A multi-performance comparison of long-span structural systems

C.T. Griffin, E. Douville, B. Thompson
Department of Architecture, Portland State University, Portland, Oregon, United States

M. Hoffman
KPFF Consulting Engineers, Portland, Oregon, United States

ABSTRACT: When a building requires a long span, especially on the ground floor of a multi-story building, the long span often determines the structural system used early in the design process without any other consideration. Commercial and residential buildings are responsible for roughly 40% of all carbon emissions and energy use, more than any other sector in the USA. Moreover, this excludes the significant energy and emissions required to extract, process, transport and assemble building components. Globally, the production of cement alone accounts for 4% of carbon dioxide emissions. Consequently, reducing the environmental impact of building construction and operations is critical to address interrelated issues such as global climate change. The role of structural systems in the overall performance of a building has been largely neglected. Very little consideration is given to other ways the structure could contribute to improving sustainable outcomes. This is in spite of the fact that the structure of a typical office building contributes roughly one-quarter of the total embodied energy and is, at the very least, the armature for all other building systems. Existing research into the embodied energy of structural systems focuses on hypothetical office buildings with uniform structural layouts, a range of comparable, existing office buildings or housing without comparing or accounting for the long spans. Like all other aspects of a building, the structural system needs to be understood in terms of wide range of sustainability issues: embodied energy, operational energy, longevity and reuse. If structural systems could be left exposed without additional finishes as well as be configured to provide a higher level of thermal comfort, more daylight and acoustic isolation, this could significantly reduce the operational energy and the initial materials required for new construction. These multi-performance structural systems, in contrast to high-performance structural materials that aim to only improve structural properties, offer considerable and largely untapped opportunities to improve new and existing buildings while potentially lowering construction costs. Using a five-story, 2,500 square-meter (27,000 square-foot) classroom building with 24.4 meters by 30.5 meters (80 feet by 100 feet) auditorium on the ground floor as a case study currently in design at Oregon State University, the multi-performance criteria for three long span systems, including steel, concrete and wood, are compared. These criteria include embodied energy and carbon, structural and spatial properties, acoustical properties, fire protection and thermal properties. This paper argues that the most efficient structural solution may not be the best in terms of overall sustainability outcomes, and the selection of a structural system should be based on multi-performance criteria.

1 INTRODUCTION

1.1 *Rationale*

In contemporary building construction, the selection of a structural system occurs early in the design process and is influenced by building codes, cost, scale of the project, and bay sizes required by the program (Griffin et al. 2010a). Consequently, architects and engineers typically only consider structural performance in relationship to the cost of structure and the building program is considered. Selecting structural systems using a multi-performance set of criteria, including environmental impact, thermal mass, thermal conductance, acoustic transmission and fire-resistance, could offer considerable and largely untapped opportunities to reduce operational energy use and improve the indoor environmental quality of new and existing buildings while potentially lowering construction costs. Long spans are often an integral part of buildings that require unobstructed spaces or need future flexibility in terms of interior space planning. Many builds make use of long spans on the lower floor of a multistory building for spaces like lobbies, atriums, auditoriums, lecture halls, and gymnasiums. Because these long spans can dictate the structural system used for the entire project, an analysis of multi-performance criteria for long span structural systems is necessary.

1.2 *Environmental impact and long-span structures*

There has been much research on the embodied energy and carbon of building materials, including structural materials, as evidenced by the Inventory of Carbon and Energy (ICE) produced by the Sustainable Energy Research Team (SERT) at the University of Bath (Hammond & Jones, 2008). This inventory surveys peer-reviewed articles on the embodied energy of construction materials and reports the average values found from these sources. For the purposes of this paper, embodied energy is defined as the total primary energy consumed during resource extraction, transportation, manufacturing and fabrication of construction materials, known as "cradle-to-gate" as opposed to the "cradle-to-grave" method of calculating embodied energy that would also include primary energy expended on the transportation, construction, maintenance and disposal of building materials. As transportation, construction methods, building maintenance, life-cycle, and demolition can vary greatly, this paper focuses on the more consistent and quantifiable components of the embodied energy of structural materials.

Current embodied energy and carbon research for structural materials and systems has focused on theoretical office building layouts with uniform grid column spacing (Cole & Kernan 1996, Scheuer et al. 2003, Guggemos and Horvath 2005). These studies show that the structural systems contribute roughly one-third to one-quarter of the total embodied energy, making these systems a target for reducing the environmental impact of buildings. While the occupation phase of a building's life cycle currently dominates total energy usage, as operational energy is minimized through high performance design, construction and equipment, embodied energy will play a larger role in the overall energy consumption of a building (Thormark 2002). Therefore, the structural system should be a main target for reducing the environmental impact of a building (Griffin et al. 2010b).

It is difficult to apply the results of studies that have calculated the embodied energy and carbon of structural systems in "typical" office buildings to long-span structural systems due to uniform structural grids and relatively short spans associated with these theoretical buildings. Consequently, this paper will compare alternative structural systems using the three primary structural materials – concrete, steel and wood – for the design of a space that requires long spans. This research is geared towards providing a long-span system to meet the multi-performance needs of a specific case study, a 24.4m by 30.5m (80ft by 100ft) auditorium in a new classroom building on the Oregon State University campus. Before discussing the case study in more detail (Section 3), this paper will outline the multi-performance criteria that should be used in evaluating structural systems during the selection process.

2 MULTI-PERFORMANCE CRITERIA

2.1 *Structural efficiency and longevity*

Like all other structures, a multi-performance structural system should be designed to meet applicable building codes and design loads. Structural systems should be optimized to reduce the amount of structural material used while meeting programmatic requirements. This has the potential of reducing the first cost and the initial environmental impact of a building. Lighter structural alternatives that may at first glance look more expensive per square foot, such as castellated or cellular steel beams, in comparison to conventional systems could improve other multi-performance criteria such as improving daylight distribution and reducing material needed for foundations. In the end, once fully integrated with other systems, these buildings with more efficient structural systems could cost the same if not less. In particular, this study looks at two concrete structural systems that use post-tensioned beams, one with a post-tensioned slab and one with conventionally reinforced joists and slab, to study the material efficiency of each and the consequences on other multi-performance criteria.

In conflict with the goal of minimizing structural materials, increasing the longevity of a building's structure should be considered during the initial phases of the design process. In regions with high environmental loads, such as special wind or seismic zones, meeting building codes will not ensure a building can be repaired and returned to occupancy after an extreme loading event. Consequently, structural alternatives that use more material should be considered if they could significantly increase the life span of a building or its ability to be repaired and returned to full occupancy rapidly.

2.2 *Embodied energy and carbon*

As highlighted in Section 1.2, this study uses cradle-to-gate embodied energy and carbon values from the ICE database (Hammond & Jones 2008). The values used for concrete materials can be found in Table 1, those for steel materials can be found in Table 2 and those for wood can be found in Table 3. These values are extrapolated from worldwide averages in the ICE database, which focuses on the implications for the United Kingdom. Consequently, these values are not reflective of the specific conditions and primary energy sources used in the Pacific Northwest of the United States but are the most credible, peer reviewed embodied energy values in the authors' opinion. It should be noted that there is a potential plus or minus 30% range in embodied energy and carbon values and detailed in the ICE database.

Table 1. "Cradle-to-gate" embodied energy (MJ/kg) and carbon (kg CO^2/kg) of structural concrete with various portland cement replacement rates with fly ash. Data extrapolated from ICE (Hammond and Jones 2008).

PSI (MPa)	0% Fly Ash Replacement		20% Fly Ash Replacement	
	MJ/kg	kg CO^2/kg	MJ/kg	kg CO^2/kg
4,000 (27.6)	0.94	0.14	0.87	0.11
6,000 (41.4)	1.19	0.18	1.07	0.16

Table 2. "Cradle-to-gate" embodied energy (MJ/kg) and carbon (kg CO^2/kg) of virgin and 93% recycled structural steel products. Data extrapolated from ICE (Hammond and Jones 2008).

Material	Virgin		93% Recycled Content	
	MJ/kg	kg CO^2/kg	MJ/kg	kg CO^2/kg
Structural Sections	38.0	3.03	12.0	0.58
Decking (Cold Formed Galvanized)	40.0	3.01	12.2	0.69
Reinforcing Bar	29.2	2.77	10.8	0.61
PT Tendons	35.4	2.89	11.3	0.64

Table 3. "Cradle-to-gate" embodied energy (MJ/kg) and carbon (kg CO^2/kg) of structural wood products excluding bio-energy or carbon stored in the wood itself. Data from ICE (Hammond and Jones 2008).

Material	MJ/kg	kg CO^2/kg
Glue-laminated timber	7.1	0.42
Sawn timber	3.2	0.20
Plywood	7.9	0.45

The comparison between the use of virgin materials and materials with a high cement replacement, in this case with fly ash, and recycled content highlights the impact that the use of recycled material can have on the embodied energy of a structure. For this study we assumed that structural concrete used in the spans could have a maximum replacement of 20%. This is the maximum replacement value at which no significant change is needed in mix design and typically specified by structural engineering firm collaborating on this research. This study uses a recycled content of 93% for steel, which is typical in the steel mills found in the United States.

2.3 *Thermal performance*

Thermal conductivity is defined as the rate at which heat flows through a solid object. Conductivity is an important factor in passive heating or cooling, and depends heavily upon the rate at which heat is conducted into a material from its surface. For each structural system, the thermal conductivity, K, is measured by surface area of the object times its thickness (inches) per meter. Each material has a characteristic rate in which heat will flow through it. In conduction, heat is transferred directly from the molecules of warmer building surfaces to the molecules of cooler solids (such as earth), in contact with the building.

Thermal resistance is a heat property and a measure of a temperature difference by which an object or material resists a heat flow (heat per time unit or thermal resistance). Thermal resistance is the reciprocal of thermal conductance and measured in units of m^2*K*W^{-1}. Resistance is especially useful when comparing insulating materials or insulating assemblies; the greater the R-value the more effective a material acts as an insulator. While this may not be relevant for internal floor systems that have similar air temperatures on either side of the structural elements, it is relevant for structural systems that are used as external walls or roofs where one side of the structural element is exposed to exterior conditions. As the thermal resistance of the structural system increase, less resources need to be spent on other materials, such as foam insulation, is required to reduce energy loss and increase thermal comfort.

Specific heat capacity is the measurement of a material's capacity for a unit of energy (heat) to change that material's temperature by a given amount. This value measures a material's ability to store heat per unit of mass. SI Units for specific heat capacity are $J*kg^{-1}*K^{-1}$. The specific heat capacities for structural materials used in this study are in Table 4.

Table 4. Specific heat capacities values used to calculate the thermal mass capacity of structural elements.

Material	Specific Heat ($J*kg^{-1}*K^{-1}$)
Steel	480
Concrete	840
Wood	1,700

Thermal mass capacity is defined as the capacity of a certain amount of material or object to store heat when the temperature is raised one-degree Celsius. The SI Units for thermal mass capacity are $J*K^{-1}$. A higher value is advantageous as it means a structural element has a greater ability to store thermal energy and moderate temperature swings. Thermal mass capacity is a more useful for making comparisons between selecting a structural systems as it accounts for the mass of material each system uses as well as the specific heat of the materials used.

2.4 *Acoustic performance*

Acoustical properties must be considered when dealing with certain types of spaces that are predicated upon creating a specific environment, such as lecture halls, auditoriums, or gymnasiums. In an untreated room, of normal construction, when the sound waves strikes the walls or ceiling, a small portion is transmitted, a small portion is absorbed, and most of the sound is reflected. This research evaluates the acoustic properties of the long span assemblies based upon the sound transmission coefficient (STC) and impact isolation class (IIC).

Various attempts at using a single number average transmission loss to describe a barrier's characteristics have been made with only limited success. These averages can be misleading since they ignored both deficiencies and proficiencies at particular frequencies. To avoid the shortcomings of averages and yet to benefit from the indisputable conveniences from single number ratings, a system of standard contours was developed in the United States, called STC contours. The STC number for a particular barrier construction is derived by comparing actual test results, measured in a series of 16 one-third-octave bands to the standard STC contours according to a fixed procedure. ICC ratings measure structure-borne sounds resulting from sound producers like footfalls or other direct impacts.

2.5 *Fire resistance*

Fire resistance is accounted for in two ways with respect to the international building code. The first is the fire-rating of a specific floor or wall assembly in hours it takes for the fire to penetrate the assembly. The second is the classification of the entire building structure from Type I, the most fire-resistant and using non-combustible structural materials, to Type V, the least fire-resistant and the possibility of combustible structural materials.

3 CASE STUDY

3.1 *Overview*

A real building in the midst of schematic design was used to explore the role of multi-performance criteria in the selection of structural system. Working with the architecture and engineering firms, this study was centered on the design of a lecture hall within a general-purpose classroom building at Oregon State University in Corvallis, Oregon. This five-story building near the historic center of the campus needed to accommodate three major lecture halls on the ground floor. The large spaces uninterrupted by columns required the use of long spans supporting classrooms above. Collaboration with the architects and engineers in this analysis yielded information integral to the project including, but not limited to, its general programmatic and spatial layout, sizes of spaces and stacking of program to accommodate for all necessary academic elements, and sustainable factors that will enable project goals specific to the designers, engineers, and the client to be met. Calculating the multi-performance criteria of these structural systems included five major areas: embodied energy and carbon, structural and spatial properties, acoustical properties, fire protection and thermal properties.

3.2 *Defining the long-span structural systems*

In order to simplify the parameters of this study, a single, ground floor lecture hall with long span requirements was selected from the case study project. The dimension of the lecture hall is 24.4 meters by 30.5 meters (80 feet by 100 feet) for a total area of 8,000 square feet (743 m^2). This study focuses solely on the spanning elements – girders, beams and decking – that support a 100 lb/ft^2 live load on the floor above as well as the self weight of the long span. The maximum deflection was limited at the span length divided by 240. Columns and foundations were not considered, as they would be part of a larger system and subject to loads from other spanning elements and floors. The spanning elements for these structural systems were sized, and the weights of construction materials for each assembly in steel, wood, and two post-tensioned concrete systems were calculated (Figure 1). Materials for all systems were restricted to structural members; no finishes or enclosures were considered.

The assembly of the steel structural system consisted of a 3.5 in (8.9 cm) concrete topping on a 3 in (7.6 cm) deep galvanized steel deck, wide flange beams and wide flange girders. A steel strength of 50 ksi (345 MPa) was used, and 4000 psi (28 MPa) concrete was used for the slab. Bolts, plates, and other connection materials were omitted.

Two post-tensioned concrete long span systems were examined in this study. The first consisted of a 3-inch (7.6 cm) conventionally reinforced slab with joists and post-tensioned beams. The second was an 8-inch (20.3 cm) post-tensioned slab with post-tensioned beams. Concrete with a strength of 4,000 psi (28 MPa) was used for conventionally reinforced joists and slabs and 6,000 psi (41.4 MPa) concrete for post-tensioned (PT) girders and slabs. A steel strength of 60 ksi (414 MPa) was assumed for any concrete reinforcement.

The assembly of the timber structural system consisted of a ¾ in (1.9 cm) plywood deck, 2 in by 12 in (5.1 cm by 28.6 cm) sawn wood joists, glue-laminated beams, glue-laminated perimeter girders and glue-laminated trusses for three central long spans. Bolts, plates, and other connection materials were omitted. The material totals for the four systems can be found in Table 5.

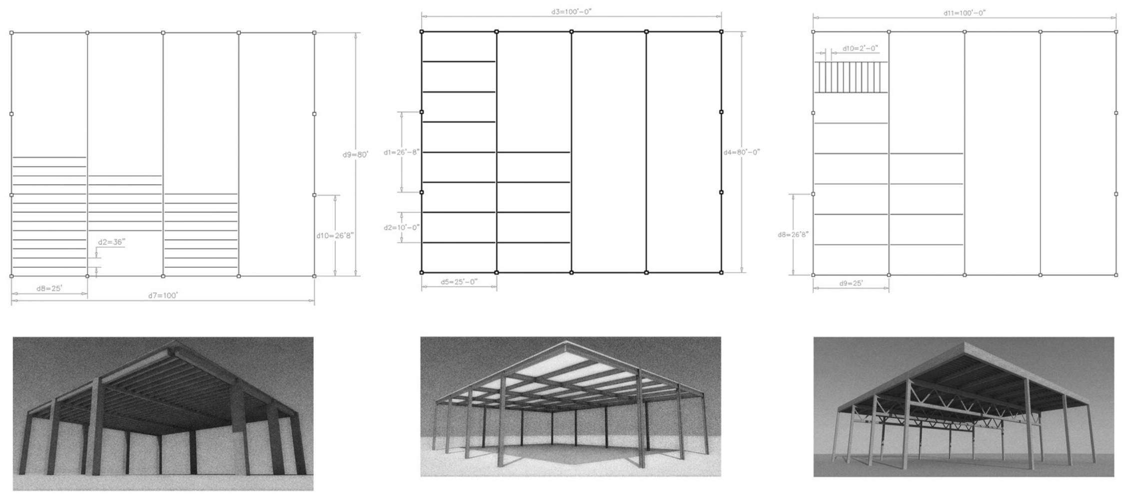

Figure 1. Three long span floor systems considered in this study (left to right): concrete joists and post-tensioned concrete beams, steel wide-flange beams and girders, wood joists, glue-laminated beams and trusses. A fourth long span, post-tensioned concrete slab and beams, is not shown but is identical to the layout of the other concrete system without the joists.

Table 5. Total weight (1,000 kg) of materials used in the four long span structures.

Structural System	Concrete	Steel	Wood
PT Concrete Slab	422	8.1	
Concrete Joist	324	8.3	
Steel Wide-Flange	219	67.3	
Wood Truss			53.9

3.3 *Embodied energy and carbon of long span structural systems*

The relative environmental impacts of the four long span systems using virgin and non-virgin materials are compared in Table 6. These values were calculated using the embodied energy and carbon values outlined in Section 2.2 multiplied by the various material quantities of each system. Rather than assuming a certain or average value for cement replacement or recycled steel content, this paper calculates the embodied energy and carbon of the four structural systems using virgin materials and a set of non-virgin materials that represents the highest percentages of replacement typically found in United States, 20% portland cement replacement with fly ash for concrete and 93% recycled content for all structural steel. This generates a range of environmental impacts for each system that can allow assessments depending on material availability. This method also shows where the greatest impacts are found in terms of using non-virgin materials. In this study, shifting from virgin to non-virgin for the steel long span system would reduce the embodied energy by 63% and the embodied carbon by 72%. The wood system has the lowest embodied energy and carbon of any system while the steel system has the highest embodied energy.

Table 6. Embodied energy and embodied carbon of long span systems.

Structural System	Embodied Energy (TJ)		Embodied Carbon (1,000 kg CO_2)	
	Virgin	Non-Virgin*	Virgin	Non-Virgin*
PT Concrete Slab	0.77	0.54	99	73
Concrete Joist	0.60	0.40	74	47
Steel Wide-Flange	2.62	0.98	229	65
Wood Truss	0.35	n/a	21	n/a

*Non-virgin materials include 20% portland cement replacement with fly ash for concrete and 93% recycled content for all structural steel.

3.4 *Other multi-performance characteristics of long span systems*

The four systems were analyzed in term of other multi-performance criteria including structural and spatial properties, acoustical properties, fire protection and thermal properties (Tables 7 and 8). The structural system that could reach the most criteria without the need for addition of extra materials (for example, adding acoustical paneling or fire proofing to a structure) should have greater value as it could reduce the overall building cost for construction and environmental impact. Structural and spatial considerations include the weight per area, which will affect column and foundation sizes, and the depth of the structure that could create conflicts with other systems or programmatic needs.

Table 7. Multi-performance characteristics of long span systems.

Structural System	Weight (kg/m^2)	Depth (m)	STC	ICC	Fire-rating	IBC Cat.
PT Concrete Slab	579	1.57	55	30	3 hr	I, II, III, V
Concrete Joist	447	1.63	50	30	3 hr	I, II, III, V
Steel Wide-Flange	385	1.17	51*	21*	0 hr*	I, II, III, V
Wood Truss	72	3.05	38**	32**	1 hr**	V, VI

*These values assume no additional fire protection or materials beyond what is required for the structure, however there are several strategies, all requiring additional materials, for increasing both the acoustic performance and fire-rating of the steel structures.
**These values assume a 5/8-inch sheet of fire-rated gypsum board is attached to the bottom of the sub-purlins and could be increased with the use of additional materials.

Table 8. Thermal multi-performance characteristics of long span systems.

Structural System	Mass (MJ*K^{-1})	Conductivity (W*m^{-1}*K^{-1})	Resistance (m^2*K*W^{-1})*
PT Concrete Slab	358	1.13	0.112
Concrete Joist	276	1.13	0.042
Steel Wide-Flange	216	45.0	0.056
Wood Truss	92	0.14	0.44

*Multiply by 5.75 to get ft^2-^{o}F-hr/Btu.

3.5 *Multi-performance comparison of long span systems*

An analysis of the data reveals the benefits of a wood long span structural system in terms of embodied energy and embodied carbon and weight. However, the wood system has poor acoustic qualities and low thermal mass potential, but has potential to carry HVAC and MEP systems within the truss system – taking full advantage of integrated spatial design strategies. It also requires heavy amounts of gypsum board fireproofing and potentially sprinkler systems to ensure fire safety. If the steel long span structure has a high recycled content, its embodied carbon is comparable to concrete systems with fly ash replacement. The steel system has a lower thermal performance, in terms of both thermal resistance and thermal mass capacity, when compared to concrete. The steel system is also the worst at reducing sound transmission due to impacts and requires fireproofing. The concrete systems were the heaviest and deeper overall than the steel system. They have a significantly higher amount of embodied carbon than the wood system even when fly ash replace is taken into account, but the concrete systems have the best thermal mass capacity. The concrete pan joist system, using post-tensioned girders and 20% fly ash performed well for a concrete system. The amount of material for a concrete system is greater – three to four times that of wood. Concrete structural systems also require a diligent coordination effort for integration of MEP/HVAC systems, but can be used as an interior finish and an acoustic insulator without additional materials.

4 CONCLUSIONS

The objective of this research were to inform integrated design teams during schematic design phases and project development processes to be more mindful of the performance of structural systems in terms of other aspects, including thermal, acoustic, environmental, and fire resistance, versus simply acting as the structure alone. While there are advantages and disadvantages to each long span system, this research can help architects and engineers make more informed decisions early in the design process. One important criteria to add to this study would be the cost not just of the structural materials in isolation, but the cost for each system to meet certain acoustic, fire-rating and thermal criteria and the additional materials it would entail. Future research should examine other alternative long span systems including cellular steel beams as well as the further optimization of structural layouts used in this study.

5 ACKNOWLEGEMENTS

The authors would like to thank the National Council of Architecture Registration Boards (NCARB) for sponsoring this multidisciplinary research collaboration between the academy and practice. The authors would also like to thank Michael Tingley at BOORA Architects and Aaron Burkhardt at KPFF consulting engineers for their support and assistance with this research.

6 REFERENCES

Alcorn, J.A. & Baird, G. 1996. Use of a hybrid energy analysis method for evaluating the embodied energy of building materials. *Renewable Energy* 8 (1–4): 319-322.

Cole, R. & Kernan, P. 1996. Life-Cycle Energy Use in Office Buildings. *Building & Environment* 31 (4): 307-317

Cole, R.J. 1998. "Energy and greenhouse gas emissions associated with the construction of alternative structural systems." *Building and Environment* 34 (3): 335-348.

Dimoudi, A. & Tompa, C. 2008. Energy and environmental indicators related to construction of office buildings. *Resources, Conservation and Recycling* 53 (1–2): 86-95.

González, M.J., & Navarro, J.G. 2006. Assessment of the decrease of CO_2 emissions in the construction field through the selection of materials: Practical case study of three houses of low environmental impact." *Building and Environment* 41 (7): 902-909.

Griffin, C.T., Knowles, C., Theodoropoulos, C., & Allen, J. 2010a. Barriers to the implementation of sustainable structural materials in green buildings. In: Cruz P, editor. *Structures and Architecture: Proceedings of the 1st International Conference on Structures & Architecture (ICSA2010)*. Guimarães, Portugal, 21-23 July 2010. 1315-1323.

Griffin, C.T., Reed, B., & Hsu, S. 2010b. Comparing the embodied energy of structural systems in buildings. In: Cruz P, editor. *Structures and Architecture: Proceedings of the 1st International Conference on Structures & Architecture (ICSA2010)*. Guimarães, Portugal, 21-23 July 2010. 1333-1339.

Gustavsson, L. & Sathre, R. 2006. Variability in energy and carbon dioxide balances of wood and concrete building materials. *Building and Environment* 41 (7): 940-951.

Hammond, G. P. & Jones, C. 2011. *Inventory of Carbon & Energy*. Tech. 2nd ed. Bath, U.K.: University of Bath. Print.

Hammond, G. P. & Jones, C. 2008. Embodied energy and carbon in construction materials. *Proceedings of the Institution of Civil Engineers*, *Energy*, 161 (2): 87-98

Junnila, S., Horvath, A., & Guggemos, A. A. 2006. Life-Cycle Assessments of Office Building in Europe and the United States. *Journal of Infrastructure Systems*, 12(1), 10-17.

Lenzen, M, & Treloar, G. 2002. "Embodied energy in buildings: wood versus concrete—reply to Börjesson and Gustavsson." *Energy Policy* 30 (3): 249-255.

Scheuer, C., Keoleian, G., & Reppe, P. 2003. Life cycle energy and environmental performance of a new university building: modeling challenges and design implications. *Energy and Buildings* 35;1049-1064.

Suzuki, M. & Oka, T. 1998. Estimation of life cycle energy consumption and CO_2 emission of office buildings in Japan. *Energy and Buildings* 28: 33-41

Treloar, G.J., Fay, R., Ilozor, B., & Love, P.E.D. 2001. An analysis of the embodied energy of office buildings by height." *Facilities* 19 (5/6): 204-214.

Thormark, C. 2002. A low energy building in a life cycle – its embodied energy, energy need for operation and recycling potential. *Building and Environment* 37: 429-435

Thormark, C. 2006. The effect of material choice on the total energy need and recycling potential of a building. *Building and Environment* 41 (8): 1019-1026.

Venkatarama Reddy, B.V, & Jagadish. K.S. 2003. Embodied energy of common and alternative building materials and technologies." *Energy and Buildings* 35 (2): 129-137.

Yohanis, Y.G., & Norton, B. 2002. Life-cycle operational and embodied energy for a generic single-storey office building in the UK. *Energy* 27 (1): 77-92.