Improving the environmental performance of the construction supply chain

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Abstract

Improving the environmental performance of the construction industry has typically focused on reducing energy and water consumption and the production of waste on the construction site. Studies have shown that this direct requirement for resources and waste is responsible for only a small proportion of the total environmental impacts of construction. Indirect requirements represent a much greater proportion of the energy and water demand of construction and are typically associated with the manufacture of materials upstream in the supply chain. Previous attempts to quantify these requirements in order to prioritise environmental improvement efforts have failed to adequately cover the multitude of processes involved in the supply chain. The complexity of this supply chain makes it virtually impossible to use traditional techniques to quantify the environmental impacts associated with every individual process necessary to support construction. Input-output analysis, with its systemically complete framework, provides an ideal solution to this problem.

This study uses input-output analysis to model the energy and water consumption associated with each individual process within the entire Australian residential construction supply chain. It was found that the indirect requirements account for at least 96% of the total energy and water consumption associated with construction. The remaining proportion represents the direct energy or water consumed on-site. The findings from this study also provide a greater understanding of the significance of the resource demands for each individual process across the construction supply chain, that has until now been lacking. This indicates that further improvement to the environmental performance of the construction industry requires greater emphasis on the processes located further up the supply chain. Only with this detailed level of information can the construction industry make considerable improvements to its environmental performance.

Keywords: construction, supply chain, input-output analysis, energy, water.

1. Introduction

Buildings are responsible for a significant proportion of total energy demand, greenhouse gas emissions and other environmental loadings in most industrialised countries around the world. Existing efforts to reduce the environmental impact of buildings tend to focus on minimising energy and water consumption and greenhouse gas emissions associated with building operation and on-site construction. Indirect or embodied resource requirements and

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emissions are often overlooked and previous research shows that these can be just as significant, and increasingly so as building operational efficiencies improve.

An understanding of where the greatest impacts occur within the supply chain is essential for improving the environmental performance of the construction industry. Traditional approaches for identifying indirect resource demands and emissions suffer from considerable flaws. The most notable being the truncation of the system boundary, resulting in a large proportion of processes being excluded from the analysis. More recent methods involve the use of economic input-output (I-O) data. However, this is most often used as a black box, which does not facilitate the easy identification of the most significant processes within the supply chain, so that these can be prioritised for environmental improvement. More recent assessment models that further disaggregate this I-O data allow it to be much more transparent and useful for targeting environmental improvement efforts.

The aim of this paper is to demonstrate how I-O data can be used to provide a more comprehensive understanding of the environmental loadings associated with the construction industry and identify strategies for environmental improvement.

2. Background

Our current understanding of how best to improve the environmental performance of the construction industry is based on information developed using incomplete assessment techniques and a limited knowledge of the processes occurring across the entire construction supply chain. This has the potential to result in a focus on processes that are much less important than others that are often much higher up in the supply chain. For example, a focus on reducing the waste produced and energy and water consumed during the construction process itself stems, in part, from a belief that these areas are significant in terms of the overall impacts related to construction. However, a number of studies have shown that the on-site requirement for energy and water accounts for less than 5% of total demand for these resources (Crawford and Treloar 2005; McCormack *et al.* 2007; Crawford 2012). An understanding and knowledge of the indirect resource demands and pollutant releases occurring across the entire construction supply chain is thus vitally important.

Process analysis, based on physical quantities of materials and fuel, is the approach typically used to quantify the inputs required across a supply chain. This approach usually quantifies the inputs to the supply chain to two or three tiers upstream of the main product (such as a building). This may include the energy associated with steel production and fuel required for transporting iron ore to the steel manufacturer, for example. A significant number of these inputs can occur further upstream. However, tracing an entire supply chain using a process analysis approach is virtually impossible due to the time, cost and complexity involved in physically analysing each transaction within the supply chain (Treloar 2007). Because of this, a considerable proportion of the inputs within the supply chain of any product are often excluded. Previous research by Lenzen (2000), Lenzen and Dey (2000) and Crawford (2008) indicate that this may be as high as 87%. I-O analysis provides a solution to this truncation issue as it is based on a systemically complete framework and can thus be used to quantify a much larger number of the inputs associated with construction.

2.1 Input-output analysis

I-O analysis is a top-down economic technique, which uses matrices of sector-based monetary transactions (I-O tables) describing complex interdependencies of industries in order to trace resource requirements and pollutant releases throughout a whole economy. These I-O tables describe, in economic terms, the inputs required by each industry sector from each and every other sector in order to produce a certain quantity of output. The system boundary of I-O analysis is economic, such that if a sector pays for any product or service, the inputs to that product or service are included. This results in an almost limitless number of potential transactions upstream through the supply chain.

Total requirements coefficients for each sector provide the sum of direct requirements and indirect (or upstream) requirements of inputs to a sector. The sum of the indirect requirements can be deduced by subtracting the direct requirements from the total requirements; however, modelling individual indirect requirements (such as the inputs required in mining the iron ore needed to produce steel) is much more complex and time-consuming due to the shear number of processes involved. This is the reason why I-O analysis is often used as a black box. A disaggregated I-O model is needed to identify the significance of individual inputs occurring throughout the supply chain.

3. Identifying and prioritising strategies for improving the environmental performance of construction

A disaggregated I-O model of the construction sector includes every flow or relationship associated with the entire construction supply chain. This model, when combined with environmental data, can then be used to identify where the most significant environmental loadings occur across the supply chain. These loadings may be related to specific material manufacturing processes (e.g. mining and production), the provision of services to construction processes (e.g. finance, communications and advertising) or the provision of capital equipment and machinery to any of these processes (e.g. for factory buildings or the equipment and machinery required for extracting, transporting and processing iron ore).

The number of sectors into which an entire economy is disaggregated varies by country and even over time. I-O models depicting the flows within the Australian economy are typically disaggregated into around 100 sectors. For a product produced by any one of these sectors (e.g. a building), there is a requirement for goods or services from potentially all of these 100 sectors at the first tier in the supply chain (Tier 1). For a building, this would typically include the main construction materials (steel, glass, concrete etc.). The potential number of goods and services requirements increases exponentially at an alarming rate at each further tier upstream in the supply chain. At Tier 2, the number of potential inputs is 100^2 as each of the 100 sectors may require inputs from every other sector to produce the main output of that sector (e.g. the purchase of cement used in concrete production). At Tier 3 of the supply chain there is potentially 100^3 additional inputs at the sector level (e.g. limestone used for making cement). At Tier 4 there are 100^4 potential inputs, which might include the provision of capital equipment to mine the limestone, amortised over its life (i.e. just the share of that equipment's value used to mine that limestone). At Tier 5 there are 100^5 potential inputs at the sector level (e.g. sheet steel used to make the machinery used for mining the limestone). This would result in a total number of inputs at the sector level, at only 5 tiers upstream in the supply chain, according to these simplified calculations, of 10,101,010,100. Figure 1 depicts the individual flow of goods and services between sectors for residential building construction. This shows just the top 1,500 most significant inputs, representing 46% of the total energy requirement of the Australian *Residential building* sector.

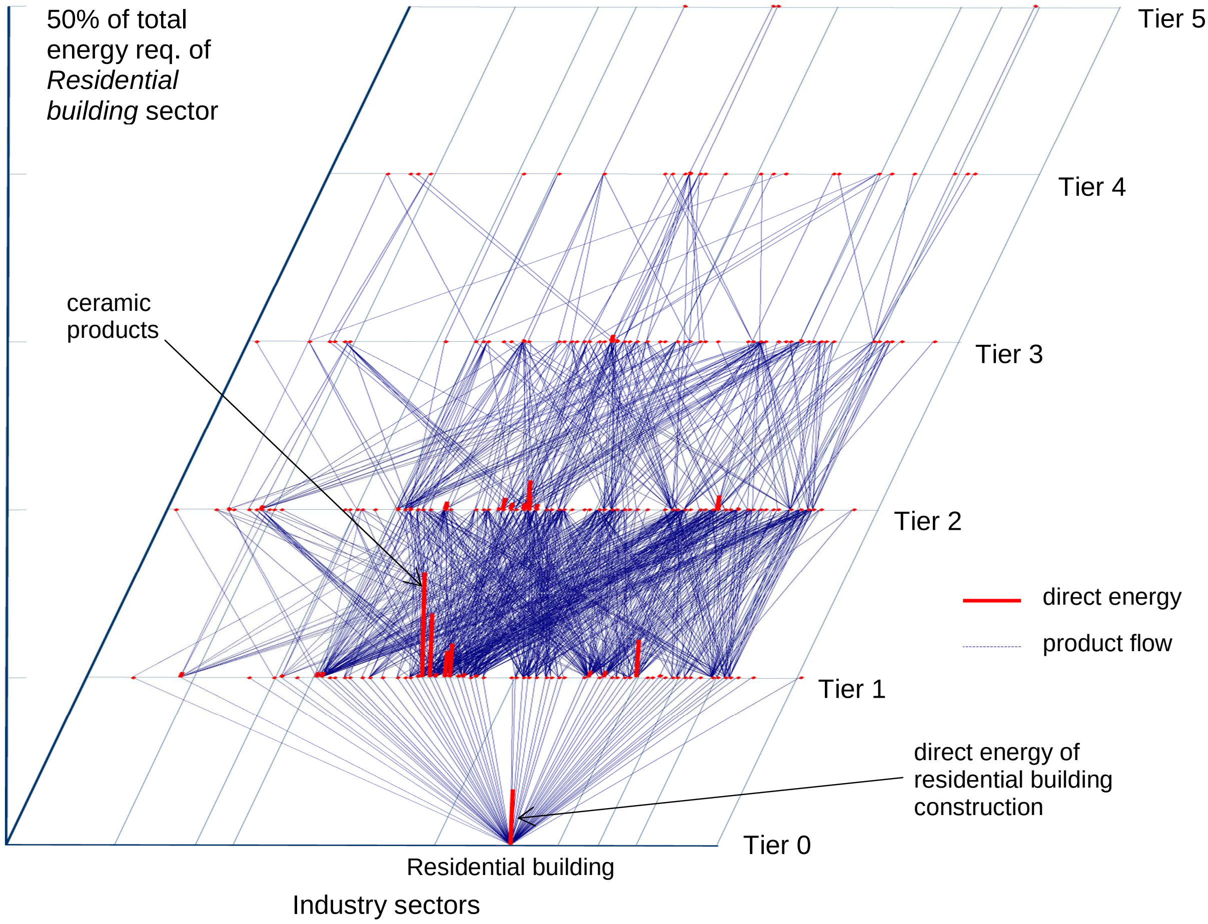

Figure 1: Diagram showing flows of goods and services within the Residential building supply chain, by sector

For the construction industry, some of the most important environmental concerns are energy and water resource depletion and the release of greenhouse gas emissions. I-O models that model energy and water flows and the greenhouse gas emissions resulting from particular processes across the supply chain are thus the most common types of I-O models used to assess the environmental performance of construction products.

Almost any type of environment-related data can be integrated into an I-O table, including energy, water and raw material consumption, as well as waste and emissions, such as carbon dioxide. To enable the integration process to occur, the environmental data must be in the correct format, giving values for inputs of resources or outputs of waste or emissions per economic sector. Based on the total resource requirements or emissions associated with a particular sector as well as the total monetary value of all outputs from that sector, it is then possible to determine the quantity of resources required or emissions released per monetary unit of output for each sector. In simple terms, this is done by dividing the total resource requirements or emissions by the total monetary value of sector outputs, which results in a sector-level *total requirements coefficient* in units per monetary unit of output (e.g. GJ of energy per dollar). The quantity of resources or emissions associated with a particular quantity of output from any sector of the economy, including the indirect inputs of goods and services required to support the production or supply of that output, can then be determined.

Generalised I-O models have been applied extensively to environmental analysis since the late 1960s (see for example Isard *et al.* 1967; Leontief and Ford 1970; Bicknell *et al.* 1998). A detailed introduction to I-O analysis and its application to environmental problems can be found in studies by Leontief and Ford (1970), Proops (1977) and Dixon (1996).

3.1 Approach

The following sections provide an I-O-based analysis of the Australian residential construction supply chain for two common environmental parameters – energy use and water use. This analysis is based on an I-O model of the Australian economy using 1996-97 I-O data, combined with energy and water consumption data from Australia's National Accounts. The resultant model provides not only an indication of the specific flows of goods and services occurring between each of the sectors involved in the construction supply chain, but also the quantity of energy and water associated with each one of these flows, in GJ and kL, respectively. The initial use of this model is an analysis of the total resource requirements associated with the construction of a building. The total monetary value of the building is simply multiplied by the total energy or water requirement of the *Residential building* sector to determine the total I-O-based resource requirement for the building. This process is demonstrated in Crawford (2011: 93) and is beyond the scope of this study.

An innovative tool developed by Treloar (1998) has been used to disaggregate the energy- and water-based I-O models at the individual process level. For example, this includes the process of iron ore mining, transporting iron ore for processing as well as the process of manufacturing steel from the iron ore, as separate items. With this information, environmental improvement strategies can then be prioritised based on the areas of greatest potential environmental improvement.

3.2 Analysing energy use across the construction supply chain

This section presents an analysis of the energy demand associated with the Australian residential construction supply chain using a disaggregated I-O model of Australian direct and indirect energy use based on Australian Bureau of Statistics National Accounts (ABS 2001a) and National Energy Accounts (ABS 2001b). The total energy requirement of the *Residential building* sector, based on 1996-7 I-O data is 10.3 GJ/$1000 of sector output (construction and maintenance of residential buildings). Figure 2 shows the distribution of energy demand associated with residential building construction by supply chain tier. From this it is evident that direct energy consumed during the construction process (Direct - Tier 0) is insignificant in relation to the total energy requirement of the sector (3.3%). A total of 86% of the total energy requirements occur within the first 5 tiers of the supply chain.

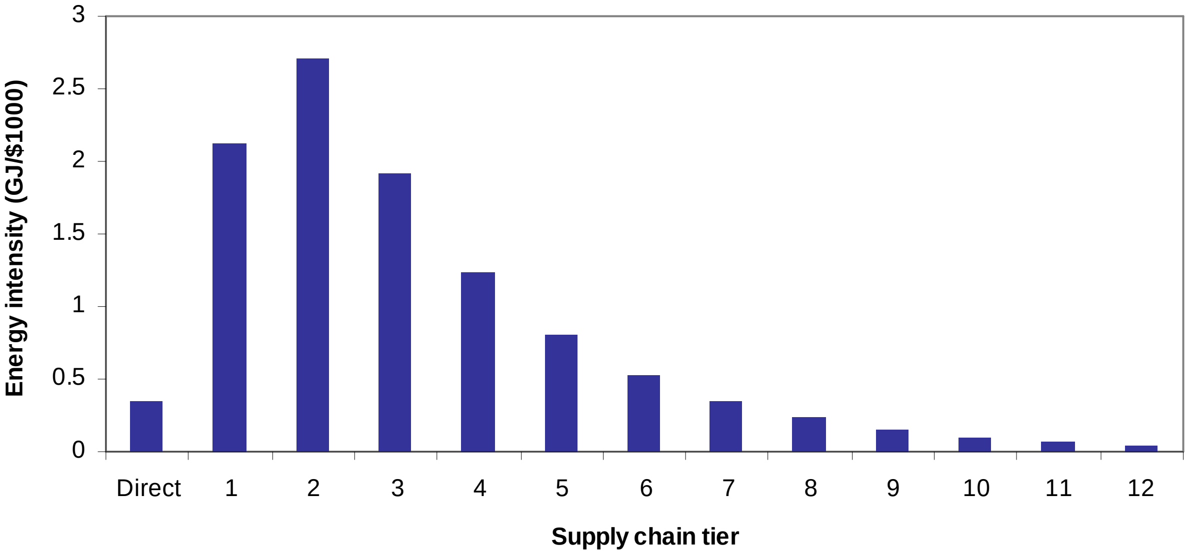

Figure 2: Total energy requirement of the Australian Residential building sector, by supply chain tier

Figure 3 shows the total energy requirement for each of the top 25 most significant Tier 1 inputs into the *Residential building* sector. Each column includes the energy associated with the main process (e.g. for *Road transport* this will be the fuel required to operate transport vehicles) as well as all indirect requirements for energy upstream of this Tier 1 process (covering all minor goods and services required to support the provision of road transport).

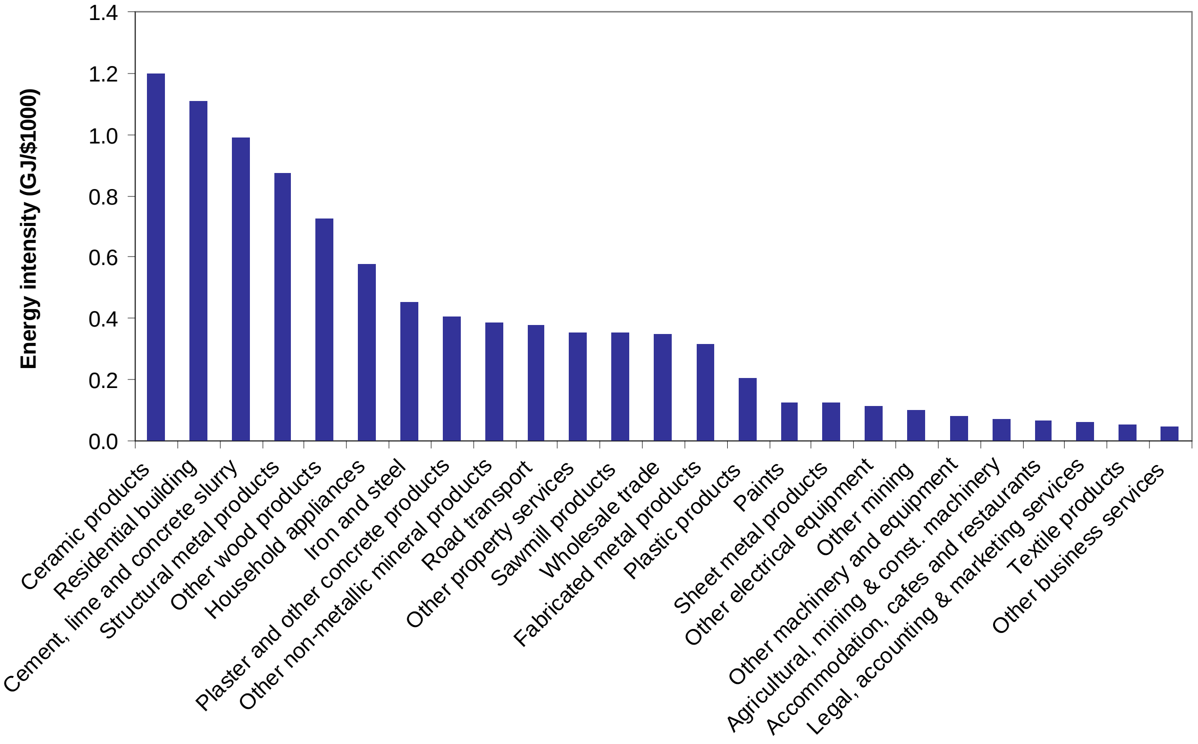

Figure 3: Total energy requirement of the top 25 Tier 1 inputs into residential building construction, by sector

Figure 3 shows that at the sector level, ceramic products represent the largest proportion of energy demand for residential building construction (11.3%). This includes the production of clay bricks, ceramic tiles and sanitary ware. The energy associated with the production of concrete (9.3%) (for floor slabs, driveways and paths), structural metal products (8.2%) (for steel reinforcement, structural steel members and aluminium window frames) and wood products (6.8%) (for structural framing, window frames, doors and joinery) is also significant.

3.2.1 Identifying the most significant energy demands

A further disaggregation of the I-O model can help to identify the individual processes that are most energy intensive within each of the most significant sectors identified in Figure 3. Table 1 shows the direct energy requirements (DER) for the 10 most significant inputs associated with the production of goods (bricks, tiles etc.) from the ceramic products sector required in residential building construction. This list is only a small fraction of the millions of individual processes associated with residential building construction, of which, individually, the vast majority represent an insignificant proportion of the total energy requirement (TER).

Table 1: The direct energy requirement of the top 10 most significant inputs for ceramic products production into the Residential building sector

	DER (GJ/$1000)	Tier 2 of *Residential building* sector	Tier 3 of *Residential building* sector
1	0.6629	Direct energy for ceramics production	
2	0.0411	Other non-metallic mineral products	
3	0.0326	Road transport	
4	0.0063	Ceramic products	
5	0.0057	Cement, lime and concrete slurry	
6	0.0050	Other mining	
7	0.0049	Other chemical products	Basic chemicals
8	0.0042	Other non-metallic mineral products	Road transport
9	0.0036	Road transport	Road transport
10	0.0035	Rail, pipeline and other transport	
Total	0.7700	% of TER of Ceramic products into Residential building construction: 64%	

NB. Tier 1 is *Ceramic products*

One of the limitations of I-O analysis is the inability to identify the exact process that is responsible for consuming energy, especially for the more aggregated sectors where multiple products are produced within the one sector. In this case, assumptions can be made, based on knowledge of the goods and services that are most likely to be purchased from these sectors for the construction of a residential building and knowledge of the processes that are most likely to be the most energy intensive in the manufacture or provision of these goods or services. For example, Table 1 indicates that the most significant energy requirement for ceramic products is the direct energy required for production (6.2% of the total energy required for residential building construction). It can be assumed that a large proportion of this relates to the production of clay bricks due to the considerable quantity typically required in the average residential building and the energy-intensive nature of their production (for kiln firing). The next most significant energy requirements associated with the use of ceramic products are for the production of lime (from the *Other non-metallic* *mineral products* sector) and the transport of ceramic products to the construction site (*Road transport*). These two processes represent 0.4% and 0.3% of the total energy requirement associated with residential construction, respectively. Individually, the remaining processes account for less than 0.1% of the total energy required for residential building construction. A similar analysis can be performed for each of the other Tier 1 inputs into residential construction using the disaggregated I-O model.

3.2.2 Potential improvement strategies

The above analysis suggests that a number of strategies for reducing the energy demands of construction are possible. The first of these is either to look for alternatives to the use of clay bricks or to source bricks from manufacturers with the highest operational energy efficiencies in production (using modern firing technologies or fuelled by renewable energy sources). The input from the *Residential building* sector (Figure 3) refers to the materials required in building repair and maintenance. As such, utilising more durable materials may also result in significant environmental benefits. These strategies do not consider the potential impact that might result from any alternatives, but merely suggest areas where considerable savings in energy requirements may be possible.

3.3 Analysing water use across the construction supply chain

The analysis of water requirements associated with the Australian residential construction supply chain used a disaggregated I-O model of Australian direct and indirect water requirements based on Australian Bureau of Statistics National Accounts (ABS 2001a) and National Water Accounts (ABS 2000). The later are generated from water supply-and-use tables based on financial and physical data which describe the economic consumption of water and show linkages between the economy and the environment.

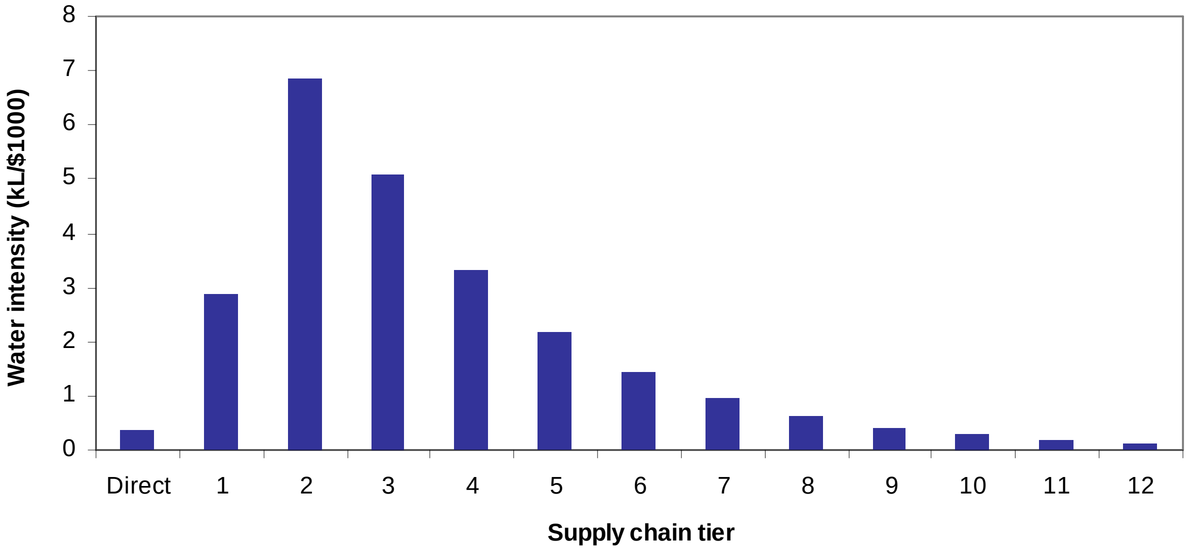

Figure 4: Total water requirement of the Australian Residential building sector, by supply chain tier

The total water requirement of the *Residential building* sector, based on 1996-7 I-O data is 24.73 kL/$1000 of sector output. Figure 4 shows the distribution of water demand associated with residential building construction by supply chain tier. As for energy, it is evident that direct water consumed during the construction process (Direct - Tier 0) is insignificant in relation to the total water requirement of the sector (1.5%). A total of 84% of the total water requirements occur within the first 5 tiers of the supply chain.

Figure 5 shows the total water requirement for each of the top 25 most significant Tier 1 inputs into the *Residential building* sector. Each column includes the water associated with the main process as well as all indirect requirements for water upstream of this Tier 1 process.

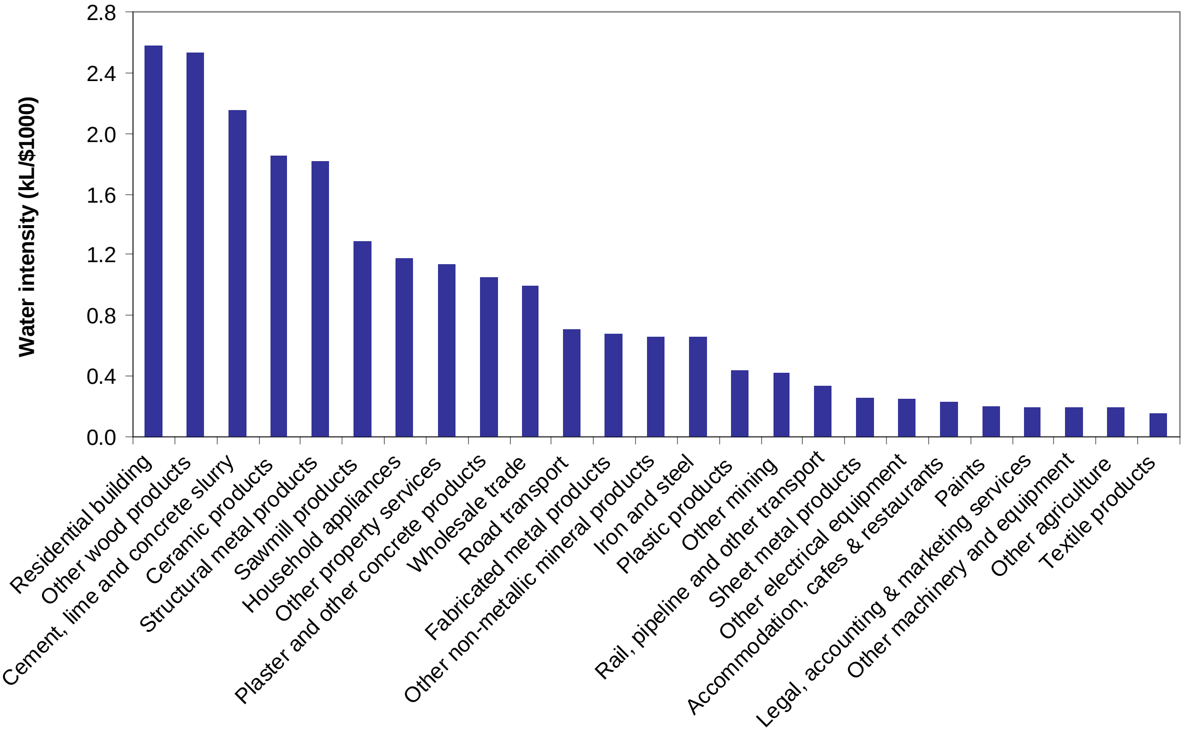

Figure 5: Total water requirement of the top 25 Tier 1 inputs into residential building construction, by sector

Figure 5 shows that at the sector level, goods or services provided by the *Residential building* sector are responsible for the largest proportion of water demand for residential building construction (10.4%). Current I-O models do not allow for a more detailed understanding of the actual source of demand for this water, but it is likely to be related to the repair and maintenance of residential buildings (the only other output of the *Residential building* sector other than residential building construction). The water demand associated with the production of wood products (10.2%) and concrete (8.7%) are also significant. This is followed by ceramic products (7.5%) and structural metal products (7.4%), which are also significant in terms of total water demand.

3.3.1 Identifying the most significant water demands

Further disaggregation of the *Other wood products* sector into the processes associated with the production of wood products (structural framing, window frames, doors and joinery) required in residential building construction shows that the direct water required for production is the most significant water requirement for wood products (2.2% of the total water required for residential building construction and 22% of the total water required in the production of wood products). The next most significant water requirement associated with the use of wood products is for the production of sawmill products (i.e. sawn and dressed timber) at 3.7% of the total water required for the production of wood products. Individually, the remaining processes account for less than 0.2% of the total water required for residential building construction.

3.3.2 Potential improvement strategies

As for the energy parameter, the significance of building repair and maintenance (*Residential building* input) on total water demand is likely to mean that more durable materials will result in considerable indirect water savings associated with construction. Specifying more durable materials that require less ongoing maintenance and lower frequency of replacement reduces the demand for water in their production.

In addition, the analysis has highlighted the significance of water demand associated with the production of wood products and concrete. For wood products, considerable water savings may be achieved by selecting products from manufacturers with higher water efficiencies in production. Avoiding the use of wood products altogether may not be an ideal solution as these products bring other environmental benefits such as carbon storage.

4. Discussion

The list of discrete inputs, ranked from most to least significant in terms of resource requirements, represents an ideal starting point for the construction industry to prioritise environmental improvement efforts. These efforts may focus on a range of strategies from materials substitution or development to process efficiencies and specific design interventions. This initial analysis shows that structural metal products, ceramic products, concrete and wood products appear in the top five inputs for both environmental parameters. This suggests that the production of these materials provides the greatest opportunities for improving the environmental performance of residential construction.

I-O analysis has its strengths, as discussed earlier, however the aggregation of commodities and establishments into sectors reduces the relevance of these findings to any particular product or region. The economic system boundary that gives I-O analysis its depth and breadth results in errors when these financial flows are attributed to physical quantities of materials or environmental loadings. For this reason, physical material and process specific data is needed in order to provide a detailed understanding of the environmental loadings associated with specific materials and products. Also, this analysis and the conclusions that can be drawn from it, relate only to the average product of the residential building sector and not to any one specific residential building. This may be acceptable for houses that are similar to the national average house, but is much less relevant to houses that aren't constructed from conventional building materials or by traditional construction methods. For example, a house clad externally with timber weatherboards is not likely to rely as heavily on products from the *Ceramic products* sector as the national average I-O model suggests.

Another limitation of this study is the use of I-O data that relates to production that occurred over a decade ago. Over time manufacturing technologies and efficiencies of production can change and this can alter the environmental profile of particular products. However, in general, *total requirements coefficients* change only marginally from one year to the next and any efficiency improvements are often offset by an increase in the cost of products. Also, there is a time lag of at least 2-3 years in the release of I-O tables and so even the most recently released data may not necessarily reflect the current-day situation.

In addressing the environmental impacts of the construction industry it is also important to consider other types of construction such as commercial buildings, infrastructure and prefabricated buildings, which may or may not result in a range of different impacts on the environment. Also, the inputs that represent the greatest resource demands and environmental impacts may differ from those identified for residential construction.

5. Conclusion

The aim of this paper was to demonstrate how I-O data can be used to provide a more comprehensive understanding of the environmental loadings associated with the construction industry and help to identify strategies for further environmental improvement.

Through the use of disaggregated I-O models, this paper has demonstrated the significance of indirect inputs on the environmental loadings associated with construction. The I-O models used provide an ideal approach for identifying these loadings and prioritising environmental improvement efforts within the industry. Only with this broad view of the entire supply chain is it possible to know whether existing and future environmental improvement efforts are addressing the most critical environmental impacts associated with construction.

This study shows that the greatest scope for improvement to the environmental performance of residential construction across the two environmental parameters considered is in the manufacture of ceramic products, structural metal products, wood products and concrete. Once this initial scoping process has been completed, more detailed environmental information specific to particular materials, products and processes can then be obtained.

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