Improving the reliability of embodied energy methods for project life-cycle decision making

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Keywords

Energy, Input/output analysis, Buildings, Construction management, Error cause identification

Abstract

Embodied energy is the total amount of energy required to produce a product, and is significant because it occurs immediately and can be equal over the life cycle of a building to the transient requirements for operational energy. Methods for embodied energy analysis include process analysis, input-output analysis and hybrid analysis. Proposes to improve the reliability of estimating embodied energy based on input-output models by using an algorithm to extract systematically the most important energy paths for the "other construction" sector from an Australian input-output model. Demonstrates the application of these energy paths to the embodied energy analysis of an individual commercial building, highlighting improvements in reliability due to the modification of energy paths with process analysis data. Compares materials and elements for the building, and estimates likely ranges of error.

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Introduction

In evaluating and managing the environmental impacts of construction projects, the analysis of embodied energy is an important issue (Stein *et al.*, 1981; Treloar *et al.*, 1999). The embodied energy of a process comprises its direct and indirect energy requirements. The direct energy comprises the energy used directly during the main process. The indirect energy comprises the energy required for the manufacture of inputs of goods and services to the process, and so forth. Basic methods for embodied energy analysis are process analysis, input-output analysis and hybrid analysis.

The direct energy of the construction process can be considered to be a single "energy path", even though there may be many different activities involved and fuels used. The indirect energy may comprise dozens or hundreds of energy paths that are worth quantifying in an embodied energy analysis. Indirect energy paths are crucial for understanding feedback circuits (Mateti and Deo, 1976), and for evaluating greenhouse gas emissions associated with products (West *et al.*, 1994). The effort used to collect energy and other environmental information for a process should be based on an estimate of its relative direct energy value (Treloar *et al.*, 2000a). Input-output analysis provides the basis for such estimates, but is a "black box" and thus lacks reliability.

For many processes required for construction, process analysis data may only need to be collected every few years, if the products are representative and the processes consistent. However, in practice, process analysis data are not always available for all inputs to construction projects. Missing data affect the reliability of embodied energy analyses, because the level of incompleteness may be different for competing materials, construction systems or design options. An input-output model provides these missing data for a hybrid analysis, but only if it is disaggregated into energy paths.

The aim of this paper therefore is to demonstrate methods for assessing and improving the reliability of embodied energy

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assessments of individual construction projects, especially pertaining to the issue of missing data. An algorithm for systematically extracting energy paths from the input-output model is presented.

Embodied energy analysis methods

Methods for embodied energy analysis can be classified as:
- process analysis;
- input-output analysis; and
- hybrid analysis (Bullard *et al.*, 1978).

In the process analysis method, most effort is typically directed towards the main process, and hence little time is spent evaluating indirect energy paths (Boustead and Hancock, 1979). However, the focus for construction projects is generally the main building material manufacturing processes, rather than the direct energy of the construction process (Alcorn, 1996). Although process analysis methods are often accurate, they are inevitably incomplete in system boundary, to some degree.

Input-output tables comprise flows between sectors of an economy. Input-output analysis is capable of representing extremely complex networks that some have considered impossible to analyse in terms of discrete "flows" (Patten and Higashi, 1995). However, it is subject to errors relating to the use of national economic statistics to model physical activities (Bullard *et al.*, 1978; Pullen, 1998; Lenzen, 2000).

All direct and indirect energy paths in the input-output model are summed by the matrix inversion process (Leontief, 1966). While this is a positive aspect in terms of system boundary completeness, it is a negative aspect in terms of transparency.

Hybrid analysis methods involve the combination of the two methods discussed above to form two distinct methods:
(1) process-based hybrid analysis; and
(2) input-output-based hybrid analysis (Treloar, 1997).

The intention of both hybrid analysis methods is to reduce the errors associated with either of the two original methods on which they are based. However, the problems inherent to each of the original methods tend to remain to some degree in the associated hybrid analysis methods.

Process-based hybrid analysis methods tend to be incomplete, due to typical exclusions associated with the process analysis framework, including:
- small items;
- processes required to support the main processes, but that are not an obvious part of the main flow of raw materials evident in the finished product;
- processes involving the transformation of basic materials into complex products;
- services, such as banking and insurance; and
- some non-feedstock components of the energy embodied in fuels and energy supplies (Bullard *et al.*, 1978; Treloar *et al.*, 2000a).

For example, Alcorn (1996) used input-output data to complete the upstream system boundary of the inputs of some products used in the manufacture of steel products, but missed many of the above processes entirely.

Input-output-based hybrid analysis methods are varied. One involves substituting process analysis data into the direct input-output matrix prior to deriving total energy intensities using the Leontief inverse input-output matrix (Bullard *et al.*, 1978). However, this can result in unwanted flow-on effects where data that may represent the purchase of one product are assumed to apply to all other indirect purchases from that sector. This is only an acceptable assumption in trivial cases, where the indirect purchases are near zero in total value.

Other variations of input-output-based hybrid analysis involve the use of process-based hybrid analysis models and input-output models in parallel, but the process-based hybrid analysis is guided using a framework based on input-output analysis (e.g. Vringer and Blok, 1995).

However, the same problems arise for these two variations of input-output-based hybrid analysis as for previously discussed process-based methods. The main issue is the lack of an objective method of selecting and prioritising energy paths for which process analysis data are to be derived. A key deficiency in previous input-output-based hybrid analysis methods is thus that the input-output model is a "black box". Important energy paths in the input-output model cannot be substituted with process analysis data without unwanted flow-on effects.

Stein *et al.* (1981) suggested that input-output models could be disaggregated into discrete energy paths (without providing a method for doing so), but failed to apply the concept to input-output-based hybrid analysis. An algorithm for systematically identifying important energy paths for the Australian residential building construction sector was developed by Treloar (1997). However, this algorithm has not yet been applied to the Australian "other construction" sector, nor used in the input-output-based hybrid analysis of a commercial building. Before demonstrating this algorithm on the Australian "other construction" sector, the issue of input-output model decomposition is first elucidated.

Input-output model decomposition

An input-output table maps the relationships between compartments of a system (Miller and Blair, 1985). They have been used by many researchers for embodied energy analysis of sectors of national economies (Stein *et al.*, 1981), and for the derivation of embodied energy data for building materials using process-based hybrid analysis (Alcorn, 1996). Process analysis is subject to gross incompleteness, process-based hybrid analysis is incomplete in system boundary and input-output analysis is a "black box", subject to many inherent errors. Input-output-based hybrid analysis is the preferred method, but requires the dissagregation of the input-output model so that:

- the collection of process analysis data can be objectively prioritised; and
- process analysis data can be integrated without unwanted flow-on effects.

There are two types of input-output tables commonly used in input-output embodied energy analysis methods:

(1) direct input-output matrices; and
(2) Leontief inverse input-output matrices.

Elements of the direct input-output matrix (also known as the direct requirements coefficients matrix) represent the amount of the "row" sector in dollars required directly to make each dollar of output of the "column" sector (for example, cement required for concrete manufacture). There are 113 sectors in the Australian economy. Every sector requires energy directly from at least one of the energy supply sectors (ABS, 1996). Using average energy tariffs, quantities of energy consumed directly by any sector of the economy can be estimated (Miller and Blair, 1985).

Energy paths can be traced manually through the direct input-output matrix, but this is time consuming (Ulanowicz, 1983). More conveniently, the Leontief inverse input-output matrix (also known as the total requirements coefficients matrix) gives the sum of the direct and indirect energy paths. A direct input-output matrix (A) has a Leontief inverse, $(I\text{-}A)^{-1}$, where I is the identity matrix (Miller and Blair, 1985). The indirect requirements are determined by deduction of the direct requirements from the total requirements, and theoretically represent the sum of an infinite series of upstream inputs (Leontief, 1966).

The "power series approximation" of the Leontief inverse input-output matrix derives practically identical results to the Leontief inverse input-output matrix (Miller and Blair, 1985), but the sum of the energy paths at each upstream stage can be disaggregated horizontally (as demonstrated in equation (1)). This allows the direct impact of all processes at each upstream stage to be evaluated. However, the results given by the power series approximation are still vertically a "black box". They also need to be disaggregated within each upstream stage into energy paths. As suggested by equation (1), an individual stage 3 energy path (involving a series of transactions between the sectors k into j into i into n) can be represented by $D_{in}.D_{ji}.D_{kj}.\varepsilon_k$.

$$X_n = \varepsilon_n + \sum_{i=1}^{N} D_{in}\left[\varepsilon_i + \sum_{j=1}^{N} D_{ji}\left[\varepsilon_j + \sum_{k=1}^{N} D_{kj}[\varepsilon_k + ...]\right]\right], \quad (1)$$

where: $n, i, j, k, \ldots$ are any stage 0, 1, 2, 3, ... sector respectively, and:

X_n = the total energy intensity of the target sector, n;
ε_n = the direct energy intensity of the target sector, n, and so forth;
N = the total number of sectors in the economy (equal for $i, j, k, \ldots$); and
D_{in} = the direct input of i into n, and so forth (for j into i, k into j, ...).

In the 113-sector Australian economy, there are an average of 90 non-zero coefficients in each column of the direct input-output matrix

(ABS, 1996). The number of energy paths at each stage is an exponent of the number of the upstream stage. Therefore, for any sector in the Australian economy, the number of potentially important energy paths up to stage 5 would be approximately six billion (equation (2)).

$$(90)^0 + (90)^1 + (90)^2 + (90)^3 + (90)^4 + (90)^5 = 5,971,247,191. \quad (2)$$

However, this is only an approximation of the actual number of potentially important energy paths (despite the apparent accuracy of the result given by equation (2)), because:

- the number of non-zero coefficients in the columns of the direct input-output matrix for particular sectors may vary; and
- almost all of these non-zero energy paths will be near-zero in value.

Since the sum of the energy path values at stage 5 can be significant (determined using the power series approximation (Miller and Blair, 1985)), all non-zero energy paths of up to this length should be evaluated in the search for the most important energy paths. It is unlikely that any energy paths beyond stage 5 will be individually important, even in sectors with complex upstream supply chains. Given the exponentially increasing number of potentially important energy paths at each subsequent upstream stage, eventually the point is reached where all potentially important paths can not be extracted manually. Patten and Higashi (1995) doubted that this could be done for a reasonable number of upstream stages, even using computer algorithms for input-output models of only five sectors.

Energy paths extracted from an input-output model are an appropriate basis for hybrid analysis because they represent the finest level of disaggregation of Leontief inverse input-output model. Thus, energy paths are mutually exclusive. They can therefore be substituted with process analysis data without unwanted flow-on effects through the input-output model. For example, the energy intensity of the type of road transport used directly by construction can be modified without affecting the energy intensity of road transport used in other energy paths upstream from construction.

Process analysis data are generally acknowledged to be more reliable than input-output data, especially for representing specific products (Boustead and Hancock, 1979; Bullard *et al.*, 1978; Pullen, 1998). The reliability of embodied energy analyses can thus be improved through the substitution of energy paths extracted from the input-output model with process analysis data (i.e. either direct energy intensities or product quantities).

It is possible to integrate process analysis data into the input-output model manually, but it is difficult to decide objectively which process analysis to collect because the input-output model is a black box. Therefore, the most important energy paths need to be extracted systematically from the input-output model.

An algorithm for the systematic extraction of energy paths

The algorithm developed for the extraction of energy paths from the input-output model (initially by Treloar (1997)) sorts through potentially important energy paths in a "depth-first" manner (Ulanowicz, 1983), as opposed to a "brute-force" manner (see Figure 1). As discussed by Mateti and Deo (1976), the number of paths needing to be extracted can be greatly reduced by pruning branches of inquiry which can be shown *a priori* to be "futile". This pruning process is depicted in the "depth-first" method in Figure 1 by the small vertical lines at the end of each branch. Owing to the pruning method, the "exponential" computational problem (defined in equation 2) was reduced to a "geometric" problem, and thus computational time was eliminated as a consideration.

The definition of futile depends on circumstances. In this case, the pruning method involved comparing the total energy intensity value of each path to an arbitrarily selected "threshold value". The most important energy paths in direct energy terms were then identified by comparing them to the threshold value, because some sectors have high proportions of indirect energy (for example, the indirect energy of concrete is 92.7 per cent of the total). The pruning of futile branches is expressed as a flow diagram in Figure 2, but only the calling of the stage 2 routine from the stage 1 routine is depicted. Further stages are called as required, based on whether the total energy intensity value of the energy path under consideration is greater than the threshold value.

Figure 1 "Brute force" and "depth first" methods of systematically sorting nodes in networks

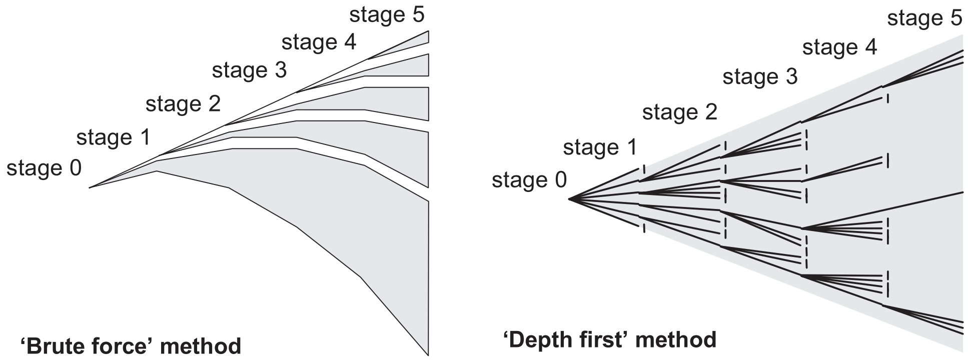
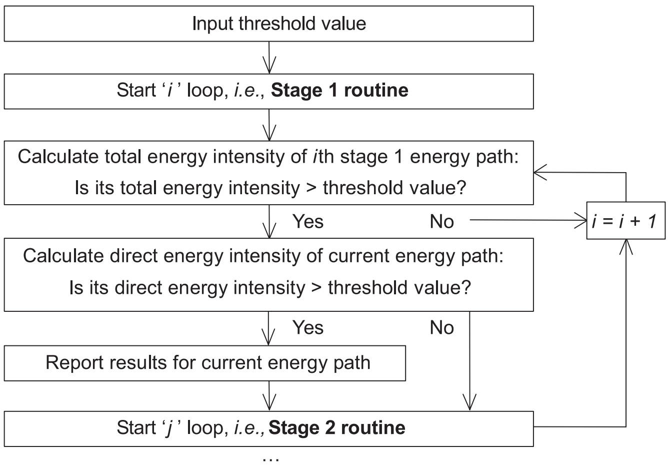


Figure 2 Algorithm for pruning futile branches of inquiry, stage 1 routine



The algorithm could continue upstream indefinitely, but, the power series approximation results for the "other construction" sector indicated that the limit could be somewhere between stages 3-5, depending upon the level of detail desired. Pruning can occur at any stage in the input-output model. The facility in the algorithm for choosing an arbitrary threshold value, combined with the capacity for rapid repetition of the algorithm facilitated by the pruning of futile branches of inquiry, provides considerable flexibility. The use of yet smaller threshold values will result in more detailed sets of paths being returned.

Energy paths for the Australian "other construction" sector

In this section, energy paths for the "other construction's" sector are extracted from an Australian input-output model. The input-output model used was based on the 1992-1993 direct requirements coefficients matrix (ABS, 1996). It was derived using fixed, national average energy tariffs and primary energy factors, with energy supply sector purchases truncated to avoid double counting (described more fully in Treloar (1997)). The primary energy factors and energy tariffs used are listed in Table I.

Based on the input-output model described above, the total energy intensity of the "other construction" sector was 0.618 GJ/$100. By trial and error, the most important energy paths giving exactly 90 per cent of the total energy intensity were extracted using a threshold value of 0.00002475GJ/$100, which represented 0.004 per cent of the total energy intensity (summarised in Table II). There were 863 such energy paths.

The direct energy intensity (i.e. the single energy path at stage 0) was 0.154GJ/$100 (representing 24.9 per cent of the total energy intensity for the "other construction's" sector). This was the most important energy path. The energy used directly in the manufacture of cement used in concrete manufacture (i.e. a stage 2 energy path) was the second most important energy path at 0.0461GJ/$100 (representing 7.5 per cent of the total, which is not ascertainable from Table II). The third most important energy path was road transport, representing 3.7 per cent of the total. The next three important energy paths were:

(1) ceramic products (3.0 per cent of the total);
(2) iron and steel (3.0 per cent of the total); and
(3) other property services (2.9 per cent of the total).

Further listings of the most important energy paths giving 90 per cent of the total energy intensity of "other construction" are not desirable at this point, due to their complexity. Energy paths for "other construction" modified and unmodified with process

Table I Energy tariffs and primary energy factors for the Australian input-output model, 1992-1993

	Energy supply sectors			
	Coal, oil and gas	Petroleum, coal products	Electricity supply	Gas supply
Energy tariffs (GJ/$)	0.425	0.156	0.039	0.322
Primary energy factors	1.2	1.4	3.4	1.4

Table II Summary of the most important energy paths giving 90 per cent of the total energy intensity, by upstream stage, for the Australian "other construction" sector, 1992-1993

	Upstream stage						
	0	1	2	3	4	5	Total
Number of energy paths	1	69	447	274	65	6	863
Proportion of total energy intensity (%)	24.9	30.5	29.0	4.94	0.63	0.03	90.0

analysis data in the commercial building case study are discussed later in this paper.

Figure 3 illustrates as an "energy path tree", the 863 most important energy paths for the Australian "other construction" sector (i.e. those required to describe 90 per cent of the total energy intensity). The purpose of this diagram is to map the energy paths into sector groups and upstream stages. Each energy path comprises a product quantity value (on the x-y plane) and a direct energy intensity value (on the z-axis).

The horizontal x-axis of Figure 3 categorises the 113 Australian sectors into eight groups:
(1) primary production (15 sectors);
(2) food and drink (12 sectors);
(3) textiles (seven sectors);
(4) other manufacturing (30 sectors);
(5) capital equipment and construction (18 sectors);
(6) trade and repairs (five sectors);
(7) transport and communication (six sectors); and
(8) financial and other services (20 sectors).

Stages of upstream transactions up to stage 5 are represented on the diagonal y-axis of Figure 3. The x-axis "tickmarks" are extended parallel to the diagonal y-axis, to aid visual evaluation of the location of energy paths in the various sector groups, listed above. The tickmarks on the vertical z-axis coincide with the horizontal tickmarks on the y-axis, so that energy path values for energy paths at stages 1 to 5 can be read more easily.

The purpose of Figure 3 was to demonstrate the complexity of energy paths of varying lengths and their extent across the whole economy. There were a few energy paths extending to stage 5. At least one energy path was represented in each of the eight sector groups, including "food and drink". This seems impossible, but if a construction establishment paid for goods and services from this sector, then the energy embodied in those products is included in the total energy requirements automatically in the input-output model. The system boundary of the input-output model is thus economic, rather than physical (as in the process analysis method). There were also a large number of energy paths in the "financial and other services" sector group, which was not expected.

Commercial building case study

The input-output-based hybrid analysis method is demonstrated in this section for an individual commercial building, based on energy paths for the Australian "other construction" sector. The case study building was a typical 15-storey Melbourne commercial building, with a reinforced concrete substructure and frame, and a gross floor area (GFA) of 47,000m^2. The cladding was mainly granite veneer with aluminium-framed windows. The function of the building was mainly offices, with some retail space, and several under- and above-ground car-parking levels.

The building was previously analysed using a process-based hybrid analysis method in Treloar (1996), however the results are not directly comparable to this study due to discrepancies between the data and methods used. Nevertheless, the product quantities could be re-used for an input-output-based hybrid analysis in this study.

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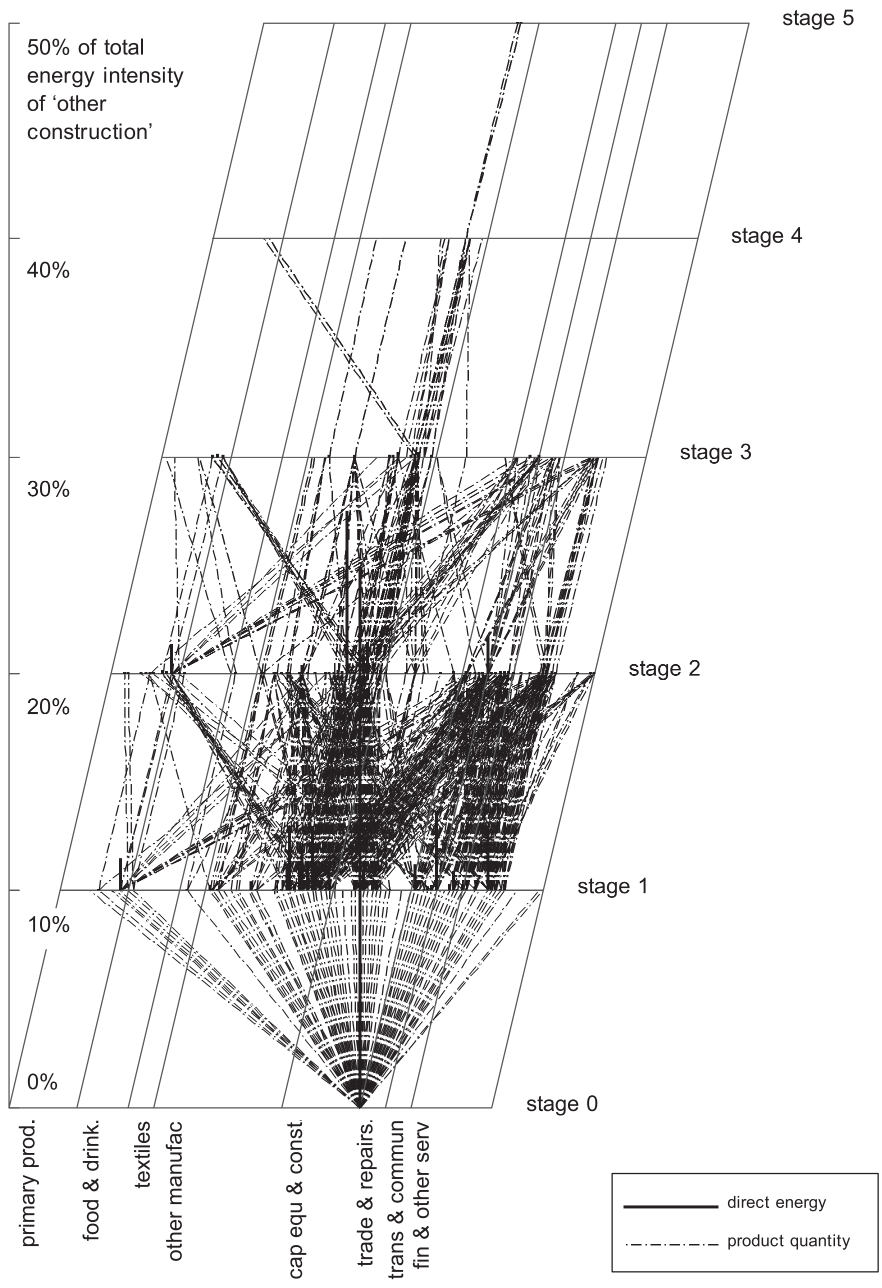
Figure 3 Most important energy paths for the Australian "other construction" sector, giving 90 per cent of the total energy intensity, 1992-1993



Quantities for the various materials required for the construction of elements of the building were derived from a bill of quantities, comprising 2,000 items. In some cases, quantities were derived directly from the bill of quantities, such as cubic metres of concrete and tonnes of steel. In other cases, the quantities had to be manipulated to allow correlation to the units of the embodied energy values. For example, quantities of windows of a certain size had to be converted to square metres of glass sheet, tonnes of aluminium framing and so forth.

All elements of the building were analysed, including substructure, walls, roof, finishes, fitments, services and external (NPWC, 1980). Most of the services elements were given in the bill of quantities as "prime cost" items, and construction documents had to be consulted to enable product quantities for these elements to be derived.

Process analysis data for the direct energy intensities of building material manufacturing processes were derived from various sources (Table III). In some cases, assumptions were required, for example, for the thicknesses of certain materials or the raw material content.

The materials in some cases included a limited range of upstream processes, such as main raw material extraction and transport.

The direct energy intensity, total energy intensity and energy path results for the "other construction" sector were applied to the individual commercial building using an assumed price of 1,200$/m^2 GFA. The pure input-output embodied energy total for the building was given by the product of the building price and the total energy intensity of the "other construction" sector: i.e. 7.41GJ/m^2 GFA. This value is comparable to previous embodied energy studies of commercial buildings (e.g. Treloar, 1996), despite methodological discrepancies.

The input-output-based hybrid analysis of the case study building comprised subtracting the input-output values for the modified energy paths from the total energy intensity for the building derived from the input-output model, and adding the remainder to the sum of the modified energy path values (equation (3)). The energy paths subtracted from the input-output model to make way for the process analysis data listed in Table III are listed in the Appendix. They are analysed in the discussion section of this paper.

$$\mathrm{TEI_{HA}} = \mathrm{TEI_{IO}} - \sum_{n=1}^{N} [\mathrm{DEP}_n - \mathrm{PA}_n] \quad (3)$$

where:

$\mathrm{TEI_{HA}}$ = hybrid analysis total energy intensity for the building;
$\mathrm{TEI_{IO}}$ = input-output analysis total energy intensity for the building;
DEP_n = the input-output values for the modified energy paths, n; and
PA_n = the modified values for the modified energy paths, n.

The proportion of the total embodied energy of the building modified by the integration of process analysis data was also determined (i.e. the "modified proportion"). Equation (4) was used for energy paths where only the product quantity was derived using process analysis. The direct energy intensity value of such energy paths was halved in equation (4), thus giving a 50 per cent weighting to the product quantity components of these energy paths. This weighting was based on the equal sensitivity of the direct energy value of an energy path to both the product quantity and direct energy intensity components of that energy path:

Table III Process analysis data derived for case study analysis

Material	Unit	Embodied energy (GJ/unit)	Source
Concrete	m^3	0.4	RMIT Centre for Design (2000)
Cement	t	11.2	RMIT Centre for Design (2000)
Glass	t	16.4	RMIT Centre for Design (2000)
Aluminium	t	225.6	RMIT Centre for Design (2000)
Plastic	t	73.6	RMIT Centre for Design (2000)
Steel	t	77.0	RMIT Centre for Design (2000)
Hardwood timber	t	0.9	RMIT Centre for Design (2000)
Softwood timber	t	1.7	RMIT Centre for Design (2000)
Clay bricks	m^2	0.75	Wagner (1995)
Concrete blocks, hollow 200mm	m^2	0.21	Alcorn (1996)
Concrete roofing tiles	m^2	0.03	Alcorn (1996)
Water-based paints	m^2	0.014	Alcorn (1996)
Oil-based paints	m^2	0.016	Alcorn (1996)
Tile, ceramic	m^2	0.29	Alcorn (1996)
Carpet, nylon	m^2	0.804	Hamilton and Sutcliff (1996)
Carpet, wool	m^2	0.217	Alcorn (1996)
Copper	t	70.6	Alcorn (1996)
Plasterboard	m^2	0.035	Alcorn (1996)
Fibreglass insulation, R2.5	m^2	0.097	Alcorn (1996)
Polystyrene, 50mm	m^2	0.117	Alcorn (1996)
MDF/particleboard	m^3	15.14	Alcorn (1996)

Note: The embodied energy figures in this table do not include the input-output components added through hybrid analysis. The sources are identified fully in the references section

$$MP = \frac{DEI_{IO}}{2 \times TEI_{IO}}, \quad (4)$$

where:

- MP = the modified proportion (i.e. for the "product quantity" component);
- DEI_{IO} = the direct energy intensity derived using input-output analysis; and
- TEI_{IO} = total energy intensity derived using input-output analysis.

Equation (5) was used for calculating the modified proportion for energy paths where process analysis data (i.e. both direct energy intensities and product quantities) were derived for various direct, and in some cases indirect, energy paths. There were no energy paths where only direct energy intensities and no product quantities were derived. Thus, the energy path values did not have to be weighted for product quantity and direct energy-intensity components in the manner described for equation (4).

$$MP = \frac{\sum_{n=1}^{N} [DE_n]}{TEI_{HA}}, \quad (5)$$

where:

- MP = the modified proportion of the energy path under consideration;
- DE_n = the direct energy value of modified energy paths, n; and
- TEI_{HA} = hybrid analysis total energy intensity of the energy path under consideration.

The modified proportion for the entire building was then calculated according to equation (6). The modified proportions of the individual energy paths, n, were given by either equation (4) or equation (5).

$$MP_{BLDG} = \frac{\sum_{n=1}^{N} [MP_n \times EE_{HA}n]}{EE_{HA}BLDG}, \quad (6)$$

where:

- MP_{BLDG} = the modified proportion for the entire building;
- MP_n = the modified proportion of energy paths, n, from 1 to N;
- $EE_{HA}n$ = the hybrid analysis total embodied energy of energy paths; and
- $EE_{HA}BLDG$ = total hybrid analysis embodied energy of the entire building.

Table IV gives a summary of the embodied energy results for the material groups used in the commercial building case study, including process analysis and input-output analysis components. As there were over 40 individual materials used, the material groups were required. The "other" material group included energy paths for which process analysis data were not derived, such as the direct energy of construction and inputs of financial and other services.

The sum of the process analysis data derived for the commercial building case study was 12.18GJ/m^2 GFA. This is the value that would have been derived by a pure process analysis (i.e. using no input-output data whatsoever).

The sum of the input-output data added for the items that were quantified using process analysis data was 2.88GJ/m^2 GFA. This is the value that would have been added to the pure process analysis result above in a process-based hybrid analysis (bringing the total to 15.06GJ/m^2 GFA). The input-output data comprised 19.1 per cent of the process-based hybrid analysis total. This is the truncation error solved by the application of the process-based hybrid analysis method, compared to a pure process analysis.

The sum of the input-output values of energy paths not modified in the process-based hybrid analysis was 2.33GJ/m^2 GFA, bringing the input-output-based hybrid analysis total to 17.38GJ/m^2 GFA. Thus, the truncation error of the process-based hybrid analysis, compared to the input-output-based hybrid analysis, was 13.4 per cent.

These two truncation errors are not addable, due to the revision of the total in each case. However, the process analysis component above (i.e. 12.18) can be divided by the input-output-based hybrid analysis total (i.e. 17.38GJ/m^2 GFA) to give the overall modified proportion for the entire building (i.e. 70.0 per cent). The input-output data comprised the corollary figure (i.e. 30.0 per cent). Therefore, if input-output analysis was not used in the study, the result would have been 30 per cent lower. This would significantly affect comparisons between materials and elements, and comparisons of the embodied energy with the operational energy, and other phases of the life-cycle energy requirements of the building. The modified proportion varied between building materials and elements (analysed in

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Table IV Embodied energy results for commercial building, by material group

Material group	Embodied energy (GJ/m^2 of GFA) Process analysis component (A)	Input-output component (B)	New hybrid analysis total (A + B)
Steel products	8.87	2.14	11.01
Concrete products	2.27	0.34	2.61
Aluminium products	0.47	0.01	0.48
Copper	0.16	0.15	0.31
Carpet	0.13	0.12	0.25
Plastic products	0.14	0.05	0.19
Plasterboard	0.04	0.01	0.05
Glass sheet	0.03	0.02	0.05
Ceramic products	0.02	0.02	0.04
Insulation	0.01	0.01	0.02
Paint	0.01	0.00	0.02
Timber products	0.01	0.00	0.01
Others	0.00[a]	2.33	2.33
Total	12.18	5.20	17.38

Note: Only the single item indicated by [a] actually had a zero value. Others that are apparently zero have been obscured by rounding. Input-output components were derived from the entire input-output model (by deduction of the input-output values of the modified energy paths from the input-output total energy intensity), not just the energy paths giving 90 per cent of the total energy intensity of the "other construction" sector

the next section), and was crucial to the reliability of comparisons.

Assessment of reliability for the commercial building case study

By assuming error rates for the process analysis data and input-output analysis, high and low values were able to be derived for the materials and elements in the case study building. The error rate assumed for the process analysis data was a flat rate of ±10 per cent (based on information in Boustead and Hancock (1979), while for the input-output analysis data a flat rate of ±50 per cent was assumed (based on information in Bullard *et al.* (1978); Pullen (1998); Lenzen (2000)). This is a fairly crude assessment of reliability, but serves to give a measure of the comparative ranges of error for the mix of process analysis and input-output analysis data in a hybrid analysis figure.

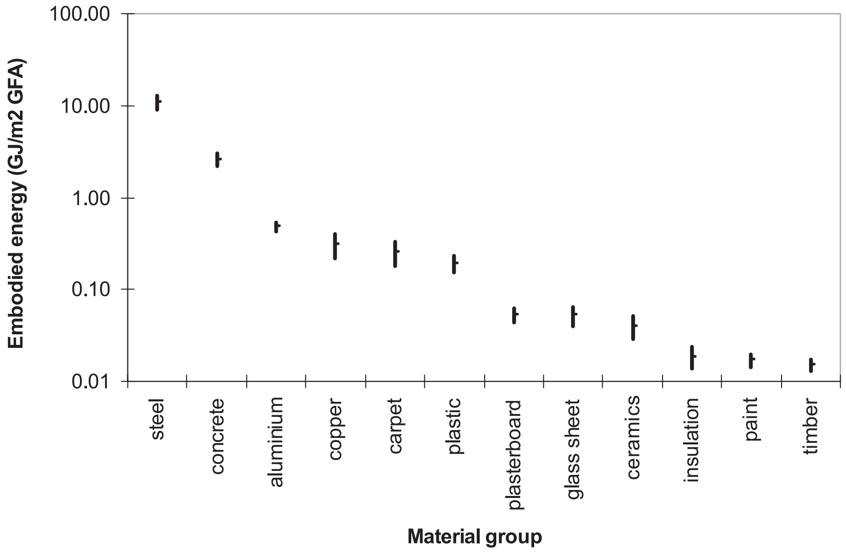
Figure 4 gives the embodied energy results for the commercial building case study, by material group, with error bars. The material groups were arranged in descending order, by initial embodied energy value (i.e. not accounting for error ranges). A logarithmic scale was used for the *y*-axis, so that the smaller materials are visible. This tended to reduce the apparent absolute value of the error bars, but the relative comparisons between error ranges for adjacent material groups remain valid. For example, the error bars for the first four material groups (steel, concrete, aluminium and copper) were sufficiently separate to indicate that, with expected variability and errors in the embodied energy data, the rankings of these four were not affected. Conversely, the fifth material group, carpet, overlapped the fourth, copper. Expected variations in embodied energy values could well have caused a change in ranking of these two particular material groups, possibly altering priorities for the development of design optimisation strategies based on this information. Note that the error ranges varied significantly between material groups.

However, analysis by material does not adequately model a building and its systems. Elemental analysis is also required, to enable more fundamental design optimisation strategies to be developed.

Table V gives the embodied energy results for the commercial building case study, by element group, based on the NPWC (1980) classifications. In each case, the high and low values are given, based on the error ranges for the proportions of process analysis and input-output analysis data (as outlined above).

Figure 5 gives the embodied energy results for the commercial building case study, by

Figure 4 Embodied energy results for commercial building, by material group, with error bars



Note: The y-axis of this figure is logarithmic, to enhance clarity (but the error bars appear to be more compressed than they are)

Table V Embodied energy results for commercial building, by element group

	Embodied energy (GJ/m^2 GFA)		
Element group	**High value**	**Low value**	**Initial value**
Upper floors	6.75	4.78	5.77
Services	3.90	2.67	3.28
External walls	3.44	2.45	2.95
Internal walls	1.37	0.98	1.18
Substructure	1.37	0.97	1.17
Finishes	0.67	0.42	0.54
Roof	0.12	0.08	0.10
Fitments	0.06	0.04	0.05
External	0.04	0.02	0.03

Note: This table includes only the elements measured in the bill of quantities, and excludes items otherwise included from the input-output model, such as the direct energy of construction. High and low values were based on error ranges for process analysis data of ±10 per cent and for input-output analysis data of ±50 per cent

element group, based on the NPWC (1980) classifications, with error bars based on high and low values as outlined in the previous paragraph. The element groups are arranged in descending order, by initial embodied energy value (i.e. not taking into account error ranges). The distribution of embodied energy by element group is much flatter than the distribution by material group, probably because each element comprised a range of materials, in various combinations. Similarly, the error ranges in the elemental analysis are more consistent than the material analysis.

The error bars in Figure 5 highlight where pitfalls can occur in comparing elements of the building. For example, the error bars for the element groups upper floors and services did not overlap, indicating that there was a significant difference between these element groups. On the other hand, the error bars for the second and third element groups services and external walls overlapped considerably. Thus, even though the initial value for services was 11 per cent higher than the initial value for external walls, this difference was not significant in terms of the likely error ranges.

Discussion

The energy path results for any sector are dependent upon the quality of the initial input-output model. Energy paths extracted from the input-output model will never be completely reliable because input-output models are inherently unreliable, particularly when used to analyse specific cases such as individual buildings. Therefore, regardless of the quality of the initial input-output model, the integration of case specific data into the input-output framework will always increase the reliability of its application to an individual building. Improvements nonetheless are required to the input-output model, including but not limited to:

- the derivation of variable energy tariffs (i.e. a set for each sector);
- the derivation of more reliable and comprehensive primary energy factors; and

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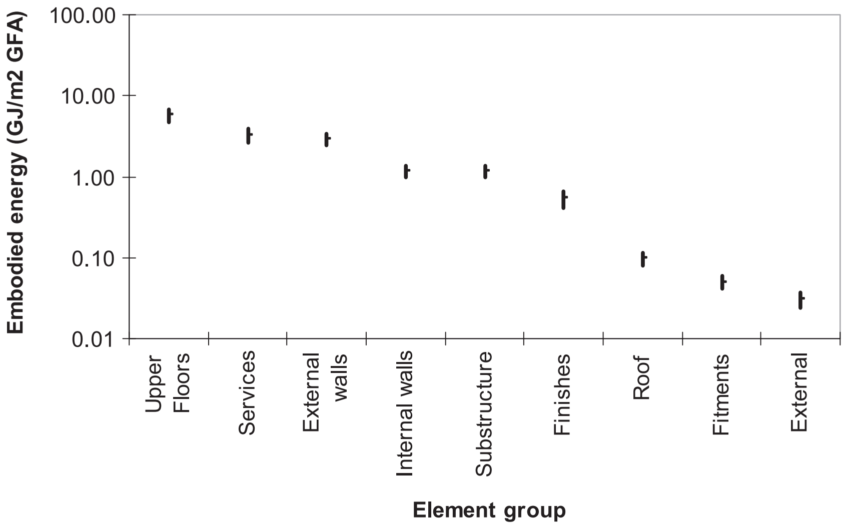
Figure 5 Embodied energy results for commercial building, by element group, with error bars



Note: The y-axis of this figure is logarithmic, to enhance clarity (but the error bars appear to be more compressed than they are)

- improvements to treatment of the energy embodied in capital equipment.

The "other construction" sector comprises construction of all non-residential buildings (including commercial buildings) and all non-building construction (such as civil engineering structures). Despite this diversity, the energy paths for this sector can be used to complete the system boundary of an embodied energy analysis of a commercial building, because there is no other source for these data. Otherwise the embodied energy results could be 30 per cent incomplete. This rate could vary for different materials or elements in the building, potentially causing comparisons between competing design options to be invalid. Therefore, despite the inherent errors, the inclusion of input-output data for missing items in a process analysis will always increase the reliability.

Furthermore, input-output estimates of energy paths for which there are currently no process analysis data are useful for prioritising the collection of process analysis data, regardless of their accuracy. Unmodified energy paths for the commercial building case study comprised the following types of processes:

- the direct energy of construction;
- some direct and indirect uses of various forms of transport;
- financial and other services;
- mechanical repairs; and
- the transformation of basic materials into complex products.

Although the error analysis method used herein was relatively simplistic, it is sufficiently sophisticated to indicate whether a comparison may be valid. Furthermore, the data required for a more sophisticated error analysis are not available. Treloar (1996) used Monte Carlo analysis to simulate error ranges, and found similar results as those found herein. However, the more sophisticated analysis was based on the same type of embodied energy data used herein – which is not statistically reliable enough for deriving the "probablity distributions" required for Monte Carlo analysis.

The commercial building assessed in this paper was previously analysed using a process-based hybrid analysis method in Treloar *et al.* (1999). The context there was the life-cycle energy requirements of the building, which included:

- initial embodied energy, including direct energy of construction;
- operational energy, including heating, cooling, ventilation, lighting, and lifts;
- energy embodied in maintenance and refurbishment; and
- energy embodied in initial and replaced items of furniture and fitout.

In Treloar *et al.* (1999), it was found that the initial embodied energy of the case study building was 9.48GJ/m^2 GFA. This is 22.2 per cent lower than the pure process analysis result found herein, 37.0 per cent lower than the process-based hybrid analysis result found herein, and 45.5 per cent lower than the

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input-output-based hybrid analysis result found herein. This discrepancy is probably due to increases in the number of process analysis data derived, and recent changes in the process analysis values (Table III).

In Treloar *et al.* (1999), the truncation error between the process-based hybrid analysis and input-output-based hybrid analysis methods was estimated to be 20 per cent. In this paper it was found to be 13.4 per cent. This figure comprises energy paths for which no process analysis data are available. However, since the pure input-output figure for the building (of 7.41GJ/m^2 GFA) was more than doubled due to the integration of process analysis data, it can be surmised that the result of 13.4 per cent may be conservative.

Incidentally, Stein *et al.* (1981) found a pure input-output figure for commercial building construction in the USA of 18.6GJ/m^2 GFA, which was 2.5 times higher than that found in this paper. Possible reasons for this discrepancy include that:

- the US input-output tables have more sectors than the Australian tables;
- since the late 1970s (the period when the US input-output data used by Stein *et al.* (1981) were derived), manufacturing processes may have increased their efficiency;
- the Australian "other construction" sector includes other non-residential building construction and non-building construction (as noted above), possibly causing errors in the pure input-output total for Australia; and
- there may be differences in the type of input-output energy analysis methods used, for example, in the treatment of primary energy, the energy embodied in fuels.

In Treloar *et al.* (1999), the operational energy of the building was estimated to be 0.4GJ/m^2 GFA per annum in primary energy terms. Thus, the period of time taken for the operational energy to become equivalent to the initial embodied energy calculated herein using input-output-based hybrid analysis was over 43 years. However, this building was a relatively efficient building, and Melbourne's climate is relatively benign (Treloar *et al.*, 2000b), so this result is not expected to be representative of other cases.

The energy embodied in maintenance and refurbishment activities was found by Treloar *et al.* (1999) to be 3.13GJ/m^2 GFA over a 40-year period. This added a further 33.0 per cent to the initial embodied energy found therein. If this rate is applied to the input-output-based hybrid analysis result found herein, the initial embodied energy would have increased by 5.74GJ/m^2 GFA over the same 40-year period.

The life-cycle energy embodied in furniture and fitout items was also modelled by Treloar *et al.* (1999), and was found to comprise a small proportion of the initial embodied energy (1.5GJ/m^2 GFA) but a much larger proportion of the life-cycle embodied energy of the building (i.e., including the energy embodied in maintenance and refurbishment activities, 9.9GJ/m^2 GFA over the 40-year period), equal to 104 per cent of the initial embodied energy. If this rate is applied to the input-output-based hybrid analysis result herein, the energy embodied in furniture would be 20.20GJ/m^2 GFA over a 40-year life cycle.

The total life-cycle energy in input-output-based hybrid analysis terms over a 40-year period would now comprise:

- initial embodied energy (17.38GJ/m^2 GFA);
- operational energy (16.0GJ/m^2 GFA);
- maintenance and refurbishment embodied energy (5.74GJ/m^2 GFA); and
- initial and replaced furniture (20.20GJ/m^2 GFA).

Items requiring embodied energy analysis (i.e. all but the operational energy) thus comprise 73 per cent of the total life-cycle energy of the building over a 40-year period.

Conclusion

This paper has demonstrated methods for assessing and improving the reliability of embodied energy assessments of individual construction projects. An input-output-based hybrid analysis was performed for a typical Melbourne commercial building, based on energy paths extracted from the Australian input-output model for the "other construction" sector. Process analysis data for building material manufacturing processes were also integrated into the input-output model, thus removing the potential for gross errors inherent to input-output analysis.

The total embodied energy of the building was found to be 17.4GJ/m^2 of gross floor area. This figure comprised 70 per cent process analysis data, including the derivation of quantities of building materials and products for the construction of the building. The corollary figure, 30 per cent, comprised input-output data that would have significantly reduced the embodied energy found for some items. Therefore, the inclusion of input-output analysis data improved the reliability of the embodied energy analysis.

An analysis of the energy paths not modified with process analysis data in the hybrid analysis of the commercial building case study revealed that process analysis data need to be derived for several types of processes in order to improve further the reliability of construction project embodied energy assessments. These include the direct energy of the construction process, direct and indirect requirements for transport, financial and other services, and the transformation of building materials into complex products. Further improvements to the input-output model are also required.

The building was also analysed in terms of its life-cycle energy requirements over a 40-year period, including maintenance, operation, refurbishment and initial and replaced furniture and fitout items. Items requiring embodied energy analysis (i.e. all but the operational energy) comprised 73 per cent of the total life-cycle energy of the building over a 40-year period. Therefore, implementation actions designed to conserve energy should probably be directed at the conservation of goods and services used in the construction and operation of facilities, rather than the direct consumption of energy by buildings. The errors associated with embodied energy analysis methods should be acknowledged.

References

Alcorn, A. (1996), *Embodied Energy Coefficients of Building Materials*, report for the Building Research Association of New Zealand, Wellington, June.

Australian Bureau of Statistics (ABS) (1996), *Australian National Accounts: Input-Output Tables*, Cat. No. 5209.0, Australian Bureau of Statistics, Canberra.

Boustead, I. and Hancock, G.F. (1979), *Handbook of Industrial Energy Analysis*, Ellis Horwood, Chichester.

Bullard, C.W., Penner, P.S. and Pilati, D.A. (1978), "Net energy analysis: handbook for combining process and input-output analysis", *Resources and Energy*, Vol. 1, pp. 267-313.

Hamilton, J.D. and Sutcliff, R. (1996), "Life cycle assessment of polymers", *Ecological Assessment of Polymers*, Van Nostrand Reinhold, Melbourne, Ch. 16, pp. 307-35.

Lenzen, M. (2000), "Truncation error in embodied energy analyses of basic iron and steel products", *Energy*, Vol. 25 No. 6, pp. 577-89.

Leontief, W. (1966), *Input-Output Economics*, Oxford University Press, New York, NY.

Mateti, P. and Deo, N. (1976), "On algorithms for enumerating all circuits of a graph", *SIAM Journal of Computing*, Vol. 5, pp. 90-9.

Miller, R.E. and Blair, P.D. (1985), *Input-Output Analysis*, Prentice-Hall, Englewood Cliffs, NJ.

National Public Works Council (NPWC) (1980), *Standard Elements and Sub-elements, NPWC Cost Control Manual*, Australian Procurement and Construction Council, Deakin.

Patten, B.C. and Higashi, M. (1995), "First passage flows in ecological networks: measurement by input-output flow analysis", *Ecological Modelling*, Vol. 79, pp. 67-74.

Pullen, S. (1998), "Data quality of embodied energy methods", *Proceedings 1996 Embodied Energy Seminar*, Deakin University, Geelong, 28-29 November 1996.

RMIT Centre for Design (2000), *Australian Life Cycle Assessment Data for SIMAPRO LCA Software*, Distributed in Australia by RMIT Centre for Design, Melbourne.

Stein, R.G., Stein, C., Buckley, M. and Green, M. (1981), *Handbook of Energy Use for Building Construction*, US Department of Energy, Washington, DC, March.

Treloar, G.J. (1996), *The Environmental Impact of Construction – A Case Study*, Australia and New Zealand Architectural Science Association Monographs, No. 001, Australia and New Zealand Architectural Science Association, Sydney, November.

Treloar, G.J. (1997), "Extracting embodied energy paths from input-output tables: towards an input-output based hybrid energy analysis method", *Economic Systems Research*, Vol. 9 No. 4, pp. 375-91.

Treloar, G.J., Love, P.E.D., Iyer-Raniga, U. and Faniran, O.O. (2000a), "A hybrid life cycle assessment method for construction", *Construction, Management and Economics*, Vol. 18, pp. 5-9.

Treloar, G.J., Fay, R., Love, P.E.D and Iyer-Raniga, U. (2000b), "Analysing the life cycle energy of a residential building and its householders", *Building Research and Information*, Vol. 28 No. 5, pp. 184-95.

Treloar, G.J., McCoubrie, A., Love, P.E.D. and Iyer-Raniga, U. (1999), "Embodied energy of fixtures, fittings and furniture in office buildings", *Facilities*, Vol. 17 No. 11, pp. 403-9.

Ulanowicz, R.E. (1983), "Identifying the structure of cycling in ecosystems" *Mathematical Biosciences*, Vol. 65, pp. 219-37.

Vringer, K. and Blok, K. (1995), "The direct and indirect energy requirements of households in The Netherlands", *Energy Policy*, Vol. 23 No. 10, pp. 893-910.

Wagner, G. (1995), *Nubrick Greenhouse Gases, Nubrick Brick and Pipe Draft Report*, Scoresby, 26 October.

West, J., Atkinson, C. and Howard, N. (1994), "Embodied energy and carbon dioxide emissions for building materials", *Proceedings of CIB Task Group 8 Conference*, Watford, 16-20 May.

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Appendix. List of sample energy paths not substituted with process analysis data

In all cases, the stage 0 sector was the "other construction" sector. This list (Table AI) is limited to the first 50 energy paths that were extracted from the input-output model, that process analysis data were not derived for the input-output-based hybrid analysis of the case study commercial building. The direct energy value of each energy path is expressed in GJ/m^2 GFA for the commercial building case study assessed in this paper (i.e. pure input-output values for the energy paths were multiplied by $12\$100/m^2$ GFA, the assumed price for the case study building). The energy paths listed here do not completely describe the remainder of energy paths in the input-output model that process analysis data were not derived for.

Table AI List of sample energy paths not substituted with process analysis data

	Stage 1	Stage 2	Stage 3
1.85	Direct energy of "other construction"		
0.27	Road transport		
0.21	Other property services		
0.14	Plaster and other concrete products	Road transport	
0.11	Other mining	Other mining	
0.09	Fabricated metal products		
0.09	Wholesale trade		
0.07	Other electrical equipment		
0.07	Services to transport; storage	Basic non-ferrous metal and products	
0.06	Structural metal products	Basic non-ferrous metal and products	
0.05	Iron and steel		
0.03	Other electrical equipment	Other basic chemicals	
0.02	Legal, accounting, marketing, etc.		
0.02	Air and space transport		
0.02	Fabricated metal products	Iron and steel	
0.02	Plaster and other concrete products	Road transport	
0.02	Scientific research, technical, etc.		
0.02	Government administration		
0.02	Banking		
0.02	Mining and construction machinery, etc.	Iron and steel	
0.02	Other machinery and equipment	Iron and steel	
0.02	Other property services	Legal, accounting, marketing, etc.	
0.02	Structural metal products	Fabricated metal products	
0.01	Accommodation, cafes and restaurants		
0.01	Structural metal products	Iron and steel	Basic non-fe
0.01	Other machinery and equipment		
0.01	Mining and construction machinery, etc.		
0.01	Other property services	Scientific research, technical, etc.	
0.01	Plaster and other concrete products	Iron and steel	
0.01	Insurance		
0.01	Other property services	Water supply; sewerage and drainage services	
0.01	Other repairs		
0.01	Iron and steel	Ceramic products	
0.01	Electronic equipment	Wholesale trade	
0.01	Other business services		
0.01	Wholesale trade	Services to transport; storage	
0.01	Other property services	Communication services	
0.01	Wholesale trade	Air and space transport	
0.01	Other electrical equipment	Ceramic products	
0.01	Other property services	Air and space transport	
0.01	Wholesale trade	Legal, accounting, marketing, etc.	
0.01	Other property services	Other business services	
0.01	Mining and construction machinery, etc.	Basic non-ferrous metal and products	
0.01	Household appliances		
0.01	Other electrical equipment	Other electrical equipment	
0.01	Structural metal products	Road transport	
0.01	Mechanical repairs		
0.01	Other property services	Services to transport; storage	
0.01	Communication services		
0.00	Other electrical equipment	Wholesale trade	