New sectoral demands after second-tier effects were:

$$\begin{bmatrix} \mathbf{d}_{111} \\ \mathbf{d}_{222} \end{bmatrix} = \begin{bmatrix} \mathbf{5.42} \\ \mathbf{13.05} \end{bmatrix} \tag{8}$$

After the third-tier effects, the total outputs were:

$$\text{T-O Wood}_3 = \text{T-O Wood}_2 + [\mathbf{a}_{11} \quad \mathbf{a}_{12}] \times \begin{bmatrix} \mathbf{d}_{111} \\ \mathbf{d}_{222} \end{bmatrix} = 102.93 + 1.76 = 104.69 \tag{9}$$

$$\text{T-O Cement}_3 = \text{T-O Cement}_2 + [\mathbf{a}_{21} \quad \mathbf{a}_{22}] \times \begin{bmatrix} \mathbf{d}_{111} \\ \mathbf{d}_{222} \end{bmatrix} = 100.97 + 4.27 = 105.24 \tag{10}$$

After the fourth-tier effects, the total outputs were:

$$\text{T-O Wood}_4 = 104.69 + [\mathbf{0.182} \quad \mathbf{0.059}] \times \begin{bmatrix} \mathbf{1.76} \\ \mathbf{4.27} \end{bmatrix} = 104.69 + 0.57 = 105.26 \tag{11}$$

$$\text{T-O Cement}_4 = 105.24 + [\mathbf{0.364} \quad \mathbf{0.176}] \times \begin{bmatrix} \mathbf{1.76} \\ \mathbf{4.27} \end{bmatrix} = 105.24 + 1.39 = 106.63 \tag{12}$$

After the fifth-tier effects, the total outputs were:

$$\text{T-O Wood}_5 = 105.26 + [\mathbf{0.182} \quad \mathbf{0.059}] \times \begin{bmatrix} \mathbf{0.57} \\ \mathbf{1.39} \end{bmatrix} = 105.26 + 0.19 = 105.45 \tag{13}$$

$$\text{T-O Cement}_5 = 106.63 + [\mathbf{0.364} \quad \mathbf{0.176}] \times \begin{bmatrix} \mathbf{0.57} \\ \mathbf{1.39} \end{bmatrix} = 106.63 + 0.45 = 107.08 \tag{14}$$

After the fifth-tier effects generated by a change in Household demand for wood products from \$40 to \$80, the total output for the Wood sector increased from \$55 to \$105.45 and the total output for the Cement sector increased from \$85 to \$107.08.

Following the above algorithm, new multi-tier effects continue to add up to the total output but the values are so small that can be ignored. Although this method of calculating the effects of the change in demand on total sectoral outputs is very intuitive, the volume of calculation on a nation-wide input-output table will become enormous and therefore, using this approach is unrealistic. However, Leontief proposed an analytical method consisting in the following equation:

$$\mathrm{X} = (\mathrm{I} - \mathrm{A})^{-1}\mathrm{y} \tag{15}$$

Where X is the new output matrix, I is the unit matrix, A is the input coefficient matrix and y is the new demand matrix. The expression $(\mathrm{I} - \mathrm{A})^{-1}$ is often called in the literature the *Leontief inverse*.

Returning to the numeric example above, Equation 15 can be written as follows:

$$\mathbf{X} = \left(\begin{bmatrix} \mathbf{1} & \mathbf{0} \\ \mathbf{0} & \mathbf{1} \end{bmatrix} - \begin{bmatrix} \mathbf{a}_{11} & \mathbf{a}_{12} \\ \mathbf{a}_{21} & \mathbf{a}_{22} \end{bmatrix} \right)^{-1} \times \begin{bmatrix} \mathbf{d}_1 \\ \mathbf{d}_2 \end{bmatrix} \tag{16}$$

By solving Equation 16, the actual values for the sectoral output, as a result of the change in demand from \$40 to \$80 in the Wood sector, are shown in Equation 17. After five iterations using the empirical approach (Equation 13 and Equation 14), the obtained values were very close to the analytically calculated ones: \$105.45 vs \$105.48 for the Wood sector and \$107.08 vs \$107.29 for the Cement sector, a validation of the fact that the empirical method leads to same results.

$$\mathbf{X} = \begin{bmatrix} \mathbf{105.48} \\ \mathbf{107.29} \end{bmatrix} \tag{17}$$

At the time it was proposed as a method to estimate input-output nation-wide economic effects from changes in demand, calculation of the Leontief inverse was extremely laborious, taking weeks of hard computation work. Nowadays, thanks to the advance in technology, software can solve it in less than a second.

Knowing the new sectoral total outputs one can easily estimate the new inputs (effects) for each sector by using the same input coefficients, as shown in Table 3.

Table 3. New monetary transactions (economic effects) between sectors, adjusted to the new demand (all values represent \$)

into: / from:	**Wood**	**Cement**	**Household (demand)**	**Total output (T-O)**
Wood	19	6	80	105
Cement	38	19	50	107
Household (labour/salaries)	57	63	10	130
Total Input (T-I)	114	88	140	342

RESEARCH METHOD

WCC is a hybrid product having potential applications within both concrete materials and wood products-related sectors. Moreover, WCC can be utilized as a decorative product but it can also have a structural role as a building material. It seems that neither ELCA nor EIO-LCA alone could provide an accurate assessment on environmental burdens and impacts associated with manufacturing WCC. However, as a relatively new product which differs significantly from representative output of each of the two major sectors to which it belongs, WCC may be evaluated better by using a hybrid life cycle assessment method which combines attributes from both ELCA and EIO-LCA.

Therefore, the life cycle assessment of the WCC should be based on a hybrid life cycle assessment (HLCA) which has been proposed for complex products. This approach combines the scope of economy-wide EIO-LCA with the detailed of process analysis of ELCA (Treloar et al., 2000; Suh et al., 2004; Florin and Horvath, 2004; Hendrickson et al., 2006). Specific unit processes associated with the use and end-of-life stages can be added to the EIO-LCA of WCC to yield improved results.

The following steps are part of the proposed method for conducting a HLCA on WCC:

Step 1: Develop a comprehensive EIO-LCA for a wood-based panel or concrete product manufacturing sector within a nation-wide product price model and identify the most important sectors related to the functional unit;

Step 2: Derive case-specific ELCA data appropriate for the various phases of the life cycle (new process and materials, energy generation, use, recycle, etc); and,

Step 3: Substitute the data back into the input-output model.

This study employed the EIO-LCA on-line tool (http://www.eiolca.net) developed at Carnegie Mellon University and funded in part by the National Science Foundation, the US Environmental Protection Agency, and the Green Design Consortium. EIO-LCA on-line tool can use either the 1997 US Industry Benchmark model or the 2002 US Benchmark model. The 1997 model includes 491 sectors of the US economy, is based on the producer price, and produces effects on monetary transactions, conventional air pollutants, greenhouse gases, energy, toxic releases and employment. As the biggest economy in the world, US economy can be considered to be self-sufficient; therefore the US statistical input-output tables are one of the most exhaustive works ever produced. One advantage of using relative old data (1997) is the fact that, at that time, US economy was not much reliant on imports from overseas, so most of the economic transactions were completed within the national economic system.

Because a specific wood-cement product sector is not included into the existing database of economic sectors, manipulation in conducting EIO-LCA is required in order to adjust those existing sectors that can better resemble the manufacturing process of WCC. The mix of wood and Portland cement can generate various products, from wood-cement particle boards and cement-fibre boards to wood-cement blocks (e.g. Durisol® ICF Wall Forms, Beetlecrete™, etc). The boards are usually manufactured after a process relatively similar to manufacturing wood-based panels (e.g. plywood, OSB, MDF, etc); on the other hand, fabrication of blocks is similar to the process of making ordinary concrete products. We consider the WCC as a wood-cement block and building material, manufactured following the main stages of fabricating concrete block products: mixing, forming, pouring, etc.

In this study, conducting HLCA for WCC starts by running EIO-LCA on the "Concrete block and brick manufacturing" sector, under "Plastic, Rubber and Non-metallic Mineral Products" broad sector group. Because wood particles become the new aggregate in WCC by replacing the mineral aggregate in regular concrete, the economic effect of the "Sand, gravel, clay, and refractory mining" sector is diminished accordingly and the equivalent direct economic effect is transferred to the "Sawmills" sector. Although in most cases the WCC are made of wood waste resulted from various wood product manufactures, in this study we consider wood being sourced directly from the sawmill site and the purchase price of wood particles being the same to the purchase price of mineral aggregates. Consequently, all inter-sectoral transactions will be affected as well.

RESULTS AND DISCUSSION

Data has been processed in the custom model section of the on-line tool, which allows for an adjusted analysis of WCC, as a hybrid material. In order to conduct EIO-LCA on the "Concrete block and brick manufacturing" a new demand for this sector is required. A value of $10,000 has been used. This is the estimated cost of the concrete blocks per average house in the US market. The first ten inter-sectoral transactions, by the total economic effect, are listed in Table 4.

Table 4. Top ten inter-sectoral transactions ranked by the total economic effect and corresponding energy and emissions values, as result of $10,000 demand for "Concrete block and brick manufacturing"

Sector ID	Sector	Total economic effects ($)	(%)	Energy (GJ)	Emissions ($kgCO_2e$)
	Total for all 491 sectors	*20,700*	*76.3*	*177.0*	*14,700*
327331	Concrete block and brick manufacturing	10,000	100.0	45.7	2,370
327310	Cement manufacturing	1,040	90.8	54.3	6,300
484000	Truck transportation	793	72.9	8.8	1,230
550000	Management of companies and enterprises	663	64.2	0.5	17
420000	Wholesale trade	496	49.6	0.7	36
212320	Sand, gravel, clay, and refractory mining	428	91.4	4.3	234
212310	Stone mining and quarrying	308	83.4	1.5	87
221100	Power generation and supply	283	38.9	33.0	2,790
531000	Real estate	259	31.7	0.3	12
811300	Commercial machinery repair and maintenance	200	81.6	0.1	5

Note: Table generated using EIO-LCA on-line tool at http://www.eiolca.net

Energy and emissions associated with each sector are included as well. As expected, "Cement manufacturing" sector accounts for over 40% of the total carbon dioxide emissions followed by "Power generation and supply" sector, although the latter ranks eighth by the total economic effect. The energy (54.3 GJ) required to manufacture $1,040 worth of Portland cement is higher than the total energy (45.7 GJ) needed to fabricate $10,000 worth of concrete blocks.

"Sand, gravel, clay, and refractory mining" sector has a direct economic effect component on the "Concrete block and brick manufacturing" sector of 91.4%. The complete economic supply chain of purchases from the "Sand, gravel, clay, and refractory mining" sector is $428, that means $391 (91.4%) is the direct purchase of sand and gravel needed to manufacture concrete blocks. This amount will be removed from this sector and added to the "Sawmills" sector, as the equivalent sawdust/fibre aggregate needed to manufacture WCC blocks. Consequently, the total economic effect for the "Sand, gravel, clay, and refractory mining" sector drops to $37, while the monetary transaction from the "Sawmills" sector increases from $17 to $408. All other economic transactions between sectors are affected by this change. For example, the purchase from the "Logging" sector increases from $17 to $208 (Table 5). Both "Sawmills" and "Logging" sectors make now the top ten list of transactions for the new hybrid "WCC block manufacturing" sector.

The total purchase within the entire supply chain is $21,000 which is more than double the original demand of $10,000. By comparison, the total economic effect generated by the sector "Concrete block and brick manufacturing" is $20,700. This is $300 increase in overall purchases per house built with WCC blocks. Also, the total energy used dropped from 177 to 174 GJ, while the carbon dioxide emissions decreased with 300 $kgCO_2e$, from 14,700 to 14,400 $kgCO_2e$. These are the very effects of diminishing the impact of energy intensive mineral aggregate mining sector and replacing it with relatively less energy intensive forestry-related sectors.

It is worthwhile mentioning that between the top three non-process related sectors, namely "Management of companies and enterprises", "Wholesale trade" and "Real estate", the economic effect is $1,423, representing almost 7% of the total economic effect, while the emissions related to these three sectors account for only 0.5% of the total emissions.

Table 5. Top ten inter-sectoral transactions ranked by the total economic effect and corresponding energy and emissions values, as result of $10,000 demand for a new hybrid product "WCC block manufacturing"

Sector ID	Sector	Total economic effects ($)	(%)	Energy (GJ)	Emissions ($kgCO_2e$)
	Total for all 491 sectors	*21,000*	*75.7*	*173.0*	*14,400*
327331*	WCC block manufacturing	10,000	100	45.7	2,370
327310	Cement manufacturing	1,040	90.8	54.3	6,300
484000	Truck transportation	803	72.8	8.9	1,220
550000	Management of companies and enterprises	650	63.5	0.4	17
420000	Wholesale trade	515	49.9	0.7	37
321113	Sawmills	457	94.9	0.7	30
212310	Stone mining and quarrying	305	83.3	1.5	86
221100	Power generation and supply	274	36.8	31.9	2,660
531000	Real estate	258	30.7	0.3	12
113300	Logging	208	64.8	0.6	36

Note: Table generated using EIO-LCA on-line tool at http://www.eiolca.net

CONCLUSION

The economic input-output model is a relative simple and flexible process that has numerous uses and a comprehensive approach, with a consistent boundary definition. Running EIO-LCA takes significantly less time (in order of hours) than the time required to conducting traditional ELCA (in order of months). Moreover, some EIO-LCA software is available free-of-charge and so it represents an excellent tool for research and education. However, EIO-LCA has a major disadvantage because it uses aggregate data for a sector rather than detailed figures for a specific process, as in ELCA. Therefore, it is appropriate for comparing products from different sectors but the inherent approximations make it difficult for accurate analysis among different products belonging to the same commodity sector (Joshi, 2000). Another limitation of EIO-LCA is the fact that, since it mainly focuses on upstream production stages (materials acquisition and manufacturing), it usually neglects end-of-life, reuse or recycling options.

Nevertheless, the main benefit of the input-output method is the possibility of developing custom models for hybrid products and processes. This study was a HLCA simulation based on a rather simplistic approach: substituting wood for mineral aggregate in developing the new hybrid WCC. However, detailed data associated with specific processes, including end-of-life practices, can improve the proposed model.

Caution should be taken when reporting environmental impacts, such as CO_2 emissions, because the aggregate data may miscalculate energy figures related to particular jurisdictions. Converting energy into GHG emissions may be challenging since it depends largely on the source for electricity generation. It also depends on the share the electricity has among other fuels used to power various processes, especially those related to cement fabrication. Our analysis showed approximately 300 $kgCO_2e$ reduction in emissions from substituting WCC for ordinary concrete per new house built of wood-cement blocks in US. Running EIO-LCA on hybrid products can also provide useful data on the overall financial impact, economic diversification and employment.

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