

# A comprehensive database of environmental flow coefficients for construction materials: closing the loop in environmental design

Robert H. Crawford<sup>1</sup>, André Stephan<sup>1,2</sup> and Fabian Prideaux<sup>1</sup>

<sup>1</sup> *The University of Melbourne, Melbourne, Australia*

*rhcr@unimelb.edu.au, andre.stephan@unimelb.edu.au, fprideaux@unimelb.edu.au*

<sup>2</sup> *Université Catholique de Louvain, Louvain-La-Neuve, Belgium*

*andre.stephan@uclouvain.be*

**Abstract:** Life cycle assessment is increasingly used to quantify and reduce the environmental effects of buildings. Embodied environmental effects, resulting from material production and replacement as well as construction, are typically quantified using coefficients from readily available databases. However, most existing databases of embodied environmental coefficients for construction materials suffer from limitations, such as inconsistency in the life cycle inventory method used or system boundary incompleteness. This paper introduces a new database of hybrid environmental flow coefficients for construction materials, covering flows of energy, water and greenhouse gas emissions for over 100 common construction materials. The hybrid approach used combines bottom-up industrial process data and top-down macroeconomic input-output data, making it more comprehensive than process analysis and more accurate and specific than input-output analysis alone. A case study building is used to demonstrate the importance of using hybrid coefficients for improving environmental performance. This study shows that the use of process coefficients can lead to a significant underestimation of the total environmental effects associated with the construction of a building, by up to 64%. This has considerable implications for decision-making relating to building design, including the focus of improvement efforts. This database of coefficients will enable building professionals to more effectively analyse and improve the environmental performance of buildings. This will also help inform the focus of environmental policy and improve the implementation of life cycle thinking in environmental design.

**Keywords:** Life cycle assessment; construction; embodied environmental flows, environmental design.

## 1. Introduction

Buildings account for a significant proportion of global energy demand, greenhouse gas emissions, waste generation and resource demands. This is likely to increase in future years due to a growing global population as well as rising living standards and expectations in many developing countries. Hence, buildings, and the construction industry more broadly, offer a considerable opportunity to reduce global environmental effects resulting from human activities. Much effort has already gone into addressing these issues, but more is needed as recent achievements have mostly been offset by rising resource demands and greenhouse gas emissions brought about by increasing consumption and construction activity.

Strategies such as ‘Design for Environment’ (DfE) target improvements to the environmental performance of man-made products, such as buildings. This approach often uses tools such as life cycle assessment (LCA) to inform holistic environmental design decision-making. While the LCA approach has been used in the construction sector for several decades, its use is not widespread, mainly because it can be a time consuming and complex process, requiring project-specific analysis of materials and processes. Attempts have been made to streamline LCA using material-based environmental flow coefficients. These provide pre-calculated values based on detailed analysis of manufacturing processes or economic data. Coefficients represent the environmental flows of resources, waste or emissions associated with the extraction, processing and manufacture of specific construction materials. When multiplied by the quantity of specific materials within a building, they provide an estimation of the total environmental flows associated with the building. Although environmental flow coefficients for construction materials exist, these typically suffer from a variety of limitations.

There are three approaches commonly used to compile data on environmental flows for construction materials, known as life cycle inventories: process analysis, input-output analysis and hybrid analysis. Process analysis estimates environmental flows based on an examination of manufacturing supply chain processes. It uses data collected from industry and provides a detailed representation of environmental flows associated with specific processes. While providing the most reliable data, it excludes many smaller goods and services-based processes due to the complexity of the supply chain. This can significantly affect the comprehensiveness and usefulness of the results. Input-output analysis uses macro-economic data to estimate environmental flows, covering the entire supply chain. Sector wide data is extrapolated to determine product specific environmental flows based on their cost. Due to this extrapolation, it can be difficult to reliably disaggregate the data and use it to inform project-level decision-making. Hybrid analysis uses the more reliable process data where it is available, and supplements it with environmentally-extended economic data to fill remaining gaps. This paper introduces a newly created database of hybrid environmental flow coefficients for construction materials, compiled using a combination of international process data and Australian national economic data. It covers flows of energy, water and greenhouse gas emissions for over 100 common construction materials.

### **1.1 Existing databases of environmental flow coefficients**

Numerous databases of environmental flow coefficients exist around the world. They tend to be limited to embodied energy or embodied greenhouse gas emissions coefficients and can cover construction materials as well as other processes, such as transport and electricity production. The main differences between the coefficients provided by existing databases are the range of materials covered, geographical relevance, and the life cycle inventory technique used in their compilation. This last difference is one of the most critical factors affecting the reliability and completeness of any coefficient. The process analysis approach generally leads to the greatest truncation of the system boundary for a material due to the time involved and difficulty in collecting data in this manner (Crawford, 2011, p. 48). Input-output analysis solves the truncation issue by using top-down economic data to model environmental flows across economic sectors. However, input-output analysis can produce highly unreliable coefficients, despite its comprehensive coverage of the system boundary. This is due to products being allocated to generic sectors for which environmental flows are derived. The average environmental intensity of a sector can be very different from that of a particular product. A combination of process analysis and input-output analysis in the form of a hybrid analysis can help resolve the limitations of each of these individual approaches. The very few publicly available databases of hybrid environmental flow coefficients are now

considerably out of date. Coefficients contained within all other available databases suffer from varying levels of inconsistency and/or incompleteness. Table 1 provides a summary of some of the most commonly used databases.

Table 1: Summary of key environmental flow coefficient databases.

Database	Flows	No. of products covered	Country of relevance	LCI approach	Latest version
Athena Sustainable Materials Institute <sup>1</sup>	GHG emissions, acidification (Air) Potential, Human Health Particulate, Eutrophication (air & water) Potential, Smog (air) Potential, Ozone Depletion (air) Potential, Total Primary Energy Consumption, Non-Renewable Energy Consumption, Fossil Fuel Consumption	200+	Canada & United States	Process analysis	2019
Inventory of Carbon and Energy (ICE) <sup>2</sup>	Energy, GHG emissions	300+	United Kingdom*	Varies*	2019
Tool to Optimise the Total Environmental impact of Materials (TOTEM) <sup>3</sup>	Global warming, ozone depletion, acidification, eutrophication, photochemical ozone creation, depletion of abiotic resources, human toxicity, particulate matter, ionising radiation, ecotoxicity, land use	801	Belgium	Process analysis	2018
Wuppertal Institute material intensity database <sup>4</sup>	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
BEES <sup>5</sup>	Energy, GHG emissions	230	United States	Process analysis	2010
Balancing Act <sup>6</sup>	Energy, GHG emissions, water, land	135	Australia	Input-output analysis	2005
Embodied Energy and CO <sub>2</sub> Coefficients for NZ Building Materials <sup>7</sup>	Energy, GHG emissions	61	New Zealand	Hybrid analysis	2003
Lawson (1996)	Energy	32	Australia	Process analysis	1996

\*Data sourced from various geographic regions, using different life cycle inventory approaches. <sup>1</sup>Athena Sustainable Materials Institute (2019), <sup>2</sup>University of Bath (2011), <sup>3</sup>TOTEM (2018), <sup>4</sup>Wuppertal Institute (2014), <sup>5</sup>NIST (2007), <sup>6</sup>Foran *et al.* (2005), <sup>7</sup>Alcorn (2003).

This paper presents a new database of environmental flow coefficients for construction materials. The following sections describe how these coefficients were compiled, how they would be applied in practice and demonstrate the importance of the use of more comprehensive hybrid coefficients over the process-based coefficients contained in other similar databases.

## 2. Compiling environmental flow coefficients for construction materials

Several methods can be used to produce hybrid life cycle inventories, as reviewed by Crawford *et al.* (2018b). The coefficients presented here rely on the Path Exchange method for hybridisation, as it does not require a full integration of process and input-output data (only selected processes are replaced). This technique was first developed by Treloar (1998) and formalised by Lenzen and Crawford (2009). Stephan *et al.* (2018) developed a semi-automated model for compiling hybrid coefficients using this approach.

### 2.1 Data sources and data processing

The input-output and related environmental data used to develop the coefficients are sourced from official Australian government reports, for the 2014-2015 financial year. A detailed description of the input-output data sources is available in Crawford *et al.* (2018a) and the data are available freely for download from Bontinck (2018). The Australian Life Cycle Inventory Database Initiative (AusLCI) process database is used as a technological matrix to compile coefficients. It consists of locally collected Australian data, complemented with European ecoinvent data where no Australian data is available. New processes were created for materials for which no data existed in the database.

The input-output and process data are processed using automated routines as described in Crawford *et al.* (2018a) and Stephan *et al.* (2018). The final input-output and process data are presented as square technological matrices. Environmental satellites and metadata are formatted as a list, giving each process/sector a direct and total environmental intensity, for each flow. Using this approach provides a standardised data format which enables a transparent compilation of coefficients.

### 2.2 Compiling coefficients

Details pertaining to the compilation of coefficients using the automated model developed by the authors are provided in Stephan *et al.* (2018). In summary, coefficients are produced in three steps:

- Step 1: Conduct two structural path analyses (SPA), one on the process and the other on the input-output sector representing the construction material. The outcome of this analysis is a list of mutually exclusive nodes, each representing a good or service provided from one tier to another (and the associated environmental flow) within the supply chain analysed. This enables the assessor to quickly identify flow hotspots at different stages of the supply chain.
- Step 2: Data hybridisation by replacing input-output nodes with process nodes. This manual step consists of exchanging input-output nodes representing averages at the economy level with product-specific process data for the equivalent process in the supply chain.
- Step 3: Calculation of a hybrid coefficient. This step uses the process and input-output nodes deemed to represent the supply chain of the material to quantify the total hybrid environmental flows. During this step, input-output data is combined with process data using the price of the construction material.

The benefits of using an automated model for the three steps above is that all the information is kept at every step, making the process completely transparent and reproducible. For example, a summary report, containing all the information for a simple construction material, contains more than 200,000 data points. In addition, the use of an automated model provides the user with an opportunity to analyse process, input-output and hybrid data in more detail than was previously possible. For instance, it is possible to analyse the input-output component of the hybrid coefficient in detail or to easily compare pure process, input-output and hybrid values.

While the database is too large to present in full within this paper, it can be accessed at <https://doi.org/10.26188/5d89599871990>. A summary of its key attributes is given in Table 2.

Table 2: Key attributes of the new hybrid environmental flow coefficient database.

No. of materials	Data source	Flows covered	Broad categories of materials covered	Functional units
100*	Process data - AusLCI and ecoinvent 2.2 shadow database (4,531 processes) Input-output data - 2014/15, 114 sectors + fixed capital)	Energy, water, greenhouse gas emissions <sup>^</sup>	Ferrous and non-ferrous metals, concrete, timber, plastics, insulation, glass, ceramics	Energy - GJ per kg/m <sup>2</sup> /m <sup>3</sup> Water - L per kg/m <sup>2</sup> /m <sup>3</sup> Greenhouse gas emissions - kgCO <sub>2</sub> -e per kg/m <sup>2</sup> /m <sup>3</sup>

\*current estimate, however materials continue to be added. <sup>^</sup>waste, land, resource depletion flows are also available for some materials.

### 3. Using environmental flow coefficients to inform environmental design

Environmental design is rarely considered from a life cycle perspective, focusing predominately on improving building operational performance. This section describes how to use the hybrid environmental flow coefficients to inform more holistic environmental design. There are a number of ways in which these coefficients may be used:

- As part of a life cycle assessment to understand the life cycle environmental performance of a construction project (to identify areas or life cycle stages, for greatest potential improvement);
- To quantify the embodied environmental flows associated with a construction project (to identify areas of greatest potential improvement);
- To select materials with lowest environmental effects within one or across a range of environmental flows, informing design aimed at maximising project environmental performance;
- To demonstrate compliance with particular performance benchmarks.

Each of these goals requires an understanding of the project being analysed, including the type and quantity of materials. This information can usually be extracted from construction documentation, including drawings, specifications and schedules. If a bill of quantities (BoQ) is available, this can significantly streamline the assessment process. In its basic form, this information is best presented as a spreadsheet listing all of the different materials contained within the project and their respective quantities. If the quantities are not in the same unit as the respective material coefficient (e.g. kg vs tonnes), they will need to be adjusted to avoid unit-related calculation errors.

Once all material quantities have been confirmed, each material quantity ( $Q_m$ ) is then multiplied by its respective environmental flow coefficient ( $EFC_m$ ). In order to account for on-site construction wastage

and thus the need to order more materials than will end up in the project, a wastage factor ( $W_m$ ) may then be applied (see Wainwright and Wood (1981); CSIRO (1994) for a list of common wastage factors). The resultant values provide the embodied environmental flows for each material within the project, which when summed provide the material-based total embodied environmental flows ( $EEF_p$ ) for the project (replace EF with E, for energy flows (i.e.  $EE_p$ ), or W, for water flows (i.e.  $EW_p$ ), for example).

In a hybrid analysis, any minor material or non-material-related environmental flows (e.g. materials not accounted for in a process analysis, direct flows associated with on-site activities or site-support activities such as financing, machinery and equipment) can be accounted for using pure input-output data. This is a unique characteristic of the Path Exchange hybrid approach and accounts for processes and related environmental flows not typically included in a process analysis. These flows, referred to as the 'remainder' (or 'other items' as in Figure 2) are determined by subtracting the total input-output-based flows associated with the material production processes for which process data is available ( $TEFR_m$ ) (this data is extracted from a pure input-output model) from the total input-output-based environmental flow requirement of the relevant economic sector,  $n$  ( $TEFR_n$ ). This input-output remainder needs to be scaled to the level of the project by multiplying it by the cost of the project ( $C_p$ ).

$$EEF_p = \sum_{m=1}^M (Q_m \times EFC_m \times W_m) + \left( TEFR_n - \sum_{m=1}^M TEFR_m \right) \times C_p \quad (1)$$

## 4. Demonstrating the importance of using hybrid coefficients

This section demonstrates the importance of using the more comprehensive hybrid coefficients compared to traditional process-based coefficients and analysis. This is achieved by comparing hybrid and process values at the material and whole building level to show how the use of a specific type of coefficient may influence the choices being made during design of construction projects and the emphasis or importance that may be placed on indirect, or embodied environmental flows.

### 4.1 The effect of coefficient type on material selection

While hybrid coefficients generally provide a much more comprehensive coverage of the system boundary for a particular material, it may be possible for a process-based coefficient to be higher for the same material. This can occur when the input-output component of the hybrid coefficient is lower than the value of process data excluded from the hybrid coefficient (for processes outside of the SPA threshold). An example of where this occurs is for '50MPa concrete', with a hybrid coefficient of 4 GJ/m<sup>3</sup> and a process coefficient, based on the same process data, of 4.3 GJ/m<sup>3</sup>.

Another situation in which system boundary completeness 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<sup>3</sup>) than 'KD Softwood' (12.2 GJ/m<sup>3</sup>), but a higher process coefficient (4.6 v 2.5 GJ/m<sup>3</sup>). One of the main reasons why the ranking of process and hybrid coefficients varies is due to the inconsistent system boundary used for process coefficients. This is due to varying levels of detail in available process data across materials/processes. 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 'KD softwood' would be preferred if using process coefficients. Mixing coefficient types can create a similar issue, potentially exacerbated by the even greater difference between values due to variation in system boundary coverage. Several databases, such as the Inventory of Carbon and Energy (University of Bath, 2011), suffer from this significant issue.

Differences between process and hybrid coefficients may not matter much when comparing individual materials, assuming the same coefficient type is used consistently. However, in instances where an absolute value for the environmental performance of a material or project is required, the use of process-based coefficients will most often result in an underestimation of the total environmental flows.

#### 4.2 The effect of coefficient type on the significance of embodied environmental flows

This section uses a case study house to demonstrate the variation in the proportion of embodied energy in the life cycle energy of the house that may occur depending on which type of coefficient is used. A life cycle energy analysis was conducted for a three-bedroom, brick veneer house located in Melbourne, Australia. Details of the house can be found in Crawford *et al.* (2016). The scope of the analysis can be found in Figure 1 and is based on European Standard 15978 (2011).

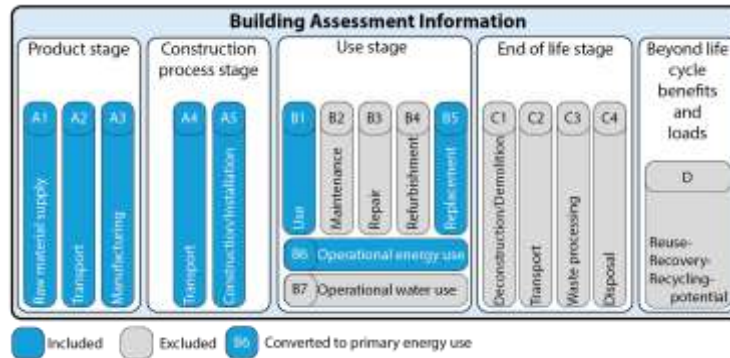


Figure 1: System boundary for the life cycle energy analysis of the case study house (based on EN15978).

The initial embodied energy of the house was calculated using the approach outlined in Section 3 and Equation 1, based on a detailed bill of quantities and the new hybrid coefficients. Recurrent embodied energy associated with replacement of materials and maintenance of the house throughout its assumed life of 50 years was calculated using Equation 2, as outlined in Crawford *et al.* (2016).

$$REE_h = \sum_{m=1}^M \left[ \left[ \frac{POA}{SL_m} - 1 \right] \times \left[ (Q_{m,h} \times EC_m \times W_m) + (TER_n - TER_m - NATER_m) \times C_{m,h} \right] \right] \quad (2)$$

Where  $REE_h$  is the recurrent embodied energy of the house  $h$  in GJ;  $POA$  is the period of analysis, in years;  $SL_m$  is the service life of the material  $m$ , in years;  $NATER_m$  is the total energy requirement of all input-output pathways not associated with the installation or production process of material  $m$  being replaced, in GJ/AUD, e.g. pathways representing concrete production when replacing aluminium; and  $C_{m,h}$  is the cost of the material  $m$  in AUD in the house  $h$ . Other variables are the same as in Equation 1, with EF replaced with the specific flow, E, for energy.

The heating and cooling related energy demand of the house was calculated using FirstRate5 (FR5) software. The values from the previous study of the same house by Crawford *et al.* (2016) were used in this study. Final heating and cooling energy demands from the software were converted to primary energy terms using primary energy factors, constraint factors and system efficiencies as per Equation 3.

$$LCTOPE_h = POA \times \left( PEF^H \times \frac{FE_h^H \times CF^H}{\eta_h^H} + PEF^C \times \frac{FE_h^C \times CF^C}{\eta_h^C} \right) \quad (3)$$

Where  $LCTOPE_h$  is the life cycle primary thermal operational energy of the house  $h$  in GJ;  $PEF^H$  and  $PEF^C$  are the primary energy conversion factors for the heating and cooling energy sources, respectively, in GJ/GJ;  $FE_h^H$  and  $FE_h^C$  are the final annual heating and cooling energy demands of house  $h$  (as calculated by FirstRate5), respectively, in GJ;  $CF^H$  and  $CF^C$  are the heating and cooling constraint factors; and  $\eta_h^H$  and  $\eta_h^C$  are the heating and cooling systems efficiency in house  $h$ , respectively.

Non-thermal operational energy demand (e.g. for cooking, hot water, appliances) was calculated based on data from DEWhA (2008). While operational energy demands are highly household specific, the intention here was not to provide a precise estimate of energy demands but rather a value for a typical household in the Melbourne climate. Data on total energy demand in Victoria for each end use was divided by the total number of Victorian households to determine the average energy demand per household per end use. Each value was converted to primary energy terms based on an assumed fuel type (hot water – natural gas, appliances – electricity, cooking – mixed fuels) and extrapolated out to 50 years assuming consistent demand.

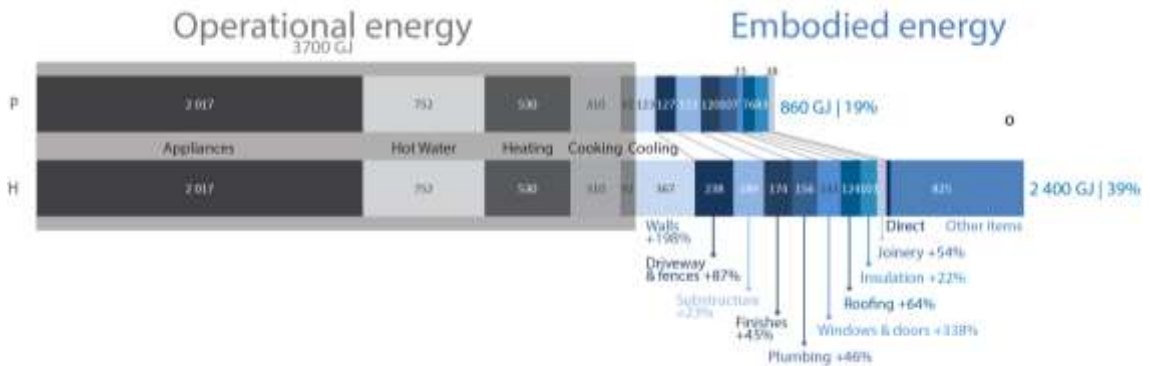


Figure 2: Life cycle energy of case study house based on process (P) and hybrid (H) analysis, by use.

These findings are specific to the case analysed as variations in climate, materials, occupancy and usage patterns and fuel types will vary the results. Yet, they reveal that the use of hybrid coefficients can significantly increase the value of embodied energy needed over the life of the house (from 860 GJ for process data to 2,400 GJ for hybrid data (See Figure 2)) and increase the perceived significance of the embodied energy component of the life cycle energy demand (from 19% to 39%). The widespread use of process analysis and process-based material coefficients for analysing the embodied environmental performance of construction projects has usually led to the underestimation of embodied environmental flows, such as energy. This has contributed to their limited consideration in environmental design, policy and regulations, compared to operational flows.

## 5. Discussion and Conclusions

This paper presents a new database of environmental flow coefficients for construction materials, developed using a hybrid life cycle inventory approach. The level of transparency offered by this database is unprecedented, with hundreds of thousands of data points available for each coefficient. The

importance of this hybrid approach has been highlighted, compared to the use of process-based coefficients at a material and whole building scale. This shows that material selection and design decisions based on process-based coefficients and life cycle inventory data are highly likely to be compromised by inconsistent and incomplete system boundaries. This issue is made even more prominent by the fact that embodied environmental flows have been shown to account for a large proportion of the total life cycle environmental flows of a building. For example, the findings from this study show that life cycle embodied energy demand may account for up to 39% of the life cycle energy associated with a house. This aligns closely with similar studies that have used a hybrid approach for assessing embodied flows (*inter alia*, Fay *et al.* (2000); Crawford and Pullen (2011); Stephan *et al.* (2013)). Some of these studies, such as that by Stephan *et al.* (2013), have even shown that embodied energy may account for up to 77% of the life cycle energy demand of a house. This is mostly due to a lower operational energy demand rather than an increase in embodied energy, due to a more thermally efficient building envelope. This trend is likely to continue as the operational performance of buildings continues to improve. Embodied environmental flows will thus only become more significant and important to address into the future. For flows like energy, those embodied in present day construction are particularly important to address as they occur within a much more emissions intensive energy system than the one in which future energy demands are likely to occur.

While the database presented here is specific to the Australian context, it can be used in other regions that have a similar economic structure, manufacturing approaches and fuel mix. This would have to be judged at the material level, whether material characteristics (e.g. concrete) are equivalent across regions. The database is however perfectly suited to Australian construction materials being used in other countries. The approach used to compile the database can also be used to produce similar coefficients for other regions, as long as the appropriate input data are available.

Despite the benefits that they provide, it is acknowledged that hybrid coefficients suffer from their own unique limitations and deficiencies, such as homogeneity and proportionality assumptions and aggregation errors inherent to input-output data (Crawford, 2011, p. 69). However, Crawford (2008) and Lenzen (2000) have demonstrated that the inclusion of input-output data, despite its inherent limitations, is preferred given the considerable system boundary completeness issues that pervade process analysis, data and coefficients. Others, such as Dixit (2017) and Majeau-Bettez *et al.* (2011) have also shown that hybrid approach is preferred over process analysis.

While process data is often regarded as more reliable, variations in temporal and geographical relevance to the material being analysed can reduce the representativeness of the process data. This can be particularly evident with the use of pre-compiled process coefficients, often with little transparency in their original source. In addition to this, the continued use of process-based coefficients may only continue to limit the awareness of the significance of embodied environmental flows and the speed and degree to which efforts are targeted at reducing these flows in relation to building design and construction.

This study shows that the use of hybrid coefficients can lead to a significant increase in the total quantity of environmental flows associated with the manufacture of specific construction materials and the construction of a building. This has considerable implications for decision-making relating to building design, including material selection, and in the worst case can shift the focus of environmental design from an area which might otherwise be considered important. These coefficients will enable building professionals to rapidly analyse the environmental performance of buildings, empowering them to make informed decisions that can improve the environmental performance of buildings based on consistent

and comprehensive data. This will help close the loop in environmental design, enabling a comprehensive life cycle approach that considers and optimises a building's environmental performance across its entire life. They also provide a platform to inform environmental policy improvements and assist in the mainstreaming of life cycle environmental assessment for design, construction, retrofitting, maintenance and improvements to existing buildings.

## Acknowledgements

This research was supported by the Australian Research Council's Discovery Projects funding scheme (project number DP150100962) and the Australian Research Council's Linkage Infrastructure, Equipment and Facilities funding scheme (project number LE160100066).

## References

- Athena Sustainable Materials Institute (2019) *User Manual and Transparency Document Impact Estimator for Buildings v.5*, Ottawa, Canada, 52.
- Bontinck, P.-A. (2018) *2014-15 Australian input-output data and associated environmental satellites (energy, water and greenhouse gas emissions)*, in The University of Melbourne (ed.).
- Crawford, R.H. (2008) Validation of a hybrid life cycle inventory analysis method, *Journal of Environmental Management*, 88(3), 496-506.
- Crawford, R.H. (2011) *Life Cycle Assessment in the Built Environment*, ed., Taylor and Francis, London.
- Crawford, R.H., Bartak, E.L., Stephan, A. and Jensen, C.A. (2016) Evaluating the life cycle energy benefits of energy efficiency regulations for buildings, *Renewable and Sustainable Energy Reviews*, 63, 435-451.
- Crawford, R.H., Bontinck, P.-A. and Stephan, A. (2018a) Establishing a comprehensive database of construction material environmental flow coefficients for Australia, Priya Rajagopalan, *Engaging Architectural Science: Meeting the Challenges of Higher Density: 52<sup>nd</sup> International Conference of the Architectural Science Association 2018*, pp., 28 November - 1 December, The Architectural Science Association and RMIT University, Melbourne, Australia.
- Crawford, R.H., Bontinck, P.-A., Stephan, A., Wiedmann, T. and Yu, M. (2018b) Hybrid life cycle inventory methods – a review, *Journal of Cleaner Production*, 172, 1273-1288.
- Crawford, R.H. and Pullen, S. (2011) Life cycle water analysis of a residential building and its occupants, *Building Research and Information*, 39(6), 589-602.
- Crawford, R.H. and Treloar, G.J. (2010) *Database of embodied energy and water values for materials*, The University of Melbourne, <https://dx.doi.org/10.4225/49/588eeeeda28af>, Melbourne.
- CSIRO (1994) *Quote: Cost Estimating System for House Builders*, CSIRO, Division of Building, Construction and Engineering, Australia, Highett.
- DEWHA (2008) *Energy Use in the Australian Residential Sector, 1986 to 2020*, Department of the Environment, Water, Heritage and the Arts, Canberra, 212p.
- 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.
- European Standard 15978 (2011) *Sustainability of construction works -Assessment of environmental performance of buildings - Calculation method*, European Committee for Standardization (CEN), Brussels, 66.
- Fay, R., Treloar, G. and Iyer-Raniga, U. (2000) Life cycle energy analysis of buildings: a case study, *Building Research and Information*, 28(1), 31-41.
- Lawson, W.R. (1996) *Building Materials, Energy and the Environment: Towards Ecologically Sustainable Development*, The Royal Australian Institute of Architects, Red Hill, 135p.
- Lenzen, M. (2000) Errors in conventional and input-output-based life cycle inventories, *Journal of Industrial Ecology*, 4(4), 127-148.
- Lenzen, M. and Crawford, R.H. (2009) The Path Exchange Method for Hybrid LCA, *Environmental Science & Technology*, 43(21), 8251-8256.

- Majeau-Bettez, G., Strømman, A.H. and 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.
- Stephan, A., Crawford, R.H. and Bontinck, P.-A. (2018) A model for streamlining and automating path exchange hybrid life cycle assessment, *The International Journal of Life Cycle Assessment*, 24(2), 237-252.
- Stephan, A., Crawford, R.H. and de Myttenaere, K. (2013) A comprehensive assessment of the life cycle energy demand of passive houses, *Applied Energy*, 112, 23-34.
- TOTEM (2018) *Tool to Optimise the Total Environmental impact of Materials*. Available from: <<https://www.totem-building.be/>> (accessed 28/07).
- Treloar, G.J. (1998) *A comprehensive embodied energy analysis framework*, Ph.D. Thesis, School of Architecture and Building, Deakin University, Geelong.
- University of Bath (2011) *Inventory of carbon and energy (ICE) version 2.0*, Sustainable Energy Research Team (SERT), Department of Mechanical Engineering, University of Bath, UK, Bath, United Kingdom, 8p.
- Wainwright, W.H. and Wood, A.A.B. (1981) *Practical Builders' Estimating*, ed., Hutchinson, London.
- Wuppertal Institute (2014) *Material Intensity Factors*. Available from: <<https://wupperinst.org/en/a/wi/a/s/ad/365/>> (accessed 28/07).