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VALIDATION OF THE USE OF AUSTRALIAN INPUT-OUTPUT DATA FOR BUILDING EMBODIED ENERGY SIMULATION

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ABSTRACT

Traditionally, the simulation of buildings has focused on operational energy consumption in an attempt to determine the potential for energy savings. Whilst operational energy of Australian buildings accounts for around 20% of total energy consumption nationally, embodied energy represents 20 to 50 times the annual operational energy of most Australian buildings. Lower values have been shown through a number of studies that have analysed the embodied energy of buildings and their products, however these have now shown to be incomplete in system boundary. Many of these studies have used traditional embodied energy analysis methods, such as process analysis and input-output analysis. Hybrid embodied energy analysis methods have been developed, but these need to be compared and validated. This paper reports on preliminary work on this topic. The findings so far suggest that current best-practice methods are sufficiently accurate for most typical applications, but this is heavily dependant upon data quality and availability.

INTRODUCTION

Although the operational energy consumption of buildings accounts for the highest proportion of the total energy consumed in the life cycle of a building, there is still a considerable amount of energy that is consumed in the other stages of a building's life. These stages include the extraction of raw materials; processing of raw materials; manufacture of building materials and products; construction of the building; use; maintenance; refurbishment; demolition; and disposal. The manufacture of building products and the construction of the building incorporates the embodied energy of the building, resulting from the extraction of raw materials; manufacture of building materials and products; and transport at all stages. Fay, Treloar and Iyer-Raniga (2000) have shown that the embodied energy portion of a building's life cycle energy consumption can account for a significant portion of the total life cycle energy consumption of a building. There is therefore a need to assess the life cycle energy consumption and loadings of buildings and building products in order to determine the areas in which the majority of this energy is being consumed and where and how a reduction in this consumption is possible.

Traditional methods of quantifying embodied energy, namely process analysis and input-output analysis, have been shown to have significant limitations, despite the different benefits each method offers. The most important stage of an embodied energy analysis is the quantification of the inputs to the product or system. Traditionally, a boundary has been drawn around the quantification of inputs to the product being assessed, mainly due to difficulties in obtaining necessary data and the understanding of this data. Many inputs are therefore neglected in the quantification of inputs to a product, and thus the system boundary is incomplete.

Due to the inherent problems with process analysis and input-output analysis, hybrid methods of life cycle inventory analysis have been developed in an attempt to minimise the limitations and errors of these traditional methods. Hybrid methods combine both process data and input-output data in a variety of formats. Few attempts have been made to validate particularly recently developed hybrid embodied energy analysis methods. **Therefore the aim of this paper is to compare the results from various embodied energy analysis methods as applied to a range of building types and products.**

BACKGROUND

Embodied energy incorporates the energy which is used through the combined processes of extracting raw materials from the ground, processing, manufacturing, use, maintenance, and disposal or recycling. The embodied energy of an entire building, or an item, or a basic material in a building, comprises direct and indirect energy. Indirect energy is used to create the inputs of goods and services to the main process, whereas direct energy is that used directly for the main process, whether it be the construction of the building, product assembly, or material manufacture (Figure 1).

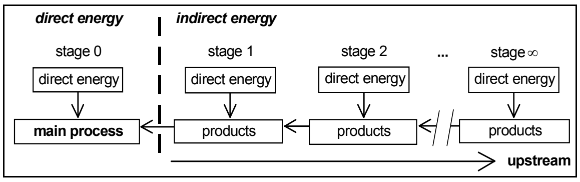


Figure 1 Embodied energy analysis system boundary (after Boustead and Hancock, 1979)

Embodied energy analysis methods

The accuracy and extent of an embodied energy analysis is dependent on which of the main analysis methods is chosen: process analysis, input-output analysis or hybrid analysis (Treloar, 1997). The two base methods of embodied energy analysis are susceptible to different types of errors and have different benefits. The most widely used of these methods, process analysis, can be significantly incomplete. This is primarily due to the complexity of the upstream requirements for goods and services (Lave *et al.*, 1995). The magnitude of the incompleteness varies with the type of product or process and depth of study but can be 50% or more (Treloar, 1998; Lenzen, 2001). While the accuracy of the process analysis method can be high, it is only relevant to the particular system considered and can be subject to considerable variability (Tucker and Treloar, 1994).

In most cases process analysis is also used to quantify more than just the direct energy and goods and services inputs to the main process. A material input into the main product can be quantified in terms of the material quantity and direct energy inputs. In this case the upstream incompleteness is reduced, however the system boundary may still be truncated both downstream (the direct energy input into the main product) and horizontally (other material inputs into the main product). These errors can be exacerbated as more and more process analysis data is collected, due to the flawed paradigm (Treloar, 1997).

Results of studies by Bullard, Penner and Pilati (1978), Miller and Blair (1985), Peet and Baines (1986) and Lenzen (1999) have proved that even extensive process-based inventories do not achieve sufficient system completeness. This is not as important in some studies as the system completeness may be identical for both products or processes, but when this is not even able to be estimated, validation can be impossible. This issue can have a much greater impact when considering the environmental impacts of a single product or process in a non-comparative study.

The second base method of embodied energy analysis is input-output analysis. This method uses national average data for each sector of the economy and is considered by many researchers to be more comprehensive than process analysis (eg *inter alia*, Treloar, 1997; 1998; Lenzen, 2000; 2001; and Lave *et al.*, 1995). This method has a systemically complete system boundary, which can therefore potentially solve the major drawback of the process analysis method. However, input-output analysis is generally used as a black box, with no understanding of the values being assumed in the model for each process.

Furthermore, because they are based on many inherent assumptions appropriate for national modelling, a perfect input-output model may not result in valid results for a particular product (Carnegie Mellon University, 2002; Suh, 2000). For this reason, the input-output model should be seen as scoping tool or an estimation method for missing data from the process analysis method. While input-output analysis is systemically complete, some input-output systems are inappropriately constructed, and may leave out significant aspects of the economy (for example, capital investment, Lenzen, 2001). Some of the other main limitations of input-output analysis include; the age of the input-output data; homogeneity assumption; proportionality assumption; the conversion of economic data to energy data; the use of national averages; and sector classification and aggregation.

Hybrid techniques attempt to combine the benefits of both base methods, while minimising their respective limitations. Process-based hybrid analysis (after Bullard, Penner and Pilati, 1978) is almost exclusively based on incomplete process analysis data, suffering similar limitations to those outlined above for the two base embodied energy analysis methods (Treloar, 1998). The input-output systemic completeness is only applied to the components of the model upstream from the process analysis data. Downstream and horizontal truncation can still occur, to significant levels. To some extent, these errors can therefore be compounded, despite the practitioner's best efforts to minimise them.

Input-output-based hybrid analysis combines process data and input-output data in a different way to process-based hybrid analysis, in order to exclude downstream and horizontal truncation. The direct inputs to a specific product or process being studied are calculated using process analysis. While process data is not usually easy to obtain, its use maximises the reliability of the analysis at this stage. Further upstream indirect processes are accounted for by either further applications of process analysis or input-output analysis when the process analysis data is unavailable or is considered too time consuming to collect relative to the significance of the process in question (Treloar, 1997). The input-output model is disaggregated to allow the activities for which process analysis data is available to be subtracted, leaving a remainder that can be applied to the study in an holistic manner to fill all the remaining gaps (as demonstrated in Treloar, Love and Holt, 2001).

Past embodied energy studies of buildings and building related products

Embodied energy studies have been performed on a number of building types and building related products, including; commercial, residential, and recreational; washing machines and other household appliances; hot water systems; and photovoltaics. These studies have used the range of methods outlined above, and thus, depending on which method has been used, end up with varying and, in some cases, conflicting results.

An individual residential building embodies about 2000 gigajoules (GJ) (Treloar, Love and Holt, 2001). Previous studies, now shown to be incomplete in system boundary, have shown significantly lower values (for example, Hill, 1978; Bekker, 1982; Viljoen, 1995; Lawson, 1996; Adalberth, 1997; Pullen, 2000; and Fay, Treloar and Iyer-Raniga, 2000).

The actual difference in values here is immaterial, suffice to say that the fundamental cause is often the use of different methods. Therefore, this suggests that a comparison of methods is required.

The input-output-based hybrid analysis method proposed by Treloar (1997) has been used in several life cycle and embodied energy studies (Crawford, 2000; Crawford, Treloar, and Bazilian, 2002), which have demonstrated the possible significance of the choice of embodied energy analysis methods. This input-output-based hybrid analysis method is currently preferred, but has yet to be evaluated against the base embodied energy analysis methods and the process-based hybrid analysis method.

METHOD

The necessity to test the input-output-based hybrid embodied energy analysis method comes about by the compounding errors evident in the process-based hybrid analysis method. In the past, researchers have used a number of techniques to evaluate the various methods of embodied energy analysis. These have included error analysis (various types), 'gap' analysis and 'comparative' analysis (Treloar, 1998; Lenzen, 2001). Error analysis is used to assess the error associated with the use of input-output data (Lenzen, 2000). Truncation error analysis is used to assess the extent of truncation associated with the use of process analysis data in a process-based hybrid analysis context (Bullard, Penner and Pilati, 1978). Error analysis evaluates initial data inputs, however often these are so complex that the sum of the effects of the errors in a national input-output model can be quite different when applied to an individual product.

Other methods have since been developed to overcome this limitation in error analysis by focussing on the outputs of the embodied energy analysis methods. Gap analysis is used to assess the difference between process analysis results and hybrid results, as an evaluation of the completeness of each method (Treloar, 1998). Comparative analysis is used to compare the input-output values for the process analysis components that are used in an input-output-based hybrid analysis (Treloar, 1998). These last two methods are best used together to evaluate and compare embodied energy analysis methods. These methods have been developed and demonstrated by Treloar (1998), however they have only been applied to a single residential building.

In order to compare the results from the four embodied energy analysis methods, and to provide a more accurate representation of the completeness of each of these methods, each method needs to be applied to a range of building types and products. The steps involved in each of the four embodied energy analysis methods are detailed below. Each method is described separately, even though the hybrid methods involve the use of the methods described before each of them. In other words, for an input-output-based hybrid analysis, these method descriptions can also be seen as the four main steps to this analysis.

Input-output analysis

The first step of an input-output analysis is to determine the direct and total energy intensities for the appropriate sector for the product being studied. The retail price of the product is obtained from the supplier of the product, or if this is unavailable, for example for buildings, an estimate is made based on literature and/or necessary assumptions. National input-output tables, produced by the Australian Bureau of Statistics (ABS) on an irregular basis (www.abs.gov.au) are then combined with national energy data from the Australian Bureau of Agricultural and Resource Economics (ABARE) to develop an energy-based input-output model of the economy. A number of these models have been developed for Australia (eg, Treloar, 1997; Lenzen 2000). The input-output tables are divided into the sectors of the Australian economy (for example; 'household appliances', 'road transport', 'residential construction'). Each one of these economic sectors has a respective direct energy intensity and total energy intensity, both quantified in GJ/$100 of product. It is therefore necessary to determine which sector the product being studied belongs to in order to determine the total energy intensity to be applied to that product.

Process analysis

Process analysis involves collecting process specific data for the product being studied. This usually includes only those inputs that are seen as those which are easily obtainable, as this method lends itself to the quantification of direct inputs and only a limited number of indirect inputs. For products such as buildings, this may include those inputs that are quantified in a bill of quantities or by CAD software.

The quantities of material inputs into the main product are measured. Any direct inputs of energy into the main product and those material inputs (direct energy into upstream material inputs are considered as indirect energy into the main product) are also quantified, if available. These energy inputs are then summed to give the embodied energy using process analysis.

Whilst the direct energy inputs to the main product and the material inputs may be accurate, energy inputs such as those further upstream and downstream of those materials, as well as those of other materials at the same level, are omitted.

This process analysis figure has been used as the 'total' figure for the embodied energy of a particular product for many past, and even more recent embodied energy analyses, and is often assumed to be substantially complete.

For the method of process analysis used in this study, the data was obtained from a material energy intensity database, derived from Australian industries from the mid 1990s (Grant, 2000).

Process-based hybrid analysis

The quantities of basic materials obtained through the process analysis are used as the basis for a process-based hybrid analysis. This method of embodied energy analysis usually requires the use of a number of hybrid material energy intensity figures.

A hybrid energy intensity figure (containing both process analysis and input-output analysis data) is calculated for all of the most common basic materials, such as steel, timber, bricks and glass. These figures are expressed in GJ/unit (usually t, kg, m^2, m^3) of material and represent a simplified method of incorporating process analysis data into the analysis, giving the amount of embodied energy contained in, for example, a kilogram of that material.

Once the material energy intensities have been calculated, they are multiplied by the quantities of basic materials of the product. These individual material embodied energy figures are then summed to obtain the embodied energy for the product.

The direct energy of the product is then calculated by input-output analysis where a process value is unavailable. The direct energy intensity figure (GJ/$100) from the input-output model used in the initial input-output analysis is multiplied by the price of the product, divided by 100, to give the quantity of direct energy input to the product (GJ/product).

For simple energy intensive products, the inclusion of input-output data may have little impact on the final result as there may be only a small number of inputs to the process. Therefore, the process analysis data will provide a fairly complete representation of the product. However, for more complex products such as buildings this type of analysis will be made less complete by; the complexity of inputs, and thus difficulty in obtaining process data for all of these inputs; and the truncation errors already mentioned.

Input-output-based hybrid analysis

The incompleteness associated with the previous three embodied energy analysis methods can be overcome by using a hybrid method based on input-output tables, increasing the completeness of even a process-based hybrid analysis. This method is based on the data gathered in the process analysis, and uses the figure from the process-based hybrid analysis to increase the completeness of the embodied energy analysis even further. The first of these steps is to extract the inputs from the relevant sector of the economy from which the product belongs, by using an algorithm developed by Treloar (1997).

Secondly, from the inputs extracted, the inputs that have been counted in the process analysis inventory are identified. The total energy intensity of each of the inputs represented in the process analysis inventory is subtracted from the total energy intensity of the sector. If a process analysis value is available then the relevant input from the input extraction must be subtracted from the total energy intensity of the sector to avoid double counting. The remainder of the unmodified inputs (the total energy intensity of the sector minus those inputs subtracted, in GJ/$100) are then multiplied by the price of the product ($) and divided by 100 to give the additional embodied energy for the product, in GJ. The process-based hybrid analysis embodied energy value (obtained previously) is then added to this figure, minus the direct energy component (as this is included in the remainder of unmodified inputs) to give the input-output-based hybrid analysis embodied energy total.

The use of this method can help to minimise time by determining the inputs to a product that may not be significant, in order to focus on those that are.

Evaluation method

The following provides a description of the detailed evaluation method applied to a range of products, systems and materials to provide a more detailed assessment of the use of input-output data. The evaluation methods that have been used for the evaluation of the embodied energy analysis methods in this study include;

- gap analysis; and
- comparative analysis.

Gap analysis has been used to assess the difference between the process analysis values and the input-output-based hybrid analysis values for each of the case studies. This is done by subtracting the equivalent process analysis value from the input-output-based hybrid analysis value. The purpose of this is to then show the embodied energy added through the use of input-output data, through the application of the more complete input-output-based hybrid analysis method.

The gap can also be expressed as the percentage of completeness of the process analysis value when compared to the input-output-based hybrid analysis values (Equation 1).

$$GAP = \frac{IOBHA - PA}{IOBHA} \times 100 \qquad \text{(Equation 1)}$$

Where *PA*, is the embodied energy of the main product through process analysis; and

IOBHA = the embodied energy of the main product through input-output-based hybrid analysis.

The comparative analysis is used to compare the process analysis and input-output analysis values of embodied energy for the whole building or product, individual components and materials. The input-output analysis values being those input-output figures from the input-output model which are, through the process of the input-output-based hybrid analysis, substituted with process analysis data. The process analysis values are therefore those process analysis figures which are substituted in place of the input-output figures in the input-output model. These two comparable figures are then plotted on an x-y graph to visually compare the input-output values, against the more reliable process analysis values.

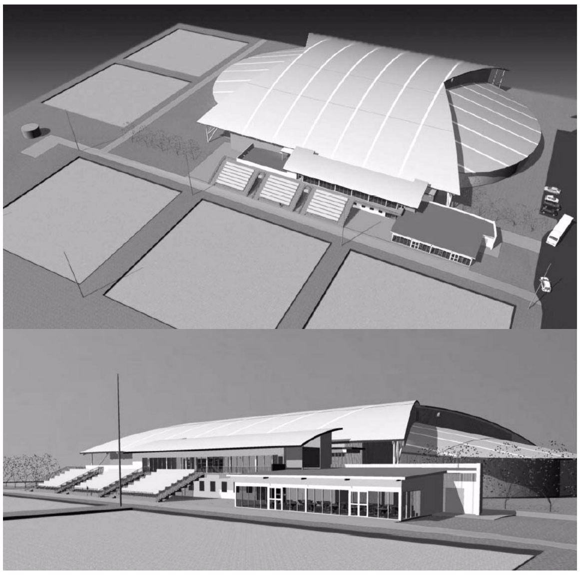
Application of method to case studies

In order to test the use of the input-output-based hybrid analysis, the evaluation techniques are applied to a range of different elements, materials, systems and products and at different levels of detail and depth. Due to the significant environmental concerns on the energy consumption of buildings, the focus of the selection of these items was towards those related directly to buildings. A number of case studies were selected, all of which required a reasonable amount of process data quantities to be available to enable a valid comparison to the equivalent input-output values.

Once the input-output-based hybrid analysis was applied to each case study and the results of the embodied energy analysis determined, the evaluation methods were applied. The results obtained from these evaluations were then used to determine any advantages to using the input-output-based hybrid analysis over traditional embodied energy analysis methods. The quantities of materials used in each of the case studies were determined. Information regarding components, materials, masses, areas and volumes was obtained from various sources. These usually included the architectural plans, specifications and/or bill of quantities, the manufacturers of the various products, or through assumptions where information was unavailable or unknown.

Case study description

The first case study chosen for this study was the Velodrome for the 2006 Melbourne Commonwealth Games. The building is to be constructed in the city of Melbourne, Australia and consists of a two-storey building, with a gross floor area of 8947 m^2, which also includes change rooms, function rooms and spectator seating. The construction of the building incorporates concrete slabs and walls; steel trusses and framing; metal clad roof and external walls; and aluminium windows (Figure 2).



Source: McKerrell Lynch Design, 2002.

Figure 2 View of Velodrome

A number of other case studies have also been used. These have been summarized below and include both residential and commercial buildings, and other building products, such as a washing machine, solar hot water system and building integrated photovoltaics.

Table 1
Building case study details

Case study	No. of storeys	GFA (m^2)	Construction type
Velodrome (1)	2	8947	Steel frame and precast concrete
Commercial building (2)	1	11588	Steel frame and precast concrete
Residential building (3)	1	109	Brick veneer

Table 2
Building product case study details

Case study	Price ($)	Size	Description
Washing machine (4)	1050	5kg	Typical model
Solar hot water system (5)	2986	300L tank, 3.96m^2 collector	Electric boosted, 2 collectors
Building integrated PVs (6)	1560	1.26m^2 (2 x 0.63m^2)	75W c:Si modules

RESULTS

The embodied energy of each of the case studies, using each of the embodied energy analysis methods, is shown below (Table 3 and Table 4), showing both the modified (process analysis) and unmodified (input-output analysis) proportions.

Table 3
Embodied energy of building case studies for each analysis method (GJ/m^2)

	PA (a)	IOA	PBHA	IOBHA		
				Total (b)	% PA value	% IO value
1	10.5	6.8	14.9	16.8	62	38
2	9.0	7.7	14.0	16.4	55	45
3	6.6	5.1	10.2	11.1	59	41

Table 4
Embodied energy of building product case studies for each analysis method (GJ)

	PA (a)	IOA	PBHA	IOBHA		
				Total (b)	% PA value	% IO value
4	3.6	8.1	4.5	6.8	53	47
5	17	23.1	25.7	33.6	51	49
6	7.9	17.5	11.2	14.9	53	47

Table 5 shows the results of the gap analysis for each of the case studies. This gap is expressed as the percentage of completeness of the process analysis value (a) when compared to the input-output-based hybrid analysis values (b) (refer to Table 3 and 4).

Table 5
PA and IOBHA embodied energy gap

Case study	GAP $\left(\frac{b-a}{b}\right)$
Velodrome (1)	38%
Commercial building (2)	45%
Residential building (3)	41%
Washing machine (4)	47%
Solar hot water system (5)	49%
Building integrated PVs (6)	47%

The gap between the process analysis value and input-output-based hybrid analysis value can be up to 50% (Table 5).

Figure 3 shows the results of the comparative analysis for each of the case studies. The initial input-output values for each case study are compared to the modified process analysis values of embodied energy to determine the validity of the input-output values, against the more reliable process analysis values. A logarithmic scale is used to avoid smaller values being lost for the sake of visual comparison. The intent here is not to show a strong correlation, but rather to indicate that the national average input-output data is not always a perfect model for the process analysis data.

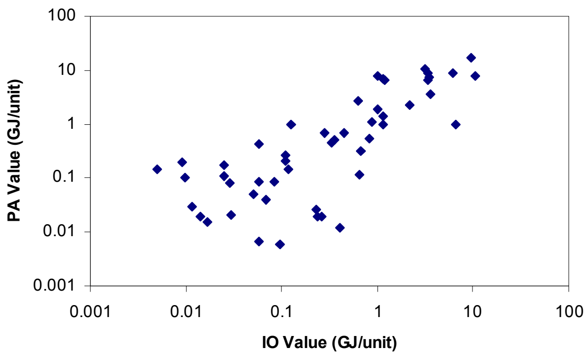


Figure 3 Comparison of input-output values and process analysis values

With the majority of points in Figure 3 being above the left-bottom to right-top diagonal, the initial input-output values are shown to be conservative. The use of input-output data to fill gaps in the hybrid model is also likely to be conservative.

The relatively large discrepancies between the input-output and process analysis methods highlighted in Figure 3 will be substantially resolved by the application of a new input-output model in this year's work on the project. Furthermore, the application of the technique to building material and element level will allow many more data points to be produced and consequently allow a statistical analysis of the results.

CONCLUSION

In this paper, the main embodied energy analysis methods were evaluated across a range of building types and products. The results showed that current methods are sufficient for the data typically available. Input-output-based hybrid analysis is currently the preferred method. The use of the input-output model combined with the process analysis data can assist in determining what process analysis data to collect, and even how much time should be spent on each process. Furthermore, the input-output model can be used to fill gaps in other previous methods.

Further research includes updating the input-output model and adding several more case studies. The new input-output model may lead to improvements in the input-output and hybrid embodied energy analysis methods.

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