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# The EPiC Database: hybrid embodied environmental flow coefficients for construction materials

Demand for new buildings and infrastructure continues to grow and will only increase in coming years to cater for forecast growth in global population. This demand will result in considerable strain on the natural environment, resulting from the operation of these new built assets as well as the demand for resources required to construct and maintain them. Life cycle assessment is a tool that can be used during the design or refurbishment of new or existing buildings or infrastructure projects, to assess and improve their environmental performance. A life cycle assessment is often time consuming and complex, especially when used for the analysis of entire construction projects. This is particularly true when it is used to analyse construction-related, or embodied, environmental flows (e.g. embodied greenhouse gas emissions). To simplify the process, especially with projects that have tight time or budget constraints, product-based environmental flow coefficients are often used, which provide an indication of the environmental flows associated with specific construction materials. However, existing coefficients are typically based on process data, inherent with truncated product system boundaries. This paper introduces the Environmental Performance in Construction (EPiC) Database, a comprehensive database of hybrid embodied environmental flow coefficients for construction materials in Australia. EPiC uses a hybrid life cycle inventory approach to fill the gaps that exist in process data and provide embodied environmental flow coefficients that are systemically complete. This study has shown that existing process data for materials is on average 55% incomplete, but considerable inconsistency in system boundary coverage means that this incompleteness varies from 2% to 99% across materials and environmental flows. Other key strengths of EPiC are its transparency, providing open access to all data, and methodological consistency, with coefficient data sources and methods the same for all materials. Environmental flow coefficients from EPiC can be used on their own or integrated into existing life cycle assessment tools, informing improvements to the environmental performance of construction projects.

**Keywords:** Construction materials; embodied energy; embodied greenhouse gas emissions; embodied water; life cycle assessment.

## 1. Introduction

Our built environment, including the buildings and infrastructure of our towns and cities, contribute more than any other single sector to global energy use (36%) and greenhouse gas (GHG) emissions (39%) (IEA, 2019), in addition to their demand for other resources. Energy use and GHG emissions have continued to increase, and in 2018, they reached record highs, up 7% from 2010 levels, despite global efforts to reduce them (IEA, 2019, p. 12). Improvements to building envelopes and building energy systems have offset some of the growth in building-related energy demand and GHG emissions in recent years (IEA, 2019, p. 14). However, they have continued to rise due to increasing demand for energy and other resources (IEA, 2019, p. 13). Unprecedented global population growth is driving demand for new buildings and infrastructure (IEA, 2019, p. 14), increasing demand for materials and leading to an expected threefold increase in air conditioning use by 2050 (IEA, 2018), exacerbating existing environmental issues, including climate change and resource depletion (Krausmann *et al.*, 2017). In response to these challenges, the 2018 IPCC Special Report on Climate Change and Land (SRCCL) has called for broad transformations within the building sector, including a rapid phase out of $CO_2$ emissions (IPCC, 2018), with buildings representing one of the most important and cost-effective options for mitigating global energy demand and GHG emissions (IPCC, 2014).

Historically, reducing energy demand associated with heating and cooling, cooking, hot water, and appliance use has been the focus of global building-related energy and GHG emissions reduction efforts (Karimpour *et al.*, 2014). However, embodied energy associated with the manufacture of building materials accounts for around a third of all building-related GHG emissions (Adams *et al.*, 2019) and up to 100% of a building's total life cycle energy (Chastas *et al.*, 2016). As buildings head towards net-zero operational energy and GHG emissions, their embodied energy and GHG emissions become more significant. In order to achieve the significant emissions reductions required to meet the goals of the Paris Agreement (UNFCCC, 2015), embodied GHG emissions need to be urgently addressed. In response to this, the World Green Building Council has called for a 40% reduction in construction-related embodied GHG emissions by 2030 and net-zero embodied GHG emissions by 2050 (Adams *et al.*, 2019).

A detailed, well-informed understanding of the embodied energy and GHG emissions implications of construction projects, especially during the design phase, based on reliable data and a comprehensive analysis, is crucial in our efforts to reduce their life cycle embodied energy demand and GHG emissions (Adams *et al.*, 2019). This understanding is usually informed using software-based life cycle assessment (LCA) tools. Life cycle assessment is being used across a range of contexts to help understand the environmental performance of construction projects. Building rating tools used in several countries (e.g. LEED in the US and Green Star in Australia) as well as government policy in a small, but increasing number of countries, promote the use of LCA during the design process (e.g. de Klijn-Chevalerias & Javed, 2017).

However, for most projects, this comes at a significant cost to the project with detailed LCAs being costly and time intensive, relying on complex analyses of material supply chains (Crawford, 2011). This is of even more concern where the required data does not exist, often resulting in compromises on data quality or relevance when imperfect data is used (Lasvaux *et al.*, 2015). Streamlining the LCA process is considered critical for its broader uptake. While software tools can help facilitate this, they often rely on high quality data to produce reliable and meaningful results. The data required typically includes the quantity of inputs (resources) and outputs (products, emissions, and waste) associated with resource extraction/harvesting, manufacturing, transport, and assembly processes. The most reliable data for specific construction materials is usually obtained by engaging with the organisations involved (e.g., miners, manufacturers, assemblers), collecting data specific to individual processes, utilising a 'process analysis' approach. This data comes in multiple forms, including energy bills, invoices, orders, observation etc.. However, this can be very costly and time-consuming, and impractical for a single construction project given the aforementioned project constraints (Islam *et al.*, 2016). Environmental Product Declarations (EPDs), which collate information on the inputs and outputs for specific products in a uniform and accessible format (ISO, 2006a) can help streamline the quantification of embodied environmental flows when this precompiled information is made publicly available. A specific standard for compiling EPDs has been developed for construction products – EN 15804 (CEN, 2019), with the number of EPDs available for construction products increasing over recent years (Anderson, 2021). However, EPDs suffer from a number of limitations, including reliance on inconsistent data sources and methodologies, variations in system boundary coverage, and lack of transparency, which can make comparing products problematic (Gelowitz & McArthur, 2016).

With material production and assembly processes varying infrequently, this data can generally be reused across multiple projects in the form of material embodied environmental flow coefficients. Environmental flow coefficients can provide a quantitative measure of the environmental flows associated with specific construction materials and often include indicators such as energy use, water use, waste production and GHG emissions. Their use minimises the requirements for data collection on individual projects and helps streamline the use of LCA to inform environmental decision making.

The use of embodied environmental flow coefficients enables an alternative streamlined approach to a full LCA. However, the quality of the data used, particularly in terms of geographic and temporal relevance, can vary greatly (Reap *et al.*, 2008). Some of the key reasons why the embodied environmental flows associated with the production of construction materials may vary include differences in manufacturing processes, variation in production efficiencies, quantity and treatment of waste, regional differences in fuel mix, and transport distances. These values will also vary over time, as manufacturing processes change and become more efficient, as demonstrated by Crawford and Stephan (2020). This means that the older the data, the less likely it is to be representative of the environmental performance of current material production (De Smet & Stalmans, 1996). This, as well as other indicators of data quality are often assessed using a pedigree matrix approach (Weidema & Wesnæs, 1996).

Most existing databases of environmental flow coefficients rely on the use of process analysis in their compilation, which results in incomplete coverage of the environmental flows associated with specific material supply chains, also known as a truncation error (Lenzen & Dey, 2000). Coefficient databases known to provide more comprehensive coverage of the supply chain (e.g. Alcorn (2003); Crawford and Treloar (2010)) are considerably out of date. Environmental flow coefficients that address the above issues, including data age and completeness are desperately needed as demand for reliable, comprehensive data on embodied environmental flows intensifies.

This study examines the Environmental Performance in Construction (EPiC) Database, a recently developed open access repository of hybrid embodied environmental flow coefficients for construction materials in Australia. The database contains 284 coefficients (with 131 examined here), compiled using a Path Exchange hybrid approach (Lenzen & Crawford, 2009) that uses bottom-up process data combined with top-down macroeconomic input-output data (Crawford *et al.*, 2019b), which aims to address the truncation and other issues with existing databases outlined above.

The aim of this paper is to introduce the EPiC Database and demonstrate its key strengths in informing improvements to the environmental performance of construction projects. The approach described here for compiling hybrid embodied environmental flow coefficients, including a novel approach for automating the process, is transferrable to other regions where the equivalent input data is available.

## 2. Quantifying embodied environmental flows

Throughout their life cycle, buildings, infrastructure assets and other construction projects result in significant environmental effects. Raw material extraction, material production and manufacture, transport, assembly, replacement, renovation and ultimately deconstruction and recycling all require inputs of energy, water and materials and result in outputs, such as GHG emissions and waste. The European Standard 15978 (2011) describes standardised life cycle stages for built assets and codifies them, providing a consistent reporting framework.

Despite environmental effects occurring throughout the life cycle of construction projects, there has been a historical focus on operational environmental flows, notably operational energy. This is reflected by the myriad energy efficiency regulations across different countries, such as the 6 Star Standard in Australia (ABCB, 2020) and the European Energy Performance of Buildings Directive (European Commission, 2010). Yet, the significance of embodied environmental flows has been demonstrated by multiple studies across different countries, e.g. Australia (Crawford *et al.*, 2016), Belgium (Allacker, 2010; Stephan *et al.*, 2013), Italy (Blengini & Di Carlo, 2010), Lebanon (Stephan & Stephan, 2020), Norway (Dahlstrøm *et al.*, 2012; Lausselet *et al.*, 2019), and more globally (Chastas *et al.*, 2016; Dixit, 2017; Habert *et al.*, 2020). The importance of embodied environmental flows has also been recognised by major international bodies (e.g. UN-Habitat (2017), RICS (2017) and the World Green Building Council (Adams *et al.*, 2019)), calling for their reduction in construction projects. Many building certifications have recently integrated embodied environmental flows into their assessments, e.g. Green Star (GBCA, 2021), LEED (USGBC, 2021), BREEAM (BRE, 2021) and DGNB System (DGNB, 2021). Quantifying the life cycle environmental flows of a project is therefore critical, encompassing its embodied and operational flows (and even mobility-related flows (Stephan *et al.*, 2012)) to ensure that design decisions result in net improvements to life cycle environmental performance, not simply shifting flows from one life cycle stage to another.

LCA can be used to quantify a construction project's environmental performance across its entire life cycle by measuring inputs and outputs and their associated environmental effects (CEN, 2011; Crawford, 2011). With this information, designers can identify design elements or life cycle stages with the greatest effects on the environment and modify the design to improve its environmental performance (Basbagill *et al.*, 2013). The life cycle inventory (LCI) stage of an LCA is used to map the processes and flows associated with a product and quantify its specific inputs and outputs (ISO, 2006b). However, LCA has several limitations (Curran, 2014). When used to assess construction projects, it is usually costly and time-consuming, and can often become quite complex, involving thousands of processes that are contributing to the assembly, operation, maintenance, and eventual demolition and disposal of the project, meaning that compiling an LCI for this type of product can be a tedious task (Meex *et al.*, 2018). This complexity means that LCAs are rarely conducted for an entire construction project (Saunders *et al.*, 2013). The financial, time, and expertise-related constraints associated with conducting an LCA of a construction project often result in either the assessment being abandoned, outsourcing it to specialised consultants, streamlining the assessment so that it is manageable (e.g., by focusing on a single flow, such as GHG emissions) or relying on pre-compiled environmental flow coefficients (Zabalza Bribián *et al.*, 2009).

## 2.1. Environmental flow coefficients

Coefficients, representing the environmental flows (resources, waste, or emissions) associated with a particular quantity of material, are regularly used to streamline the compilation of an LCI for a construction project in order to assess its environmental performance. As these coefficients represent the environmental flows associated with the production of a material (representing stages A1-A3 in EN 15978 (CEN, 2011)), they are 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 construction project to determine the total embodied flows associated with all uses of that material within the project. While coefficients facilitate the streamlined application of LCA, current embodied environmental flow coefficients for construction materials suffer from a range of limitations, including limited information on the data and process used to compile them. This lack of transparency severely limits their validity and acceptability as a reliable representation of a material's embodied environmental flows (De Wolf *et al.*, 2017). Furthermore, some databases provide average values based on multiple sources that are temporally, geographically, and methodologically different. These averages are devoid of any physical meaning and have been shown to be up to four orders of magnitude higher than manufacturer-specific process data (Lasvaux *et al.*, 2015).

In addition, most existing coefficients tend to systematically underestimate environmental flows because the process analysis LCI technique used to compile them truncates the system boundary compared to more comprehensive LCI techniques (Crawford, 2008; Lenzen & Dey, 2000). Process analysis involves an in-depth analysis of manufacturing processes to develop an inventory of resource inputs, and waste and emission outputs (Bullard *et al.*, 1978). A high degree of reliability is a typical characteristic of this approach; however, it often suffers from system boundary inconsistency, which varies considerably depending on the depth and quality of data available (Lenzen & Dey, 2000). An alternative approach for compiling coefficients is environmentally extended input-output analysis (EEIO). EEIO analysis combines macroeconomic data with environmental data to quantify the environmental flows associated with each sector of a nation's economy (Kitzes, 2013). By covering the entire economy, this approach enables almost complete system coverage, but at the same time is limited in its specificity to particular processes or products as the average environmental intensity of a sector can be very different to that of a particular process or product (Heijungs & Suh, 2002). Hybrid analysis combines EEIO analysis with process analysis; capitalising on the increased system coverage of EEIO analysis and the reliability of process analysis (Bullard *et al.*, 1978; Crawford *et al.*, 2018b; Suh *et al.*, 2004).

The environmental flow coefficient databases that exist are typically limited to embodied energy or embodied carbon[1] coefficients and generally cover construction materials as well as other processes, such as electricity production and transport. The main differences between these databases are the range of products covered, geographical relevance, and the LCI technique used for their compilation. This last difference is one of the most crucial factors affecting a coefficient's reliability and completeness (Majeau-Bettez *et al.*, 2011). With a reliance on process analysis, most coefficients contained within existing databases suffer from varying levels of inconsistency and/or incompleteness. Table 1 summarises some of the more commonly used databases for construction materials, and further examples are provided by Martínez-Rocamora *et al.* (2016). Databases of hybrid embodied environmental flow coefficients are limited but include those produced by Alcorn (2003); and Crawford and Treloar (2010). These databases rely on old data, typically from the 1990s, and cover a limited number of materials. As such, embodied environmental flows quantified using these databases suffer from a significant amount of uncertainty.

*Table 1: Selected material embodied environmental flow coefficient databases*

| Database | Flows | No. of products covered | Country of relevance | LCI approach | Latest version |
|---|---|---|---|---|---|
| ÖKOBAUDAT[a] | Global warming potential, ozone depletion, acidification, eutrophication, photochemical ozone creation, depletion of abiotic fossil fuels, depletion of abiotic non-fossil resources | 1,400+ | Germany and other parts of Europe and the world | Process analysis | 2021 |
| Tool to Optimise the Total Environmental impact of Materials (TOTEM)[b] | Global warming, ozone depletion, acidification, eutrophication, photochemical ozone creation, human toxicity, depletion of abiotic resources, particulate matter, ionising radiation, ecotoxicity, land use | 1,463 | Belgium | Process analysis | 2021 |
| Athena Sustainable Materials Institute[c] | GHG emissions, acidification (air) potential, human health particulate, eutrophication (air & water) potential, smog (air) potential, ozone depletion (air) potential, fossil fuel consumption, total primary energy consumption, non-renewable energy consumption | 200+ | Canada & United States | Process analysis | 2019 |
| Inventory of Carbon and Energy (ICE)[d] | Energy, GHG emissions | 300+ | United Kingdom* | Varies* | 2019 |
| BEES[e] | Energy, GHG emissions | 230+ | United States | Process analysis | 2018 |
| Wuppertal Institute Material Intensity Database[f] | Abiotic materials, biotic materials, water, air, earth movement in agriculture and silviculture | 193 | Germany and other parts of Europe and the world | Process analysis | 2014 |
| Crawford and Treloar (2010) | Energy, water | 58 | Australia | Hybrid analysis | 2010 |
| Balancing Act[g] | Energy, water, GHG emissions, land | 135 | Australia | Input-output | 2005 |

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[1] While 'embodied carbon' has become a commonly used term, the authors prefer the scientifically more correct term 'embodied greenhouse gas emissions'.

| | | | | | |
|---|---|---|---|---|---|
| | | | | analysis | |
| Embodied Energy and $CO_2$ Coefficients for NZ Building Materials[h] | Energy, GHG emissions | 61 | New Zealand | Hybrid analysis | 2003 |
| Lawson (1996) | Energy | 32 | Australia | Process analysis | 1996 |

[a]Federal Ministry of the Interior Building and Community (BMI) (2021), [b]TOTEM (2021), [c]Athena Sustainable Materials Institute (2019), [d]Jones and Hammond (2019), [e]NIST (2018), [f]Wuppertal Institute (2014), [g]Foran *et al.* (2005), [h]Alcorn (2003). *Data sourced from various geographic regions, using different life cycle inventory approaches.

Very recently, Agez *et al.* (2020) have successfully hybridised the entire ecoinvent 3.5 process database and EXIOBASE3 input-output database (Stadler *et al.*, 2018), by using an automated hybridisation approach to match processes and input-output sectors. While this is a significant advance for the field of hybridisation, the study does not take into account capital expenditure in its input-output model, underestimating embodied flows by up to 20% (Lenzen & Treloar, 2004). Also, the automated matching of process and input-output data, although highly sophisticated, might not provide the same resolution compared to what is obtained through the Path Exchange method for hybridisation (Lenzen & Crawford, 2009). Finally, the resulting hybrid database is not specific to construction materials and does not provide embodied environmental flow coefficients in its current form.

Considering the above, there is a clear need for a hybrid database of embodied environmental flow coefficients, specific to construction materials, and providing consistent, complete, and transparent data. Such a database, covering a large number of materials, would enable a rapid, yet comprehensive quantification of embodied environmental flows of a building, infrastructure asset or other construction project.

## 2.2. What is the EPiC Database?

The Environmental Performance in Construction (EPiC) Database is an open access repository that contains embodied energy, water and GHG emissions coefficients for over 280 construction materials. It aims to provide easily accessible, consistent, and transparent data to inform material selection and environmental decision-making for construction projects. Released at the end of 2019, the development of the database had three key priorities: maximising the *completeness* of the system boundary coverage to avoid truncation issues inherent in process data; ensuring complete *transparency* in how the data was compiled and the data itself; and a *consistency* in the approach used for the compilation of coefficients to maintain comparability between materials. While the database is too large to present in full within this paper, it can be accessed at https://doi.org/10.26188/5dc228ef98c5a. A summary of its key attributes is given in Table 2.

*Table 2: Key attributes of the EPiC Database of hybrid embodied environmental flow coefficients*

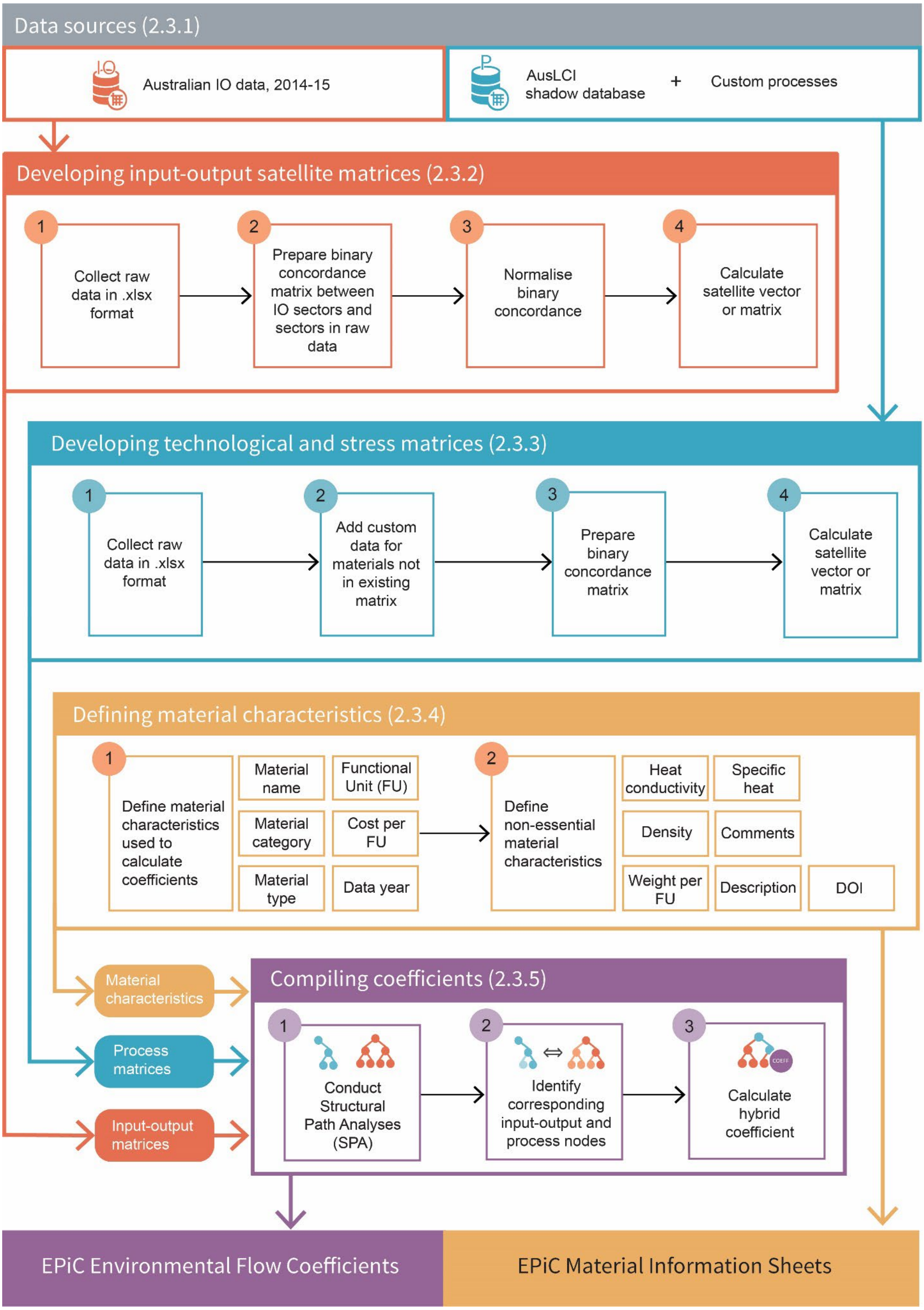
| No. of materials | Data source | Flows covered | Broad categories of materials covered | Flows/functional units |
|---|---|---|---|---|
| 284* | **Process data** - Based on AusLCI data (ALCAS, 2019) with ecoinvent2.2 shadow database (4,531 processes, 2015 version)<br>**Input-output data** - Based on 2014-15 input-output tables (ABS, 2017), 114 sectors + fixed capital | Energy, water, greenhouse gas emissions | Concrete and plaster products; insulation; glass; metals; sand, stone, and ceramics; plastics; timber products; miscellaneous | **Energy** - MJ per kg/m$^2$/m$^3$/no.<br>**Water** - L per kg/m$^2$/m$^3$/no.<br>**Greenhouse gas emissions** - kgCO$_2$-e per kg/m$^2$/m$^3$/no. |

*includes 89 unique materials and 195 variations to these.

While it was intended that the database would include coefficients across a broader range of environmental flows, including various pollutant emissions, waste, resource use and land use, national level raw environmental flow data for Australia (such as national pollutant inventories) needed to create the respective satellite matrices (see Section 2.3.2.) was incomplete or lacking for all but the three environmental flows included. This meant that reliable hybrid coefficients were not able to be created for other environmental flows.

## 2.3. Creating the EPiC Database

Several methods can be used to produce hybrid life cycle inventories, as reviewed by Crawford *et al.* (2018b). The coefficients within the EPiC Database rely on the Path Exchange method for hybridisation, as it does not require a full integration of process and input-output data. This technique was first developed by Treloar (1998), validated by Crawford (2008) and formalised by Lenzen and Crawford (2009) and these studies provide a more detailed overview of the method. A semi-automated model was developed for the compilation of the EPiC hybrid coefficients, with its own graphical user interface (GUI). Stephan *et al.* (2019) provide a detailed description and validation of this model and its first appearance in the literature can be found in Crawford *et al.* (2017). Figure 1 shows the steps involved in creating the coefficients within the EPiC Database.


Data sources (2.3.1)
Australian IO data, 2014-15
AusLCI shadow database
+
Custom processes
Developing input-output satellite matrices (2.3.2)
1
Collect raw data in .xlsx format
2
Prepare binary concordance matrix between IO sectors and sectors in raw data
3
Normalise binary concordance
4
Calculate satellite vector or matrix
Developing technological and stress matrices (2.3.3)
1
Collect raw data in .xlsx format
2
Add custom data for materials not in existing matrix
3
Prepare binary concordance matrix
4
Calculate satellite vector or matrix
Defining material characteristics (2.3.4)
1
Define material characteristics used to calculate coefficients
Material name
Functional Unit (FU)
Material category
Cost per FU
Material type
Data year
2
Define non-essential material characteristics
Heat conductivity
Specific heat
Density
Comments
Weight per FU
Description
DOI
Material characteristics
Process matrices
Input-output matrices
Compiling coefficients (2.3.5)
1
Conduct Structural Path Analyses (SPA)
2
⇔
Identify corresponding input-output and process nodes
3
COEFF
Calculate hybrid coefficient
EPiC Environmental Flow Coefficients
EPiC Material Information Sheets

### 2.3.1. Data sources

The process database used is the Australian Life Cycle Inventory Database (AusLCI) (ALCAS, 2019; Grant, 2016). This was collected as a technological matrix from the SimaPro LCA software. AusLCI is a set of process data collected from Australian sources, supplemented with ecoinvent data where local data does not exist, reducing gaps in the process data. Additional processes were created by the authors to represent processed materials, such as laminated MDF or extruded PVC pipe, where they did not already exist. These were based on Environmental Product Declarations (EPDs) or data from international databases.

Input-output tables are combined with environmental flow data to produce EEIO tables and satellites. Input-output data and related environmental flow data used to develop the coefficients were sourced from Australian government departments, covering the 2014-15 financial year. Input-output tables were sourced from the Australian Bureau of Statistics (ABS) disaggregated to 114 sectors (ABS, 2017). GHG emissions accounts were sourced from the Department of the Environment and Energy (2015), water accounts from the ABS (2016), and energy accounts were collected from the Department of Industry (2016). All input-output data and related environmental flow data have been compiled in Excel tables and are available at Bontinck (2018).

The following sections briefly outline the data processing required prior to using the raw data to create the hybrid coefficients. A key aim was to automate the compilation and subsequent update of hybrid coefficients where possible. In this regard, several elements of data handling are automated. However, the raw data must be formatted in a way that can be easily read and so the first step is the preparation of the raw data.

### 2.3.2. Developing input-output satellite matrices

The input-output tables require minimal preparation, as data is collected in spreadsheet format and already include the supply, use, and import tables required. Raw environmental flow data are processed in the same way, following the four-step process shown in Figure 2. This process is used to allocate environmental flows as reported by government departments to economic sectors as reported in input-output tables. This is assisted by the fact that most data follows a sector nomenclature based on the Australian and New Zealand Standard Industrial Classification (ANZSIC) (ABS, 2006), although the resolution at which data is reported can vary significantly.

As an example, the 2015 input-output tables are disaggregated to 114 sectors, while the water accounts are reported across 31 sectors. In this situation a concordance matrix is required to match sectors between the input-output tables and the water accounts (Step 2, Figure 2). In this example, some of the sectors within the water accounts relate to multiple input-output sectors, and therefore the water consumption data should be allocated between these input-output sectors, using a normalised version of the concordance matrix (Step 3, Figure 2). An example of this is the 'Metal ore mining' sector reported in the water accounts, which covers both the 'Iron ore mining' and 'Non-ferrous metal ore mining' sectors in the input-output tables. In this case, the water consumption of the 'Metal ore mining' sector reported in the water accounts is allocated using the expenditure data for 'Water supply, sewerage and drainage services' reported in the input-output tables for these two mining sectors. This is a fundamental hypothesis that assumes a direct correlation between expenditure in this sector and physical water consumption.

Finally, the raw environmental flow data and normalised concordance matrix 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 2). This process is repeated for each environmental flow based on the data available. For example, satellite data for energy covers 27 different energy sources for each sector (in GJ/AUD) and for GHG emissions a total of eight different gas types (in kg/AUD).

The input-output data is augmented by four additional sectors that represent capital expenditure. Capital goods are therefore endogenised using the augmentation technique described by Lenzen and Treloar (2004), across the sectors of 'Machinery and weapons', 'IP Products', 'Biological resources' and 'Construction'. Endogenising capital provides a more comprehensive coverage of the economy and results in a 10-20% increase in the total environmental flow intensities of sectors. Most existing hybrid or process databases do not take into account capital expenditure in their models (e.g. Agez *et al.* (2020)).

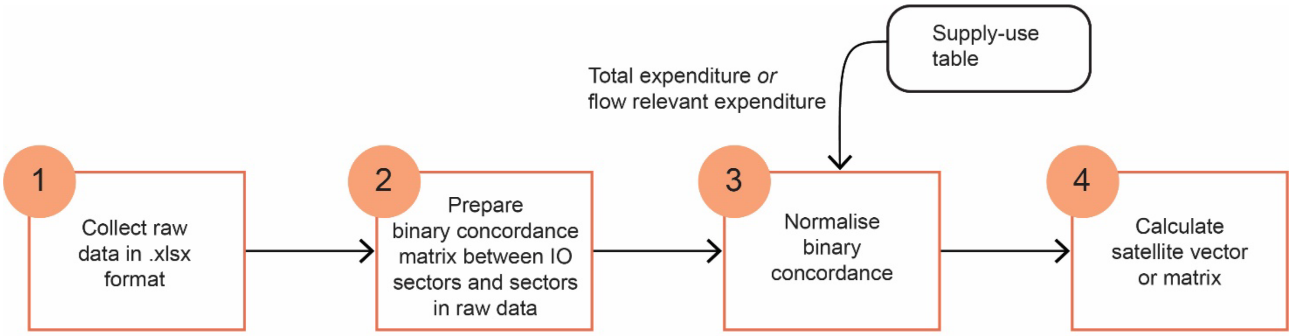


*Figure 2: Steps in processing raw data to obtain an input-output satellite*

### 2.3.3. Developing technological and stress matrices

The process data is collected in a standardised format that requires minimal manipulation before it is loaded into the model. The entire AusLCI database is collected from the SimaPro LCA software as a matrix (PRé Sustainability, 2021), including the 'shadow database' described in the AusLCI Database Manual (Grant, 2016). This includes a technological and stress matrix, which are very similar to an input-output table and its satellites (Figure 3).

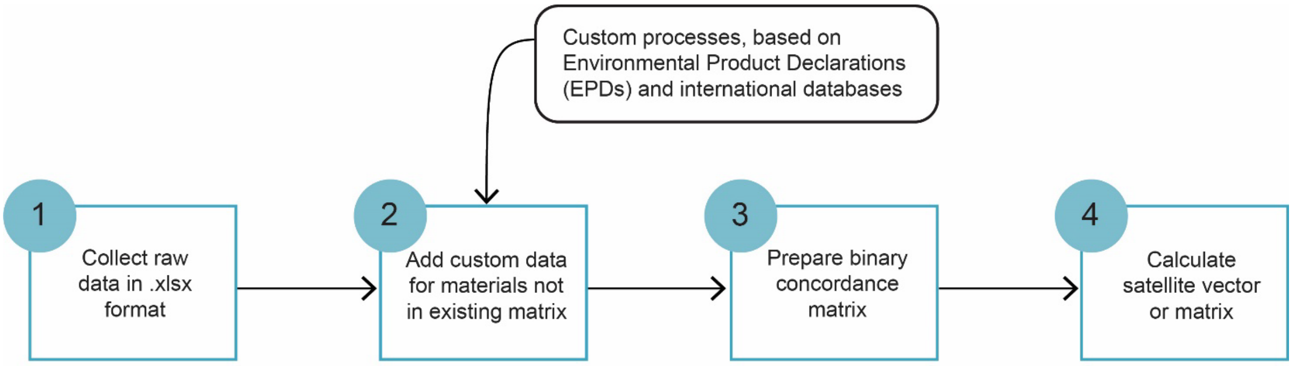


*Figure 3: Steps in processing raw data to obtain technological and stress matrices*

Once the process and input-output data have been collected and formatted as required, they can be read by the model, with all information collated into a single file object. The input-output and process data are processed using automated routines as described in Crawford *et al.* (2018a) and Stephan *et al.* (2019). The final input-output and process data are presented as square technological matrices. Environmental satellites and metadata are formatted as lists, attributing a direct and total environmental intensity to each process/sector, for each flow (in MJ of energy, or kg $CO_2$-e of emissions per monetary unit, for example). Using this approach provides a standardised data format which enables a transparent compilation of coefficients.

### 2.3.4. Defining material characteristics

A range of characteristics are determined for each of the materials for which a coefficient is to be compiled. Some material characteristics are essential for compiling the coefficients, while some are useful for future analysis, comparisons, and building-based life cycle studies. Essential data to be collected or determined and entered into the GUI include: material name; material category (see SI, Table S1); material type (see SI, Table S1); country of production; functional unit (kg, m, $m^2$, $m^3$, no.); cost per functional unit and data year (Step 1, Figure 4). Non-essential data includes: description; common uses; digital object identifier (DOI); weight per functional unit; specific heat; density; heat conductivity and comments (Step 2, Figure 4). A list of material characteristics can be found for each material at (https://figshare.com/projects/Environmental_Performance_in_Construction_EPiC_Database/68177) (Crawford *et al.*, 2019b).

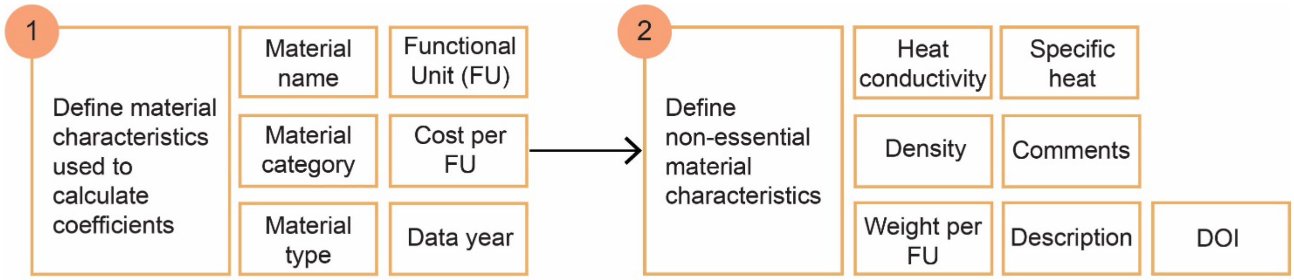


*Figure 4: Defining material characteristics for the EPiC Database*

*Note: FU = Functional Unit, DOI = Digital Object Identifier*

### 2.3.5. Compiling coefficients

The technological matrices, satellites and key material characteristics are then used to compile the coefficients. The coefficients are produced in three steps, as per Figure 5. A detailed description of the automated model used to compile the coefficients is outlined in Stephan *et al.* (2019).

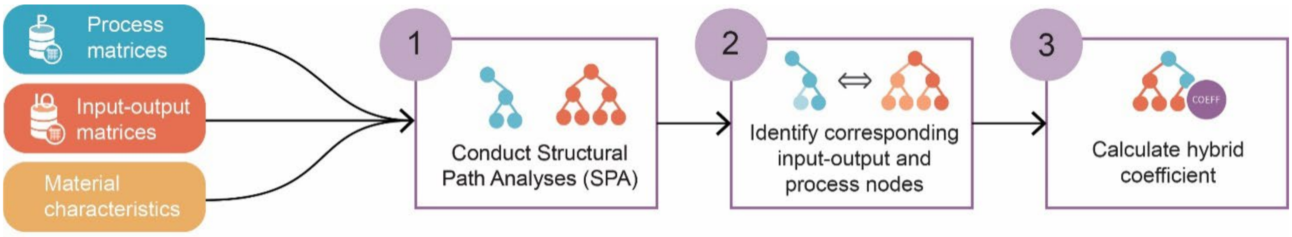


*Figure 5: Steps in compiling a hybrid coefficient*

Step 1: Conduct Structural Path Analyses (SPA)

The process and input-output databases are loaded within the GUI. This presents the full list of processes and input-output sectors covered by the two matrices. The relevant process and input-output sector specific to the material for which the hybrid coefficient is being compiled are selected. Next, the supply chains of the relevant process and sector are analysed using a structural path analysis (SPA). This approach is common to both input-output and process analysis, with the mathematical framework detailed in the literature (Crawford *et al*., 2018b; Defourny & Thorbecke, 1984; Lenzen & Crawford, 2009). Several key parameters must be set for the SPA, including environmental flow/s to be modelled; threshold at which nodes are excluded for both process and input-output SPAs (needed to meet current computer processing capabilities); number of stages upstream of the main process/sector included. The outcome of the SPA is a series of mutually exclusive nodes. Each node represents a good or service provided from one stage to another (and the associated environmental flow) within the supply chain analysed. The model analyses multiple flows at the same time and automatically ranks nodes in order of importance. Environmental flow hotspots at various stages of the supply chain can then be identified. Stephan *et al.* (2019) describe the automated approach for conducting the SPA, and an open-source version of this part of the model (pyspa) is available at https://github.com/hybridlca/pyspa (Stephan & Bontinck, 2019).

Step 2: Identify and exchange nodes

This is where the particular hybrid approach used to produce the EPiC Database, Path Exchange hybrid, gets its name. The output of both SPAs is reviewed, and equivalent nodes identified. The equivalent nodes are then matched within the GUI and saved. A critical 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 example, 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 equivalent representations of the production of concrete and its supply chain. Assuming this is true, it is possible to identify process and input-output nodes (or entire supply chain paths) that are equivalent, i.e., that aim to represent the same aspect of the supply chain. This process of identifying equivalent nodes is the essence of the second step of the hybridisation process and is important to avoid double counting. It is important to flag that the GUI displays the contribution of a node towards the total intensity of the process/input-output environmental flow of a material. All process nodes that represented less than 0.02% of the total intensity were not matched due to the limited added value of identifying relevant input-output nodes for such insignificant contribution. This is where the value of the Path Exchange method lies: use the most significant and reliable process data where available and represent the rest of the supply chain using input-output data.

Step 3: Calculate hybrid coefficient

The model uses the information from Step 2 to calculate a hybrid coefficient for a material (Step 3, Figure 5). The environmental flows associated with each process node selected are summed, forming 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 relevant input-output sector. The cost of the material is used to convert the remaining environmental flow values from a flow per unit of currency (e.g., kg $CO_2$-e/AUD) to a flow per physical unit of material (e.g., kg $CO_2$-e/$m^3$). This input-output component is added to the process component to produce the hybrid coefficient.

### 2.3.6. A word on automation

The semi-automated model used to compile the EPiC Database is described in detail in Stephan *et al.* (2019), and ensures that coefficients are complete, consistent, and transparent. Completeness is ensured by the combination of input-output and process data processes, providing full coverage of the supply chain for each material. Consistency is provided by using the exact same algorithm to compile all coefficients, by the same user (to avoid human error). Transparency is where the power of automation is most demonstrated, as all the data associated with a coefficient is saved and can be routinely accessed, extracted, and compared, across the entire database. The consistency in the data behind each coefficient streamlines these routines and enables not only the generation of all metadata in a homogenous format for all materials (see Section 6), but it also enables the extraction of in-depth information, shedding light on the detail of coefficients in ways that would otherwise take weeks to compile using Excel or similar programs, as demonstrated in Sections 3.4 and 3.5.

## 3. Analysis of the EPiC Database

The following sections describe how the completeness, consistency, and transparency unique to the EPiC Database, were achieved and demonstrates the importance of these aspects for informing reliable, comprehensive material selection decisions in construction projects. To do this, this study examines the 131 primary construction materials contained within the EPiC Database. A total of 153 materials have been excluded from this study as they represent minor variations to the primary materials.

### 3.1. Completeness

Reliance on process data alone can lead to significant underestimation of the embodied environmental flows associated with the production of a material, or inconsistencies between materials, potentially leading to ill-informed material selection decisions. A key benefit of the hybridisation of process data with economic input-output data is the ability to easily resolve this issue. Therefore, the intention was to use a hybrid LCI approach to compile the coefficients to address the system boundary incompleteness associated with process-based coefficients. By beginning with a top-town economic input-output model, which covers the complete economic system, and substituting input-output nodes or entire paths with process data where it is available, the inherent completeness of the input-output model is maintained along with the specificity of the process data.

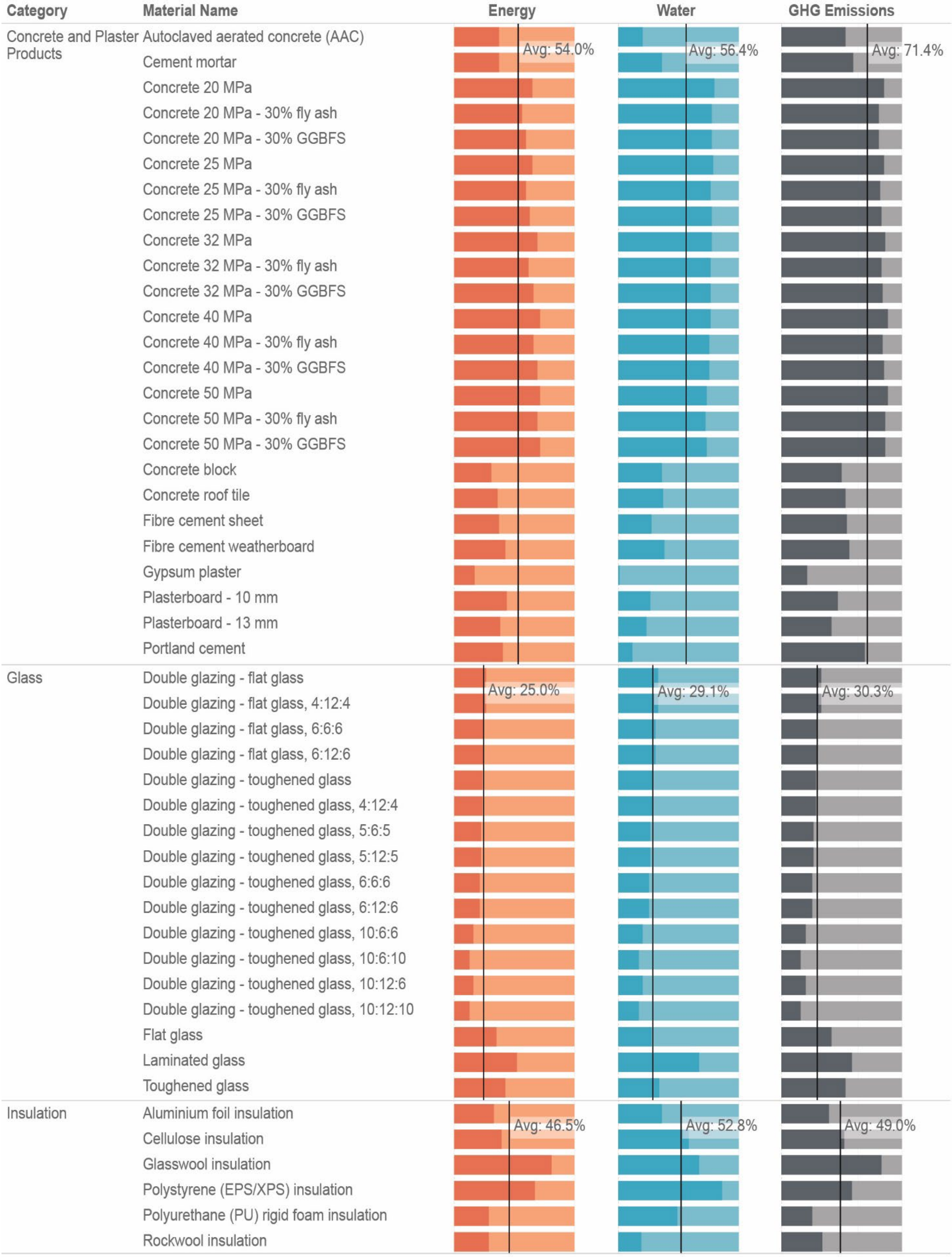
As part of the compilation of the hybrid coefficients, pure process coefficient values were also calculated for all materials (see SI, Table S2). This enables an analysis of the extent of incompleteness associated with the available process data, or conversely, an indication of the improved completeness offered by the hybrid coefficients. Figure 6 shows the proportion of pure process data across all materials, with an average of 43%, 42% and 50%, a median value of 43%, 37% and 51%, a standard deviation of 20%, 25% and 22%, minimum values of 1%, 1% and 8%, and maximum values of 88%, 98% and 89%, for energy, water and GHG emissions, respectively.

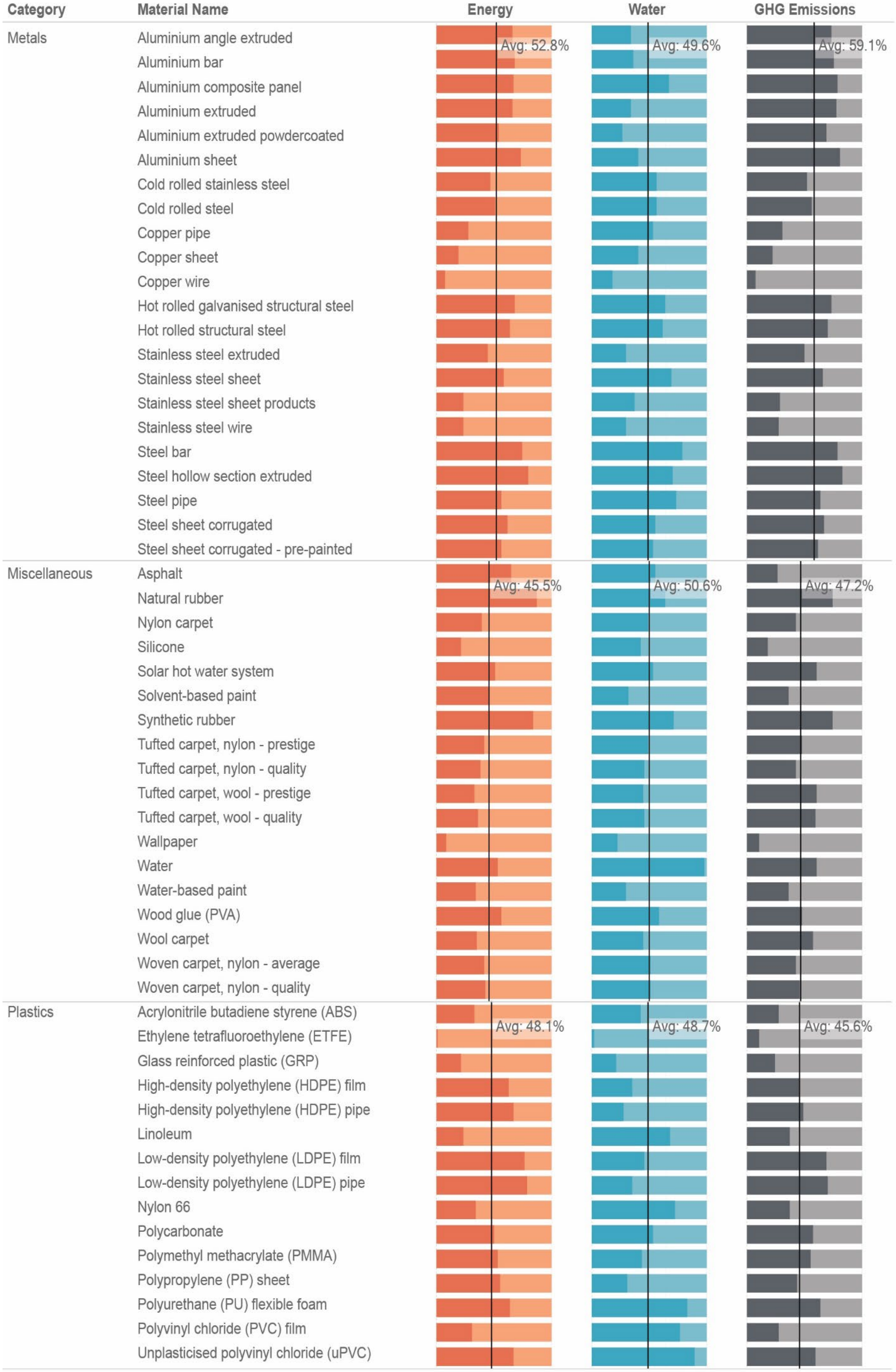
The hybrid coefficients are generally higher than the process coefficients and those reported in other similar databases. A key reason for this is due to the use of the hybrid approach, providing a more comprehensive coverage of a material's system boundary. Data from Figure 6 presents particularly interesting information as it reveals two distinct scenarios. In one scenario, process and hybrid coefficients are very similar – this is the case for 'Concrete 25 MPa', for which pure process data contributes 65%, 80%, and 85% of the hybrid coefficient (for energy, water and GHG emissions, respectively). The other scenario is for materials such as 'ETFE film', for which process data contributes a mere 1%, 2% and 11% of the total (for energy, water and GHG emissions, respectively), demonstrating a significant gap in the amount of information available on this material.

Several parameters will influence the extent of difference between the process and hybrid coefficients:

- The appropriateness of the cost value used to convert the input-output results from a flow per financial output into a flow per physical material quantity. The potential uncertainty and variability associated with this cost value means that it could have a dramatic effect on the results. Materials with a higher input-output component will be affected the most.
- The appropriateness of the input-output sector identified to represent the supply chain of the material. 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 copper 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 processes, such as electricity production, or materials, such as steel, have been studied in minute detail, and it is likely that the process models are of a very high standard. This is not always the case, especially for materials that have not had such a focus or are new to the market.

- The representativeness of the process and input-output nodes being exchanged. It is very difficult to assess with certainty whether a process and input-output node match. There is no standardised approach, so a judgement call must be made by the assessor with all associated uncertainties.


Category
Material Name
Energy
Water
GHG Emissions
Concrete and Plaster Products
Autoclaved aerated concrete (AAC)
Cement mortar
Concrete 20 MPa
Concrete 20 MPa - 30% fly ash
Concrete 20 MPa - 30% GGBFS
Concrete 25 MPa
Concrete 25 MPa - 30% fly ash
Concrete 25 MPa - 30% GGBFS
Concrete 32 MPa
Concrete 32 MPa - 30% fly ash
Concrete 32 MPa - 30% GGBFS
Concrete 40 MPa
Concrete 40 MPa - 30% fly ash
Concrete 40 MPa - 30% GGBFS
Concrete 50 MPa
Concrete 50 MPa - 30% fly ash
Concrete 50 MPa - 30% GGBFS
Concrete block
Concrete roof tile
Fibre cement sheet
Fibre cement weatherboard
Gypsum plaster
Plasterboard - 10 mm
Plasterboard - 13 mm
Portland cement
Avg: 54.0%
Avg: 56.4%
Avg: 71.4%
Glass
Double glazing - flat glass
Double glazing - flat glass, 4:12:4
Double glazing - flat glass, 6:6:6
Double glazing - flat glass, 6:12:6
Double glazing - toughened glass
Double glazing - toughened glass, 4:12:4
Double glazing - toughened glass, 5:6:5
Double glazing - toughened glass, 5:12:5
Double glazing - toughened glass, 6:6:6
Double glazing - toughened glass, 6:12:6
Double glazing - toughened glass, 10:6:6
Double glazing - toughened glass, 10:6:10
Double glazing - toughened glass, 10:12:6
Double glazing - toughened glass, 10:12:10
Flat glass
Laminated glass
Toughened glass
Avg: 25.0%
Avg: 29.1%
Avg: 30.3%
Insulation
Aluminium foil insulation
Cellulose insulation
Glasswool insulation
Polystyrene (EPS/XPS) insulation
Polyurethane (PU) rigid foam insulation
Rockwool insulation
Avg: 46.5%
Avg: 52.8%
Avg: 49.0%


Category
Material Name
Energy
Water
GHG Emissions
Metals
Aluminium angle extruded
Aluminium bar
Aluminium composite panel
Aluminium extruded
Aluminium extruded powdercoated
Aluminium sheet
Cold rolled stainless steel
Cold rolled steel
Copper pipe
Copper sheet
Copper wire
Hot rolled galvanised structural steel
Hot rolled structural steel
Stainless steel extruded
Stainless steel sheet
Stainless steel sheet products
Stainless steel wire
Steel bar
Steel hollow section extruded
Steel pipe
Steel sheet corrugated
Steel sheet corrugated - pre-painted
Avg: 52.8%
Avg: 49.6%
Avg: 59.1%
Miscellaneous
Asphalt
Natural rubber
Nylon carpet
Silicone
Solar hot water system
Solvent-based paint
Synthetic rubber
Tufted carpet, nylon - prestige
Tufted carpet, nylon - quality
Tufted carpet, wool - prestige
Tufted carpet, wool - quality
Wallpaper
Water
Water-based paint
Wood glue (PVA)
Wool carpet
Woven carpet, nylon - average
Woven carpet, nylon - quality
Avg: 45.5%
Avg: 50.6%
Avg: 47.2%
Plastics
Acrylonitrile butadiene styrene (ABS)
Ethylene tetrafluoroethylene (ETFE)
Glass reinforced plastic (GRP)
High-density polyethylene (HDPE) film
High-density polyethylene (HDPE) pipe
Linoleum
Low-density polyethylene (LDPE) film
Low-density polyethylene (LDPE) pipe
Nylon 66
Polycarbonate
Polymethyl methacrylate (PMMA)
Polypropylene (PP) sheet
Polyurethane (PU) flexible foam
Polyvinyl chloride (PVC) film
Unplasticised polyvinyl chloride (uPVC)
Avg: 48.1%
Avg: 48.7%
Avg: 45.6%

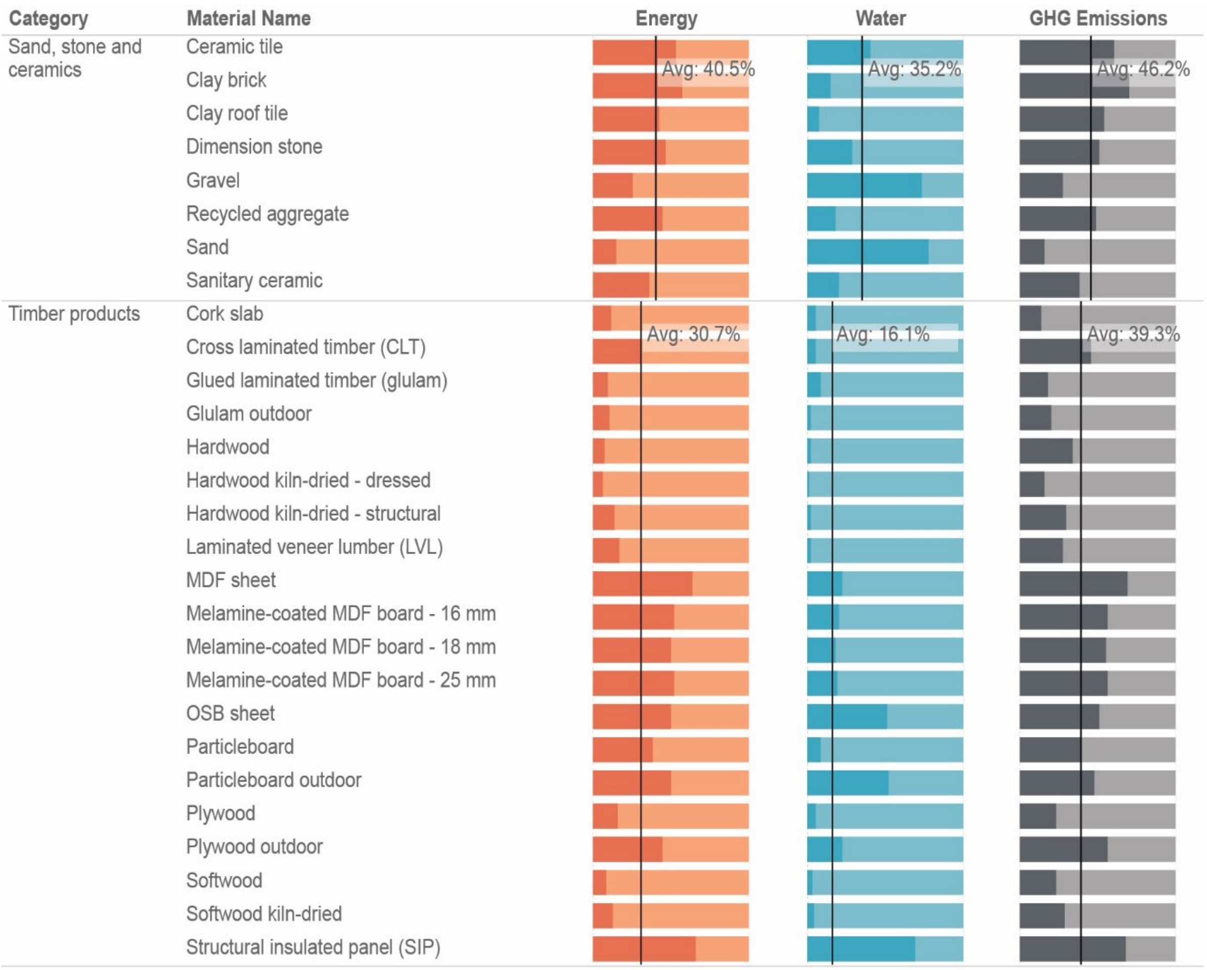


*Figure 6: Proportion of process data in EPiC hybrid coefficients*

*Note: process data proportion is indicated by the darker shade*

At the individual material level, input-output data represents a varying proportion of the total hybrid coefficient, accounting for missing process data. For instance, in the case of ‘Cold rolled steel’, the input-output proportion represents 43% to 49% of the total (for each flow), while in the case of ‘Flat glass’, it represents 58% to 72%. Across all materials, the proportion of input-output data ranges from 2% to 99% across the three environmental flows, averaging 57% for energy, 58% for water and 50% for GHG emissions. These variations are significant and warrant a more detailed analysis of the input-output component to better assess its significance.

Crawford *et al.* (2019a) have demonstrated the effect of using process-based and hybrid coefficients on the life cycle energy demand of a residential building. Using EPiC data, they revealed that the use of hybrid coefficients can significantly increase the value of embodied energy over the life of the house (from 860 GJ for process data to 2,400 GJ for hybrid data) and increase the perceived significance of the embodied energy component of the life cycle energy demand (from 19% to 39%). This reinforces the issue that the use of process-based material coefficients may lead to a significant underestimation of embodied environmental flows.

### 3.2. Consistency

The use of coefficients compiled using different data types and sources as well as LCI methods can be problematic, particularly in comparative studies. For example, the embodied environmental flows of a material may appear to be lower than those for an alternative material due to the use of process analysis to compile the material LCI or coefficient, thus truncating the system boundary. In some cases, significant flows can be excluded, which when included through a more comprehensive hybrid LCI approach, may show higher embodied environmental flows compared to the alternative material. For this reason, a consistent approach to the compilation of LCI data and environmental flow coefficients is essential, using systematically the same process database, the same input-output database, the same environmental flows and relying on the same person to perform the path exchange.

An example of a situation in which system boundary consistency is critical is where the coefficient of two interchangeable materials is lower for the opposite coefficient type. For example, ‘Cross laminated timber’ has a considerably lower hybrid coefficient (7.9 GJ/m$^3$) than ‘Softwood kiln-dried’ (12.2 GJ/m$^3$), but a higher process coefficient (4.6 v 2.5 GJ/m$^3$). This demonstrates that on a cubic metre basis, ‘Cross laminated timber’ would be the preferred option for reducing embodied energy if using hybrid coefficients, but ‘Softwood kiln-dried’ would be preferred if using process coefficients. One of the main reasons why the ranking of process and hybrid coefficients may vary is due to the inconsistent system boundary used for process coefficients and varying levels of detail in available process data across materials/processes. In this case, it is possible that the coverage of embodied energy flows for ‘Softwood kiln-dried’ through process data is lower than for ‘Cross laminated timber’, especially given the low proportion of process data in the hybrid coefficient for ‘Softwood kiln-dried’ (13%).

To achieve the goal of consistency across the coefficients within the EPiC Database, the source of data and the method of compiling the coefficients was identical for all materials. The Path Exchange hybrid LCI approach not only helped to provide an unprecedented level of system boundary completeness for the embodied environmental flows of each material, but its use in compiling all coefficients ensured consistency in system boundary coverage. This approach maximises the ability to compare materials and avoid many of the issues that can arise when comparing materials based on different LCI methods.

## 3.3. Transparency

Too often background LCI data and the approach used to compile environmental flow coefficients is hidden from those assessing the embodied environmental flows of goods or services. The data is often treated as a black box, with users often required to rely on blind faith to make important product and material selection decisions. While in many cases users are happy to rely on available data without question, it does raise issues around the quality, completeness and representativeness of the data used and ultimately the relevance of the findings of any analysis.

Throughout the compilation of the EPiC Database, a strong emphasis was placed on ensuring complete transparency in data, processes, and decisions. Transparency is considered essential as it provides users with greater confidence and insight in the use of the coefficients, enables replication and peer review, as well as in-depth analysis of coefficients and identification of hotspots. With this level of detail and transparency, the data made available as part of the EPiC Database enables more than just an indication of the total environmental flows of a material but allows a user to delve into the background data to scrutinise and analyse the upstream environmental flows needed to produce a material and enables users, such as manufacturers, to identify opportunities for improvement at any point in the supply chain.

To facilitate this level of transparency, all data has been made available as open access through figshare (See Section 6, Data Availability). This includes the coefficients themselves, an information sheet for every material that outlines its main attributes, the breakdown of its embodied energy, water and GHG emissions, as well as material variations and relevant metadata. In addition, a detailed report for every material provides: material characteristics as outlined in Section 2.3.4; a summary of the value of process and input-output pathways included/excluded from the final hybrid coefficient; the results of the hybridisation process, and a comparison with pure process and input-output data for each flow; a ranked list of pathways contributing to the hybrid (EPiC) coefficient for each flow; and a summary of the process and input-output structural path analysis (SPA) results for each flow.

## 3.4. Analysis of EPiC coefficients

The automated model (see Section 2.3.6) used to compile the EPiC coefficients enables their in-depth analysis, across environmental flows (i.e., energy, water and GHG emissions), top-contributing nodes (both process and input-output), number of nodes per material, and other aspects. This section provides an example of how the coefficients can be analysed, showing the top source of GHG emissions for a selection of materials.

### 3.4.1. Data intensity

The coverage of the structural path analyses varies from 38%-99% of the flows for each sector or material, averaging 78% coverage for input-output data and 90% for process data for all three environmental flows. In total, there are 145,541,274 individual data points (nodes) included in the SPAs, each representing a separate material, input or process. On average, there is more than one million data points per material, with process nodes representing 12% of the total. The outputs of these SPAs can be used to analyse the hybrid coefficients.

### 3.4.2. Source of greenhouse gas emissions

As an example of the type of analysis possible, the top three stage one (direct) inputs of GHG emissions were extracted for each of the 131 materials analysed. These are grouped into six categories of emission sources and displayed as a proportion of the total GHG emissions for a selection of materials (Figure 7). For some materials, such as 'Ceramic tile', the main emissions source is the fuel feedstock, whereas for others, such as 'Hot rolled structural steel' and 'Nylon carpet', the main source of emissions is associated with the production of raw materials. For 'Softwood' and 'Hardwood' the main source of emissions is shown to be transport (it should also be noted that biogenic carbon is not included in the timber coefficients). This disaggregation at the material level provides further insight into the top contributors of GHG emissions, or other environmental flows, which can be useful for targeting environmental improvement efforts.

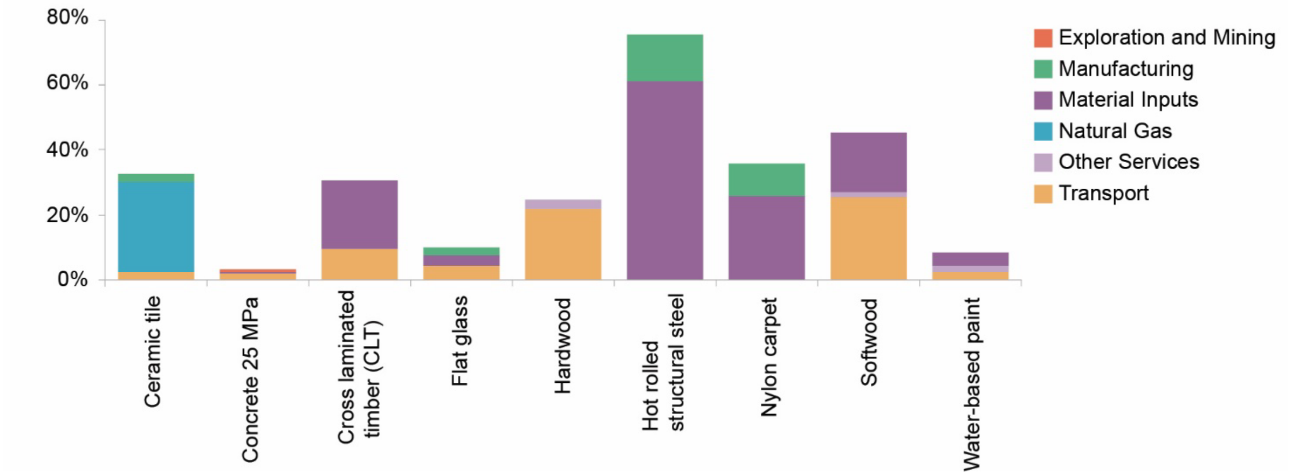


*Figure 7: Contribution of the top three stage 1 inputs towards the total hybrid GHG emissions coefficient for a selection of materials*

## 3.5. Sensitivity analysis

As discussed in Section 2.3.5, the cost of a material is a significant variable that scales up the input-output data to match the functional unit of the process data. Since there is a notable amount of uncertainty in estimating material costs, this uncertainty is automatically transferred to the EPiC coefficients. Where possible, multiple data points were used to estimate the cost of a material. When encoding the EPiC Database, this data was conserved, with the sample size, mean, median, standard deviation, minimum and maximum values for the cost data stored. Interval analysis (Moore *et al.*, 2009) was used, based on ranges of ±10%, ±20% and ±50% (these ranges were informed by the available uncertainty data on cost estimates), to evaluate the sensitivity of the EPiC coefficients to material cost. This section capitalises on the automated nature of the model to automatically modify the cost of each material, based on the underlying data. Results from this sensitivity analysis are presented in Table 3.

*Table 3: Sensitivity of EPiC embodied environmental flow coefficients to material cost*

| | **Material Name** | **EE 10% CD** | **EE 20% CD** | **EE 50% CD** | **EW 10% CD** | **EW 20% CD** | **EW 50% CD** | **EGHG 10% CD** | **EGHG 20% CD** | **EGHG 50% CD** |
|---|---|---|---|---|---|---|---|---|---|---|
| Concrete and Plaster Products | Autoclaved aerated concrete (AAC) | 6.3% | 12.7% | 31.7% | 8.0% | 16.0% | 40.1% | 4.7% | 9.3% | 23.3% |
| | Cement mortar | 6.3% | 12.6% | 31.5% | 6.4% | 12.9% | 32.2% | 4.0% | 8.0% | 19.9% |
| | Concrete 20 MPa | 3.5% | 6.9% | 17.3% | 2.0% | 4.0% | 10.0% | 1.4% | 2.8% | 6.9% |
| | Concrete 20 MPa - 30% fly ash | 4.3% | 8.6% | 21.6% | 2.2% | 4.4% | 10.9% | 1.9% | 3.9% | 9.7% |
| | Concrete 20 MPa - 30% GGBFS | 4.0% | 7.9% | 19.8% | 2.2% | 4.3% | 10.8% | 1.9% | 3.7% | 9.3% |
| | Concrete 25 MPa | 3.5% | 6.9% | 17.3% | 2.1% | 4.3% | 10.6% | 1.4% | 2.8% | 7.0% |
| | Concrete 25 MPa - 30% fly ash | 4.0% | 8.0% | 20.0% | 2.3% | 4.5% | 11.3% | 1.8% | 3.7% | 9.2% |
| | Concrete 25 MPa - 30% GGBFS | 3.7% | 7.3% | 18.3% | 2.2% | 4.4% | 11.1% | 1.7% | 3.5% | 8.7% |
| | Concrete 32 MPa | 3.1% | 6.2% | 15.5% | 2.2% | 4.4% | 11.0% | 1.3% | 2.5% | 6.3% |
| | Concrete 32 MPa - 30% fly ash | 3.8% | 7.5% | 18.8% | 2.3% | 4.7% | 11.7% | 1.7% | 3.3% | 8.3% |
| | Concrete 32 MPa - 30% GGBFS | 3.4% | 6.8% | 17.1% | 2.3% | 4.6% | 11.5% | 1.6% | 3.2% | 8.0% |
| | Concrete 40 MPa | 2.8% | 5.7% | 14.2% | 2.3% | 4.6% | 11.5% | 1.1% | 2.2% | 5.6% |
| | Concrete 40 MPa - 30% fly ash | 3.4% | 6.9% | 17.2% | 2.4% | 4.9% | 12.2% | 1.5% | 3.0% | 7.5% |
| | Concrete 40 MPa - 30% GGBFS | 3.1% | 6.3% | 15.7% | 2.4% | 4.8% | 12.0% | 1.4% | 2.8% | 7.0% |
| | Concrete 50 MPa | 2.8% | 5.6% | 14.0% | 2.6% | 5.1% | 12.8% | 1.1% | 2.1% | 5.3% |
| | Concrete 50 MPa - 30% fly ash | 3.0% | 6.1% | 15.2% | 2.7% | 5.3% | 13.3% | 1.3% | 2.7% | 6.7% |
| | Concrete 50 MPa - 30% GGBFS | 2.8% | 5.6% | 13.9% | 2.6% | 5.2% | 13.0% | 1.3% | 2.5% | 6.3% |
| | Concrete block | 6.9% | 13.9% | 34.7% | 6.4% | 12.7% | 31.9% | 5.0% | 10.0% | 24.9% |
| | Concrete roof tile | 6.4% | 12.8% | 32.1% | 6.3% | 12.7% | 31.7% | 4.6% | 9.3% | 23.1% |
| | Fibre cement sheet | 6.3% | 12.7% | 31.6% | 7.2% | 14.5% | 36.1% | 4.5% | 9.1% | 22.7% |
| | Fibre cement weatherboard | 5.8% | 11.5% | 28.4% | 6.4% | 12.7% | 31.4% | 4.5% | 8.8% | 21.8% |
| | Gypsum plaster | 8.3% | 16.5% | 41.3% | 9.9% | 19.7% | 49.3% | 7.9% | 15.8% | 39.5% |
| | Plasterboard - 10 mm | 5.6% | 11.2% | 28.1% | 7.3% | 14.6% | 36.4% | 5.3% | 10.7% | 26.7% |
| | Plasterboard - 13 mm | 6.1% | 12.1% | 30.3% | 7.6% | 15.2% | 38.1% | 5.8% | 11.6% | 28.9% |
| | Portland cement | 5.9% | 11.7% | 29.3% | 8.8% | 17.5% | 43.8% | 3.0% | 6.0% | 15.1% |
| Glass | Double glazing - flat glass | 7.3% | 14.5% | 36.4% | 6.7% | 13.4% | 33.5% | 6.7% | 13.5% | 33.6% |
| | Double glazing - flat glass, 4:12:4 | 7.3% | 14.5% | 36.4% | 6.7% | 13.4% | 33.5% | 6.7% | 13.5% | 33.6% |
| | Double glazing - flat glass, 6:12:6 | 7.5% | 14.9% | 37.4% | 6.9% | 13.8% | 34.6% | 7.0% | 13.9% | 34.8% |
| | Double glazing - flat glass, 6:6:6 | 7.5% | 14.9% | 37.4% | 6.9% | 13.8% | 34.6% | 7.0% | 13.9% | 34.8% |
| | Double glazing - toughened glass | 7.6% | 15.3% | 38.1% | 7.1% | 14.2% | 35.5% | 7.1% | 14.3% | 35.6% |
| | Double glazing - toughened glass, 10:12:10 | 8.7% | 17.4% | 43.4% | 8.3% | 16.7% | 41.7% | 8.4% | 16.7% | 41.8% |
| | Double glazing - toughened glass, 10:12:6 | 8.4% | 16.8% | 41.9% | 8.0% | 15.9% | 39.9% | 8.0% | 16.0% | 40.0% |
| | Double glazing - toughened glass, 10:6:10 | 8.7% | 17.4% | 43.4% | 8.3% | 16.7% | 41.7% | 8.4% | 16.7% | 41.8% |
| | Double glazing - toughened glass, 10:6:6 | 8.4% | 16.8% | 41.9% | 8.0% | 15.9% | 39.9% | 8.0% | 16.0% | 40.0% |
| | Double glazing - toughened glass, 4:12:4 | 7.6% | 15.3% | 38.1% | 7.1% | 14.2% | 35.5% | 7.1% | 14.3% | 35.6% |
| | Double glazing - toughened glass, 5:12:5 | 7.8% | 15.5% | 38.9% | 7.3% | 14.5% | 36.3% | 7.3% | 14.6% | 36.5% |
| | Double glazing - toughened glass, 5:6:5 | 7.8% | 15.5% | 38.9% | 7.3% | 14.5% | 36.3% | 7.3% | 14.6% | 36.5% |
| | Double glazing - toughened glass, 6:12:6 | 7.9% | 15.8% | 39.5% | 7.4% | 14.8% | 37.0% | 7.4% | 14.9% | 37.1% |
| | Double glazing - toughened glass, 6:6:6 | 7.9% | 15.8% | 39.5% | 7.4% | 14.8% | 37.0% | 7.4% | 14.9% | 37.1% |
| | Flat glass | 6.5% | 13.1% | 32.7% | 7.2% | 14.3% | 35.9% | 5.8% | 11.5% | 28.8% |
| | Laminated glass | 4.8% | 9.6% | 24.0% | 3.3% | 6.6% | 16.4% | 4.1% | 8.3% | 20.7% |

|  | **Material Name** | **EE 10% CD** | **EE 20% CD** | **EE 50% CD** | **EW 10% CD** | **EW 20% CD** | **EW 50% CD** | **EGHG 10% CD** | **EGHG 20% CD** | **EGHG 50% CD** |
|---|---|---|---|---|---|---|---|---|---|---|
|  | Toughened glass | 5.7% | 11.5% | 28.7% | 6.6% | 13.2% | 33.0% | 4.7% | 9.4% | 23.5% |
| Insulation | Aluminium foil insulation | 6.7% | 13.5% | 33.7% | 6.4% | 12.9% | 32.1% | 6.0% | 12.0% | 30.0% |
|  | Cellulose insulation | 6.0% | 12.1% | 30.2% | 4.1% | 8.2% | 20.5% | 4.8% | 9.6% | 24.0% |
|  | Glasswool insulation | 1.9% | 3.8% | 9.6% | 3.3% | 6.7% | 16.7% | 1.7% | 3.4% | 8.5% |
|  | Polystyrene (EPS/XPS) insulation | 3.3% | 6.7% | 16.7% | 1.3% | 2.6% | 6.5% | 4.1% | 8.2% | 20.5% |
|  | Polyurethane (PU) rigid foam insulation | 7.1% | 14.3% | 35.7% | 5.1% | 10.2% | 25.5% | 7.4% | 14.8% | 37.1% |
|  | Rockwool insulation | 7.1% | 14.2% | 35.6% | 8.1% | 16.2% | 40.6% | 6.6% | 13.3% | 33.2% |
| Metals | Aluminium angle extruded | 3.4% | 6.8% | 17.0% | 6.6% | 13.3% | 33.2% | 2.6% | 5.2% | 13.1% |
|  | Aluminium bar | 3.2% | 6.5% | 16.2% | 6.4% | 12.8% | 32.0% | 2.4% | 4.8% | 12.0% |
|  | Aluminium composite panel | 3.3% | 6.6% | 16.5% | 3.3% | 6.6% | 16.5% | 2.1% | 4.2% | 10.6% |
|  | Aluminium extruded | 3.4% | 6.8% | 16.9% | 6.6% | 13.1% | 32.8% | 2.2% | 4.5% | 11.1% |
|  | Aluminium extruded powdercoated | 4.5% | 9.0% | 22.4% | 7.3% | 14.6% | 36.5% | 3.0% | 6.0% | 14.9% |
|  | Aluminium sheet | 2.6% | 5.2% | 13.1% | 5.9% | 11.8% | 29.4% | 1.9% | 3.7% | 9.3% |
|  | Cold rolled stainless steel | 5.3% | 10.7% | 26.7% | 4.3% | 8.5% | 21.3% | 4.8% | 9.7% | 24.2% |
|  | Cold rolled steel | 4.9% | 9.7% | 24.3% | 4.3% | 8.5% | 21.3% | 4.3% | 8.5% | 21.3% |
|  | Copper pipe | 7.2% | 14.4% | 36.1% | 4.6% | 9.3% | 23.2% | 6.9% | 13.9% | 34.7% |
|  | Copper sheet | 8.1% | 16.1% | 40.3% | 5.9% | 11.9% | 29.7% | 7.8% | 15.7% | 39.2% |
|  | Copper wire | 9.3% | 18.6% | 46.5% | 8.2% | 16.4% | 40.9% | 9.2% | 18.3% | 45.8% |
|  | Hot rolled galvanised structural steel | 3.2% | 6.3% | 15.9% | 3.6% | 7.1% | 17.8% | 2.6% | 5.1% | 12.9% |
|  | Hot rolled structural steel | 3.6% | 7.3% | 18.2% | 3.8% | 7.6% | 19.0% | 2.9% | 5.8% | 14.4% |
|  | Stainless steel extruded | 5.5% | 10.9% | 27.4% | 7.0% | 13.9% | 34.8% | 5.0% | 10.0% | 25.1% |
|  | Stainless steel sheet | 4.1% | 8.3% | 20.6% | 3.1% | 6.3% | 15.7% | 3.4% | 6.9% | 17.2% |
|  | Stainless steel sheet products | 7.6% | 15.1% | 37.8% | 6.3% | 12.7% | 31.7% | 7.1% | 14.2% | 35.4% |
|  | Stainless steel wire | 7.7% | 15.3% | 38.3% | 7.0% | 14.0% | 35.0% | 7.2% | 14.4% | 35.9% |
|  | Steel bar | 2.5% | 5.1% | 12.7% | 2.1% | 4.2% | 10.4% | 2.1% | 4.3% | 10.7% |
|  | Steel hollow section extruded | 2.0% | 4.0% | 10.0% | 2.9% | 5.7% | 14.3% | 1.7% | 3.3% | 8.3% |
|  | Steel pipe | 4.3% | 8.6% | 21.4% | 2.6% | 5.3% | 13.2% | 3.6% | 7.2% | 18.0% |
|  | Steel sheet corrugated | 3.8% | 7.7% | 19.2% | 4.4% | 8.8% | 22.0% | 3.3% | 6.5% | 16.3% |
|  | Steel sheet corrugated - pre-painted | 4.3% | 8.7% | 21.7% | 4.6% | 9.3% | 23.2% | 3.8% | 7.7% | 19.2% |
| Miscellaneous | Asphalt | 3.5% | 7.0% | 17.4% | 4.4% | 8.8% | 22.0% | 7.3% | 14.6% | 36.5% |
|  | Natural rubber | 1.2% | 2.5% | 6.1% | 3.6% | 7.2% | 17.9% | 2.5% | 5.0% | 12.6% |
|  | Nylon carpet | 6.0% | 12.1% | 30.2% | 5.1% | 10.3% | 25.7% | 5.7% | 11.4% | 28.5% |
|  | Silicone | 7.9% | 15.8% | 39.5% | 5.7% | 11.3% | 28.3% | 8.2% | 16.4% | 40.9% |
|  | Solar hot water system | 4.9% | 9.8% | 24.4% | 4.7% | 9.4% | 23.6% | 3.9% | 7.7% | 19.3% |
|  | Solvent-based paint | 5.4% | 10.9% | 27.2% | 6.8% | 13.5% | 33.8% | 6.4% | 12.8% | 32.0% |
|  | Synthetic rubber | 1.6% | 3.2% | 8.1% | 2.8% | 5.6% | 14.1% | 2.5% | 5.1% | 12.7% |
|  | Tufted carpet, nylon - prestige | 5.8% | 11.5% | 28.8% | 5.1% | 10.2% | 25.6% | 5.2% | 10.4% | 26.0% |
|  | Tufted carpet, nylon - quality | 6.1% | 12.2% | 30.6% | 5.4% | 10.7% | 26.9% | 5.7% | 11.3% | 28.3% |
|  | Tufted carpet, wool - prestige | 6.7% | 13.3% | 33.3% | 5.5% | 11.0% | 27.6% | 3.9% | 7.9% | 19.6% |
|  | Tufted carpet, wool - quality | 6.4% | 12.8% | 32.1% | 5.4% | 10.7% | 26.8% | 4.0% | 7.9% | 19.8% |
|  | Wallpaper | 9.1% | 18.2% | 45.6% | 7.8% | 15.5% | 38.8% | 8.9% | 17.7% | 44.4% |
|  | Water | 3.7% | 8.2% | 21.7% | 0.7% | 0.6% | 0.3% | 2.4% | 1.4% | 12.6% |
|  | Water-based paint | 6.6% | 13.2% | 32.9% | 7.0% | 13.9% | 34.9% | 6.4% | 12.9% | 32.1% |
|  | Wood glue (PVA) | 4.3% | 8.7% | 21.7% | 4.1% | 8.3% | 20.7% | 5.2% | 10.4% | 26.0% |
|  | Wool carpet | 6.5% | 12.9% | 32.3% | 5.5% | 10.9% | 27.4% | 4.2% | 8.4% | 21.1% |
|  | Woven carpet, nylon - average | 5.8% | 11.7% | 29.2% | 4.9% | 9.9% | 24.7% | 5.7% | 11.3% | 28.3% |

|  | Material Name | EE 10% CD | EE 20% CD | EE 50% CD | EW 10% CD | EW 20% CD | EW 50% CD | EGHG 10% CD | EGHG 20% CD | EGHG 50% CD |
|---|---|---|---|---|---|---|---|---|---|---|
|  | Woven carpet, nylon - quality | 5.7% | 11.3% | 28.3% | 4.9% | 9.8% | 24.6% | 5.4% | 10.9% | 27.2% |
| Plastics | Acrylonitrile butadiene styrene (ABS) | 6.7% | 13.5% | 33.7% | 5.7% | 11.4% | 28.6% | 7.2% | 14.4% | 36.1% |
|  | Ethylene tetrafluoroethylene (ETFE) | 9.9% | 19.7% | 49.3% | 9.8% | 19.6% | 49.0% | 8.9% | 17.7% | 44.4% |
|  | Glass reinforced plastic (GRP) | 7.9% | 15.8% | 39.4% | 7.9% | 15.9% | 39.6% | 7.5% | 15.0% | 37.6% |
|  | High-density polyethylene (HDPE) film | 3.7% | 7.4% | 18.6% | 6.5% | 12.9% | 32.3% | 5.4% | 10.8% | 27.1% |
|  | High-density polyethylene (HDPE) pipe | 3.3% | 6.6% | 16.5% | 7.2% | 14.4% | 36.0% | 5.1% | 10.1% | 25.3% |
|  | Linoleum | 7.6% | 15.2% | 38.0% | 3.2% | 6.4% | 15.9% | 6.3% | 12.6% | 31.6% |
|  | Low-density polyethylene (LDPE) film | 2.3% | 4.7% | 11.7% | 5.4% | 10.9% | 27.2% | 3.0% | 6.1% | 15.2% |
|  | Low-density polyethylene (LDPE) pipe | 2.1% | 4.3% | 10.7% | 6.5% | 13.0% | 32.4% | 2.9% | 5.9% | 14.7% |
|  | Nylon 66 | 6.6% | 13.1% | 32.8% | 2.7% | 5.4% | 13.6% | 6.3% | 12.6% | 31.5% |
|  | Polycarbonate | 5.0% | 10.1% | 25.1% | 4.6% | 9.3% | 23.2% | 4.2% | 8.4% | 20.9% |
|  | Polymethyl methacrylate (PMMA) | 4.6% | 9.2% | 23.1% | 5.6% | 11.1% | 27.9% | 4.4% | 8.7% | 21.8% |
|  | Polypropylene (PP) sheet | 4.4% | 8.8% | 22.0% | 6.9% | 13.9% | 34.7% | 5.6% | 11.2% | 28.0% |
|  | Polyurethane (PU) flexible foam | 3.6% | 7.3% | 18.2% | 1.7% | 3.4% | 8.5% | 3.6% | 7.3% | 18.2% |
|  | Polyvinyl chloride (PVC) film | 6.9% | 13.8% | 34.4% | 2.3% | 4.5% | 11.3% | 7.2% | 14.4% | 35.9% |
|  | Unplasticised polyvinyl chloride (uPVC) | 3.3% | 6.5% | 16.3% | 1.0% | 2.0% | 5.1% | 4.0% | 7.9% | 19.8% |
| Sand, stone and ceramics | Ceramic tile | 4.6% | 9.2% | 22.9% | 5.9% | 11.8% | 29.6% | 3.9% | 7.8% | 19.5% |
|  | Clay brick | 4.2% | 8.3% | 20.8% | 8.5% | 16.9% | 42.3% | 2.9% | 5.8% | 14.5% |
|  | Clay roof tile | 5.7% | 11.4% | 28.5% | 9.3% | 18.6% | 46.5% | 4.5% | 9.0% | 22.5% |
|  | Dimension stone | 5.3% | 10.6% | 26.4% | 7.1% | 14.1% | 35.4% | 4.9% | 9.7% | 24.3% |
|  | Gravel | 7.4% | 14.8% | 37.1% | 2.6% | 5.3% | 13.2% | 7.2% | 14.3% | 35.8% |
|  | Recycled aggregate | 5.5% | 11.1% | 27.7% | 8.2% | 16.5% | 41.2% | 5.1% | 10.2% | 25.6% |
|  | Sand | 8.5% | 17.1% | 42.7% | 2.2% | 4.4% | 11.1% | 8.4% | 16.7% | 41.8% |
|  | Sanitary ceramic | 6.4% | 12.8% | 31.9% | 8.0% | 16.0% | 40.0% | 6.1% | 12.2% | 30.4% |
| Timber products | Cork slab | 8.8% | 17.6% | 44.0% | 9.5% | 19.1% | 47.7% | 8.6% | 17.2% | 43.1% |
|  | Cross laminated timber (CLT) | 6.9% | 13.9% | 34.7% | 9.5% | 19.1% | 47.6% | 5.4% | 10.8% | 27.0% |
|  | Glued laminated timber (glulam) | 9.0% | 18.0% | 45.1% | 9.1% | 18.3% | 45.7% | 8.2% | 16.5% | 41.2% |
|  | Glulam outdoor | 8.9% | 17.7% | 44.3% | 9.8% | 19.6% | 48.9% | 8.0% | 16.1% | 40.2% |
|  | Hardwood | 9.2% | 18.5% | 46.2% | 9.8% | 19.7% | 49.2% | 6.6% | 13.1% | 32.8% |
|  | Hardwood kiln-dried - dressed | 9.4% | 18.7% | 46.8% | 9.9% | 19.9% | 49.6% | 8.4% | 16.9% | 42.1% |
|  | Hardwood kiln-dried - structural | 8.6% | 17.3% | 43.1% | 9.8% | 19.7% | 49.2% | 7.0% | 13.9% | 34.9% |
|  | Laminated veneer lumber (LVL) | 8.3% | 16.6% | 41.6% | 9.8% | 19.6% | 48.9% | 7.2% | 14.4% | 36.0% |
|  | MDF sheet | 3.6% | 7.2% | 17.9% | 7.8% | 15.6% | 38.9% | 3.1% | 6.2% | 15.4% |
|  | Melamine-coated MDF board - 16 mm | 4.8% | 9.7% | 24.2% | 8.0% | 16.1% | 40.2% | 4.3% | 8.6% | 21.5% |
|  | Melamine-coated MDF board - 18 mm | 5.0% | 10.0% | 24.9% | 8.2% | 16.4% | 41.1% | 4.4% | 8.8% | 22.0% |
|  | Melamine-coated MDF board - 25 mm | 4.8% | 9.7% | 24.2% | 8.1% | 16.3% | 40.7% | 4.3% | 8.5% | 21.3% |
|  | OSB sheet | 5.0% | 10.0% | 24.9% | 4.9% | 9.8% | 24.4% | 4.9% | 9.9% | 24.6% |
|  | Particleboard | 6.2% | 12.4% | 31.0% | 9.1% | 18.2% | 45.6% | 6.0% | 11.9% | 29.8% |
|  | Particleboard outdoor | 5.0% | 10.0% | 25.1% | 4.8% | 9.5% | 23.9% | 5.2% | 10.4% | 26.0% |
|  | Plywood | 8.4% | 16.8% | 41.9% | 9.5% | 19.0% | 47.6% | 7.6% | 15.2% | 37.9% |
|  | Plywood outdoor | 5.5% | 11.0% | 27.5% | 7.8% | 15.5% | 38.9% | 4.3% | 8.5% | 21.4% |
|  | Softwood | 9.1% | 18.1% | 45.3% | 9.7% | 19.4% | 48.4% | 7.6% | 15.2% | 38.0% |
|  | Softwood kiln-dried | 8.7% | 17.4% | 43.4% | 9.6% | 19.3% | 48.2% | 7.1% | 14.3% | 35.7% |

|  | **Material Name** | **EE 10% CD** | **EE 20% CD** | **EE 50% CD** | **EW 10% CD** | **EW 20% CD** | **EW 50% CD** | **EGHG 10% CD** | **EGHG 20% CD** | **EGHG 50% CD** |
|---|---|---|---|---|---|---|---|---|---|---|
|  | Structural insulated panel (SIP) | 3.4% | 6.7% | 16.9% | 3.0% | 5.9% | 14.8% | 3.2% | 6.3% | 15.8% |

*Note: EE = embodied energy, EW = embodied water, EGHG = embodied greenhouse gas emissions, CD = cost deviation. Original in colour.*

The sensitivity analysis demonstrates the significant influence of the cost uncertainty on the EPiC coefficients, as the input-output component varies linearly with cost. This can lead to materials with a high proportion of input-output data having their coefficients underestimated/overestimated by up to ±49.6% for a ±50% variation in cost (i.e., embodied water for 'Hardwood kiln-dried - dressed'). The uncertainty associated with the cost is inherent to the use of input-output analysis. This significant variation in hybrid LCI results was also recently observed by Jakobs *et al.* (2021) that found it could affect the total carbon footprint of Swiss households from -28% to +90% (with 95% confidence intervals). Given the potentially large variability associated with the use of input-output data, cost values should be as up-to-date (aligned with the age of input-output data) and representative as possible. Another way of minimising the effect of cost variability on hybrid coefficients is to minimise the use of input-output data as much as possible while maintaining complete system boundary coverage. Maximising the use of process data is the best way of achieving this, which may require greater efforts from industry and governments to make this data available to the broader LCA community, especially in countries where limited process data currently exists.

## 4. Discussion

### 4.1. Contribution

This paper has provided detailed information about the EPiC Database, which provides consistent, transparent and systemically complete embodied environmental flow coefficients for a range of construction materials. The main innovations in the EPiC Database are the semi-automation of the path exchange process for hybrid life cycle assessment (see Stephan *et al.* (2019)), the significant amount of data behind each coefficient produced (on average, more than 1 million individual nodes for each coefficient), the availability of all data in open access format (see Section 6), and the coverage of a broad range of materials (131 core materials + 153 material variations, for a total of 284 materials). EPiC is the first database of hybrid embodied environmental flow coefficients for construction materials that provides such a high data resolution, globally.

The high data resolution of the EPiC Database, and its structured and object-oriented programming, enable a detailed analysis of its embodied environmental flow coefficients, as evidenced in this paper. To date, there are no other databases of embodied environmental flow coefficients for construction materials that enable researchers to extract individual nodes contributing to embodied environmental flows, rank them, compare them, and test the sensitivity of input variables (e.g. material cost), on the input-output component of hybrid coefficients. This level of transparency has been called for by various researchers, such as Azari and Abbasabadi (2018) and Dossche *et al.* (2017).

The proportion of process data used within hybrid coefficients varies widely (e.g., from 8% to 89% in the case of GHG emissions). This reveals that while process data can be abundant for commonly used materials such as concrete and plaster products (average coverage of at least 54%), it can be highly incomplete for others (e.g., less than 12% for 'ETFE film'). It is important to flag that the coefficients for timber products have a relatively lower share of process data because of the large contribution of transport, which has been calculated using input-output data. Process-based transport data could not be used because it was incomplete and unrepresentative of local conditions, thus considered less reliable than the input-output data alternative.

It is difficult to compare the analysis of the EPiC Database to existing literature because of the scarcity of transparent comparisons of process versus hybrid life cycle inventories applied to construction materials. Despite this limitation, some general comparisons can be drawn. In their comparison of the effect of different wall assemblies on the life cycle energy use and GHG emissions of two buildings in the United States of America, Venkatraj and Dixit (2021) demonstrate that using a disaggregated input-output based hybrid life cycle inventory results in embodied energy intensities up to 300% higher, compared to process-based life cycle inventories. This result at a whole building level confirms those obtained with the EPiC Database (Crawford *et al.*, 2019a).

Comparing EPiC coefficients to existing process-based coefficients is a much easier task but provides limited insights due to the large variability in process-based embodied environmental flow coefficients. As such, value ranges are used for embodied energy (the most elementary flow identified, and a good proxy for other environmental effects) from Martínez-Rocamora *et al.* (2016), that have looked at different process-based databases (*inter alia* ecoinvent, GaBi, Athena). Martínez-Rocamora *et al.* (2016) report values of 10.6-35 MJ/kg, 53-70 MJ/kg, 7.7-161 MJ/kg and 3.7-3.8 MJ/kg for steel, PVC, Aluminium and EPS, respectively. Comparatively, the EPiC coefficients for these materials are 38.8 MJ/kg, 76.3 MJ/kg, 358 MJ/kg, and 155 MJ/kg, respectively, showing significantly higher values for Aluminium and EPS.

It is important to note that different databases relying on process-based life cycle inventories (e.g. ecoinvent, GaBi, Athena) as well as EPDs, result in significant variability in the embodied environmental flows of the same material. While Moncaster and Song (2012) identified variability in process-based life cycle inventories a decade ago, they expressed hope that EPDs would standardise the compilation of process-based life cycle inventories. Yet, results from Resalati *et al.* (2019) demonstrate a great variability between embodied environmental intensities from different EPDs for the same product. The product with the largest variability was cellulose fibre insulation, with its embodied energy varying between ~0 and 2.5 GJ/m² (median of 1.1 GJ/m²). This variability between process-based embodied environmental flows is further confirmed at a whole building level by Lasvaux *et al.* (2015), Häfliger *et al.* (2017) and Emami *et al.* (2019). This reinforces the choice of relying on a single source of process data in the case of the EPiC coefficients.

## 4.2. Limitations and future research

Despite the increased supply chain coverage, hybrid coefficients suffer from their own limitations. Firstly, the homogeneity and proportionality assumptions and aggregation errors inherent to input-output data (Crawford, 2011, p. 69) can result in significant uncertainty, as partially demonstrated by the sensitivity analysis in Section 3.5. This could be reduced by improving the resolution of input-output data and producing more detailed input-output tables, as well as having more reliable material cost estimates. Yet, previous research (*inter alia* Lenzen (2000), Crawford (2008)) have demonstrated that the inclusion of input-output data, albeit coarse, is preferred to its exclusion and truncation of the system boundary. The benefits of a hybrid approach have also been highlighted by Majeau-Bettez *et al.* (2011), Dixit (2017), and Pomponi and Lenzen (2018). Secondly, and as clearly flagged by Agez *et al.* (2020), hybrid coefficients can only be combined for the common environmental flows between process and input-output data. The limited number of environmental flows for input-output data currently restricts the compilation of (sufficiently reliable) hybrid coefficients for more specific environmental flows (e.g., particulate matter), for which process data is already available. Efforts to develop dedicated environmental extensions to input-output datasets should be sustained to address this issue. Thirdly, the compilation of hybrid coefficients, despite the significant advances in automation achieved in this work, still relies significantly on human input and therefore is highly time-consuming and requires advanced expertise. Further automation, notably using Artificial Intelligence, might be the next step in streamlining the compilation of hybrid embodied environmental flow coefficients. Fourthly, variability in process databases and EPDs hinders the compilation of hybrid coefficients, due to different system boundaries, the age of the data, and the environmental intensities of processes. More consistent, transparent, and open access process data needs to be produced (Azari & Abbasabadi, 2018;

Dossche *et al.*, 2017; Lasvaux *et al.*, 2015; Moncaster & Song, 2012). Finally, databases, whether containing EPDs or environmental flow coefficients, are typically generic in nature and limited in their specificity for particular products. Time and cost savings from their use must be balanced with the potential loss of reliability compared to the use of company-specific process data (Modahl *et al.*, 2013).

Considering these limitations, further research is needed. Other statistical information could be used to develop coefficients for a broader range of environmental flows, such as pollutant emissions - using the National Pollutant Inventory (NPI) (Department of the Environment and Energy, 2018), waste - using national waste accounts (ABS, 2014), or raw materials - using material flow data (ABARES, 2017; ABS, 2018; Britt *et al.*, 2016; Department of Industry, 2017). This will help expand the number of environmental flows covered and the usefulness of the database to address other environmental issues. The EPiC Database sets the precedent for the development of other databases of hybrid embodied environmental flows for different regions as the process has been successfully trialed and tested and the computer model is transferable to any location, as long as the input data is available. A global database of hybrid coefficients that account for local manufacturing processes, fuel mixes and other regional differences is crucial given the global trade of materials. The effect of variability in process data on hybrid environmental flow coefficients needs to be tested. It is not clear if the final value of a hybrid coefficient that relies on different sources for process data will be significantly different, as input-output pathways will tend to fill more or less data gaps. Finally, the integration of hybrid embodied environmental flow coefficients into existing and new design and LCA tools as well as streamlined workflows for practitioners to assess and improve the environmental performance of construction projects based on this data is needed and will help increase the uptake of this more comprehensive data for environmental decision making, and lead to further reductions in embodied environmental flows.

## 5. Conclusion

There is a demonstrated imperative to significantly improve the environmental performance of construction projects. As human population continues to increase, the need for new buildings, infrastructure and cities will further exacerbate that imperative. The ageing of building stocks will also create increasing demand for materials and other resources. Actors of the built environment, including architects, engineers, construction managers, urban designers, landscape architects, planners, decision-makers and others will all require robust information to inform their design decisions and improve building environmental performance. Yet, consistent, transparent, complete, and open access data on the environmental performance of construction materials is currently lacking, globally. The EPiC Database helps to fill this gap. Even though hybrid embodied environmental flow coefficients are highly unlikely to accurately represent the exact materials used in a particular project, their use can lead to considerable time and cost savings compared to conducting a full LCA, while providing a consistent approach that develops greater industry awareness and understanding of embodied environmental flows and informs improvement to construction project environmental performance.

The key strengths of the EPiC Database are reflected in its transparency (automation of the compilation process enabling the generation of millions of data points in a systematic manner; and open access to all background data for all coefficients allowing detailed comparison and analysis), consistency (the same base datasets used for all materials; all coefficients compiled by the same researchers; and all cost data from the same sources) and completeness (using the Path Exchange hybrid LCI approach). An analysis of the EPiC coefficients found that process data represents on average 45% of the hybrid coefficients, but varied significantly across materials and environmental flows, from 1 to 98%. This highlights the considerable data gaps and truncation errors in process data as well as significant inconsistencies in the extent of system boundary coverage. In the most extreme case, this led to a reversal of the comparative ranking of materials based on their environmental flows. The hybrid LCI approach used here improves the ability to reliably compare materials due to its consistency in system boundary coverage.

As the awareness to tackle the increasing significance of embodied environmental flows grows, it is critical that the data we rely on to quantify embodied environmental flows is complete, consistent, and transparent. This will enable us to more rapidly reduce human-induced environmental effects associated with the built environment.

## 6. Data availability

The EPiC Database, along with all metadata associated with each of its materials, a total of 3.55 GB and 145,541,274 datapoints (structural path analysis nodes), are available in open access at https://figshare.com/account/home#/projects/68177 or accessible at www.epicdatabase.com.au.

## 7. Author's contributions

RC and AS secured funding for the project. RC and AS conceptualised the research. RC, AS and FP conducted the research and compiled the database. RC, AS and FP wrote the paper. FP ran the analyses and produced the figures under the guidance of RC and AS.

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## 9. References

ABARES. (2017). *Australian Forest and Wood Products Statistics, March and June Quarter 2017*. Canberra, Australia, https://daff.ent.sirsidynix.net.au/client/en_AU/search/asset/1027133/0

ABCB. (2020). *Building Code of Australia (BCA) 2020*. Australia: Australian Building Codes Board.

ABS. (2006). *1292.0 - Australian and New Zeland Standard Industrial Classification (ANZSIC)*. Canberra, Australia: Australian Bureau of Statistics. https://www.abs.gov.au/AUSSTATS/abs@.nsf/Lookup/1292.0Main+Features12006%20(Revision%202.0)?OpenDocument.

ABS. (2014). *4602.0.55.006 - Waste Account, Australia, 2010-11*. Canberra, Australia: Australian Bureau of Statistics. https://www.abs.gov.au/ausstats/abs@.nsf/mf/4602.0.55.006.

ABS. (2016). *4610.0 - Water Account, Australia, 2014-15*. Canberra, Australia: Australian Bureau of Statistics. http://www.abs.gov.au/AUSSTATS/abs@.nsf/allprimarymainfeatures/F100A84BC5C0973BCA2581E00010808B?opendocument.

ABS. (2017). *5209.0.55.001 - Australian National Accounts: Input-Output Tables, 2014-15*. Canberra, Australia: Australian Bureau of Statistics. https://www.abs.gov.au/AUSSTATS/abs@.nsf/Lookup/5209.0.55.001Main+Features12014-15?OpenDocument.

ABS. (2018). *4655.0 - Australian Environmental-Economic Accounts, 2018*. Canberra, Australia: Australian Bureau of Statistics. http://www.abs.gov.au/AUSSTATS/abs@.nsf/Lookup/4655.0Main+Features12018?OpenDocument.

Adams, M., Burrows, V. & Richardson, S. (2019). *Bringing embodied carbon upfront*. London: World Green Building Council.

Agez, M., Wood, R., Margni, M., Strømman, A.H., Samson, R. & Majeau-Bettez, G. (2020). Hybridization of complete PLCA and MRIO databases for a comprehensive product system coverage. *Journal of Industrial Ecology, 24*(4), 774-790. 10.1111/jiec.12979

ALCAS. (2019). *The Australian National Life Cycle Inventory Database (AusLCI)*. Australia: Australian Life Cycle Assessment Society. www.auslci.com.au.

Alcorn, A. (2003). *Embodied energy and $CO_2$ coefficients for New Zealand building materials*. Wellington: Centre for Building Performance Research Victoria University of Wellington.

Allacker, K. (2010). *Sustainable building. The development of an evaluation method.* (PhD thesis), Katholieke Universiteit Leuven, Leuven.

Anderson, J. (2021). *ConstructionLCA's 2021 Guide to Environmental Product Declarations (EPD)*. https://infogram.com/constructionlcas-2021-guide-to-epd-1h1749vwlxy7l6z?live

Athena Sustainable Materials Institute. (2019). *User Manual and Transparency Document Impact Estimator for Buildings v.5*. Ottawa, Canada, https://calculatelca.com/wp-content/uploads/2019/05/IE4B_v5.4_User_Guide_May_2019.pdf

Azari, R. & Abbasabadi, N. (2018). Embodied energy of buildings: A review of data, methods, challenges, and research trends. *Energy and Buildings, 168*, 225-235. doi: www.doi.org/10.1016/j.enbuild.2018.03.003

Basbagill, J., Flager, F., Lepech, M. & Fischer, M. (2013). Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts. *Building and Environment, 60*, 81–92. doi: www.doi.org/10.1016/j.buildenv.2012.11.009

Blengini, G.A. & Di Carlo, T. (2010). The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings. *Energy and Buildings, 42*(6), 869-880. doi: www.doi.org/10.1016/j.enbuild.2009.12.009

Bontinck, P.A. (2018). *2014-15 Australian input-output data and associated environmental satellites (energy, water and greenhouse gas emissions)*. Melbourne: The University of Melbourne. doi: www.doi.org/10.4225/49/5b2b41da4f39d.

BRE. (2021). Building Research Establishment Environmental Assessment Method (BREEAM). United Kingdom: Building Research Establishment. https://www.breeam.com.

Britt, A., Summerfield, D., Senior, A., Roberts, D., Kay, P., Hitchman, A., Champion, D., Huston, D., Simpson, R., Smith, M., Sexton, M. & Schofield, A. (2016). Australia's identified mineral resources 2016. Canberra, Australia: Geoscience Australia. doi: www.doi.org/10.11636/1327-1466.2016.

Bullard, C.W., Penner, P.S. & Pilati, D.A. (1978). Net Energy Analysis: Handbook for Combining Process and Input-Output Analysis. *Resources and Energy, 1*, 267-313.

CEN. (2011). *EN 15978:2011: Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method* (First edition 1 July 2006). Brussels, https://www.en-standard.eu/bs-en-15978-2011-sustainability-of-construction-works-assessment-of-environmental-performance-of-buildings-calculation-method/

CEN. (2019). *EN 15804:2012+A2:2019: Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products*. Brussels, https://www.en-standard.eu/csn-en-15804-a2-sustainability-of-construction-works-environmental-product-declarations-core-rules-for-the-product-category-of-construction-products/

Chastas, P., Theodosiou, T. & Bikas, D. (2016). Embodied energy in residential buildings-towards the nearly zero energy building: A literature review. *Building and Environment, 105*, 267-282. doi: www.doi.org/10.1016/j.buildenv.2016.05.040

Crawford, R.H. (2008). Validation of a hybrid life cycle inventory analysis method. *Journal of Environmental Management, 88*(3), 496-506. doi: https://doi.org/10.1016/j.jenvman.2007.03.024

Crawford, R.H. (2011). *Life Cycle Assessment in the Built Environment*. London: Taylor and Francis.

Crawford, R.H., Bartak, E.L., Stephan, A. & Jensen, C.A. (2016). Evaluating the life cycle energy benefits of energy efficiency regulations for buildings. *Renewable and Sustainable Energy Reviews, 63*, 435-451. doi: www.doi.org/10.1016/j.rser.2016.05.061

Crawford, R.H., Bontinck, P.-A. & Stephan, A. (2018a). *Establishing a comprehensive database of construction material environmental flow coefficients for Australia*. Paper presented at the Engaging Architectural Science: Meeting the Challenges of Higher Density: 52nd International Conference of the Architectural Science Association 2018, Melbourne, Australia.

Crawford, R.H., Bontinck, P.-A., Stephan, A. & Wiedmann, T. (2017). Towards an automated approach for compiling hybrid life cycle iInventories. *Procedia Engineering, 180*, 157-166. doi: www.doi.org/10.1016/j.proeng.2017.04.175

Crawford, R.H., Bontinck, P.-A., Stephan, A., Wiedmann, T. & Yu, M. (2018b). Hybrid life cycle inventory methods – A review. *Journal of Cleaner Production, 172*, 1273-1288. doi: www.doi.org/10.1016/j.jclepro.2017.10.176

Crawford, R.H. & Stephan, A. (2020). *The effect of data age on the assessment of a building's embodied energy.* Paper presented at the Imaginable Futures: Design Thinking, and the Scientific Method: 54th International Conference of the Architectural Science Association, Auckland.

Crawford, R.H., Stephan, A. & Prideaux, F. (2019a). *A comprehensive database of environmental flow coefficients for construction materials: closing the loop in environmental design.* Paper presented at the Revisiting the Role of Architecture for 'Surviving' Development: 53rd International Conference of the Architectural Science Association, Roorkee, India.

Crawford, R.H., Stephan, A. & Prideaux, F. (2019b). *Environmental Performance in Construction (EPiC) Database*. Melbourne: The University of Melbourne. doi: www.doi.org/10.26188/5dc228ef98c5a.

Crawford, R.H. & Treloar, G.J. (2010). *Database of embodied energy and water values for materials*. Melbourne: The University of Melbourne. doi: www.doi.org/10.4225/49/588eeeeda28af.

Curran, M.A. (2014). Strengths and Limitations of Life Cycle Assessment. In W. Klöpffer (Ed.), *Background and Future Prospects in Life Cycle Assessment* (pp. 189-206). Dordrecht: Springer Netherlands.

Dahlstrøm, O., Sørnes, K., Eriksen, S.T. & Hertwich, E.G. (2012). Life cycle assessment of a single-family residence built to either conventional- or passive house standard. *Energy and Buildings, 54*(0), 470-479. doi: www.doi.org/10.1016/j.enbuild.2012.07.029

de Klijn-Chevalerias, M. & Javed, S. (2017). The Dutch approach for assessing and reducing environmental impacts of building materials. *Building and Environment, 111*(Supplement C), 147-159. doi: www.doi.org/10.1016/j.buildenv.2016.11.003

De Smet, B. & Stalmans, M. (1996). LCI data and data quality. *The International Journal of Life Cycle Assessment, 1*(2), 96-104. 10.1007/BF02978653

De Wolf, C., Pomponi, F. & Moncaster, A. (2017). Measuring embodied carbon dioxide equivalent of buildings: A review and critique of current industry practice. *Energy and Buildings, 140*, 68-80. doi: www.doi.org/10.1016/j.enbuild.2017.01.075

Defourny, J. & Thorbecke, E. (1984). Structural path analysis and multiplier decomposition within a social accounting matrix framework. *Economic Journal, 94*(373), 111-136. doi: www.doi.org/10.2307/2232220

Department of Industry, Innovation and Science. (2016). *Australian energy update 2016*. Canberra, Australia, https://www.energy.gov.au/sites/default/files/2016-australian-energy-statistics.pdf

Department of Industry, Innovation and Science. (2017). *Resources and energy quarterly: September 2017*. Canberra, Australia, https://industry.gov.au/Office-of-the-Chief-Economist/Publications/Pages/Resources-and-energy-quarterly.aspx#

Department of the Environment and Energy. (2015). *National Greenhouse Gas Inventory - Paris Agreeement Inventory*. Canberra, Australia. http://ageis.climatechange.gov.au.

Department of the Environment and Energy. (2018). *National Pollutants Inventory*. Canberra, Australia. http://www.npi.gov.au.

DGNB. (2021). DGNB System: Version 2020 International. Germany: German Sustainable Building Council. https://www.dgnb-system.de/en/system/version-2020-international.

Dixit, M.K. (2017). Life cycle embodied energy analysis of residential buildings: A review of literature to investigate embodied energy parameters. *Renewable and Sustainable Energy Reviews, 79*, 390-413. doi: www.doi.org/10.1016/j.rser.2017.05.051

Dossche, C., Boel, V. & De Corte, W. (2017). Use of life cycle assessments in the construction sector: critical review. *Procedia Engineering, 171*, 302-311. doi: www.doi.org/10.1016/j.proeng.2017.01.338

Emami, N., Heinonen, J., Marteinsson, B., Säynäjoki, A., Junnonen, J.-M., Laine, J. & Junnila, S. (2019). A life cycle assessment of two residential buildings using two different LCA database-software combinations: recognizing uniformities and inconsistencies. *Buildings, 9*(1). doi: www.doi.org/10.3390/buildings9010020

European Commission. (2010). Directive 2010/31/EU of the European Parliament and the Council of the European Union of the 19 May 2010 on the Energy Performance of Buildings. *Official Journal of the European Communities* (pp. 23). Brussels: European Parliament and the Council of the European Union. https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:153:0013:0035:en:PDF.

Federal Ministry of the Interior Building and Community (BMI). (2021). *ÖKOBAUDAT Sustainable Construction Information Portal: Database*. Germany. http://www.oekobaudat.de/datenbank/aufnahme-von-daten.html.

Foran, B., Lenzen, M. & Dey, C. (2005). *Balancing Act - A Triple Bottom Line Account of the Australian Economy*. Canberra, ACT, GBCA. (2021). What is Green Star? Australia: Green Building Council of Australia. https://new.gbca.org.au/rate/green-star/.

Gelowitz, M.D.C. & McArthur, J.J. (2016). Investigating the Effect of Environmental Product Declaration Adoption in LEED® on the Construction Industry: A Case Study. *Procedia Engineering, 145*, 58-65. doi: www.doi.org/10.1016/j.proeng.2016.04.014

Grant, T. (2016). *AusLCI Database Manual v1.26*. Australia, http://auslci.com.au/Documents/AUSLCI_Manual%20V1.26.pdf

Habert, G., Röck, M., Steininger, K., Lupísek, A., Birgisdottir, H., Desing, H., Chandrakumar, C., Pittau, F., Passer, A., Rovers, R., Slavkovic, K., Hollberg, A., Hoxha, E., Jusselme, T., Nault, E., Allacker, K. & Lützkendorf, T. (2020). Carbon budgets for buildings: harmonising temporal, spatial and sectoral dimensions. *Buildings and Cities, 1*(1), 429-452. doi: www.doi.org/10.5334/bc.47

Häfliger, I.-F., John, V., Passer, A., Lasvaux, S., Hoxha, E., Saade, M.R.M. & Habert, G. (2017). Buildings environmental impacts' sensitivity related to LCA modelling choices of construction materials. *Journal of Cleaner Production, 156*, 805-816. doi: www.doi.org/10.1016/j.jclepro.2017.04.052

Heijungs, R. & Suh, S. (2002). *The computational structure of life cycle assessment* (Vol. 11): Springer Science & Business Media.

IEA. (2018). The Future of Cooling. Paris: International Energy Agency. https://www.iea.org/reports/the-future-of-cooling.

IEA. (2019). Global Status Report for Building and Construction 2019. Paris: International Energy Agency. https://www.iea.org/reports/global-status-report-for-buildings-and-construction-2019.

IPCC. (2014). *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]*. Cambridge, United Kingdom and New York, NY, USA, https://www.ipcc.ch/report/ar5/wg3/

IPCC. (2018). Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Geneva, Switzerland: World Meteorological Organization. https://www.ipcc.ch/sr15.

Islam, S., Ponnambalam, S.G. & Lam, H.L. (2016). Review on life cycle inventory: methods, examples and applications. *Journal of Cleaner Production, 136*(Part B), 266-278. doi: www.doi.org/10.1016/j.jclepro.2016.05.144

ISO. (2006a). *ISO 14025: Environmental labels and declarations - Type III environmental declarations - principles and procedures*. Switzerland: International Organization for Standardization, https://www.iso.org/standard/38131.html

ISO. (2006b). *ISO 14040: Environmenta management - life cycle assessment - principles and framework*. Geneva: International Organization for Standardization, https://www.iso.org/standard/37456.html

Jakobs, A., Schulte, S. & Pauliuk, S. (2021). Price variance in hybrid-LCA leads to significant uncertainty in carbon footprints. *Frontiers in Sustainability, 2*. doi: www.doi.org/10.3389/frsus.2021.666209

Jones, C. & Hammond, G. (2019). *Inventory of carbon and energy (ICE) database V3.0*. United Kingdom, https://circularecology.com/embodied-carbon-footprint-database.html

Karimpour, M., Belusko, M., Xing, K. & Bruno, F. (2014). Minimising the life cycle energy of buildings: Review and analysis. *Building and Environment, 73*, 106-114. doi: www.doi.org/10.1016/j.buildenv.2013.11.019

Kitzes, J. (2013). An Introduction to Environmentally-Extended Input-Output Analysis. *Resources, 2*(4). doi: www.doi.org/10.3390/resources2040489

Krausmann, F., Wiedenhofer, D., Lauk, C., Haas, W., Tanikawa, H., Fishman, T., Miatto, A., Schandl, H. & Haberl, H. (2017). Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use. *Proceedings of the National Academy of Sciences, 114*(8), 1880-1885. doi: www.doi.org/10.1073/pnas.1613773114

Lasvaux, S., Habert, G., Peuportier, B. & Chevalier, J. (2015). Comparison of generic and product-specific Life Cycle Assessment databases: application to construction materials used in building LCA studies. *The International Journal of Life Cycle Assessment, 20*(11), 1473-1490. 10.1007/s11367-015-0938-z

Lausselet, C., Ellingsen, L.A.W., Strømman, A.H. & Brattebø, H. (2019). A life-cycle assessment model for zero emission neighborhoods. *Journal of Industrial Ecology, 24*(3), 500-516. doi: www.doi.org/10.1111/jiec.12960

Lawson, W.R. (1996). *Building Materials, Energy and the Environment: Towards Ecologically Sustainable Development*. Red Hill: The Royal Australian Institute of Architects.

Lenzen, M. (2000). Errors in conventional and input-output-based life cycle inventories. *Journal of Industrial Ecology, 4*(4), 127-148. doi: www.doi.org/10.1162/10881980052541981

Lenzen, M. & Crawford, R.H. (2009). The path exchange method for hybrid LCA. *Environmental Science & Technology, 43*(21), 8251-8256. doi: www.doi.org/10.1021/es902090z

Lenzen, M. & Dey, C.J. (2000). Truncation error in embodied energy analyses of basic iron and steel products. *Energy, 25*(6), 577-585.

Lenzen, M. & Treloar, G.J. (2004). Endogenising capital: a comparison of two methods. *Journal of Applied Input-Output Analysis, 10*, 10.

Majeau-Bettez, G., Strømman, A.H. & Hertwich, E.G. (2011). Evaluation of process- and input-output-based life cycle inventory data with regard to truncation and aggregation issues. *Environmental Science & Technology, 45*(23), 10170-10177. doi: www.doi.org/10.1021/es201308x

Martínez-Rocamora, A., Solís-Guzmán, J. & Marrero, M. (2016). LCA databases focused on construction materials: A review. *Renewable and Sustainable Energy Reviews, 58*, 565-573. doi: www.doi.org/10.1016/j.rser.2015.12.243

Meex, E., Hollberg, A., Knapen, E., Hildebrand, L. & Verbeeck, G. (2018). Requirements for applying LCA-based environmental impact assessment tools in the early stages of building design. *Building and Environment, 133*, 228-236. doi: www.doi.org/10.1016/j.buildenv.2018.02.016

Modahl, I.S., Askham, C., Lyng, K.-A., Skjerve-Nielssen, C. & Nereng, G. (2013). Comparison of two versions of an EPD, using generic and specific data for the foreground system, and some methodological implications. *The International Journal of Life Cycle Assessment, 18*(1), 241-251. 10.1007/s11367-012-0449-0

Moncaster, A.M. & Song, J.Y. (2012). A comparative review of existing data and methodologies for calculating embodied energy and carbon of buildings. *International Journal of Sustainable Building Technology and Urban Development, 3*(1), 26-36. doi: www.doi.org/10.1080/2093761x.2012.673915

Moore, R.E., Kearfott, R.B. & Cloud, M.J. (2009). *Introduction to interval analysis*. Philadelphia, PA: Society for Industrial and Applied Mathematics.

NIST. (2018). *Building for environmental and economic sustainability (BEES Online 2.1)*. Washington: United States National Institute of Standards and Technology, https://ws680.nist.gov/BEES2/

Pomponi, F. & Lenzen, M. (2018). Hybrid life cycle assessment (LCA) will likely yield more accurate results than process-based LCA. *Journal of Cleaner Production, 176*, 210-215. doi: www.doi.org/10.1016/j.jclepro.2017.12.119

PRé Sustainability. (2021). *SimaPro 9*. https://simapro.com/.

Reap, J., Roman, F., Duncan, S. & Bras, B. (2008). A survey of unresolved problems in life cycle assessment. *The International Journal of Life Cycle Assessment, 13*(5), 374. doi: www.doi.org/10.1007/s11367-008-0009-9

Resalati, S., Kendrick, C.C. & Hill, C. (2019). Embodied energy data implications for optimal specification of building envelopes. *Building Research & Information, 48*(4), 429-445. doi: www.doi.org/10.1080/09613218.2019.1665980

RICS. (2017). Whole life carbon assessment for the built environment. London: Royal Institution of Chartered Surveyors. https://www.rics.org/globalassets/rics-website/media/news/whole-life-carbon-assessment-for-the--built-environment-november-2017.pdf.

Saunders, C.L., Landis, A.E., Mecca, L.P., Jones, A.K., Schaefer, L.A. & Bilec, M.M. (2013). Analyzing the Practice of Life Cycle Assessment. *Journal of Industrial Ecology, 17*(5), 777-788. doi: www.doi.org/10.1111/jiec.12028

Stadler, K., Wood, R., Bulavskaya, T., Södersten, C.-J., Simas, M., Schmidt, S., Usubiaga, A., Acosta-Fernández, J., Kuenen, J., Bruckner, M., Giljum, S., Lutter, S., Merciai, S., Schmidt, J.H., Theurl, M.C., Plutzar, C., Kastner, T., Eisenmenger, N., Erb, K.-H., de Koning, A. & Tukker, A. (2018). EXIOBASE 3: Developing a time series of detailed environmentally extended multi-regional input-output tables. *Journal of Industrial Ecology, 22*(3), 502-515. doi: www.doi.org/10.1111/jiec.12715

Stephan, A. & Bontinck, P.-A. (2019). pyspa - An object-oriented python package for structural path analysis (Version 1.4). Github.

Stephan, A., Crawford, R.H. & Bontinck, P.-A. (2019). A model for streamlining and automating path exchange hybrid life cycle assessment. *The International Journal of Life Cycle Assessment, 24*(2), 237-252. doi: www.doi.org/10.1007/s11367-018-1521-1

Stephan, A., Crawford, R.H. & de Myttenaere, K. (2012). Towards a comprehensive life cycle energy analysis framework for residential buildings. *Energy and Buildings, 55*, 592-600. doi: www.doi.org/10.1016/j.enbuild.2012.09.008

Stephan, A., Crawford, R.H. & de Myttenaere, K. (2013). A comprehensive assessment of the life cycle energy demand of passive houses. *Applied Energy, 112*, 23-34. doi: www.doi.org/10.1016/j.apenergy.2013.05.076

Stephan, A. & Stephan, L. (2020). Achieving net zero life cycle primary energy and greenhouse gas emissions apartment buildings in a Mediterranean climate. *Applied Energy, 280*, 115932. doi: www.doi.org/10.1016/j.apenergy.2020.115932

Suh, S., Lenzen, M., Treloar, G.J., Hondo, H., Horvath, A., Huppes, G., Jolliet, O., Klann, U., Krewitt, W., Moriguchi, Y., Munksgaard, J. & Norris, G. (2004). System boundary selection in life cycle inventories. *Environmental Science and Technology, 38*(3), 657-664. doi: www.doi.org/10.1021/es0263745

TOTEM. (2021). Tool to Optimise the Total Environmental impact of Materials. https://www.totem-building.be

Treloar, G.J. (1998). *A comprehensive embodied energy analysis framework.* (Ph.D. Thesis), Deakin University, Geelong.

UN-Habitat. (2017). Building sustainability assessment and benchmarking - an introduction. United Nations Settlements Programme. https://unhabitat.org/books/building-sustainability-assessment-and-benchmarking/?utm_content=buffer251ca&utm_medium=social&utm_source=linkedin.com&utm_campaign=buffer.

UNFCCC. (2015). *Paris Agreement*. Paris: United Nations Framework Convention on Climate Change.

USGBC. (2021). LEED rating system. U.S. Green Building Council. https://www.usgbc.org/leed.

Venkatraj, V. & Dixit, M.K. (2021). Life cycle embodied energy analysis of higher education buildings: A comparison between different LCI methodologies. *Renewable and Sustainable Energy Reviews, 144*. doi: www.doi.org/10.1016/j.rser.2021.110957

Weidema, B.P. & Wesnæs, M.S. (1996). Data quality management for life cycle inventories - an example of using data quality indicators. *Journal of Cleaner Production, 4*(3), 167-174. doi: www.doi.org/10.1016/S0959-6526(96)00043-1

Wuppertal Institute. (2014). Material Intensity Factors. https://wupperinst.org/en/a/wi/a/s/ad/365

Zabalza Bribián, I., Aranda Usón, A. & Scarpellini, S. (2009). Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification. *Building and Environment, 44*(12), 2510-2520. doi: www.doi.org/10.1016/j.buildenv.2009.05.001