Comparative analysis of life cycle costs of a new steel portal frame building system for industrial and commercial applications

ANALYSES THE LIFE CYCLE COSTS RELATED TO ENERGY IN USE FOR CONVENTIONAL AND NEW STEEL PORTAL FRAME BUILDING SYSTEMS FOR INDUSTRIAL AND COMMERCIAL APPLICATIONS. THE COST OF USING SANDWICH STEEL PANELS FOR CLADDINGS IN THE NEW BUILDING SYSTEM IS EVALUATED.

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The life cycle assessments of a new steel portal frame building system incorporating the energy efficient sandwich panels for use in industrial and commercial buildings are compared with those of a conventional steel portal frame building system. The economic benefits of the new steel portal frame incorporating the insulated sandwich panels have been demonstrated through cost assessment of energy in use. The results from life cycle cost assessment of both the new and conventional portal frame building systems show that despite slightly higher initial costs, the newly proposed building system using the sandwich steel panels cladding costs significantly less than the conventional steel cladding in its complete life cycle of 50 years. The new system provides not only an economic solution, but also a better energy-efficient model for commercial / industrial building design in the Australian environment.

Keywords: steel portal frame building system, energy, environment, life-cycle assessment

Life cycle assessment of building systems

The Life Cycle Assessment (LCA) is the method of compiling and evaluating all the inputs and outputs and the potential environmental impacts of a building system throughout its life cycle. The LCA approach was used to compare the performance of a new steel portal frame building system using insulated sandwich panels with that of a conventional building system. This paper presents life cycle assessment of a new steel portal frame building system for use in industrial and commercial buildings, and compares the results with those of conventional building systems. The improvements in the energy efficiency of industrial and commercial buildings due to the use of the new building system using sandwich panels have been numerically quantified. The paper investigates mainly the savings of life cycle energy in use for the new steel portal frame building system. The comparative life cycle assessment on energy and the cost-in-use information can serve as the guidelines to the building industry regarding energy consumption, operating costs and environmental impacts in order to achieve high energy efficiency and minimize environmental impacts in industrial and commercial buildings. The new building system is environmentally and structurally more efficient than the conventional system. Despite the slightly higher initial cost, this newly proposed building system using insulated sandwich panels costs significantly less than the conventional system in its complete life cycle of 50 years.

Industrial and commercial building models

The ecologically sustainable design of not only residential but also industrial and commercial buildings is a necessity for any modern built environment. The global environmental sustainability can only be achieved by efficient use of energy and natural resources. For this purpose, life cycle assessment approach is chosen to demonstrate the overall reward for environment-friendly designs. Steel portal building systems with steel portal frames and a conventional profiled steel sheeting system are commonly used in commercial and industrial buildings. Its structural efficiency and more importantly, the cost-effectiveness have always been considered to be satisfactory, which have thus led to their continued use in these applications. Previous research at Queensland University of Technology (QUT) on modeling of building frame systems had revealed the possibility of a new cladding system using sandwich panels [7], instead of the conventional profiled steel sheeting system, becoming a better alternative.

Conventional Building System

A conventional building system is made of a series of steel portal frames (columns and rafters), Z section purlins and girts and 0.42 mm thick profiled steel roof and wall sheeting. The steel portal frames are the main structural members with cross bracings added to the structure to carry longitudinal wind loads. The structural members are designed independently using two-dimensional (2-D) computer modeling. The schedules of members are obtained using the 2-D analysis and design method [8]. Figure 1 shows the layout of the conventional portal frame building system. Main structural sections required for this 25 m span x 36 m length x 7 m height building are as follows: Section 1 - portal coulmn (530 UB 82), Section 2 - portal rafter (360 UB 60), Section 3 - gable column (250 UB 31), Section 4 - purlin (Z 20020), Section 5 - purlin (Z 20016), Section 6 - girt (Z 20020), Section 7 - girt (Z 20016), Section 8 - girt (Z 20020), Section 9 - strut

(165 x 3 CHS), Section 10 - roof bracing (100 x 100 x 6 angle), and Section 11 - wall bracing (75 x 75 x 5 angle).

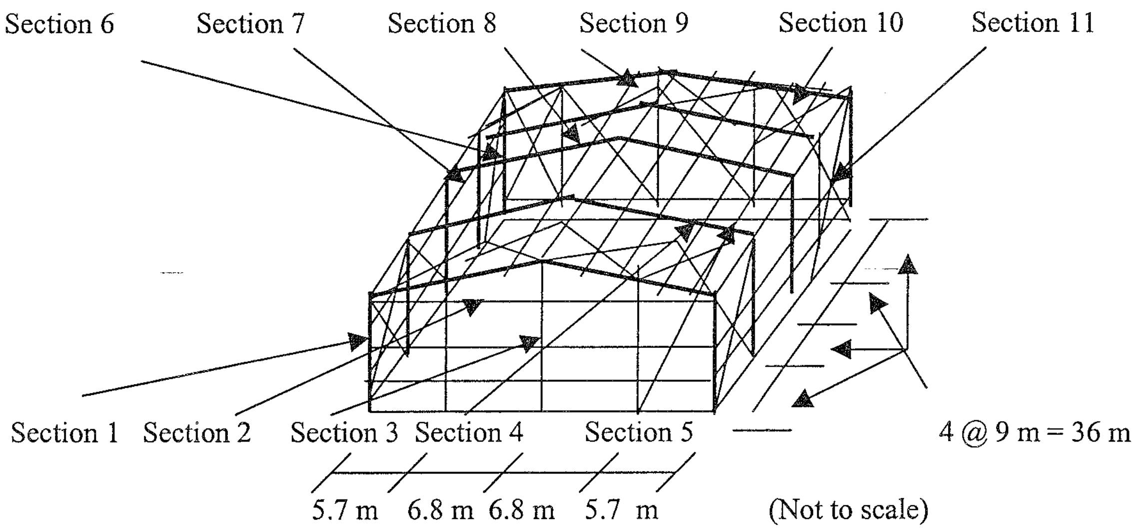

Fig. 1. Structural Layout of the Conventional Building System

New building system

Unlike the conventional building system based on a two-dimensional analysis and design method, an innovative portal frame system incorporating sandwich panels as roof and wall claddings and steel rectangular hollow sections as purlins and girts at wider spacing was developed. This new building system was based on three-dimensional (3-D) computer modeling by considering columns, rafters, purlins and girts as beam elements and roof and wall claddings as equivalent truss (tension) members. The composite sandwich panels comprise light-weight polystyrene foam core sandwiched between two steel faces. The steel faces are commonly made of 0.42-0.60 mm G300 or G550 steel whereas the foam is of SL grade and 50-200 mm thick. The composition and geometry of the panels enable them to possess both insulation and structural capacities. Even the 50 mm panels are able to span up to 3 m for Brisbane wind conditions whereas conventional sheeting systems can only span up to about 1.5 m. Despite this, the sandwich panels are essentially used in cold-rooms because of their insulation properties. Subaaharan [7] investigated the use of 50 mm sandwich panels as part of a steel portal frame building system for use in industrial and commercial buildings. The combined use of sandwich panels and steel tubular / purlin / girt system led to the following benefits in the new building system.

- reduced number of purlins and girts
- roof and wall bracing removed
- flybracing of the rafter/column removed
- less labor intensive and simpler construction process

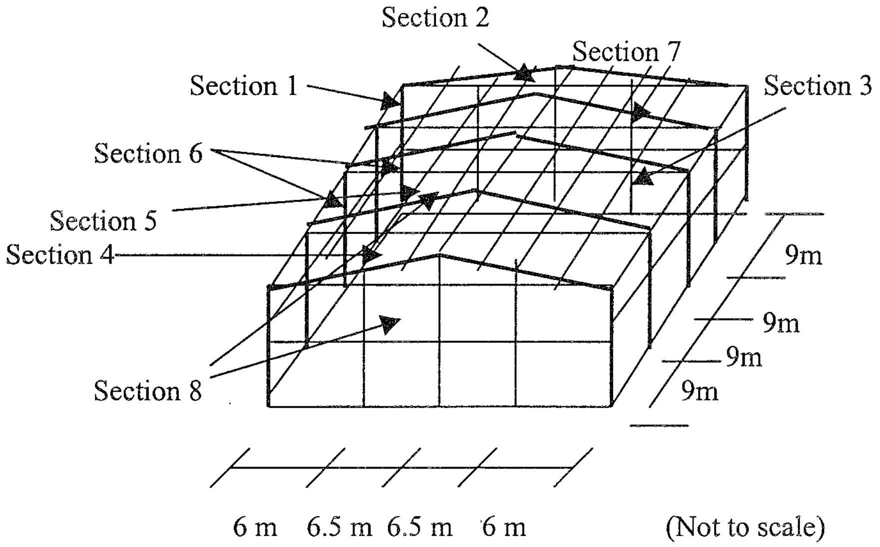

Fig. 2. Structural Layout of the New Building System

Figure 2 shows the layout of the new portal frame building system. Main structural sections in this 25 m span x 36 m length x 7 m height building are: Section 1 - portal coulmn (460 UB 82), Section 2 - portal rafter (410 UB 60), Section 3 - gable column

(250 UB 31), Section 4 - purlin (150 x 150 x 6 mm hollow section), Section 5 - purlin (125 x 125 x 6 mm hollow section), Section 6 - girt (125 x 125 x 6 mm hollow section), Section 7 - girt (100 x 100 x 5 mm hollow section), and Section 8 - profiled insulated sandwich panels (50 mm thick) as roof and wall claddings [7].

Instead of the conventional practice of using profiled steel claddings for roofs and walls, the new system incorporates insulated sandwich steel panels [4]. The new building system was considered to be more structurally efficient than the conventional system [7], however, the initial cost of procurement of the new building system was about 20% higher than that of the conventional system. This has been mainly due to the more expensive sandwich panels. The use of sandwich panels was expected to provide, not only the energy savings, but also the minimization of several toxic emission, green house gases, and environmental pollution etc. because of reduced heating and cooling needs as well as increased conservation of the embodied building energy.

Built-in environment and energy

Australia can be described as the hottest and driest non-polar continent in the Southern Hemisphere. In general, three broad climate zones; temperate, hot arid and hot humid zones are categorized. The temperate climates may need greater winter heating than for summer cooling while cooling is the dominant need in the hot humid climates. Buildings in Australia consume nearly 40% of current energy production for heating and cooling the built environment. The industrial productivity and commercial success depend on the indoor comfort level of building, which in turn depends upon the thermal energy of the indoor environment. Life-cycle energy is used as guidelines in reducing the overall energy consumption for both industrial and commercial buildings. The majority of primary energy consumption is generated during the operation-phase of the building (i.e., heating, cooling, electricity consumption for appliances). Efforts should therefore be focused on the measures that would reduce the operational phase energy consumption (eg., lowering the thermal conductance properties of the building envelope, reducing energy consumption of appliances, etc.).

Indoor Environment

In a built environment facility, the Australian Standard demands that adequate ventilation be provided in all occupied buildings [6], and even at the minimum, one needs three distinct amenities [5]:

- lighting, power and ventilation all year round;
- heating in winter; and
- cooling and de-humidifying in summer

The cooling and heating systems may be based upon local climate, comfort level and current market pressures for other buildings that are not legislated in indoor environment. The use of energy for such facilities can be justified in view of economic viability, accepted standards, planning flexibility, floor utilization, increased productivity and freedom-of-action, etc. The use of energy and physiological comfort depends upon a number of factors. Some external environmental factors are: Dry Bulb temperature (DB), Relative Humidity (RH), Air movement, Mean Radiant temperature (MR), Fresh air supply, Airborne dirt and Noise level. For indoor comfort practice, the dry bulb temperature (DB) of the room air can be maintained at 22°C to 26°C in summer and 18°C to 20°C in winter. Relative humidity (RH) of about 50% is usually satisfactory.

The local climates in Australia can be site specific and past weather records for Brisbane, Queensland were obtained from the Bureau of Meteorology [1].

In an effort to focus on the life cycle cost assessment of industrial and commercial building systems that directly influence energy use and environmental pollution, some components that are part of a building, and some external factors are not included. The excluded factors in this study are: building orientation and shape that influences the surface/volume ratio; energy consumption due to functional operation (industrial/commercial appliances); energy related to solid waste disposal and water treatment system; effect of furniture and fixtures, heat generation from industrial crews/ commercial customers; behavioral patterns of habitants, work styles, consumption habits, clothing, entertainment equipment, cleaning materials, etc. Effect of excluding these factors is minimal in this comparative study as their effects are of the same order for both systems. The environmental burdens associated with the ultimate treatment of the demolished building materials, such as landfilling, recycling, and reusing were also not evaluated. Attempting to determine the nature and efficiency of the recycling industry in 50 years would be conjectural. Basically, this paper reflects the life cycle savings due to the use of a new building system for industrial and commercial applications.

Environmental design parameters

Brisbane has a hot, humid climate and is located just south of the Tropic of Capricorn. The summer maximum average temperate is only 30°C, the summer months having some extremely hot days. The winter is mild and very pleasant. Most winter days are sunny with average temperatures of around 15°C. The indoor environment depends upon weather, climate, solar radiation, variation of temperature, humidity, air quality, day lighting etc. including the location and orientation of the building. The values of Dry-Bulb (DBs) and Wet-Bulb (WBs) temperatures, Design Dry-Bulb (DBw) temperature, Cooling load factor (C), Heating load factor (H), heating Degree Days and Equivalent Full Load Hours (EFLH) are needed for the locations under consideration.

The main data used in this study are as follows:

Location: Brisbane, Queensland, Australia (at 27.5°S, 153°E)

Life span of the buildings: 50 years

Architectural style: Portal Steel Frame Building

Number of floors: 1

Occupancy: 6-10 people

Surface floor area of the buildings: 25 m x 36 m = 900 m^2

Building volume for energy embodiment = 7 m x 25 m x 36 m = 6,300 m^3

The basic aim is to determine the saving due to the use of the new building system. Therefore, the requirement for indoor air quality (i.e., humidity, air pollution), and day lighting are assumed to be comparable in both types of traditional and new building systems. The net energy used has been estimated based upon the rate of electricity consumption in terms of kWh per annum. Actual life cycle energy assessment of industrial and commercial buildings depends upon several environmental factors. Typical design parameters are the values of Dry-Bulb (DBs) and Wet-Bulb (WBs) temperatures, Design Dry-Bulb (DBw) temperature, Cooling load factor (C), Heating load factor (H), heating Degree Days and Equivalent Full Load Hours (EFLH) for the locations under consideration. Table 1 summarises the design parameters adopted in the estimation of thermal energy consumption. Brisbane meteorological database and cooling and heating factors were used [8], typically as

- C = 60% constant + 25% dependent on DBs + 15% on WBs
- H = (21-DBw) / 13.8
- EFLH = (24 x Degree Days) / (21-DBw) hours per year

Table 1. Meteorological design parameters of Brisbane, Queensland

Parameters	Value
1. Design Summer Dry Bulb Temperature, DBs °C	31.9
2. Design Summer Wet Bulb Temperature, WBs °C	24.9
3. Winter Dry Bulb Temperature, DBw °C	9.3
4. Cooling load factor, C	1.1
5. Heating load factor, H	0.85
6. Heating Degree Days	41
7. Equivalent Full Load Hours, EFLH	84

The energy requirements for conventional and new industrial building systems under the Brisbane meteorological conditions were calculated. The sizes for openings, external walls, roofs and floors, electrical appliances, ventilation and occupants were considered in the energy calculation. Cooling and heating energy were assessed using the recommended heating and cooling strategies for Australian conditions [1, 5]. Passive energy strategies are like integration of south-facing windows with natural building ventilation, design of solar induced air flow through the building, clear heights for increased daylighting, and use of additional thermal storage to balance diurnal temperature swings. The annual energy consumption was estimated using load factor and floor area of the buildings. The load factor method was used to estimate the annual energy estimate for Industrial building. The cooling and heating loads for conventional industrial building were estimated as 60 kW and 55 kW, respectively. The cooling and heating loads for the new industrial building system were estimated as 45 kW and 46 kW, respectively due to the sandwich panel (U = 0.25 W/m^2 per °C). Typical estimation for a cooling case of conventional industrial building system is illustrated in Table 2.

Table 2. Typical thermal energy estimation for the cooling case of conventional industrial building system

Items/ Component	Size	Chart used	Value	*Load, W*	
1. Openings in sun (2 nos)	2 x 2 m^2	1	1.3 x 213	2,215	
2. External Wall in sun	36 x 7.5 m^2	2	28	7,560	
3. External Wall in shade	36 x 7.5 m^2	2	16	4,320	
4. Roof	25 x 36 m^2	3	11	9,900	
5. Floor	25 x 36 m^2	4	7	6,300	
6. Light + Appliances	25 x 36 m^2	5	18	16,200	
7. People	6 Nos.	6	220	1,320	
8. Ventilation	40 L/s	7	17	680	
Total				48,495	Watts
Cooling Capacity needed for Brisbane = C x 48.495 = 1.1 x 48.495 =				53.35	kW
Including Allowances, Cooling capacity is 1.1 x 53.35 = 58.7 say 60 kW					

Based upon these heating and cooling load factors, the annual energy requirements were estimated using heating and cooling periods. Owing to the better quality of the new sandwich panel system, the new building system was optimized based upon thermal insulating characteristics [4]. As this analysis is intended to demonstrate the annual energy saving due to the use of the new building system, the annual energy consumption was estimated using these load factors for Brisbane meteorological conditions. Total thermal energy requirements for conventional and new industrial buildings were 41,706 kWh and 18,440 kWh respectively [3]. Using a standard electricity rate of 11.59 cents/kWh [2], the annual costs were $7,437 and $3,288, respectively. Hence, the new system can save $4,149 annually, which means a total saving of $47,574 in 50 years at an interest rate of 5%. Similar exercises were carried out for commercial buildings considering the floor area requirements.

In the floor area estimate, the annual energy consumption has been estimated based upon the gross floor area, GFA = 900 m^2. Again, the heating and cooling loads were climate dependent but lighting and power energy calculations were based on 2,500 hours per annum. Typical annual energy estimate based upon the requirement for lighting, power and air conditioning for conventional commercial building is given in Table 3. The energy requirements for conventional and new commercial buildings were 84,960 kWh and 67,896 kWh, respectively [3]. Thus, the annual energy was calculated as $9,847 and $7,869 for conventional and new commercial buildings, respectively. Using the new building system, annual saving of $1,978 can be achieved. Typical cumulative saving in 50 years of life cycle will be $22,683 at 5% interest rates.

Table 3. Estimate of annual energy cost for new commercial building

Item	Estimate (w/m^2)	Quantity (kW)	Usage (kWh)	Annual Cost ($)	Remark
1. Lighting	20	18	45,000	5,216	GFA = 900 m^2
2. Power	6	5.4	13,500	1,565	for 2,500 hours pa
3. Air-condition	25	22.5	8,640	1,001	for 4m 24 @ 4h
4. Heating	10	9	756	88	for EFLH = 84h
Total			67,896	**7,869**	

The design of energy efficient buildings, while maintaining functional equivalency and correct estimation of energy usage is a difficult task. A predicted value of energy consumption is only estimation (say about ± 30%) since it depends very much on the way the buildings are managed.

Life cycle cost assessment

Life cycle analysis results in an estimated distribution of costs throughout the life cycle of the system. The total cost of constructing, operating, repairing, cleaning and maintaining can be broadly divided in terms of initial capital cost and cost-in-use. Application of life cycle costing to the design process require detail information on site location, alternatives, orientation, building material, shape, size, engineering systems and energy sources, etc. The building models and environmental design parameters were described earlier. Material rates are taken from the manufacturers' supplied prices. Cost of steel portal frame fabrication, transportation and erection costs were collected [7].

Table 4 shows initial cost estimate of industrial building systems. Contingency of 10% of the total manufacturing cost has been assumed. The initial costs of conventional and new industrial building systems are calculated as $211,709 and $232, 297, respectively. The new industrial building system cost about $20,588 more than the conventional building system at the beginning. Similarly, the initial costs of conventional and new commercial building system are estimated as $222,709 and $241,427, respectively. At the initial stage, the new commercial building system cost about $18,718 more than the conventional building system. However, the cost-in-use represents the most intensive phase of the life cycle in industrial and commercial building systems.

Table 4. Capital cost estimate of an industrial building in Brisbane

Details	Conventional ($)	Rate/GFA ($ / m^2)	New ($)	Rate/GFA ($ / m^2)	Remarks
1. Material supply cost	53,702	59.67	79,814	88.68	Base year
2. Cost of Fabrication	19,016	21.13	12,680	14.09	Cost 1999
3. Cost of Transportation	4,340	4.82	2,120	2.36	
4. Cost of Erection	12,330	13.70	7,890	8.77	
5. Internal finishing	24,000	26.67	24,000	26.67	
6. Fittings/Fixtures	4,500	5.00	5,100	5.67	
7. Sanitary appliances	10,200	11.33	10,200	11.33	
8. Electrical services	31,000	34.44	34,000	37.78	
9. Sub-structure @15%	15,375	17.08	15,375	17.08	
10. Demolition	18,000	20.00	20,000	22.22	
Sub-total	192,463		211,179		
11. Miscellaneous contingencies	19,246		21,118		
Tax (GST) @ 10 %	1924.63		2111.79		
Initial capital costs	**211,709**		**232,297**		

To determine the contributions of maintenance and building improvements on life cycle cost, a schedule of activities was created based on a building life of 50 years. In fact, there are several different categories of cost-in-use, but some of them more apparent and some other costs may be irrelevant for the decision process. In this case, the cumulative energy cost due to the operating thermal inputs plays an important role. Annual costs of heating and cooling are taken from the energy calculation. The interval of maintenance activities that are needed to keep the building in good condition (e.g., re-fix, re-paint, repair and maintenance of columns, rafters, purlins, claddings, floor and roof system) are kept the same for both new and conventional building systems. In this preliminary study, the replacement frequencies were simplified as first twenty years and then at the rate of ten years. Costs for these activities were quantified, and their life cycle values were calculated.

As the value of life cycle costing considers at the balance between initial and future expenditures by using a series of economic analysis, the methodology usually incorporates basic discounting and financial appraisal techniques. Discounting method may be defined as the application of a selected rate of interest to adjust the values of the cost distribution to a common reference point in time. This point is generally the present time, when the decisions are to be made. This procedure assures that the alternatives are evaluated in an equivalent basis. Figure 3 depicts typical life cycle analysis for building systems at 6% discount rate. The repair and maintenance periods for all building systems are simplified as 20, 30 and 40 years. Higher costs in use for conventional building systems are obvious.

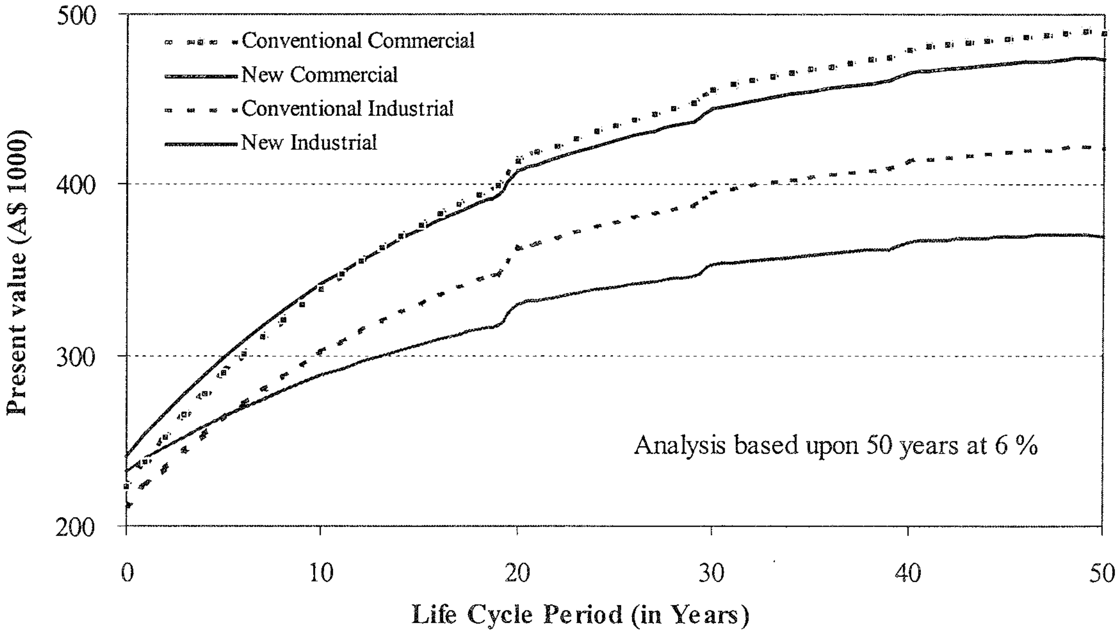

Fig. 3. Life cycle cost versus discount rates for various building systems

The forecasting process needs decision on uncertain future events and the numbers of environmental, technical, social and economical factors may influence the cost distribution. Economic factors such as interest rate, inflation, and GST affect the profile of cost significantly. In particular, inflation has increased costs of products and services in the past. Such analysis enables an evaluation of the expected effects and the comparison of different designs in an early phase (development / planning). Parametric analyses were conducted at various discount rates of 5, 7, 9 and 11% [3]. Table 5 shows the summary of life cycle cost estimates for conventional and new industrial and commercial building systems. This analysis helps to calculate the ultimate life cost in terms of a single sum that is the annual equivalent cost or the present value of all costs over the life of the building. Figure 4 shows the life cycle costs analysis at various discount rates.

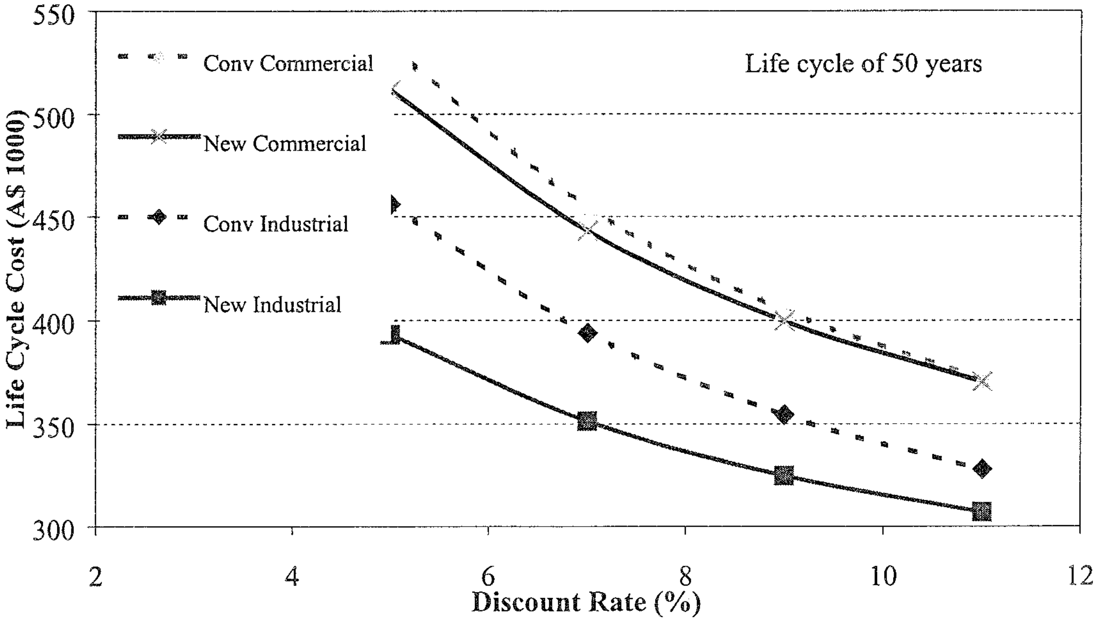

Fig. 4. Life cycle cost versus discount rates for various building systems

The new design seems more efficient than traditional one in terms of life cycle cost, total material, waste mass, heating/cooling operation and thus in terms of the energy flows (e.g. global warming potential, toxic emission and even noise reduction) due to lesser quantity of building construction materials. Further optimization of construction method, workmanship and operating styles can be accompanied during the planning and running processes. Table 5 summarizes the life cycle assessments of steel portal-framed industrial and commercial buildings for both conventional and new systems. Despite slightly higher initial costs, the new building system always demonstrates the total economy over a life cycle period.

Table 5. Summary of life cycle cost assessments

Industrial building			Life cycle cost at various discount rates			
Designs	Capital cost	Annual cost	5%	7%	9%	11%
Conventional	211,709	11,067	456,122	393,774	354,180	327,661
New system	232,297	6,918	392,940	351,159	324,613	306,892
Difference A$	-20,588	4,149	63,182	42,615	29,567	20,769
% saving	-8.9	60.0	16.1	12.1	9.1	6.8

Commercial building			Life cycle cost at various discount rates			
Designs	Capital cost	Annual cost	5%	7%	9%	11%
Conventional	222,709	14,347	532,989	454,567	404,736	371,283
New system	241,427	12,370	511,622	443,123	399,550	370,314
Difference A$	-18,718	1,977	21,367	11,444	5,186	969
% saving	-7.8	16.0	4.2	2.6	1.3	0.3

Summary

A new steel portal frame building system for industrial and commercial purposes, incorporating insulated sandwich panels as roof and wall claddings has been briefly explained. The new building system is structurally superior to the conventional system. Moreover, due to the use of thermally insulated steel panels, the energy consumption is reduced. Attempt has been made to assess the life cycle costs and energy savings in these building systems. The estimates are included for the total life cycle of fifty years for the buildings. The assessments of the new steel portal frame building system are compared with those of the conventional building system. Life cycle assessment is a tool that can be used to identify and measure both direct and indirect energy, and resource impacts associated with a product, process or service. The relationships between various costs and cost of energy are assessed and integrated with the life cycle approach.

Life cycle cost assessment helps to evaluate the total costs and net savings among uncertain alternate design systems by using parametric studies. The LCA methodology used in this paper incorporated the basic discounting method. The life cycle assessments clearly reveal the life cycle economy in using the insulated sandwich steel panels for roof and wall claddings. The new building system using insulated sandwich panels costs slightly higher initially, but the life cycle costs are always lesser than the conventional system. The new building system, thus, demonstrates a better energy-efficient model for commercial and industrial building design in the Australian environment.

References

1. Ballinger, J. A., Prasad, D.K., and Rudder, D. (1997) *Energy Efficient Australian Housing*. Australian Govt. Publishing Service, Canberra.
2. Commerce and Industry Electricity Prices (1999) *A Simple Guide for Low Voltage Supply*. Energex, 150 Charlotte St., Brisbane Queensland, Australia
3. Gurung, N. and Mahendran, M. (2000) *Life Cycle Assessment of Industrial and Commercial Buildings using a New Steel Portal Frame Building System*. Research Report 00-6, Physical Infrastructure Centre, School of Civil Engineering, Queensland University of Technology, Australia.
4. James Hardie Building Systems (1999) *Product Information Guide*. Insulated Panel Systems.
5. Parlour, R. P. (1988) *Heating and Cooling Australian Homes*. Integral Publishing, Sydney.
6. Standards Australia, AS 1668 (1998) *The use of ventilation and air-conditioning in buildings*. Homebush, NSW.
7. Subaaharan, S. S. (1998) *Improved Modelling and Design of Portal Frame Building System*. ME Thesis, School of Civil Engineering, Queensland University of Technology, Australia.
8. Walsh, P. J. and Spencer, J. W. (1980) *Heating Degree Days for Australian Localities*. Technical Paper (2nd Series) No. 35, CSIRO, Australia.
9. Woolcock, S.T. and Kitipornchai S. (1986) *Deflection limits for portal Frames*. Steel Construction, Vol. 20. No.3.