1

Building Energy and Cost Performance: An Analysis of Thirty Melbourne Case Studies

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ABSTRACT

This study investigates the energy and cost performance of thirty recent buildings in Melbourne, Australia. Commonly, building design decisions are based on issues pertaining to construction cost, and consideration of energy performance is made only within the context of the initial project budget. Even where energy is elevated to more importance, operating energy is seen as the focus and embodied energy is nearly always ignored. For the first time, a large sample of buildings has been assembled and analyzed to improve the understanding of both energy and cost performance over their full life cycle, which formed the basis of a wider doctoral study into the inherent relationship between energy and cost. The aim of this paper is to report on typical values for embodied energy, operating energy, capital cost and operating cost per square metre for a range of building functional types investigated in this research. The conclusion is that energy and cost have quite different profiles across projects, and yet the mean GJ/m^2 or cost/m^2 have relatively low coefficients of variation and therefore may be useful as benchmarks of typical building performance.

Keywords: embodied energy, operating energy, capital cost, operating cost, Melbourne buildings

INTRODUCTION

Energy has become a significant issue worldwide. Greenhouse gas emissions (GGE) and the perceived threat of climate change (caused by phenomena such as global warming and ozone depletion) is identified by Beggs (2002, p.10) as driving, "*more than any other issue*", change in energy consumption attitudes. Since the energy crisis of the mid-1970s attention has been directed towards strategies that lower operating energy demand (Robertson 1991), yet it has been only recently that the impact of energy embodied in building materials themselves has come under scrutiny.

Australia has the highest per capita GGE in the world (NAEEEC 1999, Department of Natural Resources and Environment 2000, ASEC 2001). Without targeted and effective action, these emissions are projected to grow by 28% from 1990-2010 (NAEEEC 1999). Bell and Fawcett (2000) indicate that GGE from the Australian construction industry are substantial and rapidly rising, particularly in the commercial sector. Buildings consume 40-50% of the energy and 16% of the water used annually worldwide (Lippiatt 1999, Hoglund 1992, Lam et al. 1992).

Buildings comprise a combination of embodied energy and operating energy. It is now realized that a focus on operating energy is insufficient to address either national or international GGE concerns (Fossdal 1995). Embodied energy is steadily increasing (AGO 1999) due to a greater use of energy-intensive materials (such as aluminium, stainless steel, coated glass and high strength concrete), larger buildings, more frequent refurbishment cycles, more machine utilization in construction processes, higher transportation energy and the introduction of new technologies such as photovoltaic cells and building management systems. Despite this trend, the routine analysis of embodied energy remains absent (Treloar, Ilozor et al. 2002).

Boustead and Hancock (1979) suggest that embodied energy analysis is more comprehensive than the standard industrial paradigm as the system boundary is extended to the economy of the construction sector and other related sectors. There are four types of embodied energy analysis described in the literature. These comprise process analysis, statistical analysis, input-output analysis and hybrid analysis. No method is perfect. Incompleteness in typical embodied energy analysis is estimated at around 20% (Treloar 1997).

The input-output-based hybrid method, as used in this paper, is described by Crawford (2004, p.130) as "*the most sophisticated complete life cycle inventory assessment method currently available for assessing environmental impacts associated with building and building-related products*".

Proper energy analysis during the design process can no longer be simply overlooked. ASEC (2001, p.100) indicate that "*total energy use has doubled* [in Australia] *over the last 25 years* […] *at a faster rate than GDP*". The rationale behind this paper firmly lies with the perceived lack of integration of energy analysis into current practice. Capital cost still remains the primary criterion for building procurement decisions (Brown and Yanuck 1985, Langston 1991, Bull 1992), while other criteria are given less significance either due to a narrow myopic focus (Ashworth 1988) or because a suitable multi-criteria technique has not been satisfactorily identified (van Pelt et al. 1990).

Energy analysis is costly, time-consuming and, when undertaken during the design phase, usually based on a large number of assumptions (Verbeek and Wibberley 1996). Even so, it is likely to produce conflicting advice to that generated from capital cost estimates (Arnold 1993). This occurs because energy analysis takes a long-term view, one that introduces multiple stakeholders and wider social concerns, rather than merely reflecting immediacy and profit-centred objectives. It has been argued over many years (e.g. Stone 1960, Kirk and Dell'Isola 1995, Flanagan and Norman 1983, Langston and Lauge-Kristensen 2002) that costs should also be accounted over a longer time span. Known as life cycle costs (LCCs), these comprise both initial (capital) and recurrent (operating) components that can be aggregated to give a more realistic picture of the total expenditure commitment (Fuller 1982).

The problem essentially is how two criteria, one measured in financial terms and the other in pure energy terms, can ever be reconciled to provide clear building design guidance. It is not commonly understood that the lowest LCC solution will automatically be the lowest energy solution. In fact, any comparison of particular material choices will usually indicate that cost and energy ratios vary widely (Irurah and Holm 1999). Yet at the level of an entire building this differential is expected to be less – a view that is supported to some extent by the manner in which embodied energy intensities are often determined (i.e. from national input-output financial tables) and operating energy interpreted (i.e. incurred cost).

If there is an inherent relationship between energy and cost that can be exploited to enable better design solutions to be identified, then it should be possible to quantify energy directly from an LCC investigation. The outcomes will naturally be dependent on the chosen time horizon for the study but will simplify the process of embodied energy calculation (in particular) that to date has proved elusive to common practice.

The purpose of this paper is to present the energy and cost profile, both in initial and recurrent terms, for a range of building types in Melbourne, Australia. From this information, a better understanding of facilities performance can be obtained, leading to further insight into the relationship between energy and cost. The structure of this paper is to review literature on energy and cost relationships and to highlight a gap in knowledge, to outline the method adopted in this research, to analyze the results, and to make observations and draw conclusions for practice.

BACKGROUND

Energy and cost are similar in a number of ways. The following observations can be made:

- both are a means of identifying resources and measuring deployment efficiency
- energy sources delivered by supplier organizations have a market price per unit that is tangible and understood
- energy costs incurred during product manufacture and delivery are built into the purchase price of materials (i.e. energy costs are embedded), while operating energy costs are billed based on actual consumption
- life cycle energy and LCC have similar philosophical constructs
- embodied energy intensities are often obtained from financial input-output tables
- there is usually a compromise or balance between initial (energy or cost) and recurrent (energy or cost) commitments
- both future cost and future energy comprise uncertainty in prediction
- energy and cost vary according to building scale, locality and quality of construction

Project decisions that minimize energy (including GGE) or cost are likely to result in greater net benefit to owners, users and society (Bekker 1982). Given these attributes comprise initial and recurrent characteristics, it is possible that complex trade-offs can arise, such as spending more money initially to save operating energy, or to use high embodied materials that reduce future operating costs. Therefore it is obvious that some relationship exists, even if the nature of this relationship is not well understood.

Vale et al. (2001, p.11) indicate that "*further research should be carried out to ascertain the relationship between cost and EE* [embodied energy] *for a number of sample buildings*". They believe that for the purposes of providing a default value for embodied energy, cost can be supported at a theoretical level.

But Vale et al. (2001) raise doubts over the usefulness of traditional embodied energy analysis considered in isolation. For example, they suggest that the high labour costs of apparently low embodied energy materials like mud bricks and straw bales have a hidden energy penalty because of the spending that occurs elsewhere as a result of the income received by those who contribute their labour to the construction process. This spending on goods and services attracts new embodied energy that is completely ignored in current methods, and suggests that cost may actually be more appropriate as a predictor of "social" embodied energy. Gever et al. (1991, p.103) make the point that "*the total energy cost of a dollar's worth of financial and insurance services, for example, is nearly identical to the energy used to produce a dollar's worth of primary non-ferrous metal products*".

In a radio interview[1], Dr Manfred Lenzen from the University of Sydney extended this argument further:

"Well, you have to estimate the embodied primary energy in the good that you have purchased and there's a rather crude but surprisingly accurate way of telling and that is just take the gross national product of Australia and the total national primary energy consumption and divide these two figures and you get an average amount of energy per dollar and this is about 3 kilowatt hours per Australian dollar. That means, if you buy, say you bought a CD for $30, you can calculate that there is about 90 kilowatt hours embodied in that good. You could then go more into detail and see whether there are variations between different goods and find out whether there are goods that are more energy-intensive. Other things that you might want to purchase are services like health care or you want to do money transactions, and all of these things that are usually associated with a lot of human labour are not so energy intensive, about six times less energy than purchasing goods. Energy-wise, it is better to go and see a movie or go and see a theatre play than buying recreational goods."

The link between economics and energy is largely circumstantial and in need of more objective testing.

Energy and cost are also different in a number of ways. Another set of observations can therefore be made:

- the true cost of energy may be subsidized and therefore is not fully embedded in individual product prices
- operating energy may be reduced by spending more money either initially or subsequently as part of a proactive maintenance strategy
- recycled materials have low embodied energy yet can be expensive to adapt to new uses
- the cost of human labour is rarely translated to energy units and therefore labour-intensive activities like maintenance and repair are unlikely to reflect the same relationships between energy and cost as material and plant hire
- a cursory look at a range of common building materials will show little correlation with embodied energy intensities
- future energy flows are treated as full value whereas future cost flows are normally discounted
- investment decisions are made on the basis of financial rather than energy criteria

Bullard and Herendeen (1975, p.269) come to the conclusion that "*dollar data are inferior to physical, being more subject to economies of scale* [and] *reliance on monetary data for energy transactions effectively assumes energy is sold*". The pervasive effects of economic activity on natural environments are beyond the common knowledge of economic actors (Christensen 1987). This complex interdependence involving tangible and intangible goods and services suggests that price signals alone must be inherently incomplete.

METHOD

The selected research method is sampling via case studies. Case study is an ideal methodology when a holistic in-depth investigation is needed (Feagin et al. 1991). It has been used in varied investigations, particularly in sociological studies but increasingly in construction. The procedures are robust, and when followed the approach is as well developed and tested as any in the scientific field. Whether the study is experimental or quasi-experimental, the data collection and analysis methods are known to hide some details. Case studies, on the other hand, are designed to bring out the details from the viewpoint of the participants by using multiple sources of data (Tellis 1997).

The data for the research are drawn from actual case studies obtained courtesy of the Melbourne office of Davis Langdon Australia, a large national quantity surveying practice. Case studies are located across Greater Melbourne and are specifically intended to reflect a broad range of functional purpose.

Capital cost data and floor areas are obtained direct from the elemental cost plans prepared by Davis Langdon Australia. Embodied energy intensities are estimated from the composite items of work listed in these documents using the input-output-based hybrid method developed by Dr Graham Treloar (Treloar 1998, Crawford 2004). Operating cost is estimated from reasonable cycles for future maintenance and replacement work using *LIFECOST*™ software. Operating energy is based on data obtained from the Property Council of Australia for Melbourne office buildings, adjusted to allow for extended opening hours for other functional uses. All costs are adjusted and expressed in fourth quarter 2006 dollars using published building price indices (BPI) also supplied by Davis Langdon Australia.

Thirty recent Melbourne projects are used as case studies. These projects represent diverse functions including provision of office workspace, health facilities, residential accommodation, teaching and laboratory space, retail, hotel accommodation and a number of specialist uses. Projects comprise both new construction (73.3%) and redevelopment (26.7%). So-called residential projects, comprising apartment buildings and aged care facilities, account for 23.3% of the case studies, and the remainder are constructed for various other commercial uses. One-third of the case studies are hospitals.

Projects range from 1997 to 2004, and vary in floor area from 249 m^2 to 18,821 m^2 gross floor area (GFA) and number of storeys from one to sixteen floors (although most buildings are low-rise). The mean floor area is 3,749 m^2 (coefficient of variation of 110.75%). They comprise a wide range of materials and standards, some are air-conditioned and some not, some have fire sprinkler systems, some have loose furniture and special equipment, and some have substantial external works.

This mix decreases the likelihood that projects exhibit similarities in energy and cost performance. Economies of scale also play a part in larger projects, which tend to have lower unit costs than identical designs of smaller size. The mix is therefore effectively random, enabling a range of statistical techniques to be applied to the sample.

Table 1 lists the case studies used in this research by building type. Case studies are identified by a numerical code, as the name and location of projects needs to be kept confidential (this is a non-negotiable agreement made between the researchers and Davis Langdon Australia).

Data supplied by Davis Langdon Australia comprises GFA and elemental capital costs based on abbreviated measured quantities extracted from design cost plans. The full project cost is presented, including Preliminaries, Site Works and External Services, and Special Provisions (such as allowances for loose furniture and equipment), but excluding contingencies, professional fees, land acquisition costs and goods and services tax. All other data are estimated using embodied energy models, promulgated operating energy targets (for Melbourne), expected maintenance and replacement cycles, and other operational assumptions.

Capital costs are converted to fourth quarter 2006 prices using a BPI provided by Davis Langdon Australia. Otherwise no adjustment to capital costs is undertaken and all unit rates are taken as correct and reflective of the project given applicable market conditions at the time. The BPI for fourth quarter 2006 is 175.0 (later indices were not used as they were still forecasts at the time of analysis).

Operating costs, on the other hand, are estimated using *LIFECOST*™ software provided by Computerelation Australia Pty Limited. Maintenance and replacement cycles are determined using personal experience together with a number of useful references (e.g. Dell'Isola and Kirk 1995), and priced by original unit rates with a suitable allowance for removal and disposal costs where applicable. All costs are adjusted to fourth quarter 2006 as before described.

Embodied energy, including both initial and recurrent embodied energy, is determined using a sophisticated spreadsheet model. The model is an input-output-based hybrid method that embraces both process analysis data (where it is available) supplemented with the input-output data from published government statistics (1996-1997 financial year), extracted and compiled at Deakin University by Dr Graham Treloar and Dr Robert Crawford.

ID	Year	Building Type	GFA (m^2)	100-year Life Cycle Energy (GJ/m^2)	Total Embodied Energy		Other Operating Energy ($GJ/m^2/yr$)
					Initial *(GJ/m^2)*	*Recurrent* *($GJ/m^2/yr$)*	
1	2003	Residence (new)	1,409	218.95	18.98	0.26	1.74
2	2004	Residence (new)	450	271.72	21.27	0.33	2.18
3	2004	Residence (new)	1,791	207.67	20.48	0.24	1.63
4	2000	Office (new)	2,543	143.83	23.72	0.22	0.98
5	2003	Health Centre (redevelopment)	528	148.20	18.10	0.19	1.11
6	2003	Hospital (new)	6,761	227.57	22.80	0.25	1.80
7	2003	Residence (new)	328	223.56	20.78	0.36	1.67
8	2003	Information Centre (new)	1,223	146.53	17.50	0.23	1.06
9	2004	Hospital (redevelopment)	3,278	254.26	23.76	0.24	2.07
10	2003	Hospital (redevelopment)	3,760	249.87	25.67	0.27	1.98
11	2004	Library (new)	249	166.45	24.06	0.37	1.06
12	2004	Civic Hall (new)	625	161.04	25.11	0.30	1.06
13	2004	Primary School (new)	2,696	123.81	18.34	0.26	0.80
14	2001	Residence (new)	2,790	275.34	22.24	0.34	2.19
15	2001	Hospital (redevelopment)	5,677	254.88	23.65	0.42	1.89
16	2000	Hospital (new)	378	245.95	23.83	0.26	1.96
17	1999	Hotel (redevelopment)	652	281.17	15.96	0.47	2.18
18	2000	Car Parking Station (new)	5,412	87.93	19.57	0.03	0.66
19	1998	Hospital (new)	4,281	259.83	26.20	0.31	2.02
20	1998	Health Centre (new)	787	153.51	23.28	0.26	1.04
21	1998	Hospital (new)	1,159	253.17	24.17	0.38	1.91
22	1999	Hotel (new)	12,930	284.27	22.17	0.30	2.32
23	1999	Residence (redevelopment)	18,821	234.49	13.83	0.23	1.98
24	1999	University Building (new)	10,565	161.22	24.90	0.27	1.09
25	1999	Office (new)	4,704	158.14	25.84	0.26	1.06
26	1999	Hospital (redevelopment)	1,345	240.18	18.57	0.30	1.92
27	1999	Hospital (redevelopment)	5,940	243.17	25.21	0.22	1.96
28	1998	University Building (new)	2,502	150.77	22.87	0.24	1.04
29	1998	Residence (new)	5,223	232.24	18.39	0.31	1.83
30	1997	Hospital (new)	3,649	233.87	21.55	0.21	1.91
			Mean	209.79	21.76	0.28	1.60
			CV (%)	25.77	14.61	28.75	31.00

Table 1: Case Study: Base Information & Energy Summary (per m^2 Gross Floor Area)

Operating energy is estimated using a simple model based on occupancy hours per year and “good practice guidelines” for new buildings in Melbourne (PCA 2001). The latter translates to 0.56 GJ/m^2 net lettable area per year (or 155.5 kWh/m^2/annum), comprising 70% electricity and 30% gas (where gas supply is present), or 100% electricity (where no gas supply is present), and are intended to apply to Melbourne office buildings regardless of age or condition. Delivered energy is converted to primary energy using a factor of 2.72 for electricity (based on 80% brown coal at efficiency=3.4 and 20% green power at efficiency=1) and 1.4 for gas. Office buildings assume nominal occupancy of 2,500 hours/annum (equivalent to 8am to 6pm Monday to Friday) as defined in PCA (2001). Hospitals, hotels, residential accommodation and car parking facilities are assumed to operate for 5,460 hours/annum (equivalent to 8am to 11pm Monday to Sunday), and this translates to an occupancy factor of 2.18 compared to office buildings. Note that full ‘24/7’ energy intensity (equivalent to 8,736 hours/annum) is not assumed for this purpose so as to take account of lower energy demand outside of key operating periods.

Note that the good practice guidelines were used in preference to the new building design target (PCA 2001) for the purposes of this study. The latter is a 28.5% reduction from the former, yet in the short-term this is unlikely to be achieved for the general run of projects except those that are specifically designed as energy efficient. Buildings constructed before 2001 were assumed to also follow good practice, and some have undergone minor upgrade to lift their performance.

For all operating costs and operating energy, including recurrent embodied energy, a one-hundred-year time horizon has been assumed.

RESULTS

Energy Data

Table 1 summarizes the case studies for total life cycle energy, initial embodied energy, recurrent embodied energy per annum, and other operating energy per annum. All data are expressed in primary energy terms per m^2 GFA, and simple statistical means and coefficients of variation are calculated.

Total operating energy is defined as including recurrent embodied energy; the latter comprising expected maintenance/repair and eventual replacement. This is therefore comparable with total operating cost other than cleaning (predominantly labour). Initial embodied energy relates directly to capital cost – and takes into account direct energy and direct cost for the construction process respectively.

From Table 1 it can be seen that the range of energy values for each project is quite consistent. This is surprising given the diversity of building types. In particular, the coefficient of variation for initial embodied energy per m^2 is just 14.61%. The variation is a little higher for recurrent embodied energy and other operating energy, but still shows remarkable consistency. All operating energy is related directly to the hours that the building is in use, with hospitals, hotels and residential accommodation all at the higher end of the range. Higher or lower estimates of operating energy intensity can be readily interpreted.

Total energy increases from a mean across all case studies of 21.76 GJ/m^2 at construction to 209.79 GJ/m^2 over a one-hundred-year time horizon. Of the annual increase recurrent embodied energy accounts for about 15% while the remainder (85%) is attributable to electricity and gas usage and dominates the life cycle. The coefficient of variation for total energy rises from 14.61% initially to 25.77% after one hundred years on the entire dataset.

The distribution of embodied energy between initial and recurrent is significantly different. For example, Preliminaries and Substructure elemental groups combined have 17% of total initial embodied energy but zero recurrent embodied energy. Nevertheless, Superstructure and Special Provisions are the largest categories in both cases (about half). Figures 1 and 2 illustrate the distribution and are based on the mean GJ/m^2 of embodied energy over a one-hundred-year time horizon across all case studies. Other operating energy is excluded as it is allocated to Services only and will completely dominate the chart.

Building elemental groups (i.e. Preliminaries, Substructure, Superstructure, Finishes, Fittings and Services) account for 77% of initial embodied energy and 67% of recurrent embodied energy. Special Provisions also includes other indirect energy (incompleteness) that fills the gap between the total pathways and modified (quantified) pathways. Site Works and External Services do not have an influential impact on embodied energy distribution.

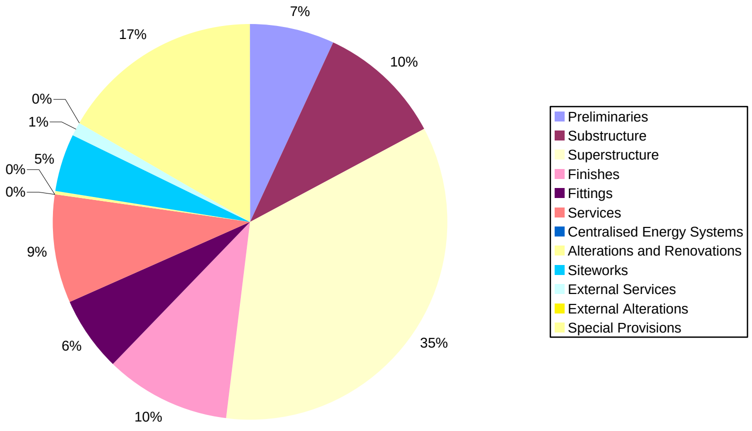

Figure 1: Initial Embodied Energy Distribution by Elemental Group

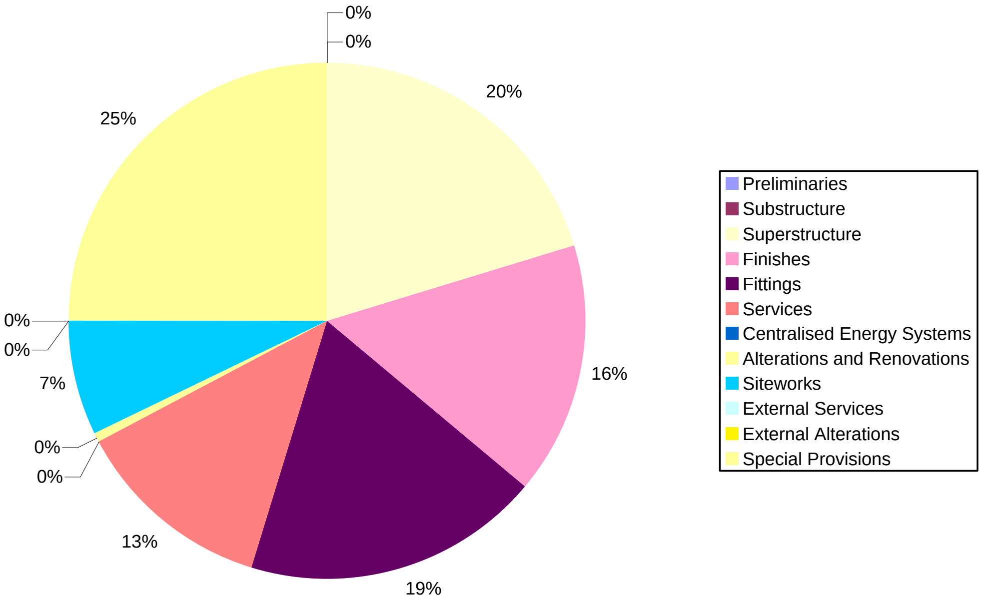

Figure 2: Recurrent Embodied Energy Distribution by Elemental Group

The distribution of energy within the major elemental groups and how this changes across the various case studies is illustrated more clearly in Figures 3 and 4. In the case of initial embodied energy there is considerable consistency, with a few notable exceptions. Building 17 has low superstructure content since this project involves substantial refurbishment of an existing hotel shell. Building 18 is a car parking station and is dominated by structure, particularly substructure that was incorrectly coded from superstructure for works below ground level, and displays a quite different profile to the remainder.

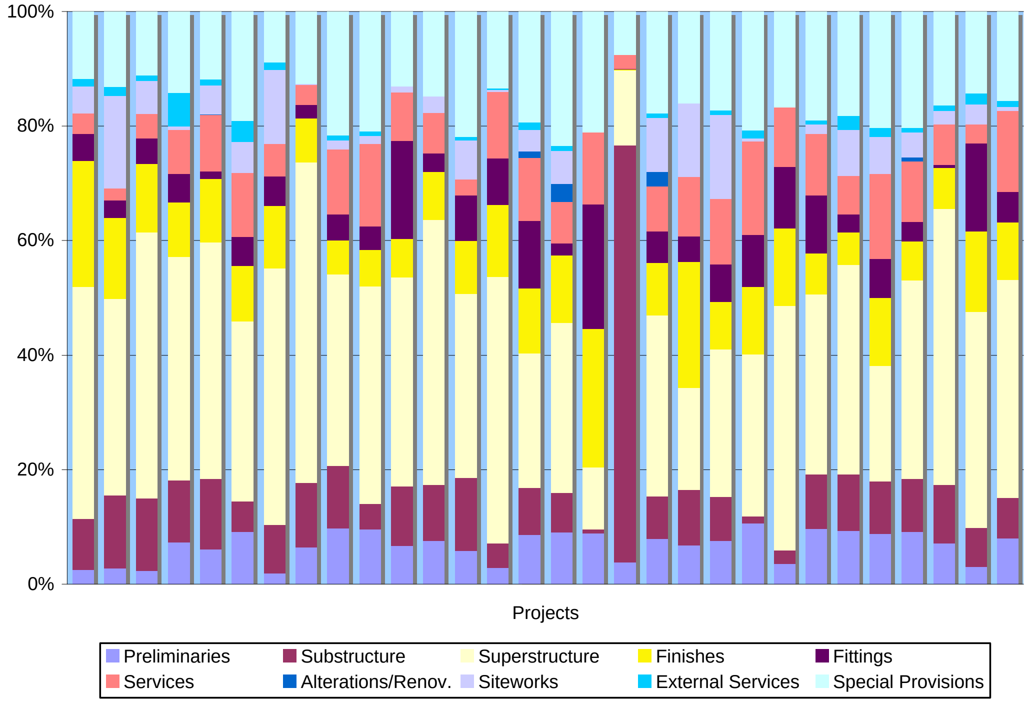

Figure 3: Distribution of Initial Embodied Energy by Project

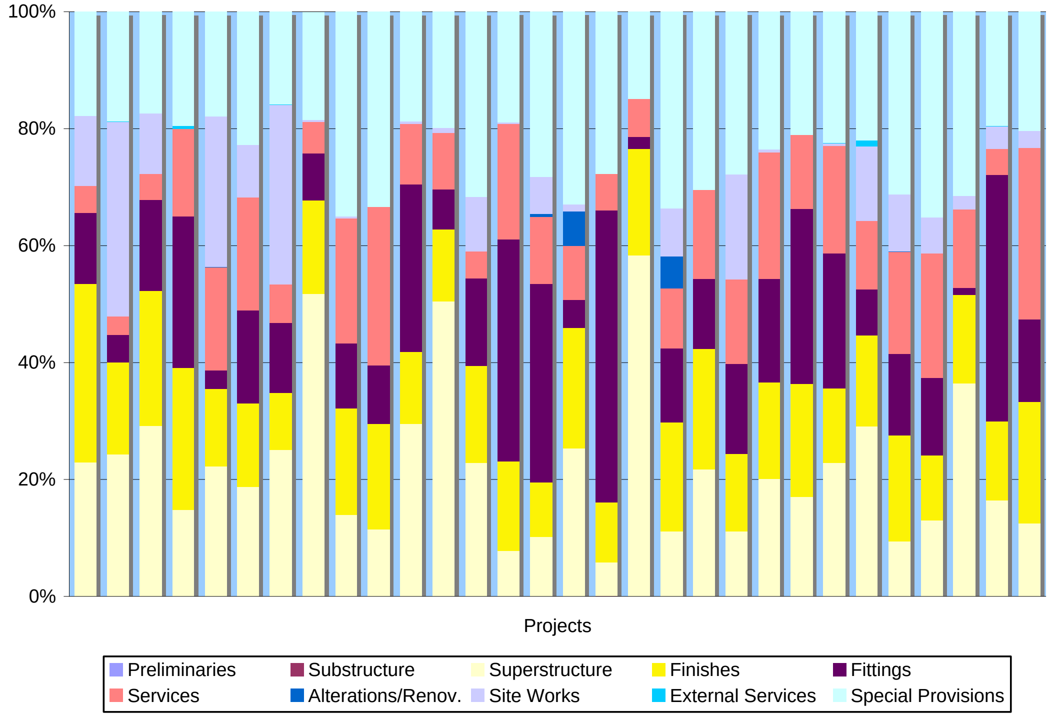

Figure 4: Distribution of Recurrent Embodied Energy by Project

Recurrent embodied energy, measured over a one-hundred-year time horizon, shows more consistency, although the lack of any significant Fittings contribution in Building 18 is apparent. Some projects have nearly 60% of their recurrent embodied energy attributable to Superstructure, while Finishes represents a relatively constant percentage in all cases.

COST DATA

Table 2 summarizes the case studies for capital cost, recurrent operating cost per annum, and energy operating cost per annum. Recurrent operating cost is defined as comprising cleaning, maintenance/repair and replacement, as well as other necessary expenditure involved in operating a building – except the cost of energy. All data is expressed in 2006 dollars (final quarter) per m^2 GFA, and simple statistical means and coefficients of variation are calculated.

ID	100-year Life Cycle Cost ($2006/$m^2$)	Capital Cost ($2006/$m^2$)	Operating Cost/yr ($2006/$m^2$)	
			Recurrent Expenditure	*Energy Expenditure*
1	9,855.72	2,128.63	53.39	23.88
2	15,592.06	2,663.61	99.37	29.91
3	10,285.65	2,167.06	57.07	24.11
4	15,706.78	2,485.70	115.45	16.76
5	9,561.95	1,577.46	64.63	15.21
6	17,803.93	2,989.71	116.93	31.22
7	18,022.06	1,755.25	137.36	25.31
8	11,797.56	1,622.32	87.15	14.61
9	16,180.06	3,335.01	94.20	34.25
10	16,787.39	3,507.53	100.96	31.84
11	14,674.93	2,319.90	109.00	14.55
12	14,625.76	2,736.97	104.28	14.61
13	12,493.22	1,535.97	98.55	11.03
14	22,880.68	2,831.93	163.48	37.01
15	19,888.52	2,924.67	132.26	37.38
16	23,137.70	3,107.15	160.14	40.17
17	22,453.04	2,033.28	164.62	39.58
18	6,042.28	1,082.40	38.43	11.17
19	19,157.62	2,979.36	117.05	44.73
20	16,592.33	2,295.05	123.34	19.63
21	25,212.92	2,625.44	184.38	41.49
22	20,014.28	3,390.48	124.50	41.74
23	15,286.00	2,199.25	88.77	42.09
24	15,398.96	3,478.50	98.76	20.44
25	18,103.70	3,471.16	127.02	19.31
26	18,389.29	2,337.28	119.68	40.84
27	17,816.30	3,329.74	103.20	41.67
28	13,757.08	2,316.59	95.24	19.16
29	18,607.71	2,511.89	126.50	34.46
30	17,572.90	2,475.32	107.96	43.01
Mean	16,456.61	2,540.49	110.46	28.71
CV (%)	26.26	25.41	29.82	39.31

Table 2: Case Study Cost Summary (per m^2 GFA) (adapted from Langston 2006)

The first observation from this data is that, on every project, energy expenditure is less than recurrent expenditure. This is in contrast to Table 1 that shows, again for every project, operating energy is more than recurrent embodied energy. The reason for this disparity lies with the subsidized price of energy in Australia and particularly the structure of pricing based on delivered rather than primary energy.

As expected, the mean capital cost/m^2 varies with project type (e.g. residential accommodation averages $2,332.52 and hospitals average $2,961.12), but are also affected by the extent of refurbishment involved (new projects are usually more expensive than redevelopment projects). While the coefficients of variation are not excessive, they are higher than the energy figures presented earlier in Table 1 in all three cases.

Total life cycle cost (life-cost), defined here as the sum of capital cost and operating cost, increases from $2,540.49/m^2 initially to $16,456.61/m^2 after one hundred years, multiplying the initial cost by nearly six-and-a-half times. The coefficient of variation rises only slightly from 25.41% to 26.26% over the same period. The cost of energy is just 20.63% of the total annual operating cost on average.

Figure 5 elaborates further on the distribution of operating cost over the full one-hundred-year time horizon across all projects. The pattern is remarkably even. The highest category is "other" costs, which includes essential staffing for general maintenance, gardening and security. The category with the highest variation by project is cleaning (CV=76.87%), followed by maintenance/repair (CV=45.40%), other costs (CV=38.60%), energy (CV=30.79%) and replacement (CV=27.40%), but these figures are significantly affected by several projects (notably Building 18) with generally very low operating costs. In the case of occupier-owned residential accommodation, routine cleaning is undertaken by the owners for no extra cost.

Operating cost is dominated by Preliminaries (46%), as seen in Figure 7. This element includes items such as municipal rates, insurances, essential staffing (maintenance, gardening, and security), garbage collection, maintenance equipment, and contract cleaning. Building elements dominate at 90% of the total. The cost of energy, in a similar way to the data presented in Figure 2, is excluded. If it had been added under the Services elemental group, both Preliminaries and Services would have each represented 36% of the total operating cost. Operating energy, on the other hand, is 85% of the total, mainly due to impact of primary energy and no price subsidization.

The distribution of capital cost across the thirty case studies yields few surprises. Figure 6 shows capital costs by elemental group. Superstructure and Services are the two largest groups (both equalling 29%) while Preliminaries and Finishes account for 10% and 11% respectively. The building elements (Preliminaries through Services) account for 89% of the total capital cost.

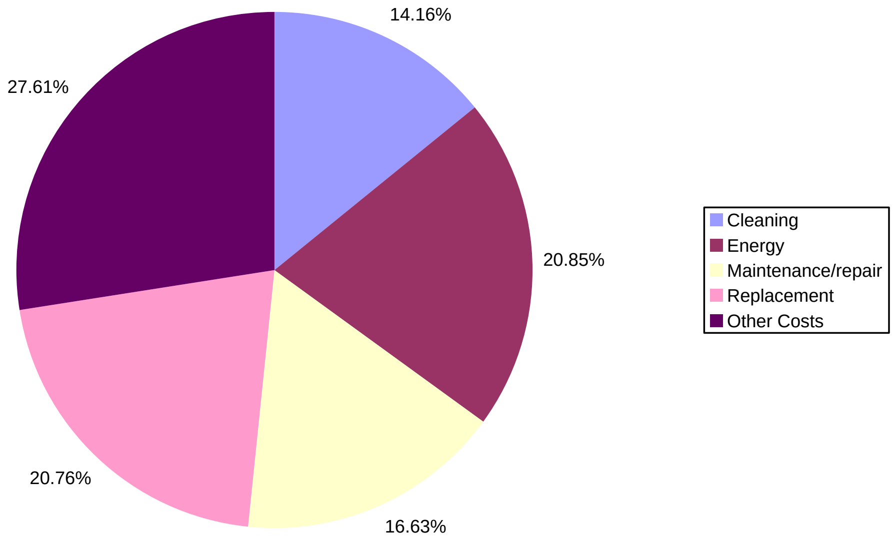

Figure 5: Overall Operating Cost Distributions

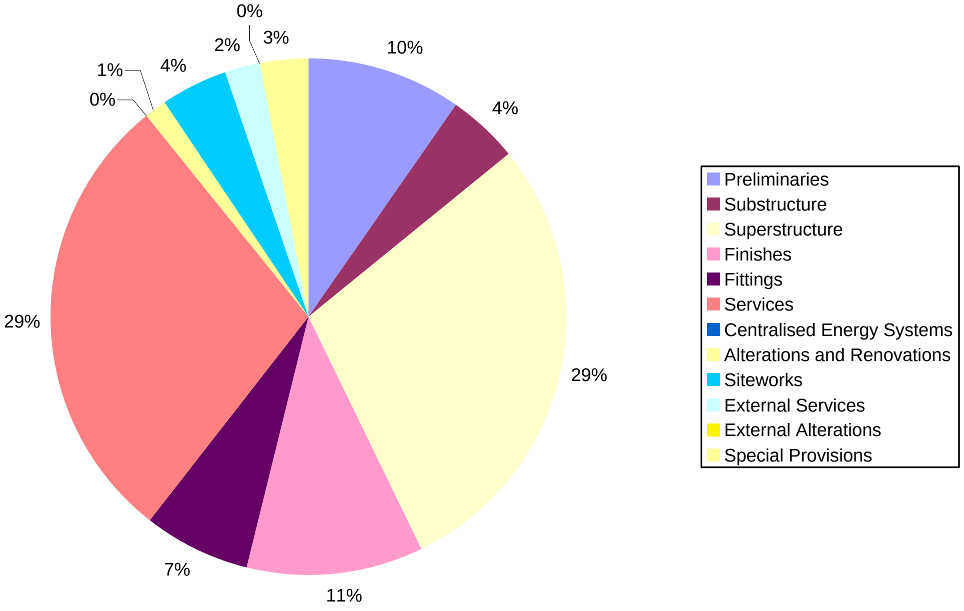

Figure 6: Capital Cost Distribution by Elemental Group

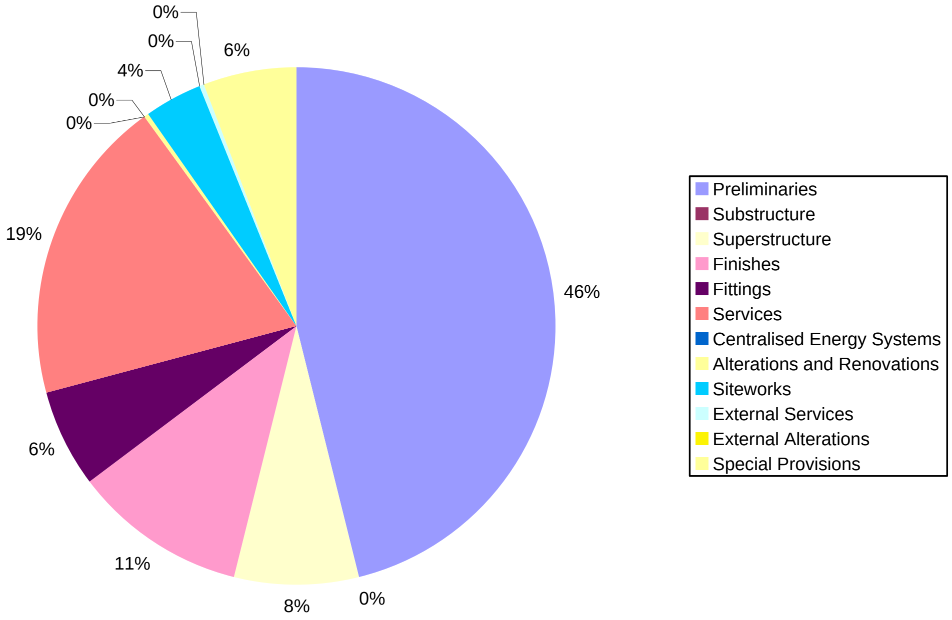

Figure 7: Operating Cost Distribution by Elemental Group

What is interesting about the distributions is that they have different patterns. This difference is not only between capital and operating cost, but also between initial embodied energy and capital cost, and between recurrent embodied energy and operating cost. This would suggest that it is unlikely that energy and cost would have any strong relationships, and may explain to some extent why a relationship, should it exist, is not well understood.

Figure 8 provides further insight into the distribution of cost within the major elemental groups. External Alterations and Renovations are not included for clarity, even though some minor costs occur. The comments made earlier in relation to embodied energy apply equally well here. The main difference in fact between Figures 3 and 8 is the decrease in the proportion of Special Provisions and the increase in the proportion of Services in cost terms.

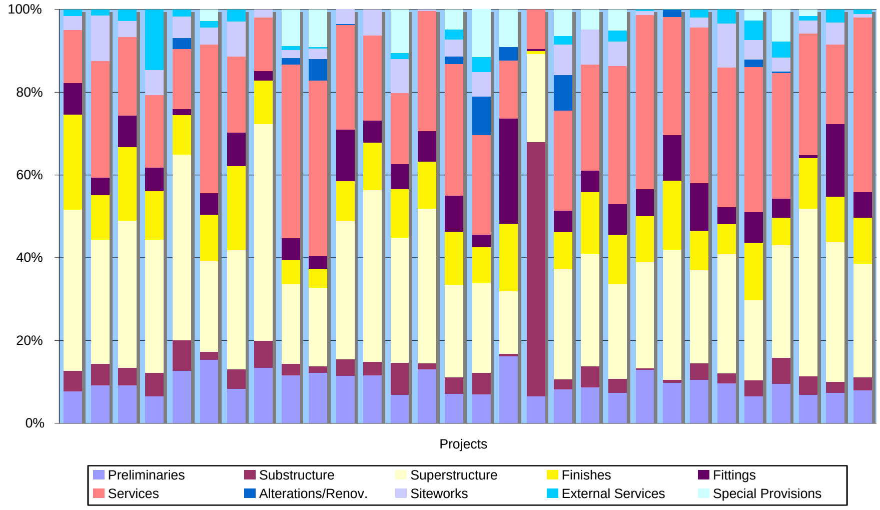

Figure 8: Distribution of Capital Cost by Project

Similarly, Figure 9 looks at operating cost excluding the cost of energy. The dominance of Preliminaries is a striking change to Figure 4 and recurrent embodied energy distribution, accounting for around half of total operating cost. Special Provisions is also less significant in cost terms. It should be noted, however, that there is no energy calculation involved in Preliminaries, and other indirect energy (incompleteness) was included in Special Provisions, and these issues do not have a comparable cost impact.

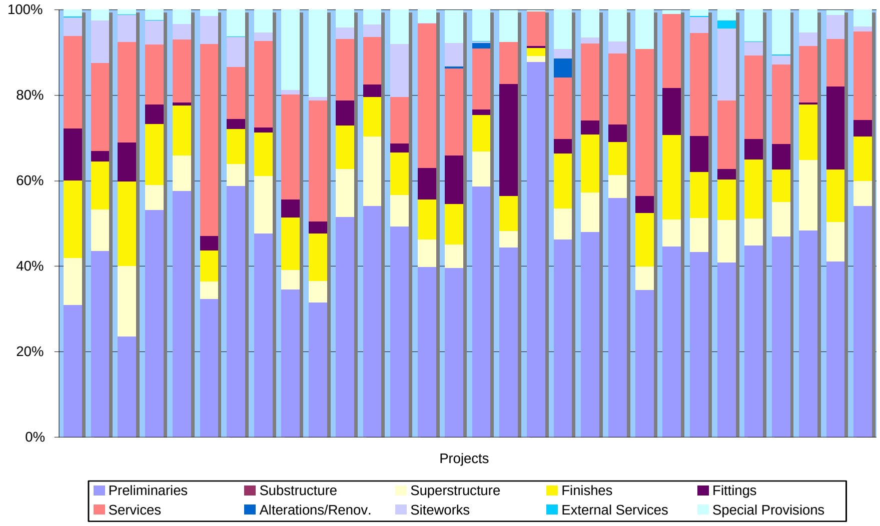

Figure 9: Distribution of Operating Cost by Project

DISCUSSION

When the data are further explored, significantly more variation is found. Not all elements are present in all case studies, and this contributes to higher coefficients of variation in most cases. Table 3 lists the mean initial embodied energy in GJ/m^2 for each element, and the mean recurrent embodied energy in GJ/m^2 over the full hundred-year time horizon, while Table 4 lists mean capital and operating costs in cost/m^2. Most coefficients of variation are high, and where the number of projects involved is also low little confidence should be taken in the mean.

Element	Projects Involved	Initial Embodied Energy		Recurrent Embodied Energy	
		Mean (GJ/m^2)	*CV (%)*	*Mean (GJ/m^2)*	*CV (%)*
PR	30	1.51	46.55	0.00	0.00
SB	30	2.25	105.73	0.00	0.00
CL	27	0.37	72.16	0.00	0.00
UF	21	1.58	76.24	0.00	0.00
SC	24	0.31	138.10	0.08	159.81
RF	30	2.27	55.36	2.09	61.96
EW	30	1.59	68.62	1.15	118.05
WW	26	0.49	97.91	1.26	94.08
ED	27	0.17	98.04	0.63	96.19
NW	30	1.04	89.78	0.10	351.81
NS	28	0.16	107.95	0.30	148.19
ND	30	0.20	103.50	0.32	184.79
WF	29	0.87	73.23	1.43	42.64
FF	30	0.65	42.98	2.57	38.21
CF	29	0.80	76.41	0.47	98.47
FT	30	1.13	70.60	3.26	75.48
SE	19	0.36	144.68	3.03	163.03
SF	24	0.23	56.29	0.64	57.20
PD	16	0.07	96.57	0.08	276.18
WS	9	0.18	35.03	0.70	55.22
AC	28	0.94	50.33	1.35	42.83
FP	28	0.09	18.90	0.04	87.80
LP	30	0.16	54.02	0.33	69.83
CM	13	0.32	33.97	0.70	36.55
GS	12	0.01	17.69	0.00	25.55
VE	8	0.25	52.45	0.12	131.35
TS	10	0.65	73.85	1.83	66.77
SS	11	0.24	87.97	0.57	98.46
AR	11	0.17	163.09	0.32	203.11
XP	19	0.05	290.50	0.01	303.96
XR	25	0.66	106.95	0.56	149.23
XN	14	0.50	109.95	2.99	106.91
XB	7	0.43	174.86	0.45	142.57
XL	21	0.17	86.43	0.06	188.25
XK	22	0.18	91.64	0.00	0.00
XD	17	0.06	54.44	0.00	0.00
XW	16	0.02	134.24	0.00	134.36
XE	9	0.18	122.88	0.04	196.86
XG	7	0.03	135.30	0.00	226.22
XF	7	0.05	131.59	0.01	127.88
XS	1	0.00	0.00	0.00	0.00
XX	5	0.00	223.61	0.00	223.61
YY	30	3.60	31.69	6.84	39.20

Table 3: Statistical Summary for Embodied Energy by Element (*Langston 2006)*

Element	Projects Involved	Capital Cost ($2006)		Operating Cost ($2006)	
		Mean ($/$m^2$)	*CV (%)*	*Mean ($/$m^2$)*	*CV (%)*
PR	30	249.71	40.58	5,098.17	37.98
SB	30	112.60	100.34	0.00	0.00
CL	27	22.43	67.19	0.00	0.00
UF	21	118.65	69.20	0.00	0.00
SC	24	17.21	96.43	10.83	140.24
RF	30	159.20	47.20	171.67	60.66
EW	30	177.73	51.26	215.74	93.03
WW	26	67.42	76.21	219.20	72.82
ED	27	30.42	80.62	116.86	75.82
NW	30	99.39	67.94	17.20	345.54
NS	28	26.73	134.07	57.25	125.56
ND	30	58.46	48.56	95.19	64.80
WF	29	117.90	52.59	396.69	35.10
FF	30	87.49	39.08	686.64	33.15
CF	29	84.34	29.54	131.48	21.68
FT	30	141.14	56.69	348.57	73.92
SE	19	51.79	148.09	510.44	161.89
SF	24	117.96	76.28	183.97	65.13
PD	16	57.36	93.74	45.87	136.58
WS	9 or 30	38.16	61.71	584.27	109.38
AC	28	260.31	55.66	469.84	51.14
FP	28	42.54	82.04	74.20	61.74
LP	30	195.55	58.52	197.21	17.13
CM	13	36.37	104.34	411.50	70.44
GS	12	27.71	54.16	0.00	0.00
VE	8	78.47	76.20	115.53	128.19
TS	10	89.44	72.39	616.77	81.60
SS	11	80.78	113.14	125.55	178.20
AR	11	94.62	105.11	71.80	223.27
XP	19	27.35	106.09	0.00	0.00
XR	25	57.20	78.20	160.00	117.41
XN	14	26.53	117.25	77.08	115.76
XB	7	37.92	157.78	50.66	165.81
XL	21	35.22	92.44	327.82	96.28
XK	22	24.61	71.05	2.52	127.98
XD	17	19.42	54.18	1.43	202.53
XW	16	6.09	80.13	0.17	400.00
XE	9	33.85	160.51	24.18	298.70
XG	7	15.25	110.92	0.10	264.58
XF	7	18.27	131.81	1.62	264.58
XS	1	70.41	0.00	0.00	0.00
XX	5	10.88	135.92	0.87	223.61
YY	13 or 30	177.53	56.74	655.58	81.41

Table 4: Statistical Summary for Cost by Element (*Langston 2006)*

There is little similarity between Table 3 and Table 4, with the exception of the coefficients of variation, which are close between energy and cost data for the majority of elements. No reason for this, other than coincidence, is apparent. Note that under Water Supply for operating cost every project is included, as the cost of water usage is allocated to this element. Several elements have no operating liabilities despite having capital cost, although the reverse is not possible. Site Works and External Services are expressed in cost/m^2 of building GFA, so care must be taken when using these figures on future projects.

CONCLUSION

This analysis of thirty Melbourne buildings, comprising a variety of functional types and construction, has led to the conclusion that the embodied energy per square metre of GFA is reasonably consistent. While this might have been expected for buildings of one functional type, such as high rise office towers, the finding that it also holds for buildings of quite different types, spanning a range of commercial and pseudo-commercial projects involving both new construction work and redevelopment, is interesting.

The lowest initial embodied energy is 13.83 GJ/m^2 for a residential redevelopment, and the highest is 26.20 GJ/m^2 for a new hospital. The mean for initial embodied energy is 21.76 GJ/m^2 with a coefficient of variation of just 14.61%. Furthermore, the lowest recurrent embodied energy is 0.03 GJ/m^2/year for a car parking station, and the highest is 0.47 GJ/m^2/year for a hotel. The mean in this instance is 0.28 GJ/m^2/year with a coefficient of variation of 28.75%. Recurrent embodied energy can be compared to other operating energy involved in powering buildings, which ranged from 0.80 GJ/m^2/year for a primary school to 2.32 GJ/m^2/year for a hotel. The mean of operating energy calculates at 1.60 GJ/m^2/year with a coefficient of variation of 31.00%. All figures are expressed in primary energy terms. The difference between new and redeveloped projects is not significant when considering recurrent energy.

Embodied energy is normally distributed across all elements and elemental groups in a project. Across the case studies it is shown that the most significant elements for initial embodied energy are (in decreasing order) Special Provisions, Roof, Substructure, External Walls, Upper Floors and Preliminaries; the first includes an allowance for incompleteness while the last includes an allowance for direct energy in construction. Recurrent embodied energy is concentrated in Special Provisions, Fitments and Special Equipment. The largest elemental group for initial embodied energy is Superstructure (35%) by a factor of two over the next largest.

These results provide useful benchmarking data for other Melbourne buildings, and indicate the significance of embodied energy compared to operating energy. Total embodied energy over one hundred years is estimated at 49.53 GJ/m^2 of GFA, while operating energy (primarily electricity and gas demand) is estimated at 160.26 GJ/m^2 of GFA. In other words, embodied energy is estimated at 23.61% of total energy needs. Over a typical building economic life of thirty years, the proportion of embodied energy rises to 38.49%, or an increase of about 63%.

Cost modelling is a well understood technique and commonly used in practice to predict building costs at various stages during the design process. The technique spans from simple algorithms through to complex models based on abbreviated measured work items. The cost/m^2 of GFA is frequently used to judge the completeness of an estimate by comparison with time-adjusted unit rates for historical projects of similar type. It is acknowledged that unit cost varies according to building type, as well as factors like location and access, market conditions, complexity and others.

The lowest capital cost (expressed in final quarter 2006 dollars) is \$1,082.40/m^2 for a new car parking station, and the highest is \$3,507.53/m^2 for a hospital redevelopment. The mean for capital cost is \$2,540.49/m^2 with a coefficient of variation of 25.41%. Furthermore, the lowest recurrent cost (excluding the cost of energy) is \$38.43/m^2/year again for a new car parking station, and the highest is \$184.38/m^2/year for a new hospital. The mean in this instance is \$110.46/m^2/year with a coefficient of variation of 29.82%. Recurrent cost can be compared to other operating cost involved in powering buildings, which ranged from \$11.03/m^2/year for a primary school to

$44.73/m^2/year for a hospital. The mean calculates at $28.71/m^2/year with a coefficient of variation of 39.31%. The cost of energy is very much linked to the hours of building usage, so hospitals, hotels and residences are generally bigger energy consumers. The contribution of electricity and gas is clearly more significant in energy terms than cost terms due particularly to its conversion from delivered to primary energy.

The most expensive elements for capital cost are (in decreasing order) Air Conditioning, Preliminaries, Electric Light and Power, External Walls and Roof. In contrast, the most expensive elements for operating cost are Preliminaries (including allowances for rates, essential maintenance personnel, garbage collection, insurances, etc.), Electric Light and Power (given that electricity costs are included here), Floor Finishes, Special Provisions, Transportation Systems and Water Supply. The largest elemental group for capital cost is equally shared between Superstructure and Services at 29% each. Operating costs are divided between cleaning (14.16%), energy (20.85%), maintenance/repair (16.63%), replacement (20.76%) and other costs (27.61%) and are measured over a one-hundred-year time horizon.

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