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Life-Cycle Energy Use in Office Buildings

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The total life-cycle energy use is examined in a 4620 *m*^{2} (50,000*ft*^{2}) *three-storey, generic office building for alternative wood, steel and concrete structural systems, with and without underground parking. Detailed estimates are made of the initial embodied energy, the recurring embodied energy associated with maintenance and repair, and operating energy. Based on currently accepted energy performance standards, operating energy represents the largest component of life-cycle energy use. At this time, strategies for reducing the life-cycle energy use should clearly progress first by introducing those design considerations which significantly reduce building operating energy.*

1. INTRODUCTION

AS the twenty-first century approaches, we can anticipate a maturing and strengthening of the public's concern and knowledge on environmental issues, and an expectation for greater environmental responsibility. Increased scrutiny of the building industry has prompted a search for criteria, approaches and practices which can guide more environmentally sound building design, construction and operation. An important part of this activity centres on the development of more comprehensive and reliable information on the environmental attributes of building materials and tools for evaluating alternative design options in terms of their overall environmental consequences. Until recently, the evaluation of the environmental impacts of buildings required the use of the two or three comprehensive data sources created during the mid-1970s–early 1980s [1, 2]. Although these were primarily directed at the energy use in material production, air emissions could be interpreted from the attendant fuel mix data. Given the significant improvements in energy efficiency and other environmental controls, this data is of limited value. There has been a significant increase in the information on the energy and environmental impacts associated with the production of building materials. In Canada, for example, Forintek Canada Corporation has generated a current, comprehensive description of the environmental attributes of the primary structural materials, components and assemblies [3–5] and the work presented in this paper represents part of this ongoing research. The project has produced a calculation model which enables designers to compare and contrast the relative merits, amounts of energy, air emissions, liquid effluent and solid waste associated with the production and installation of alternative *structural* materials and systems which satisfy similar performance requirements.

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Despite the considerable improvement in our understanding of the energy required to produce building materials, there is little work which places these in terms of the full building life-cycle. Life-cycle energy and other environmental impacts include all those incurred in the production, use and removal of a building. It is useful to distinguish between the following *four* distinct categories of a building's life-cycle energy use.

- Energy to initially produce the building.
- The recurring embodied energy required to refurbish and maintain the building over its effective life.
- Energy to operate the building — i.e. the energy required to condition (heat, cool and ventilate) and light the interior spaces and to power equipment and other services.
- Energy to demolish and dispose of the building at the end of its effective life.

This paper examines the total life-cycle energy use in office buildings and, in particular, addresses the following three questions.

- Are there significant differences between the initial embodied energy of wood, steel and concrete structural systems?
- What is the relative order of magnitude of the initial embodied energy of buildings compared to that incurred through normal maintenance and replacement over their effective life and to their operating energy use?
- For current and anticipated future levels of energy efficiency, is embodied energy and the differences created by alternate structural differences, significant when compared to the total life-cycle energy use in buildings?

These questions are addressed by examining the embodied and operating energy use of a 4620 m^2 (50,000 ft^2) three-storey, generic office building for alternative wood, steel and concrete structural systems, with and without underground parking (see Fig. 1).

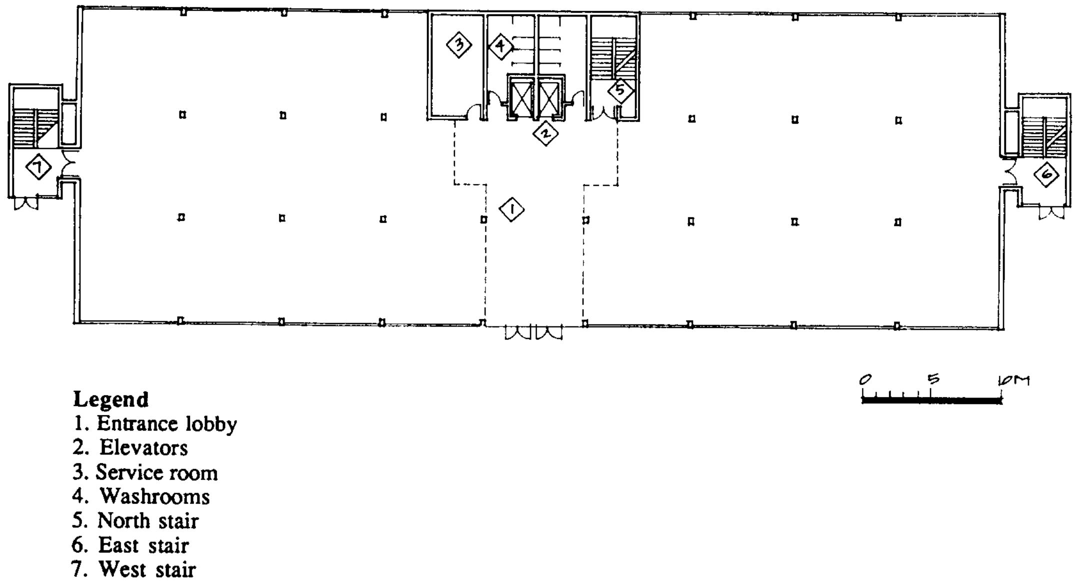

Fig. 1. Typical floor plan.

2. INITIAL EMBODIED ENERGY

The *embodied energy* of a building is the energy used to acquire raw materials and manufacture, transport and install building products in the initial construction of a building. Embodied energy typically describes only the energy to initially produce a building and does *not* include the energy associated with maintaining, repairing and replacing materials and components over the lifetime of the building, hence the importance of using the designation *initial*.

Table 1 summarizes the results of previous studies on the initial embodied energy of office buildings. Typical figures for initial embodied energy of office buildings range from 4 to 12 GJ/m^2 [6–8]. The high figure of 18.6 GJ/m^2 presented by Stein *et al.* [1] is an average U.S. figure derived from early 1970s data and, because of this generality and shifts in building performance and materials production efficiencies over the past 20 years, is less relevant to this study. The most relevant work in the context of this paper is that by Honey and Buchanan [9] who present embodied energy and CO_2 figures for two office buildings in New Zealand, two storeys (2400 m^2) and five storeys (8568 m^2) respectively. The former was analysed for both a wood and a steel frame structure and the latter with concrete and steel structure alternatives. By proportioning the amounts of materials, averaging the concrete embodied energy, and assuming the same non-structural embodied energy/m^2, the authors offer comparative figures for wood, steel and concrete structural systems that would be applicable to typical 5–8 storey commercial buildings [10]. The total embodied energy for commercial office buildings would be 3.70, 5.60 and 6.60 GJ/m^2 for the wood, concrete and steel framed structural alternatives, considerably lower than other published data. The structural embodied energies of the buildings were 1.50, 3.40 and 4.40 GJ/m^2, representing 41, 61 and 67% of the total embodied energy for the wood, concrete and steel framed buildings respectively.

2.1. *Embodied energy of structural systems*

Table 2 summarizes the initial embodied energy of the wood, steel and concrete structural systems for the case study building, presented under the general sub-headings of Below Grade Horizontal Structure, Below Grade Vertical Structure, Above Grade Horizontal Structure, Above Grade Vertical Structure and Miscellaneous.

Significant differences occur between the embodied energies of the three structural options. The initial embodied energy of the wood structure with underground parking (0.92 GJ/m^2) is significantly less than that of the equivalent steel (1.48 GJ/m^2) and concrete (1.17 GJ/m^2) structures (see Fig. 2). Proportionally, the embodied energy of the steel structure is 1.61 times greater and that of the concrete structure is 1.27 times greater than that of the wood structure. These differences are more marked in the case without underground parking. In this case, without the moderating effect of the common single level concrete underground parking facility, the steel structure is 1.82 times greater and the concrete is 1.39 times greater than the wood equivalent.

The inclusion of underground parking represents the most significant difference in structural embodied energy. The inclusion of the underground parking level structure and the inevitable requirement of concrete increases the structural embodied energy by 38, 21 and 25% for the wood, steel and concrete structures respectively. For the building with underground parking, the proportions of below grade to above grade structural embodied energy were 40.2:59.8, 25.0:75.0 and 31.8:68.2% for the wood, steel and concrete frame structures respectively. For the building without underground parking, the equivalent proportions are: 18.4:81.6, 10.2:89.8 and 15.0:85.0% respectively, again reflecting the significance of this component. These proportions are clearly only valid for the unique three-storey case-study designs in which the size of building chosen, in terms of building code compliance, permits the use of wood, steel and concrete structural frames; wood and steel could have theoretically been used

Table 1. Embodied energy studies related to office buildings

Case	Building characteristics				Embodied energy					Reference
	Size (m^2)	No. of storeys	Principal structure	Location	Structure GJ/m^2	%	Non-structure GJ/m^2	%	Total GJ/m^2	
1	Ave	Ave	—	U.S.	—		—		**18.6**	Stein *et al.* [1]
2	3253	4	Wood	U.K.	**0.45**					Gardiner and Theobald [6]
	3253	4	Steel		**2.08**					
	3253	4	Concrete		**1.34**					
3	1502	4	Concrete	Japan	**4.56**	38	**7.5**	62	**12.06**	Oka *et al.* [7]
	2802	8	Concrete/ steel		**3.03**	30	**7.06**	70	**10.09**	
	3500	8	Concrete		**3.38**	30	**7.8**	70	**11.18**	
	22,861	18	Steel		**3.75**	32	**8.12**	68	**11.87**	
	88,049	31	Steel		**3.60**	34	**6.93**	66	**10.53**	
	216,000	25	Steel		**3.34**	42	**4.69**	58	**8.03**	
4	47,000	15	Concrete	Australia	**4.10**	50	**4.13**	50	**8.23**	Tucker and Trelor [8]
5	8568	5	Concrete	New Zealand	**3.84**	59	**2.62**	41	**6.46**	Honey and Buchanan [9]
	8568	5	Steel		**5.00**	65	**2.75**	35	**7.75**	
	2400	3	Concrete		**2.31**	49	**2.44**	51	**4.75**	
	2400	3	Wood		**1.05**	31	**2.30**	69	**3.35**	
6	Ave	3–8	Wood	New Zealand	**1.50**	41	**2.2**	59	**3.7**	Buchanan and Honey [10]
	Ave	3–8	Steel		**4.40**	67	**2.2**	33	**6.6**	
	Ave	3–8	Concrete		**3.40**	61	**2.2**	39	**5.6**	
This study With u/g parking	4620	3	Wood	Canada	**0.92**	20	**3.62**	80	**4.54**	
	4620	3	Steel		**1.48**	29	**3.65**	71	**5.13**	
	4620	3	Concrete		**1.17**	24	**3.62**	76	**4.79**	
No u/g parking	4620	3	Wood		**0.67**	16	**3.6**	84	**4.26**	
	4620	3	Steel		**1.22**	25	**3.63**	75	**4.86**	
	4620	3	Concrete		**0.93**	21	**3.58**	79	**4.52**	

more extensively within the respective designs, thereby exaggerating the differences between the three solutions. Common construction practice and code requirements for combustible construction between the above and below grade structure require the use of significant quantities of concrete in each option. For taller structures, beyond three storeys, the steel structure would require the use of more significant wide flange columns and secondary structural members with an attendant increase in embodied energy/m^2. Similar arguments can be applied

Table 2. Summary of initial structural embodied energy

Component	Wood		Steel		Concrete	
	GJ	%	GJ	%	GJ	%
With underground parking						
Below grade horizontal	1347	31.6	1347	19.7	1347	25.0
Below grade vertical	366	8.6	366	5.3	366	6.8
Above grade horizontal: primary	332	7.8	1748	25.6	2572	47.6
Above grade horizontal: secondary	1747	40.9	2461	36.0		
Above grade vertical	67	1.6	327	4.8	868	16.1
Miscellaneous	409	9.6	588	8.6	245	4.5
Total	**4268**	**100.0**	**6836**	**100.0**	**5398**	**100.0**
GJ/m^2	**0.92**		**1.48**		**1.17**	
No underground parking						
Below grade horizontal	464	15.0	469	8.3	540	12.5
Below grade vertical	106	3.4	106	1.9	106	2.5
Above grade horizontal: primary	332	10.7	1748	30.9	2572	59.8
Above grade horizontal: secondary	1737	56.3	2461	43.6		
Above grade vertical	67	2.2	327	5.8	868	20.2
Miscellaneous	381	12.3	540	9.6	217	5.0
Total	**3088**	**100.0**	**5650**	**100.0**	**4303**	**100.0**
GJ/m^2	**0.67**		**1.22**		**0.93**	
Difference of u/g parking (%)	**38.2**		**21.0**		**25.4**	

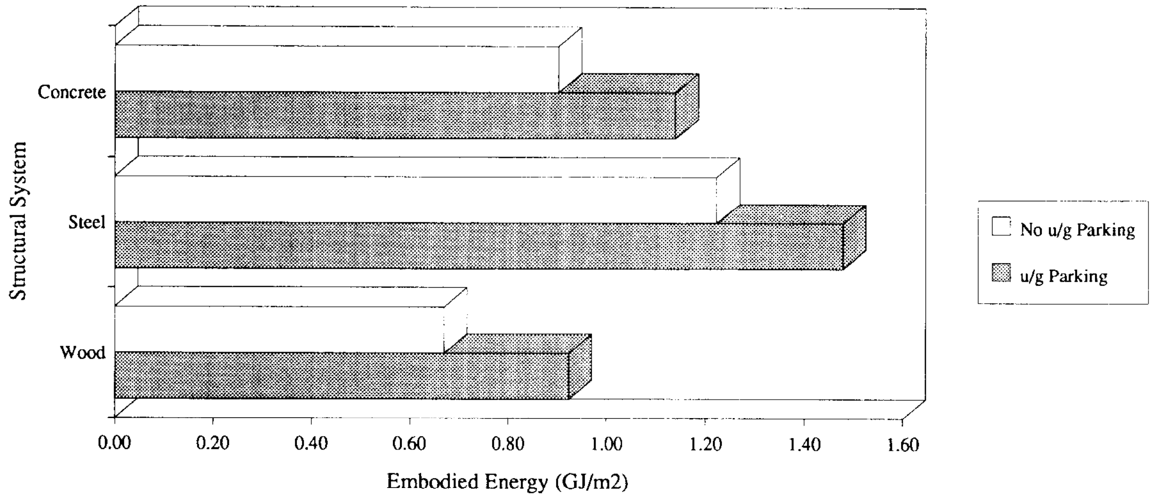

Fig. 2. Embodied energy of structure.

to the concrete structure. However, as in Honey and Buchanan's study, a direct comparison with wood is not possible given code restrictions on the use of wood above three storeys. If the number of storeys was increased, one could anticipate that the relative significance of the underground parking facility in structural embodied energy would diminish.

2.2. *Total initial embodied energy*

Table 3 summarizes the total initial embodied energy of the case-study building under the general sub-headings of Site work, Structure, Envelope, Finishes, Services and Construction for the building with and without underground parking.

The total initial embodied energy of the wood structure with underground parking (4.54 GJ/m^2) is less than that of the equivalent steel (5.13 GJ/m^2) and concrete (4.79 GJ/m^2) structures. The embodied energy of the steel framed building is 1.13 times greater than that of the wood framed building, and the embodied energy of the concrete framed building is 1.05 times greater than that of the wood framed building. The equivalent figures for the cases without underground parking are 4.26, 4.86 and 4.52 GJ/m^2 respectively. Again, the distinction is more marked in the case without underground parking with the steel building being 1.14 times greater than the wood framed building and the concrete 1.06 times greater.

The structure represents a significant, but not dominant, proportion of the total embodied energy of the building — representing 20.3, 28.9 and 24.4% for the wood, steel and concrete framed buildings for the case with underground parking and 15.7, 25.2 and 20.6% for that without. The embodied energy of the building envelope represents the largest single component in the total initial embodied energy, representing between 26 and 30%. The choice of building envelope (wood structure/wood studs, etc.) is invariably linked with the structural system. The combination of structure and building envelope represents 48.6, 54.1 and 50.7% of the total initial embodied energy for wood, steel and con-

Table 3. Summary of total initial embodied energy

Component	Wood		Steel		Concrete	
	GJ	%	GJ	%	GJ	%
With underground parking						
Site work	1246	5.9	1246	5.3	1246	5.6
Structure	4268	20.3	6836	28.9	5398	24.4
Envelope	5935	28.3	5964	25.2	5822	26.3
Finishes	2900	13.8	2825	11.9	2945	13.3
Services	5263	25.1	5263	22.2	5263	23.8
Construction	1373	6.5	1549	6.5	1447	6.5
Total	**20,984**	**100.0**	**23,683**	**100.0**	**22,121**	**100.0**
GJ/m^2	**4.54**		**5.13**		**4.79**	
No underground parking						
Site work	1344	6.8	1344	6.0	1344	6.4
Structure	3088	15.7	5650	25.2	4303	20.6
Envelope	5935	30.1	6062	27.0	5822	27.9
Finishes	2935	14.9	2799	12.5	2920	14.0
Services	5110	25.9	5110	22.8	5110	24.5
Construction	1289	6.5	1468	6.5	1365	6.5
Total	**19,699**	**100.0**	**22,433**	**100.0**	**20,863**	**100.0**
GJ/m^2	**4.26**		**4.86**		**4.52**	
Difference of u/g parking (%)	**6.5**		**5.6**		**6.0**	

crete framed structures respectively with underground parking.

The embodied energy of the building services (conveyance, HVAC, etc.) represents the next most significant component of total building embodied energy after the envelope and structure, representing approximately 20–25% of the total initial embodied energy. This component is also the one which is the most difficult to assess with any degree of confidence at this time. The embodied energy of the internal finishes constitutes between 12 and 15% of the initial total embodied energy. However, as with the building services, internal finishes are the most frequently repaired and replaced components over the life of a building and, as demonstrated in an earlier report, eventually far outweigh the structural embodied energy.

The proportion of the total initial embodied energy of the case-study building represented by the structure is less than that presented by Buchanan and Honey. Applying the energy intensity figures used by Honey and Buchanan for wood, steel and concrete products in the case-study building gives embodied energy values of 1.65, 2.55 and 2.82 GJ/m^2 for the wood, steel and concrete buildings with underground parking (compared to those using current Canadian data — 0.92, 1.48 and 1.17 GJ/m^2). The equivalent figures for the building without underground parking are 1.02, 1.91 and 2.23 GJ/m^2 and 0.67, 1.22 and 0.93 GJ/m^2 respectively. However, it is difficult to explain these differences given the limited description of what constitutes "structure" and "non-structure" in the New Zealand study. The range of non-structural embodied energy figures in their study is from 2.3 to 2.75 GJ/m^2, compared to 3.6–3.75 GJ/m^2 in the present study, suggesting a more limited range of additional considerations in the Buchanan and Honey study.

3. RECURRING EMBODIED ENERGY

The internal partitions and doors, finishes and building services are replaced, refurbished and maintained more frequently than the structure and envelope which comprise the majority of the initial embodied energy. Life-cycle energy analysis must account for the changes in embodied energy associated with building up-keep and improvements. It is useful to distinguish between regular repainting, re-carpeting, replacement of systems, lamps, etc. and major periodic refurbishment due to changes in tenancy or office restructuring.

Maintenance and replacement occur periodically over the life of a building. An approach which accounts for maintenance and replacement is identified in *Optimize* [11]. Maintenance is assumed to involve replacing less than 100% of a material or component. Maintenance can be categorised into two types as follows.

- Maintenance incurred during a completed life-cycle of a material or component. For a product which completes its life-cycle, the number of maintenance (repair) cycles required is the product life/repair interval corrected for the possibility of forgone repairs near the end of the product life.
- Maintenance incurred during the incomplete life-cycle of a product due to the expiration of the building. For the last replacement of a product, the number of repair cycles will depend on the years remaining before the life of the building expires rather than the product life.

Replacement refers to the total replacement (100%). The number of times a component is replaced is given by the building life/product life corrected for possibility that if the replacement occurs near the end of the building life, non-essential repairs and replacements would be avoided. Replacement may be as a result of functional reasons at the end of a product's useful life, aesthetic reasons or due to the replacement of another associated element in an assembly.

Currently, for many building types, particularly in the commercial and retail sectors, major refurbishment often involves substantial reconstruction and is being undertaken at increasingly shorter intervals [12]. Fit-out consists of internal partitions and doors, floor, wall and ceiling finishes and mechanical and electrical services. These elements are replaced more frequently than structural and envelope elements and use greater proportions of energy intensive materials, e.g. plastics, copper, etc. Howard and Sutcliffe [13] present the embodied energy figures associated with basic, medium and top grade office fit-out as 0.17, 0.23 and 0.34 GJ/m^2/year respectively, assuming frequent replacement annualized from a 60 year building life. Equivalent figures for infrequent replacement are 0.10, 0.13 and 0.17 GJ/m^2/year. Averaged over the same building life, the initial embodied energy of the office building was 0.08, 0.09 and 0.1 GJ/m^2/year for the three grades of accommodation. These figures suggest that the embodied energy associated with building fit-out is always greater than the initial embodied energy and, for highly frequent, top-grade changes, the difference can be as much as three-fold.

Table 4 summarizes the additional embodied energy associated with typical replacement and repair over a 25, 50 and 100 year building life for the building with a wood structure. The percentages alongside the energy figures give the increase in embodied energy compared to their values in the initial embodied energy of the building.

The embodied energy associated with replacement and repair of building elements over the life of a building is greater than that associated with any single element of the initial embodied energy. For a current typical building life of, say, 50 years, the recurring embodied energy (between 6.5 and 6.8 GJ/m^2) is equivalent to the initial embodied energy of the building (see Fig. 3). Since the basic structure of the building is assumed permanent, there is no recurring embodied energy associated with this component. The building services and interior finishes and components are the most significant categories of recurring embodied energy. The interior finishes and components, which represent only a relatively small portion of the initial embodied energy, dominate the recurring embodied energy — approximately 1.3, 3.2 and 7.3 times their initial values for 25, 50 and 100 year building life-spans respectively.

In the above analysis, all future replacement materials were assumed identical to those being replaced and their energy intensities assumed to be at current levels with no allowance for improvements in manufacturing techniques over the intervening years. The estimated values of the maintenance and replacement embodied energy

Table 4. Summary of recurring embodied energy (wood structure)

	Building life					
	25 years		50 years		100 years	
	Energy (GJ)	Increase (%)	Energy (GJ)	Increase (%)	Energy (GJ)	Increase (%)
With underground parking						
Site work	65	5.2	357	28.6	0	0.0
Structure	0	0.0	0	0.0	0	0.0
Envelope	3873	65.3	8943	150.7	20,060	338.0
Finishes	3869	133.4	9339	322.0	21,046	725.7
Services	3369	64.0	9920	188.5	23,093	438.8
Construction	671	48.9	1714	124.8	3911	284.9
Total	**11,848**	**56.5**	**30,272**	**144.3**	**68,110**	**324.6**
GJ/m^2	**2.56**		**6.55**		**14.74**	
No underground parking						
Site work	65	4.9	358	26.7	1001	74.5
Structure	0	0.0	0	0.0	0	0.0
Envelope	3873	65.3	8943	150.7	20,060	338.0
Finishes	3696	125.9	8397	286.2	18,936	645.3
Services	3338	65.3	9859	192.9	22,955	449.2
Construction	658	51.1	1653	128.3	3777	293.1
Total	**11,631**	**59.0**	**29,211**	**148.3**	**66,728**	**338.7**
GJ/m^2	**2.52**		**6.32**		**14.44**	

costs in Fig. 3 are therefore greater than will occur in practice. Over a 25–100 year time frame, materials and the construction processes can be anticipated to go through significant changes. Between 1971 and 1986, there was a 20% decrease in the energy intensity for steel, a 24% decrease for non-ferrous metals and a 33% decrease for cement [14]. These rates of improvement may not be sustained in the future, but it can be assumed that there will continue to be reductions in the energy intensity, e.g. CANMET predicts the energy intensity of steel produced in Canada will decrease from 27 MJ/kg in 1989 to 11.9 MJ/kg in 2010 [15]. Assuming a 1% reduction in energy intensity of construction materials, the resulting recurring embodied energies of the case study building would be approximately 84, 76 and 62% of the values assuming no change in energy intensity for the 25, 50 and 100 year building longevity respectively. Although there are clearly many uncertainties regarding future developments in materials and construction technologies, the recurring embodied energy will remain a significant component of life-cycle energy.

4. DEMOLITION ENERGY

Energy is used to demolish buildings and transport and dispose of "waste" material. Current demolition practice involves intense application of energy and haulage to landfill. The prime difficulty in assessing demolition energy is that of predicting demolition practices some 50 years or more in the future [16]. At that time, we can

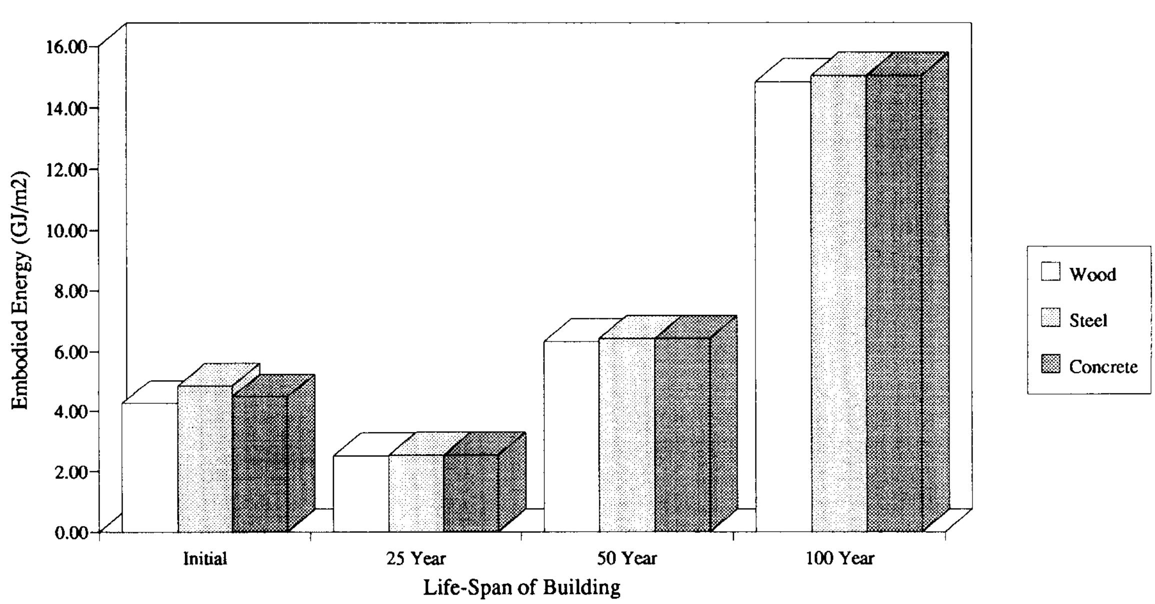

Fig. 3. Recurring embodied energy (no underground parking).

anticipate that the salvaging of materials will assume greater importance and that greater care, effort and time will be expended in removal, sorting and cleaning materials for future re-use or return to the materials' industries for recycling. It is not useful or appropriate to differentiate between the energy used to transport concrete, wood and steel from the demolition site to their final destinations. These materials are currently heaped and, unless only one or two contain hazardous wastes, are taken to a common disposal site.

Published figures on the actual amount of energy associated with the demolition and attendant transportation of recyclable materials and debris are limited. The U.S. Advisory Council on Historic Preservation [17] suggests 27.1, 81.7 and 136.2 MJ/m^2 (2400, 7200 and 12,000 Btu/ft^2) for the demolition of a 5000 m^2 wood, steel or concrete building respectively. It is unclear from the study what is included within the demolition process, i.e. if it relates only to the dismantling or whether it includes transportation. Quantitatively, these figures represent approximately 1–3% of the initial embodied energy. As such, and given the high degree of uncertainty surrounding demolition practices and the many possible commonalities between the transportation energy for demolished wood, steel and concrete structures, the demolition energy was not considered further in the life-cycle energy analysis presented in this paper.

5. OPERATING ENERGY

The energy used to heat, cool, ventilate and light buildings represents over 30% of Canada's national energy use, with approximately 20% used in residential buildings and the remainder in commercial buildings. In other countries with different industrial bases and transportation networks, space heating/cooling, water heating, lighting and power in buildings can be as high as 50% of the national energy use [13].

Operating energy varies considerably with building use patterns, climate and season and the efficiency of the building and its systems. In this regard, it is useful to distinguish between those aspects of operating energy which are directly influenced by the building and systems design, e.g. insulation standards, efficiency of lighting and other systems, and those which are dependent upon the way in which the building is used and managed (i.e. control strategies, scheduling etc.) and variations in prevailing climate. In the former case, additional material resources (and therefore embodied) energy may be required to reduce operating energy (e.g. increased insulation standards, thermal mass etc.), while in the latter, considerable energy reductions are possible independent of the physical characteristics of the building.

Conservation efforts in the building industry over the past 20 years have focused almost exclusively on reducing building operating energy and building designers now have a reasonable understanding of what constitutes an "excellent" or "poor" operating energy performance, as well as a number of valuable techniques for both assessing and improving it. Operating energy for this study was determined using the DOE-2.1D energy simulation program. The insulation standards, glazing amount and type and internal loads are consistent with those specified in the proposed Canadian 1995 National Energy Code.

The operating energy associated with changes in the glazing type and orientation ranges from 0.95 to 1.21 GJ/m^2/year. These figures are appropriate for the set of operating schedules and system efficiencies assumed in the analysis (see Table 5 for the occupancy, lighting and HVAC schedules and other key system design characteristics). Extrapolating these into the future, when there will presumably be more efficient systems, changing patterns of work, etc. will dramatically alter the annual operating energy. Considerable differences in operating energy can occur without increase or decrease in building embodied energy, e.g. increases simply as a result of a change in building orientation.

The difference in the operating energy between wood, steel and concrete framed buildings is negligible. This insensitivity between the structural options derives from the following.

- Office buildings tend to be internal load-dominated, and their operating energy less dependent on the thermal characteristics of the building envelope.
- The major influence on operating energy resulting in differences between the wood, steel and concrete structural frames would be the change in thermal mass. However, all the alternative designs have common interior finishes and concrete toppings on the floors. These are typically the most dominant factors affecting the effective thermal mass of the building, rather than the underlying structure.
- All buildings have building envelopes (walls, roof and windows) with the same thermal resistance and the potential differences in thermal bridging between wood and steel studs is negated by locating the thermal insulation layer outside of the exterior sheathing.

Values of 1.05 and 1.761 GJ/m^2/year were used for the operating energy component for the building with underground parking in Vancouver and Toronto respectively in the life-cycle energy analyses. The equivalent figures used for the building without underground parking were 0.959 and 1.636 GJ/m^2/year respectively. Assumptions were made that we can currently design to energy standards that yield an operating energy 50% below code requirement (i.e. 0.525 and 0.881 GJ/m^2year for the building with underground parking) and that in the foreseeable future, such buildings will be achieving performances 75% below current levels (i.e. 0.263 and 0.440 GJ/m^2/year for the building with underground parking). The operating energy figures were established using *current* Typical Meteorological Year (TMY) weather tapes for Vancouver and Toronto and have been considered applicable for the full life-cycle analysis. Although the potential changes in weather conditions associated with changes in both global climate and the surrounding context could have a significant effect on the operating energy over the next 50–100 years, they remain extremely difficult to both predict and account for in the analysis.

6. LIFE-CYCLE ENERGY USE

The life-cycle energy use for the building was derived by the summation of the three main components: initial

Table 5. Operating schedules for operating energy

Hour	Occupancy		Lighting		HVAC			
			Power factor		Heating set point (°C)		Cooling set point (°C)	
	Week	Weekend/ holiday	Week	Weekend/ holiday	Week	Weekend/ holiday	Week	Weekend/ holiday
1	0	0	0.15	0.15	12.8	12.8	37.0	37.0
2	0	0	0.15	0.15	12.8	12.8	37.0	37.0
3	0	0	0.15	0.15	12.8	12.8	37.0	37.0
4	0	0	0.15	0.15	12.8	12.8	37.0	37.0
5	0	0	0.15	0.15	12.8	12.8	37.0	37.0
6	0	0	0.15	0.15	12.8	12.8	37.0	37.0
7	0	0	0.15	0.15	12.8	12.8	37.0	37.0
8	Full	0	1.00	0.15	22.2	12.8	24.5	37.0
9	Full	0	1.00	0.15	22.2	12.8	24.5	37.0
10	Full	0	1.00	0.15	22.2	12.8	24.5	37.0
11	Full	0	1.00	0.15	22.2	12.8	24.5	37.0
12	Full	0	1.00	0.15	22.2	12.8	24.5	37.0
13	Full	0	1.00	0.15	22.2	12.8	24.5	37.0
14	Full	0	1.00	0.15	22.2	12.8	24.5	37.0
15	Full	0	1.00	0.15	22.2	12.8	24.5	37.0
16	Full	0	1.00	0.15	22.2	12.8	24.5	37.0
17	Full	0	1.00	0.15	22.2	12.8	24.5	37.0
18	Full	0	1.00	0.15	22.2	12.8	24.5	37.0
19	0	0	0.15	0.15	12.8	12.8	37.0	37.0
20	0	0	0.15	0.15	12.8	12.8	37.0	37.0
21	0	0	0.15	0.15	12.8	12.8	37.0	37.0
22	0	0	0.15	0.15	12.8	12.8	37.0	37.0
23	0	0	0.15	0.15	12.8	12.8	37.0	37.0
24	0	0	0.15	0.15	12.8	12.8	37.0	37.0

Air changes/hour: 2; lighting density: 20 W/m^2; plug loads: 5 W/m^2; occupancy density: 10 m^2/person.

and recurring embodied energy and operating energy. Demolition energy is insignificant. Figure 4a, b and c show the relative proportions of the embodied and operating life-cycle energy use for the wood structural building with underground parking over a 25, 50 and 100 year building life respectively. Table 6 shows a more detailed breakdown of the life-cycle energy use for a 50 year life-span.

6.1. *Significance of operating energy*

The energy used to operate the building is by far the largest component of life-cycle energy use. For a typical building life of 50 years, the energy to heat, cool, light and provide ventilation represents approximately 80% of the case-study building in Vancouver and 90% of that in Toronto. If the building operating energy was reduced by 50%, a reasonable expectation for a current energy efficient building, this component of would represent approximately 70 and 80% life-cycle energy use for Vancouver and Toronto respectively (with underground parking). Moreover, if the building operating energy was reduced by 75%, representing a performance which will likely be common-place early in the 21st century, operating energy would fall to approximately 55 and 65% life-cycle energy use for Vancouver and Toronto respectively (with underground parking).

6.2. *Significance of recurring energy*

At a building life of 50 years and current energy standards, the embodied energy for replacement and repair is approximately the same as that of the initial embodied energy — each representing approximately 7–10% of life-cycle energy use in Vancouver and 5–7% in Toronto. For short life-spans, the recurring embodied energy is less than the initial energy and for long-life buildings (say 100 years), the recurring embodied energy is between two and three times greater.

6.3. *Significance of initial embodied energy*

In the case with underground parking, in Vancouver, the initial embodied energy for the building is approximately equivalent to 4.3, 4.9 and 4.6 years of operating energy for the wood, steel and concrete structures. For the more severe Toronto climate, the number of equivalent years reduces to 2.6, 2.9 and 2.7 years respectively. Comparable figures assuming a 50% reduction in building operating energy are 9.7, 11.6 and 10.9 years and 5.8, 6.9 and 6.4 years respectively. Comparable figures assuming a 75% reduction in building operating energy are 19.5, 23.2 and 21.8 years and 11.6, 13.8 and 12.8 years respectively. For the case of no underground parking, and attendant reduced initial embodied energy, the equivalent number of years of operating energy diminishes further.

7. CONCLUSIONS

This paper has examined the relative orders of magnitude of the components of life-cycle energy use in office buildings.

The values of the initial embodied energy of the building differ from those of other recent studies, primarily due to the use of more current energy intensity data. An important conclusion is that published studies on initial

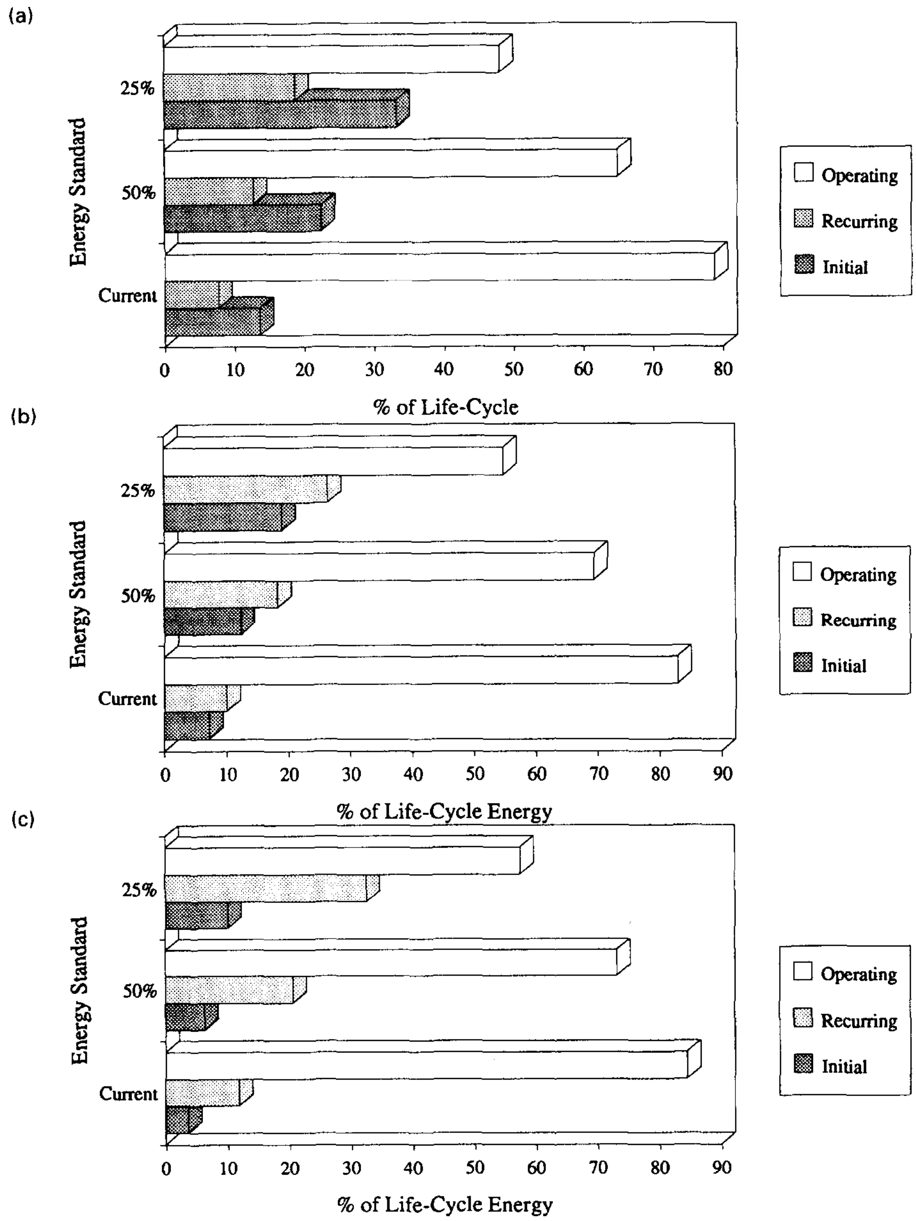

Fig. 4. Life-cycle energy (wood, Vancouver). (a) 25 years. (b) 50 years. (c) 100 years.

embodied energy of buildings provide a guide to the typical ranges for the initial embodied energy of office buildings and reinforce the notion that a detailed focus on the energy intensities and embodied energy of every material, component or system in a building while losing sight of their relative significance, is an ineffective approach. However, it is difficult to interpret and compare the studies in any detail because of the lack of definition of what was included within the total embodied energy figures (e.g. site work, level of finishes and fit-out, conveyance equipment, plumbing, etc.). Moreover, it is difficult and inappropriate to make generalizations about the relative significance of the various constituent elements of total building embodied energy; each case must be assessed on its own merits.

Structure can represent a significant proportion of the initial embodied energy of a commercial office building. The work confirms the conclusions of previous studies that structure can also be the single largest component of initial embodied energy. The differences between the embodied energy of wood, steel and concrete framed buildings designed to offer similar performance can also be significant. However, structural systems are seldom, if ever, composed of a single material type and the choice of a particular structural material or system inevitably means a series of non-structural materials or assembly choices are also dictated. The use of concrete, in particular, tempers the distinction between the embodied energy of typically "wood", "steel" and "concrete" structures.

Based on currently accepted energy performance standards, operating energy represents the largest component of life-cycle energy use. As environmental issues continue to become increasingly significant building design priorities, we can anticipate considerably improved energy standards. As the energy efficiency of buildings improves, the amount of energy required to produce them — their *embodied* energy — represents an increasing component of total energy. As operating energy is reduced below

Table 6. Life-cycle energy use — 50 year building life

	Vancouver						Toronto					
	Wood		Steel		Concrete		Wood		Steel		Concrete	
	Energy (GJ/m^2)	%	Energy (GJ/m^2)	%	Energy (GJ/m^2)	%	Energy (GJ/m^2)	%	Energy (GJ/m^2)	%	Energy (GJ/m^2)	%
With underground parking												
Initial	**4.54**	7	**5.13**	8	**4.79**	8	**4.54**	5	**5.13**	5	**4.79**	5
Replacement and repair	**6.32**	10	**6.56**	10	**6.45**	10	**6.32**	6	**6.56**	7	**6.45**	6
Operating	**52.50**	83	**52.50**	82	**52.50**	82	**88.05**	89	**88.05**	88	**88.05**	89
Total	**63.36**	100	**64.18**	100	**63.74**	100	**98.91**	100	**99.73**	100	**99.29**	100
Operating/year	1.05		1.05		1.05		1.76		1.76		1.76	
Equiv. no. of years of embodied energy	4.33		4.88		4.56		2.58		2.91		2.72	
(Operating/replace/repair)/year	1.18		1.18		1.18		1.89		1.89		1.89	
Equiv. no. of years of embodied energy	3.86		4.34		4.06		2.41		2.71		2.53	
No underground parking												
Initial	**4.26**	7	**4.86**	8	**4.52**	8	**4.26**	5	**4.86**	5	**4.52**	5
Replacement and repair	**6.32**	11	**6.6**	11	**6.42**	11	**6.32**	7	**6.60**	7	**6.42**	7
Operating	**47.95**	82	**47.95**	81	**47.95**	81	**81.80**	89	**81.80**	88	**81.80**	88
Total	**58.54**	100	**59.40**	100	**58.89**	100	**92.39**	100	**93.25**	100	**92.74**	100
Operating/year	0.96		0.96		0.96		1.64		1.64		1.64	
Equiv. no. of years of embodied energy	4.45		5.06		4.71		2.61		2.97		2.76	
Operating + replace & repair	1.09		1.09		1.09		1.76		1.77		1.76	
Equiv. no. of years of embodied energy	3.93		4.45		4.15		2.42		2.75		2.56	

50% of current standards, embodied energy will be a dominant factor. At this time, strategies for reducing the life-cycle energy use should clearly progress first by introducing those design considerations which significantly reduce building operating energy. When the operating energy has been reduced, emphasis should then be directed at reducing building embodied energy.

The building structure typically lasts the full life of the building without replacement or repair; the most significant building elements in recurring embodied energy are the building services and interior finishes. Depending on the effective life of a building, the initial embodied energy may be greater or less than the recurring energy associated with refurbishment and repair. Over a typical 50 year building life, the initial embodied energy of the structure represents a relatively small portion of life-cycle embodied energy (i.e. less than 5%) and, as a consequence, the distinction between wood, steel and concrete systems is also less marked.

Reducing embodied energy involves much more comprehensive design approaches than materials' substitution. Since the recurring embodied energy figures associated with materials' replacement and repair are significant, attention must be focused on materials' longevity and the ability to replace elements within a total building assembly.

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