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Establishing a comprehensive database of construction material environmental flow coefficients for Australia

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Abstract: A large increase in the building stock will be needed over the coming decades to cater for forecast global population growth. Such an increase could result in tremendous strain on the environment, both from operating these new buildings and from the demand for resources required to construct and maintain them. Life cycle assessment is a tool that can be used in the design of new building projects, or during the refurbishment of existing ones, to assess and improve their environmental performance. Life cycle assessment is typically complex and time consuming, especially when used for analysing whole building projects. This is particularly the case when it comes to analysing construction-related, or embodied, environmental flows. To facilitate ease of use for projects that are often highly time and budget constrained, product-based environmental flow coefficients are typically used, providing an indication of the environmental flows associated with a particular building (e.g. energy or greenhouse gas emissions). Construction-related coefficients are rare in Australia and those that do exist are out of date. In this study, we demonstrate a semi-automated approach for compiling coefficients for construction materials using the Path Exchange method. This forms the basis of a comprehensive database of construction material environmental flow coefficients that is urgently needed by the construction industry to inform environmental decision making. These values can be used independently or easily integrated within existing life cycle assessment tools to streamline improvements to the environmental performance of construction projects.

Keywords: Construction materials; environmental performance; hybrid coefficients; life cycle assessment.

1. INTRODUCTION

The unprecedented growth in world population, coupled with ever increasing standards of living is driving the need for new buildings. These in turn require significant amounts of resources for their construction, maintenance and operation, resulting in multiple environmental effects, such as climate change (IPCC, 2014) and resource depletion (Krausmann *et al.*, 2017)2017.

Life cycle assessment (LCA) is a tool that can be used to quantify the environmental performance of a building across its entire life cycle by measuring environmental inputs and outputs as well as associated environmental effects (European Standard 15978, 2011). This enables building designers to identify which component of their design or which life cycle stage has the greatest effects on the environment and to modify the design accordingly to improve its environmental performance. The life cycle inventory (LCI) stage of an LCA aims to map the processes and flows associated with a product, such as a building, and quantify its specific inputs and outputs. However, LCA has its limitations. When used to assess building projects, it is usually time-consuming and costly but can also become quite complex, involving thousands of processes that are contributing to the construction, maintenance, operation, and potentially decommissioning of a building. Therefore, the compilation of an LCI can be a tedious task. This complexity means that LCA is rarely conducted on a project by project basis and is not usually included within a project's scope.

Coefficients, representing the environmental flows associated with a particular unit of material, are often used to streamline the compilation of an LCI for a building project, and subsequently used to assess its environmental performance. These coefficients represent the environmental flows (resources, waste or emissions) embedded within the material. These flows are thus commonly referred to as a material's 'embodied energy' or 'embodied water', for example. They can be multiplied by the amount of a particular material used within a building to determine the total embodied flows associated with all uses of that material within the building. While coefficients facilitate the application of LCA, current coefficients of

embodied environmental flows for construction materials suffer from a range of limitations. Current coefficient databases do not include all the data and information that were used to compile them. This severely limits their validity and acceptability as a reliable representation of embodied environmental flows. Furthermore, some existing databases produce average values of coefficients based on multiple sources that are geographically, temporally and procedurally different. These average coefficients are devoid of any physical meaning and are highly unreliable. Most importantly, these coefficients tend to be systematically lower than the real value because the LCI technique used to compile them is not comprehensive and truncates the system boundary by up to 80% compared to more comprehensive LCI techniques, such as hybrid analysis (Crawford, 2008). Even when coefficients are compiled using a comprehensive hybrid LCI technique while maintaining geographical and temporal consistency, the limited number of materials covered is usually a major shortcoming.

The aim of this study is to outline and demonstrate a model for establishing a comprehensive database of construction material environmental flow coefficients for Australia.

2. STREAMLINING LIFE CYCLE ASSESSMENT FOR DESIGN DECISION-MAKING

Life cycle assessment is increasingly being used to better understand the environmental performance of construction projects. Building rating tools used in many countries (e.g. Green Star in Australia and LEED in the US) as well as government policy in a smaller, but increasing number of countries (e.g. de Klijn-Chevalerias and Javed, 2017), promote the use of life cycle assessment during the building design process. Yet, for the majority of projects, this comes at a hefty cost to the project budget. This is of even greater concern if relevant data doesn't exist, often resulting in compromises on data quality or relevance if imperfect data is used. Streamlining the process of conducting an LCA is seen as critical for its broader uptake. While this can be facilitated by software tools, these still rely on high quality data to produce reliable and meaningful results. The data required can include the quantities of inputs (resources) and outputs (products, waste and emissions) associated with individual resource extraction, manufacturing, transport and construction processes. The most reliable approach for obtaining this data for specific construction materials is to work with the organisations involved (e.g. miners, manufacturers, builders) to collect data related to individual processes, using what is known as a 'process analysis'. This data often comes in multiple forms, including energy bills, mandatory reporting, invoices etc.. However, this can be extremely time-consuming and costly, and impractical for an individual construction project given the imposed project constraints. As the characteristics of material production and construction processes generally change on an infrequent basis, this data can often be reused across multiple projects in the form of material environmental flow coefficients. This can minimise the data collection requirements for an individual project and help to streamline the use of LCA for environmental decision making.

2.1 Existing databases of environmental flow coefficients

Numerous databases of environmental flow coefficients exist around the world. They tend to be limited to embodied energy or embodied carbon coefficients and can cover construction materials as well as other processes, such as transport and electricity production. The main differences between the coefficients provided by the different databases are the range of materials covered, geographical relevance, and the LCI technique used in their compilation. This last difference is one of the most critical factors affecting the reliability and completeness of any coefficient. The 'process analysis' LCI technique described above generally leads to the greatest truncation of the system boundary for a material due to the time involved and difficulty in collecting data in this manner (Crawford, 2011, p. 48). Input-output analysis solves the truncation issue by using top-down economic data to model environmental flows across economic sectors. While this data is used to allocate environmental flows to products produced by individual sectors and the top-down approach ensures comprehensive coverage of the system boundary, the high level of aggregation means that the resultant coefficients can be highly unreliable. A combination of 'process analysis' and 'input-output analysis' in the form of a 'hybrid analysis' can help to resolve the limitations of each of these individual LCI techniques. The only publicly available database of hybrid environmental flow coefficients is that produced by Crawford and Treloar (2010), now considerably out of date. Table 1 provides a summary of some of the most commonly used databases.

Table 1: Summary of key material environmental flow coefficient databases.

Database	Flows and number of products covered	Country of relevance	LCI technique	Latest
Inventory of Carbon and Energy (ICE)[1]	Energy, carbon - 299	United Kingdom*	Varies*	2011
Database of Embodied Energy and Water Values for Materials[2]	Energy, water - 58	Australia	Hybrid analysis	2010
Embodied Energy and CO2 Coefficients for NZ Building Materials[3]	Energy, GHG emissions - 61	New Zealand	Hybrid analysis	2003
Building Materials, Energy and the Environment[4]	Energy - 32	Australia	Process analysis	1996
BEES[5]	Energy, GHG emissions - 230	United States	Process analysis	2010
Balancing Act[6]	Energy, GHG emissions, water, land - 135	Australia	Input-output analysis	2005

*Data sourced from various geographic regions, using different LCI techniques
[1]University of Bath (2011), [2]Crawford and Treloar (2010), [3]Alcorn (2003), [4]Lawson (1996), [5]NIST (2007), [6]Foran *et al.* (2005)

3. COMPILING HYBRID COEFFICIENTS FOR CONSTRUCTION MATERIALS

In this study, coefficients are compiled using the Path Exchange method of hybridisation, a technique first theorised by Treloar (1998) and formalised by Lenzen and Crawford (2009). A semi-automated model developed for the compilation of hybrid coefficients, with its own graphical user interface, was used to develop the coefficients. A detailed presentation of this model is available in Stephan *et al.* (2018).

3.1 Data sources

All input-output data and associated environmental flow data used to develop the coefficients in this study were sourced from government departments, and cover the 2014-15 financial year. Input-output tables (representing monetary transactions between sectors of the economy) were collected from the Australian Bureau of Statistics (ABS) at a disaggregation level of 114 sectors (ABS, 2018b). Energy accounts were collected from the Department of Industry (2016), water accounts from the ABS (2016) and greenhouse gas (GHG) emissions accounts from the Department of the Environment and Energy (2015). All input-output data and associated environmental flow data were compiled in Excel tables and are available in open access on Figshare (Bontinck, 2018a).

Other statistical information could be included to cover a broader range of environmental flows, such as waste using national waste accounts (ABS, 2014), pollutant emissions using the national pollutants inventory (NPI) (Department of the Environment and Energy, 2018), or raw materials using material flow data (Britt *et al.*, 2016; ABARES, 2017; Department of Industry, 2017; ABS, 2018a).

The process database used in the analysis is the Australian Life Cycle Inventory Database Initiative (AusLCI), which is collected as a technological matrix from the LCA software Simapro. AusLCI is a set of process data collected from Australian sources, and supplemented with ecoinvent data when no local data is available, to reduce gaps in the process data (Grant, 2016). Additional processes were created during this analysis to represent processed materials, such as rolled steel or extruded aluminium.

3.2 Data processing

This section briefly outlines the data processing required prior to loading the raw data into the model to create the hybrid coefficients. The overarching aim of the model is to automate the creation and subsequent update of hybrid coefficients as much as possible. To that end, many aspects of the data handling are automated. However, the original data needs to be formatted in a way that allows the model to read it. The first step is therefore the preparation of the raw data collected as in Section 3.1.

The input-output tables require little preparation, as data is collected from the ABS in Excel format and already include the supply, use and import tables that the model requires. Raw environmental flow data are all processed in the same manner, following a four-step process illustrated in Figure 1. This process is used to allocate environmental flows as they are reported by government departments to economic sectors as they are reported in input-output tables. This is simplified by the fact that most departments follow a sector nomenclature that is based on the Australian and New Zealand Standard Industrial Classification (ANZSIC) (ABS, 2006), but the resolution at which data is reported can vary significantly.

As an example, the 2015 input-output tables are reported at a disaggregation level of 114 sectors, while the water accounts are reported for 31 sectors. Thus, a concordance matrix is required to match sectors as reported in input-output tables and in the raw environmental flow data (Step 2, Figure 1). In this example, some of the sectors within the water accounts cover multiple input-output sectors, and therefore the water consumption data must be allocated between these input-output sectors, using a normalised version of the concordance matrix (Step 3, Figure 1). An example might be the *'Metal ore mining'* sector as reported in the water accounts, which covers both the *'Iron ore mining'* and *'Non-ferrous metal ore mining'* sectors of the input-output tables. Here, the water consumption of the *'Metal ore mining'* sector as reported in the water accounts is allocated using the expenditure in *'Water Supply, Sewerage and Drainage Services'* as reported in the input-output tables for these two mining sectors. This is a fundamental hypothesis, as it assumes a direct correlation between expenditure in this sector and physical water consumption.

Finally, the normalised concordance matrix and raw environmental flow data collected in Step 1 are multiplied to obtain a satellite vector, or matrix, where environmental flows are allocated to their respective input-output sector (Step 4, Figure 1). This process is repeated for each environmental flow, and adapted based on the data available.

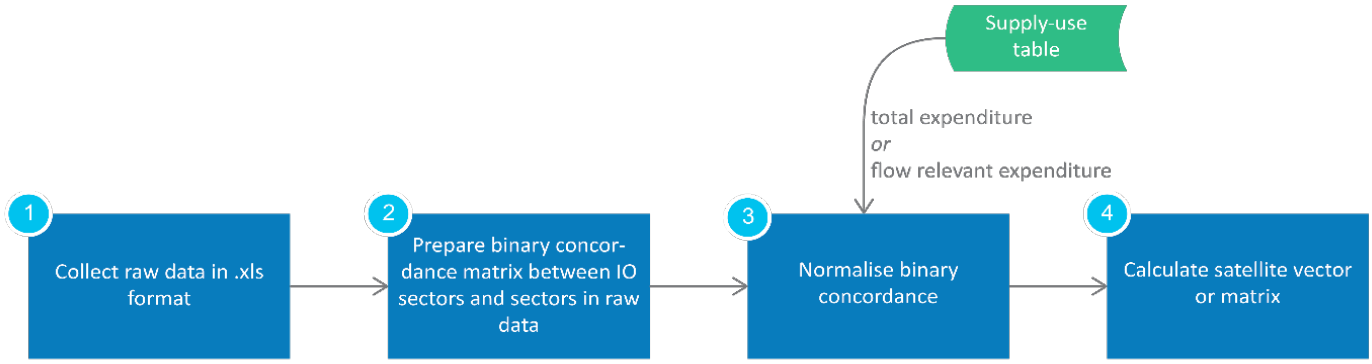

Figure 1: Steps in processing the raw data to obtain an input-output satellite.

Process data is collected in a standardised format requiring minimal manipulation before loading into the model. The entire AusLCI database is collected from the LCA software Simapro as a matrix (PRé Consultant, 2014), including the so-called 'shadow database' described in the AusLCI Database Manual (Grant, 2016). The output of this process is a technological and stress matrix, which are very similar to an input-output table and its satellites.

Once the input-output and process data have been collected and formatted as required, they can be read by the model, which collates all the information in a single file object. Using this method enables the creation of a record and easy reproduction of an analysis, with the standardised format facilitating any subsequent update of the coefficients.

3.3 Compiling coefficients

Hybrid coefficients were compiled using the Path Exchange method of hybridisation discussed in detail by Treloar (1998) and Lenzen and Crawford (2009). Only the mechanics of the model are briefly discussed here. Readers are referred to the literature for a more detailed overview of the method. The calculation model used in this analysis compiles hybrid coefficients following a three step approach illustrated in Figure 2.

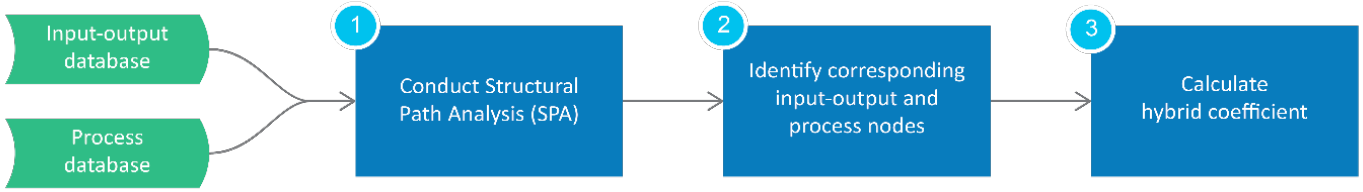

Figure 2: Steps in compiling a hybrid coefficient.

In Step 1, the supply chains of the relevant economic sector and process under study are analysed using a structural path analysis (SPA). This method of analysis is very common to both input-output and process analysis and its mathematical framework is detailed in the literature (Defourny and Thorbecke, 1984; Lenzen and Crawford, 2009; Crawford *et al.*, 2018). The outcome of the SPA is a series of mutually exclusive nodes, each representing a good or service provided from one tier to another within the supply chain analysed. The model analyses multiple flows at the same time and automatically ranks nodes in order of importance. This helps identify hotspots of emissions or resources requirements at various stages of the supply chain.

During the hybrid coefficient compilation, only Step 2 of Figure 2 is not currently automated. Here, the user reviews the output of both SPAs and identifies equivalent nodes. A fundamental assumption in the compilation of the hybrid coefficients is that the process and input-output databases provide two representations of the same supply chains. This means, for instance, that the analysis of the process *'concrete 20 MPa, at batching plant/AU U'* and the input-output sector *'Cement, Lime and Ready-Mixed Concrete Manufacturing'* provide two representations of the production of concrete and its supply chain. If that is the case, then it is possible to identify process and input-output nodes that are equivalent, i.e. that are aiming to represent the same aspect of the supply chain. This process of identification is the essence of the second step of the hybridisation process, and is critical to avoid double counting.

The model uses the information provided by the user in Step 2 to calculate a hybrid coefficient for the material assessed (Step 3, Figure 2). The environmental flows associated with each process node selected are summed and form the process component of the hybrid coefficient. Simultaneously, the environmental flows associated with the corresponding input-output nodes are summed and subtracted from the total environmental flows associated with the sector under study. The financial value of the material under study is used to convert the remaining environmental flow values from a flow per unit of currency to a flow per physical unit of material. This forms the input-output component of the hybrid coefficient.

The benefit of using an automated model is that it retains all the information collected through each step, the original data, the result of the structural path analysis, and the selection of corresponding input-output and process nodes. The coefficient is compiled as a single file, which is significant in terms of transparency and reproducibility of the analysis, as coefficients can be exchanged as files, including all raw data and assumptions made in the hybridisation process. In addition, the use of an automated model provides the user with an opportunity to analyse process, input-output and hybrid data in more detail than was previously possible. For instance, it is possible to analyse the input-output component of the hybrid coefficient in detail or to easily compare pure process, input-output and hybrid values.

4. RESULTS AND DISCUSSION

Four common building materials were selected and used to test the hybridisation model and assess the potential to produce a comprehensive database of hybrid coefficients. These include:

- **cold rolled steel**, represented by the input-output sector *'Structural Metal Product Manufacturing'*, and a process modelled by the authors using the AusLCI database;
- **20 MPa concrete**, represented by the input-output sector *'Cement, Lime and Ready-Mixed Concrete Manufacturing'*, and the process *'concrete 20 MPa, at batching plant/AU U'* using the AusLCI database;
- **flat glass**, represented by the input-output sector *'Glass and Glass Product Manufacturing'*, and the process *'Flat glass, uncoated, at plant/RER U/AusSD U'* using the AusLCI database; and
- **extruded aluminium**, represented by the input-output sector *'Basic Non-Ferrous Metal Manufacturing'*, and a process modelled by the authors using the AusLCI database.

A summary of the results is reported in Table 2 (detailed results are available from Figshare (Bontinck, 2018b). It shows a significant variation in the proportion of the input-output (IO) component for the materials modelled. For instance, in the case of cold rolled steel, the input-output remainder represents 26% to 34% of the total, while in the case of flat glass, it represents 61% to 74%. These variations are significant and would warrant a more detailed analysis of the input-output component to better assess its significance. However, this falls outside the scope of this study.

Table 2: Summary of coefficients for common construction materials.

Material	Functional unit *(FU)*	Hybrid coefficient					
		Water use *(L/FU)*	*IO %*	GHG emissions *(kg CO_2e/FU)*	*IO %*	Energy use *(GJ/FU)*	*IO %*
Steel, cold rolled	kg	61.2	26%	2.86	29%	0.040	34%
Concrete, 20 MPa	m^3	4,353	24%	339	17%	2.51	38%
Glass, flat glass	kg	35.9	71%	2.45	61%	0.033	74%
Aluminium, extruded	kg	218	66%	28.9	26%	0.36	33%

These values are generally higher than those reported in other similar databases. The main reason for this is due to the use of the hybrid approach, providing a more comprehensive coverage of each material's system boundary. Table 3 provides a comparison of the hybrid, process and input-output values for each of the materials assessed. This presents particularly interesting information as it shows two distinct scenarios. In one scenario the hybrid and process results are very similar – this is the case for steel and concrete. In addition, for these two materials, the pure process results are significantly higher than the pure input-output results. This may be due to these materials being more resource and emissions intensive than the

average product from the input-output sector used to represent these materials. In the second scenario, the input-output results are higher than the process results, which may be due to materials being less resource and emissions intensive than the average product from the input-output sector used to represent these materials, or gaps in the process data.

Several parameters, as described below, will influence the process, input-output and hybrid values.

- The appropriateness of the cost value used to convert the input-output results from a flow per financial output into a flow per physical quantity of material. The variability and uncertainty associated with this parameter means that it could have a dramatic effect on the results.
- The appropriateness of the input-output sector selected to represent the supply chain of the material assessed. An input-output sector that aggregates a range of activities, like *'Basic Non-Ferrous Metal Manufacturing'* will include many transactions for which there are no corresponding process nodes, simply because that transaction does not relate to aluminium production, for example, but to other non-ferrous metals.
- The comprehensiveness of the process model used to represent the production system of the material assessed. Some materials, such as concrete, or processes, such as electricity production, have been studied in great detail, and it is likely that the process models are of very high standard. This may not be the case for other materials that have not had such a focus, or which are new to the market.
- The representativeness of the input-output and process nodes being exchanged. It is very difficult to assess with certainty whether a process and input-output node match, there is no standard approach, and therefore a judgement call must be made by the practitioner with the uncertainties that come with it.

Table 3: Comparing hybrid, process and input-output coefficients.

Material	Functional unit *(FU)*	Water use *(L/FU)*			GHG emissions *(kg CO_2e/FU)*			Energy use *(GJ/FU)*		
		Hybrid	*Process*	*IO*	*Hybrid*	*Process*	*IO*	*Hybrid*	*Process*	*IO*
Steel, cold rolled	kg	61.2	48	24.2	2.86	2.57	1.50	0.040	0.032	0.023
Concrete, 20 MPa	m^3	4,353	3,586	1,476	339	321	157	2.51	2.13	1.91
Glass, flat glass	kg	35.9	10.2	35.4	2.45	1.05	2.98	0.033	0.011	0.046
Aluminium, extruded	kg	218	87.2	276	28.9	23.2	23.1	0.36	0.27	0.46

The advantage of using an automated model is that it facilitates further analysis of the results, at least for some of the parameters discussed above, and allows transparency on the decisions made for the others. For instance, the sensitivity of the cost value on the results could be assessed by varying the value and analysing the output, while the decisions made in terms of input-output and process node correspondence can be reported.

5. CONCLUSION

There is a well-understood imperative to improve the environmental performance of construction projects. This will only become more critical as demand for buildings escalates amid a growing global population. Building designers and decision-makers require information on the environmental performance of construction materials to enable them to select those that assist in reducing the environmental effects of a project. However, comprehensive, reliable and easily accessible data on the environmental performance of construction materials is lacking in Australia. While material coefficients are highly unlikely to accurately reflect the exact material used in a particular project due to variations in manufacturing processes, fuel mixes, production efficiencies etc. over time, their use can provide considerable time and cost savings in comparison to conducting a full LCA. With many practitioners relying on coefficients developed for other countries, which very rarely reflect Australian production practice, an up-to-date database of material coefficients for Australia is urgently needed.

This paper has described a semi-automated model for compiling hybrid material coefficients. The use of the Path Exchange method ensures that the coefficients produced are based on the most comprehensive system boundaries possible, avoiding the truncation issues inherent to coefficients compiled using a traditional process analysis. The model developed is novel as it not only streamlines the compilation of the hybrid coefficients, saving time compared to what was previously a highly manual process, but also enables more in-depth analysis of the results.

Building designers and decision-makers will be able to use these coefficients in combination with a project's bill of materials to provide an indication of the environmental flows associated with an entire project, using this information to inform improvements. These values can also be integrated into existing LCA tools to streamline the environmental assessment of construction projects.

The creation of hybrid coefficients using the semi-automated model has been demonstrated for energy, water and

greenhouse gas emissions for four common materials. The next steps include considerably expanding the number of materials covered as well as a broader range of environmental flows, including raw materials, waste and various pollutants. These will then be compiled into an updatable material coefficient database, providing the data that is urgently needed by the construction industry to inform environmental decision making.

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