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Author/s:

Crawford, RH;Bontinck, PA;Stephan, A

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Improving the uptake of hybrid life cycle assessment in the construction industry

Paul-Antoine Bontinck^a, Robert H. Crawford^{a*}, André Stephan^a

^a*Faculty of Architecture, Building and Planning, The University of Melbourne, Parkville, VIC 3010, Australia*

Abstract

The built environment is responsible for a significant proportion of humanity's pressure on the natural environment. Tremendous amounts of energy, water and materials are necessary for the construction and operation of buildings. The continued growth in global population is expected to only further exacerbate existing environmental concerns. As a key industry, the construction sector needs a better understanding of the environmental implications of decisions made during the design and construction of buildings and other construction projects. Using life cycle assessment, recent research has highlighted the significance of construction-related environmental effects over the whole life cycle of a building. This reinforces the need for a life cycle approach during the design process. Three approaches are currently used to compile a life cycle inventory capturing data on the inputs and outputs associated with a particular good or service: process, input-output and hybrid analysis. While process analysis is the method conventionally used by practitioners, it suffers from a systematically truncated system boundary. Input-output analysis offers a more complete overview of the system, but presents information aggregated for entire economic sectors. Hybrid analysis aims to combine both approaches, mitigating their limitations while retaining their strengths. However, it is still a complex and time-consuming approach, and as such is seldom used outside a narrow area of research. This study explores the potential for automating the hybridisation process using on a conceptual framework developed by the research team. A case study focusing on a construction assembly is used to demonstrate the approach. It suggests that a complete automation of the hybridisation process may be difficult to achieve, but that key steps can be automated. This would accelerate the development and broader update of hybrid inventories for materials and assemblies, a critical step in the uptake of the hybrid analysis method.

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* Corresponding author. Tel.: +61 3 8344 8745.
E-mail address: rhcr@unimelb.edu.au

1. Introduction

The built environment is responsible for a large share of humanity's pressure on the environment. The Global Material Flows Database, set up by the Vienna University of Economics and Business [1], suggests that over 84 billion tonnes of raw materials were extracted from the biosphere to enter the world economy in 2013 (including minerals, metal ores, fossil fuels and biomass). Minerals used for the construction sector represented 44% of this total, making the construction sector the single most material intensive sector of the world's economy, even without accounting for metal ores, biomass and fossil fuels it uses. Building operation also has significant environmental consequences. In 2014 the Intergovernmental Panel on Climate Change estimated that the operation of buildings accounts for 32% of global final energy use and 19% of the world's emissions of greenhouse gases [2].

In parallel, the World Bank Group forecasts a 32% population growth by 2050 – taking place exclusively in urban areas [3]. Thus, the ability to make informed decisions to meet the needs of the world's growing population while reducing the sector's overall environmental effects is critical. To this end, environmental assessment approaches have been developed over the past five decades to provide robust assessments of the environmental effects of goods and services over their entire life cycle. This is currently the only scientifically robust way of measuring the overall effects of a product, providing enough information to avoid shifting impacts from one step of the life cycle to another. Life cycle assessment is recognised as an effective assessment tool for buildings, as can be seen by its introduction into certification tools such as Green Star in Australia [4].

Three approaches are currently used to compile a life cycle inventory capturing data on the inputs and outputs associated with a particular good or service: process, input-output and hybrid analysis. Process analysis requires breaking down the system analysed in a series of steps, which when added together represent the life cycle of a product. Data is collected for each step, and include the exchange between the system and nature (i.e. emissions of pollutants to nature or inputs of raw materials from nature), and the requirements from other processes. A typical model will use a mix of primary data, collected from manufacturers or publicly reported data, and background data found in process inventory databases (e.g. ecoinvent or AusLCI [5-7]). This approach allows for specific assessments but suffers from systematic truncations of the system boundaries; it will invariably underrepresent the total environmental effects of the system analysed. Input-output analysis (IO), on the other hand, is based on the use of macroeconomic data collected by national statistics agencies [8, 9]. Input-output data are used to calculate emission factors and other environmental flows per dollar spent within a particular sector. As it represents entire economies, input-output data resolve the truncation error of process analysis, but suffer from other limitations. Amongst other things, the macroeconomics approach means that emissions or requirements are calculated at the scale of entire sectors, making the assessment of specific products or a comparison between two products almost impossible.

As a response to these limitations, scientists have developed hybrid methods combining the two approaches. The aim is to conduct assessments with the complete system boundary of an input-output analysis, while retaining the specificity of a process analysis. However, the complexity and time-consuming nature of these methods means that it is seldom applied outside a dedicated group of experts with the necessary expertise. In addition, the absence of available computational tools has been identified as a likely cause for a slow uptake [10].

1.1. Aim and scope

Four hybridisation techniques can be identified in the literature: tiered [11], path exchange (PXC) [12, 13], matrix augmentation [14] and integrated [15]. An in-depth description of these methods falls outside the scope of this work; readers are referred to existing publications for a more detailed overview [inter alia 16, 17]. This work falls under a wider project aimed at facilitating the use of hybrid methods via the development of an automated approach – specifically working on the path exchange method.

The aim of this paper is to demonstrate the conceptual framework for automating the path exchange method on a case-study, assessing its potential for its more widespread application. Applying the framework to a case-study will help to refine it, highlighting issues and providing an opportunity to correct or redevelop certain aspects. The scope of this paper is limited to one case-study, which focuses on structural insulated panels (SIPs), a

composite building material consisting of an insulating layer sandwiched between two layers of structural board. Here, the analysis uses a cradle-to-gate approach and focuses on greenhouse gas emissions.

This paper is structured into 4 Sections. Section 2 focuses on describing the path exchange method, while Section 3 focuses on the application of the PXC method to the case-study, reviewing each step required in its application, before a discussion and conclusion in Section.

2. The path exchange method

The path exchange method (PXC) can be broken down into a series of steps, as outlined in Figure 1 below and briefly described in this section. Readers are referred to the existing literature for a more comprehensive overview [inter alia 12, 13, 18].

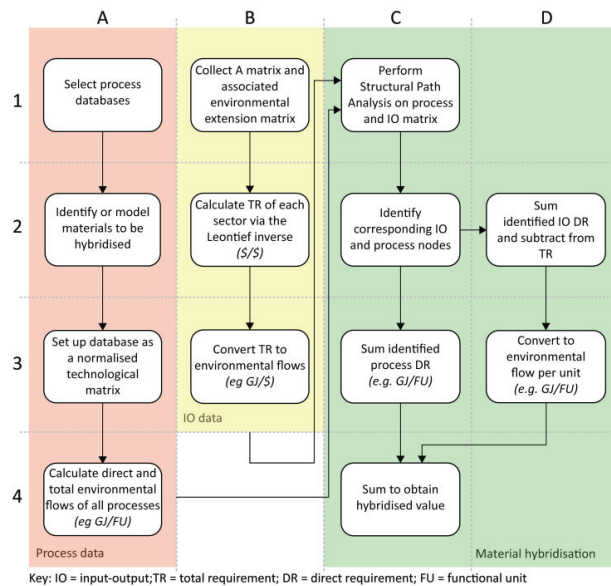


Figure 1 Step-by-step overview of the path exchange method

Data collection is the first step, where the latest available process (A) and input-output data (B) are collected in the form of square matrices alongside their respective matrices of environmental flows, representing exchange to and from nature. If the material being hybridised is not available in an existing process database, it can be modeled directly in the process matrix by adding columns and rows as needed, or by using existing LCA software prior to extracting the process matrix.

The hybridisation process starts by mathematically decomposing the two matrices (C1), thus unraveling the supply chain of the sector and corresponding process being analysed. In input-output analysis, this step is referred to as a structural path analysis (SPA). The outcome of the SPA is a series of mutually exclusive nodes, each representing a good or service provided from one tier to another within the supply chain analysed. A series of nodes, corresponding to a chain of transactions leading to the sector being assessed, is referred to as a pathway. Although the way process data is modelled differs from input-output data, a similar relationship between processes is unraveled via the SPA.

The outputs of both analyses are then reviewed to map out possible correspondence between input-output and process nodes (C2). The premise of this mapping process is that the results of the SPA on a process and its corresponding IO sector represent comparable supply chains. Thus it is possible to find corresponding nodes reporting on the same aspects of the supply chain. To finalise the PXC, the direct emissions or requirements of all input-output nodes for which corresponding process nodes have been identified are subtracted from the total

requirements or emissions of the input-output sector to obtain the ‘remainder’, and converted from environmental flow per dollar value to environmental flow per functional unit (D2-3). Summed direct requirements or emissions of the process data equivalents are then added (C3-4). Through this process, existing process data is conserved, but complemented by input-output data, creating a model that is specific to a material, while encompassing all aspects of the economic system.

3. Case-study

This section describes the case-study used to demonstrate the framework for automating the PXC hybrid method. This application was used to identify pitfalls and aspects requiring further developments.

3.1. Description

The building element chosen for this case-study is a structural insulated panel (SIPs), and the impact indicator is climate change. SIPs are constituted of an insulated core glued to two layers of structural material, as depicted in Figure 2. Typically, oriented strand board (OSB) is used for the skins of SIPs, while expanded polystyrene (EPS) is used for the core [19]. The three layers are then fixed using a thin layer of polyvinyl acetate (PVAc) adhesive. It is a relatively simple product, but it retains a level of complexity as it is very niche in the Australian market.

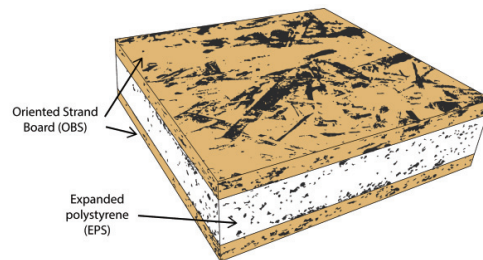


Figure 2 Structure of a typical SIP

3.2. Data

A supply-use table (SUT) representing the Australian economy in 2014 was collected from the Industrial Ecology Virtual Laboratory (IELab, <http://ielab.info>), a collaborative virtual laboratory platform developing the most detailed input-output data available to date, with 1,284 economic sectors [20]. The supply-use table was then reconciled into a square input-output table using a set of equations described by Eurostat [21] and resulting in an industry-by-industry-based input-output table based. The overall assumption of this reconciliation approach is that every product has its own specific sales structure, irrespective of the industry where it is produced [21].

The foreground data used for modelling the SIPs panel were based on publicly available information, and are summarised in Table 1 below. Modelling the upstream supply chain relied on linking the foreground data collected from available resources to the background database – here AusLCI was used [6].

3.3. Application

The first issue faced during the analysis was in finding an economic sector representing the production of SIPs. This product forms part of a very niche market in Australia, and therefore there is no direct match in existing economic sector classifications, even within the 1284 sectors disaggregation available on the IELab. To continue the analysis, it was therefore necessary to produce a hybrid coefficient for each of the three material inputs, as well as electricity, and model the production of SIPs on this basis; or to select the closest possible sector in the IOPC

classification, and apply the matrix expansion method [14] to artificially create a sector representative of SIPs production.

The first option was selected although it introduces some truncation to the system, as it is much more specific and provides a meaningful analysis. The second option requires drawing high level assumptions on the closest sector and its requirements. This would represent additional work that falls outside the scope of this analysis, without adding significant information to the results.

A structural path analysis was then conducted for the three economic sectors representative of the inputs required to produce SIPs, as well as the electricity for its assembly, as follows:

- *Particle board (including laminated) and similar board of wood or other ligneous materials* – representing oriented strand board;
- *Polystyrene* – representing polystyrene expanded slab;
- *Adhesive (excluding bituminous) and glues* – representing polyvinyl acetate adhesive; and
- *Electricity generated from fossil fuels* – representing high voltage electricity.

Table 1 Life cycle inventory for the assembly of a structural insulated panel (per m² of panel)

Material	Input	Unit	Comment
Oriented strand board (OSB)	0.022	m ³	SIPS Industries Australia Pty Ltd [22] was used to estimate the quantity of material required for a 115 mm thick panel. Thickness of OSB panel is typically 11mm per board [22-24]. OSB production was modelled based on ecoinvent 2.2 [25], modified to align it with Australian conditions, via the use AusLCI's shadow database [6].
Expanded polystyrene slab	2.79	kg	A thickness of 93 mm was assumed for a 115 mm thick panel, as reported in publicly available technical specifications [22, 24]. Density of the EPS slab is assumed to be 30 kg/m ³ [7]. National Renewable Energy Laboratory [26] was used to model EPS production and modified to align with Australian condition. Ecoinvent dataset for EPS does not allow for a meaningful analysis as only system process data are available. The production of foam slab from EPS was modelled from Wernet, et al. [7].
Polyvinyl acetate adhesive (PVAc)	0.15-0.18	kg	Rakoll [27] was used to estimate the quantity of adhesive recommended by the manufacturer as a proxy of actual practice. Production of PVAc was modelled based on the production of vinyl acetate, its precursor. Given the proportion of adhesive to other material, it was assumed that it would have minimal impact on the results. The production process is based on ecoinvent 2.2 [25], modified to align with Australian conditions, via the use AusLCI's shadow database [6].
Assembly	4.5	kWh	Gebo [28] includes an estimate of electricity requirement per area of panel, for a facility manufacturing OBS/EPS panels. Assembly only requires pressing the EPS slab between the two OSB panels to ensure adhesion. Electricity use for the assembly was modelled using AusLCI [6]

The output of a structural path analysis (SPA) is a list of pathways – each representing a chain of transactions between input-output sectors, or a chain of processes. A node refers to a specific point in that chain, representing either a purchase from a sector or the use of a process. The SPA reports direct requirements or emissions associated with each node, the total for each pathway, as well as a ranking of each pathway. In theory the number of pathways would be infinite, with increasingly small results. A threshold is applied to the calculation, so that the output is limited to significant pathways.

Once a ranked list of pathways and nodes has been produced by the SPA, the output must be reviewed and corresponding process and input-output nodes identified. During the case-study, a number of situations emerged, which necessitated a range of decisions that are discussed in the five points below. These have various implications for the automation of the PXC hybrid method.

1. ***Finding process nodes corresponding to the nodes of the input-output sector*** is the first step, and may depend on the impact category being analysed, because of the way process data is modelled. In the case of climate change, it will be necessary to trace the emissions back to the actual combustion process, which is typically found

several steps down the process chain. In addition, it will often be the case that several process nodes will represent the direct emissions or requirements of the sector.

2. **Dealing with system process datasets** is often necessary, as it may be used by the data compiler as a way to assure the primary data provider that their intellectual property rights are not at risk. This was the case in several instances during this analysis. For such a specific analysis, it was decided to remodel the process if it was in the foreground of the analysis (e.g. the production of polystyrene), but to exclude it from the mapping process if it was taking place further up the supply chain (e.g. the production of benzene used to produce styrene).
3. **Identifying all process nodes that can be associated with one input-output node** is a challenge. As discussed in the first point, the emission of greenhouse gases associated with one input-output node will reflect the combustion of a mix of fuels (or other direct emissions, depending on the sector), but can also reflect a range of processes, depending on the aggregation level of the sector. A typical example is the purchase of electricity. When analysing the process data equivalent, a number of nodes will be identified, corresponding to the combustion of the fuel mix used to produce electricity in Australia. These must all be captured to have a meaningful process to input-output node equivalence.
4. **Even using a 1284 sector disaggregation, an input-output sector will represent entire parts of the economy.** It will represent the average practice of a sector in terms of expenditure. But in an analysis aimed to be specific, it is very likely that some material expenditure will be irrelevant to the product being analysed. Therefore it should be considered whether certain input-output nodes should be deleted for a more representative output.
5. **The way specific aspects of the system are analysed should be carefully considered.** In the case of transport, for instance, it is a regular occurrence that process data include a proxy value of the distance to represent transport – using a predefined set of values to model a long or short distance based on geographical context (e.g. Australia vs Europe), and not necessarily the exact distance from the supplier to the user of a material. On the other hand, input-output data should be representative of the actual expenditure of a sector on transport, which would have a direct relation to greenhouse gas emissions – the higher the expenditure, the longer the distance, the higher the emissions. Here it was decided not to account for process nodes representative of transport, keeping information provided by input-output data.

3.4. Results

Overall, the hybrid coefficient calculated for SIPs was composed of 25% process and 75% input-output data, as depicted in Figure 3.

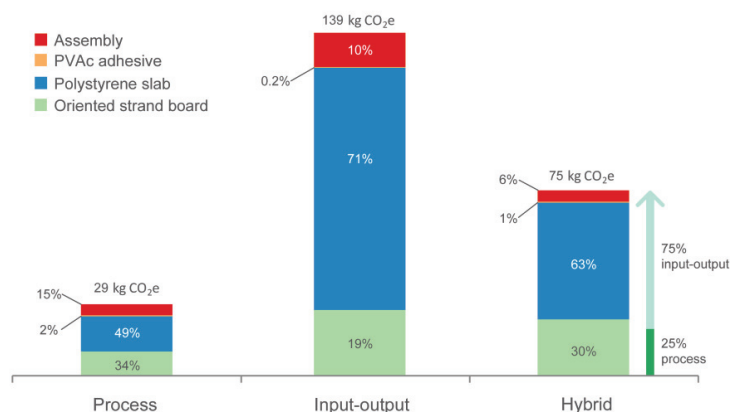


Figure 3 Cradle-to-gate greenhouse gas emissions of SIPs, using process, input-output and hybrid method (per m² of panel)

In addition, the resulting hybrid coefficient is 159% higher than its process equivalent and 46% lower than its input-output equivalent. This can be explained by the fact that in a hybrid analysis, parts of the input-output model

are replaced with process data and that in this case, the equivalent input-output values are higher than the substituted process values. It is also apparent that although absolute values vary significantly in this analysis, the order of significance with respect to the overall assembly is kept throughout.

It has to be noted that throughout the hybridisation process, it was only possible to match process and input-output nodes representing 27% to 98% of the total intensity of the process or sector analysed, as is shown in Figure 4. This is a clear limitation of the analysis, as a higher matching rate would most probably contribute to a lower hybrid coefficient. The variation from sector to sector should also be noted, between sectors where direct emissions are key (e.g. electricity), or where these are dispersed up the supply chain (e.g. PVAc adhesive).

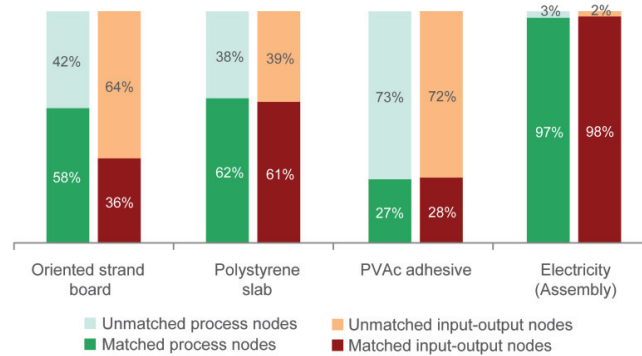


Figure 4 Matched and unmatched nodes for the processes and corresponding sectors analysed, as a proportion of the total process and input-output requirements

4. Discussion and conclusion

This analysis suggests that a full automation of the process and input-output hybridisation process will be difficult to achieve – and perhaps should not be a target *per se*. A large share of the useful information that comes out of an LCA results from knowledge gained during the modelling process itself. Automating this could affect the way in which conclusions are drawn from an analysis, preventing the assessor from being aware of potentially relevant information. Having a deeper understanding of the intricacies of a model also allows for a clearer outlook on the levers available to mitigate the environmental effects of the good or service under study, a critical output of any LCA.

However, it appears possible to use programming to assist the hybridisation process, for instance by suggesting corresponding nodes, or retaining which nodes are equivalent for future analysis. This would simplify the hybridisation process – allowing streamlining of the development of hybrid coefficients while retaining enough information to automatically update results as new data is published. Decisions made in terms of matching process and input-output nodes should rely on a consistent set of rules, which may be applied to any analysis. Developing this set of rules is critical to the success of this computer model. It will require considering different materials and impact categories, and assessing how situations may vary in each case. The work presented in this study focuses on a single assembly – a clear limitation. Therefore, the situations that were identified (see Section 3.3) in the case-study could be irrelevant for other assemblies or for more generic applications. These situations should be seen as the basis on which more robust information will be built using a range of other case studies. This will then allow their application in a broader context.

The proportion of process nodes for which an equivalent input-output node is found appears to be a critical aspect, and its effect on the final results will need to be further analysed. At present, a significant proportion of process nodes were left without match, and thus discarded from the analysis. This has an impact on the results, as replacing input-output nodes with process nodes appears to reduce embodied greenhouse gas emissions in this case. One way to address this matching issue would be to apply a maximum threshold beyond which the hybridisation process could stop (e.g. less than 2% contribution to the total).

Matching input-output nodes with process data still requires a certain level of expert knowledge in the way process and input-output databases are compiled, but also in the way manufacturing systems work, as it requires a judgment to be made on whether two nodes are likely to be equivalent or not. The matching process adds a layer of uncertainty to the final result through potential matching errors, allocation errors, human errors and others. Despite these limitations, the partial automation of this process can help put in place information gathering protocols that can improve our understanding of hybridisation and propose means to improve it over time. Overall, the analysis suggests the potential for automating key steps in the hybridisation process, potentially allowing for automated updates of coefficients. This would in turn help develop a comprehensive database of hybrid coefficients that could be used in life cycle assessments of buildings and the built environment, thus providing critical information to help reduce the environmental effects of the construction industry.

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