International Journal of Applied Science and Engineering
2005. 3, 1: 69-79

Environmental and Energy Considerations in Two Selected SC and RC School Buildings in Taiwan

Sheng-Lung Lin* and Yu-Feng Wei

*Department of Environmental Engineering and Management,
Chaoyang University of Technology,
Wufong, Taichung County 41349, Taiwan, R.O.C.*

Abstract: The incorporation of environmental and energy considerations into the building design will become the main stream of the construction industry. This paper intended to demonstrate the life-cycle assessment method employed in the analysis of energy consumptions and environmental impacts during the life time of the school buildings in Taiwan. There are two popular types of school buildings in Taiwan nowadays. One is steel-based construction (hereafter referred to SC). The other is reinforced concrete construction (hereafter referred to RC). Two selected buildings located at Taichung County have been analyzed in the study. Five stages were identified in the whole life of school buildings including material production, erection, occupation, demolition, and disposal/recycling scenario. A 50-year service time was assumed for both buildings. The results show that the most energy consumption occurs in the occupation stage for both selected school buildings. They contribute 95.8% and 87.2% of the total energy consumption in its service time for the SC and RC buildings, respectively. However, the construction processes may influence the energy consumption significantly. It also concluded that both selected buildings consumed lots of energy during the first 30 years, and then energy consumptions of the selected school buildings was leveled off. The inventory data was simulated in an LCA model and the environmental impacts for each stage were indicated as numerical scores based on the Eco-indicator 99.

Keywords: life cycle assessment; school buildings; energy consumption; environmental impacts.

1. Introduction

The sustainable development has become a new paradigm to run a business, which leads to the incorporation of environmental and energy considerations into the design of a building. Generally, a school building could serve more than 50 years before it is demolished. It cannot be ignored that the energy consumption of a school building will be tremendous during its service time as well as the associated environmental impact. On the other hand, the erection of the buildings, the processes of construction materials, and the recycling of wasted construction materials involve energy consumptions and emissions of pollutants. The energy savings become one of the most important things in the school management. This paper will discuss the energy consumptions of the school buildings through a way of the life-cycle thinking. There are two popular types of school buildings in Taiwan. One is

* Corresponding e-mail: sllin@mail.cyut.edu.tw
Accepted for Publication: March 23, 2005

the steel-based construction (hereafter referred to SC). The other is the reinforced concrete construction (hereafter referred to RC). Both types of the construction consume a lot of minerals, such as steel, aluminum, timber, glass…etc. The manufacture of construction components also consumes energy as well as the emission of pollutants. Many researchers had recognized the occupation of the building consumed most energy in its life time. However, Adalberth [1] identified the manufacturing of construction components contributed lots of energy consumption as well as the occupation of the building. For example, it consumes 107.81 kWh to produce 1 ton of Portland cement.

In order to reduce the energy and environ-mental impacts, the design of school buildings needs a complete accurate means to evaluate the energy consumption during their whole life. The life cycle assessment (hereafter referred to LCA) is a powerful tool to evaluate the energy consumptions from the cradle (i.e. processing the construction materials) to the grave (i.e. landfilling the wastes). We divided the life of a school building into the material production, erection, occupation, demolition, and disposal/recycling stages in this study. Incorporating the sustainable development into a building design will become the main stream of the building industry. This study intended to demonstrate the life cycle assessment technique employed in the analysis of energy consumptions and environmental impacts during the life time of the school buildings in Taiwan. Two selected buildings located at Taichung County have been analyzed based on the LCA and Eco-indicator 99 method.

2. The applications of LCA-based evaluating tools

There are four phases in the LCA studies, that is, the goal and definition, the inventory, the impact assessment, and the interpretation. The inventory of inputs (i.e. natural resources and energy) and outputs (i.e. pollution emissions) is the fundamental work in an LCA study. Through this in-site microscopic analysis, it is easy to identify the hot spots of the energy savings and pollution improvements in the facilities. However, the major environmental and energy impacts are occurred not only in the manufacturing stage, but also the other stages of the product life cycle. For example, main environmental impacts of durable goods, such as buildings, car, refrigerator, wash machine, and etc., occur in the use stage. The inventory within a facility is not enough to represent the "whole" impacts associated with a product during its life time. For a modern integrated product development program, the designers utilize many LCA-based tools to identify the environmental impacts and improve the product performance. Khanduri et al. [2] pointed out that almost energy consumptions (75~95%) of a building is decided in the design stage. Therefore, it must be careful to evaluate the energy consumption completely before the construction has been erected.

The applications of LCA in the school buildings have been developed in the last decades. Kuo and Lee [3] demonstrated an office building with high efficiency through the smart utilization of energy. Using the LCA study to evaluate the energy consumption has been presented in many areas, such as family houses [4], office buildings [5], laboratory buildings [6], school buildings [7], as well as the instrument rooms [8]. The researchers also employed LCA tools to analyze energy consumptions of processing construction components. Jonsson et al. [9] compared the concrete and steel building frames. Gunther and Langowski [10] evaluated 14 European manufacturers of resilient floor coverings through their whole life cycles.

To improve the energy savings of buildings, many researchers focused on the retrofit of HVAC and lighting systems. To estimate the net energy impact of the retrofit of the lighting system, we must take into account the interactions with HVAC systems. Due to the heat emitted from the conventional lights, the HVAC system may lead to the increase of energy consumption for heating in the winter. On the contrary, it leads to the decrease of energy consumption for cooling in the summer [11]. For special buildings, it requires 100% air exchange with outdoor. This increases the energy consumption of cooling the building. How can we optimize the energy management, we need different metrics [12]. These metrics are very important in the LCA study. Most common metrics used in the LCA-based energy evaluating tools are kWh/m^2 and kWh/m^2-yr. The former can be expressed as a function of micro-climate of buildings, floor areas, building envelop energy…etc., and the latter considers the total energy consumption through the whole year. The other factors influence the energy consumption of school buildings, including the number of students, energy prices, and types of energy usage…etc. [7].

3. The development of the energy evaluating model

In this study, we focused on the energy consumption of the selected school buildings through their whole life cycles. It is identified that there are five life stages in the school buildings, i.e. the manufacturing of construction components, building erection, occupation of the buildings, demolitions after the service, and disposal /recycling of wasted construction materials. Due to the lack of domestic data, we treated the disposal/recycling stage as an open-loop recycling system. We considered the wasted construction materials are partly recycled in the resource recycling plants. There was no on-site recycling. Transportation of the wasted construction materials is the most important energy consumptions in this stage.

Before the simulation, we had made the following assumptions in the evaluating energy consumption of the selected buildings:

- the selected buildings have the same service time, say 50 years, and the same functions;
- 10 major construction components were selected in the analysis;
- the transportation distances in the study were based on the database from the Taiwan Nation's Transportation Department, except the ones in the disposal stage;
- the transportation distance from the site to the landfill was set 20 km; and
- construction machines used in the erection stage have the same data sources as those used in the demolition stage.

An LCA-based energy evaluating model was developed following the Adalberth's research [1]. The total energy consumption E_{Tot} (kWh),

$$E_{Tot} = E_{manu} + E_{erect} + E_{occup} + E_{demo} + E_{dis} \quad (1)$$

where, E_{manu}, E_{erect}, E_{occup}, E_{demo}, and E_{dis} are the energy consumptions in the manufacture, erection, occupation, demolition and disposal stages, respectively. For the manufacture of construction stage, the E_{manu} can be estimated by using Equation (2),

$$E_{manu} = E_{manu,prod} + E_{manu,renov} \quad (2)$$

$$E_{manu,prod} = \sum_{i=1}^{n} m_i \times (1 + w_i / 100) \times M_i \quad (3)$$

in which, m_i, M_i, and w_i represent mass, energy multiplier, and waste mass for construction component i, respectively. For the renovation, we considered the life of construction components (such as paint) is not the same as that of a building. A modified factor was utilized, which leads to the energy consumptions of the renovation as

$$E_{manu,renov} = \sum_{i=1}^{n} m_i \times (1 + w_i / 100) \times M_i \left[\frac{Y_{bui}}{Y_{mat}} - 1 \right] \quad (4)$$

where Y_{Bui} and Y_{mat} are the life of the building and the renovation materials.

In the erection stage, the E_{erect} is

$$E_{erect} = E_{erect,proces} + E_{trans,mat} \quad (5)$$

$$E_{erect,proces} = \sum_{j=1}^{m} p_j \times P_j \quad (6)$$

$$E_{trans,mat} = \sum_{i=1}^{n} m_i \times (1 + w_i / 100) \times D_i \times T_c \quad (7)$$

where $E_{erect,\ process}$ is depends on the construction machines used in the site, and D_i is the transportation distances from manufacturers of construction components to the erection site.
In the occupation stage, we utilized the model given in the Taiwan's standard for Green Buildings.

$$E_{occup} = E_{use} + E_{trans,renov} \quad (8)$$

$$E_{use} = ENVLOAD = -20370 + 2.512 \times G - 0.326 \times L \times DH + 1.079 \times \left(\sum Mk \times IHk\right) \quad (9)$$

$$E_{trans,renov} = \sum_{i=1}^{n} m_i \times (1 + w_i / 100) \times \left[\frac{Y_{bui}}{Y_{mat}} - 1\right] \times (D_i + d_i) \times T_c \quad (10)$$

In demolition stage, the E_{demo} is

$$E_{demo} = \sum_{k=1}^{m} p_k \times P_k \quad (11)$$

The values of p_k and P_k are from the same sources. Finally, the energy consumption of disposal/recycling only considered the energy used in the transportation of wasted construction materials. The estimation of E_{dis} is

$$E_{dis} = E_{trans,recycle} + E_{trans,was} \quad (12)$$

$$E_{trans,recycle} = \sum_{i=1}^{n} W_i \times R_i \times D_i \times T_c \quad (13)$$

$$E_{trans,was} = \sum_{i=1}^{n} W_i \times (1 - R_i) \times d_i \times T_c \quad (14)$$

where, W and R represent the mass of wasted materials and recycling ratios, respectively.

4. Energy consumption of the school buildings

Two types of school buildings were selected for the estimation of the LCA-based energy evaluating model. The selected buildings are located in the middle region of Taiwan. Both buildings serve as similar functions for the school. The SC building is used for the research laboratories and classrooms. The RC building is used as faculty's study rooms and laboratories. To simplify the analysis, we assumed that there were no differences of the energy consumption in the occupation stage, which is simulated by the *ENVLOAD* model. From Figures 1 and 2, it is obviously observed that the energy consumptions in the occupation stage dominate in the life cycle stages for both selected buildings, i.e. 95.8 % for the SC building and 87.2% for the RC building, respectively. The distributions of the energy consumption in the manufacture of construction components (2.4%) and the erection (1.2%) stages are much less than that in the occupation stage for the SC building. This result also shows that the hot spot to improve the energy savings should focus on the design of SC buildings. For the selected RC building, the erection (7.5%) and the demolition (2.5%) stages contribute more energy consumptions than that in the manufacture (2.1%).

In the LCA analysis, we introduced the functional unit, kWh/m^2-yr, to compare the energy consumptions in the life cycle stages. The results are shown in Table 1. As we can observe in the table, the erection of the selected RC buildings contributes high energy consumption (i.e. 7.3 kWh/m^2-yr) compared with the one of the selected SC building (i.e. 1.8 kWh/m^2-yr). Whereas the energy consumption of the manufacture stage of the selected SC building is higher than the one of the selected RC building. This is because most RC buildings are constructed on the site, which leads to be energy intensive. RC structures also utilize lots of high energy density materials, such as concrete, steel, brick…etc. On the contrary, most construction components are prepared in manufacturing plants and are assembled on the construction site for the selected SC building, which leads to less energy consumption in the erection stage but higher energy consumption in the manufacture stage.

In Taiwan, more and more new buildings are constructed in the SC frames. It is important to monitor the energy consumptions in the manufacturers of construction components.

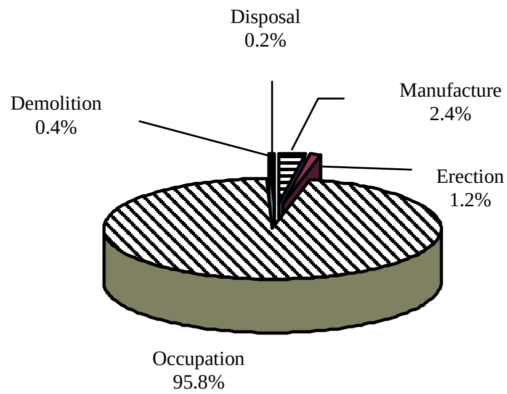

Figure 1. The distribution of the energy consumption in each stage for the selected SC school building

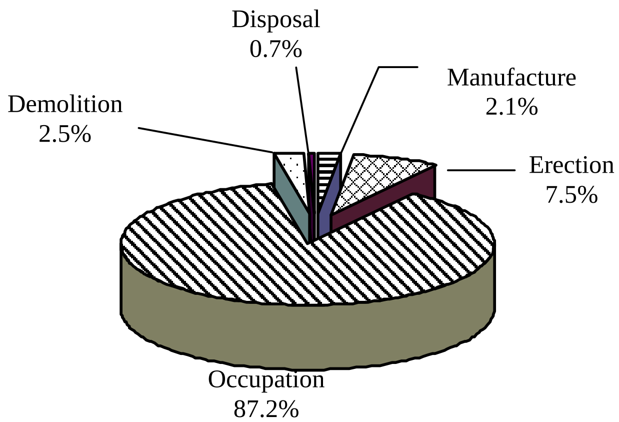

Figure 2. The distribution of the energy consumption in each stage for the selected RC school building

Table 1. The energy consumptions in each life cycle stage of both selected school buildings (unit: kWh/m^2-yr)

Life cycle stages	SC building	RC building
Production	3.5	2.0
Erection	1.8	7.3
Occupation	139.7	84.9
Demolition	0.5	2.5
Disposal	0.3	0.6
Total	145.8	97.3

As discussed above, we recognized that the most energy consumptions occur in the occupation stage. The impacts of the service time of both selected buildings were also interested. Table 2 shows the results of the simulation of the service time from 10 to 90 years of both buildings. It indicates that both selected buildings consumed lots of energy during the first 30 years, and then the energy consumption curves were leveled off. It is important to improve the energy management in the RC building due to its steep increase of the energy consumption in the low service time. The other method to improve the energy savings is to change the shading design for the building. The simulation also demonstrated that the selected SC school building with the shading board could save 29% of energy during its service time (i.e. based on the 50-year service time), whereas it only saved 13% for the RC building. The costs of retrofit, however, should be accurately evaluated before the net profit is reached.

On the uncertainty of the data, a commercial software Crystal Ball® was utilized for the Monte Carlo simulation (MCS). The MCS method utilizes the central limit theorem, and assumes that the error of the model is mainly from the input data and neglects the influences among the parameters. Firstly, the MCS assigns a probability density function for each input data. The value was randomly selected for each calculation within the assigned probability distribution. Then, the output of the calculation can be expressed as a probability distribution to identify the confidential interval. Due to the probability of the parameters used in this study, a stochastic matrix model was developed followed the Jenning's probabilistic decision analysis (PDA) [13].

$$\boldsymbol{E} = \boldsymbol{M} \times \boldsymbol{m} \qquad (15)$$

Using Crystal Ball software, the element mi was selected by a random number generator. Then, each mi was multiplied by a random number of Mi in each calculation step. The output value, Ei, represents the external energy of stage j. In fact, the output was calculated more than 10,000 times and expressed as a probability distribution. We utilized the Equation (16) to indicate the difference of the values from Equation (15).

$$\boldsymbol{E}^{*} = \boldsymbol{M}^{*} \times \boldsymbol{m}^{*} \quad (16)$$

Then we can express the E_j^* as a probability density function. The mean of E_j^* represents the estimation of the energy consumption of the jth stage, and the standard deviation of E_j^* is the confidence interval of the estimation.

Table 2. The total energy consumptions of both selected school buildings in their service life

(unit: kWh/m2-yr)

Service life	SC building	RC building
10	167.2	145.3
20	153.8	115.3
30	149.3	105.3
40	147.1	100.3
50	145.8	97.3
60	144.9	95.3
70	144.3	93.9
80	143.8	92.8
90	143.5	91.9

5. Environmental impacts of the school buildings

The environmental impacts associated with a school building were complicated through its life cycle. As mentioned above, the process of construction materials had an intense consumption of raw materials and energy during the material production. The occupation stage, nevertheless, consumed most of energy due to its long lifespan in the analysis. Table 3 illustrates the inventory results of the life cycle consumptions of materials and energy for two selected school buildings. In the life cycle stages of two school buildings, the energy consumption could be distinguished into direct energy usage (i.e., fossil fuel) and indirect energy usage (i.e., electricity). The later contributed the most energy consumption in the school buildings. Electricity was supplied by Tai-power company in Taiwan region, which owns many fossil fuel fired power plants as well as nuclear power plants around the island. Form the simulation of LCA model, the contribution of power plants was established as a localized database.

A framework of the life cycle assessment for school buildings is illustrated in Figure 3. The raw materials were extracted from the natural resources and processed in the cement plants and other mills. These construction materials were then transported to the erection site. The second stage was erection buildings on site. The occupation stage was considered the most energy consumption in the life cycle of buildings due to its long lifespan. It was assumed that the school buildings had the life of 50 years and were renovated every 10 years. There is a disposal scenario added in the simulation due to the lack of localized data in this field. Two end-of-life options were selected for the school building's materials, i.e., disposal of and recycling. The recycling of steel and aluminum were assumed as 95% and 90%, respectively. The other materials were sent to the landfill site for disposal of. The delivery of construction materials could contribute large of energy consumptions. They were considered in this simulation and were smaller than these two stages. If we plot the indicator scores based on each stage. They were illustrated in Figure 5. It was clear to distinguish the environmental impacts caused by each stage of the building's life cycle. Both of the SC and RC buildings, the order of the indicator scores (i.e., environmental impacts) is that of occupation, materials production, erection, disposal, and recycling, respectively.

The overall indicator scores were 1.61 and 1.02 MPt for selected SC and RC buildings, respectively. However, the plate areas for the two buildings were different.

Table 3. Life cycle inventory in selected school buildings

Process	Building	Substance	Category	Input/ output	Quantity	Unit	Comment
Materials production	SC	Electricity	Energy	Input	1107327	Kwh	Electricity used in production
		Sand	Material		690	m^3	
		Stone			200	m^3	
		Steel			1798	ton	
		Cement			325	ton	
		Aluminum			24	ton	
		Glass			12	ton	
		Ceramics			501	ton	
		Concrete			7779	ton	
		Red brick			3570	Block	
		Paint			47166	Kg	
	RC	Electricity	Energy		342992	Kwh	Electricity used in production
		Sand	Material		3342	m^3	
		Stone			2500	m^3	
		Steel			539	ton	
		Cement			133	ton	
		Aluminum			19	ton	
		Glass			4	ton	
		Ceramics			24	ton	
		Concrete			6067	ton	
		Red brick			11009	Block	
		Paint			12580	Kg	
Erection	SC	Electricity	Energy	Input	451892	Kwh	Transport by 16-t truck
		Truck	Transport		879719.5	Tkm	
	RC	Electricity	Energy		1179291	Kwh	
		Truck	Transport		915613	Tkm	
Occupa-tion	SC	Electricity	Energy	Input	39036978	Kwh	Use 50 year Every 10 year paint
		Paint	Material		188664	Kg	
	RC	Electricity	Energy		23701022	Kwh	
		Paint	Material		50320	Kg	
Demolition	SC	Electricity	Erengy	Input	222520	Kwh	Demolition by heavy machine
	RC				518873	Kwh	
Disposal	SC	Electricity	Erengy	Input	128856	Kwh	Landfill
	RC				134281	Kwh	
Recycling	SC, RC	Steel	Material	Output	95	%	Steel and alu-minum reuse, others landfill
		Aluminum			90	%	

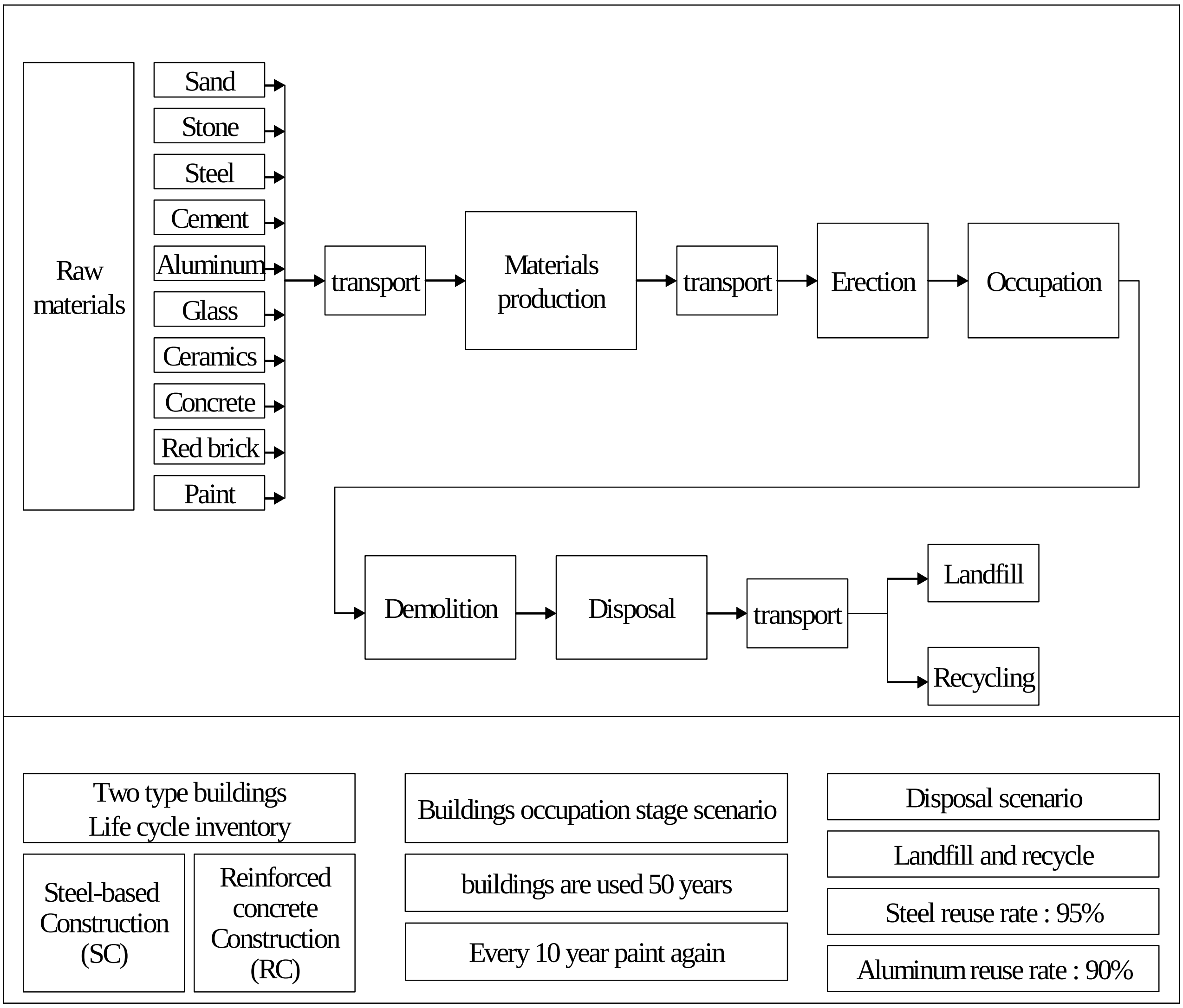

Figure 3. A framework of the life cycle assessment for the school building adapted in this study

To compare the environmental impacts of two selected buildings, the indicator scores were normalized to the plate areas of the buildings. The SC building has 8,272 m^2 and there is 4,215 m^2 for the RC building. As shown in Figure 6, the normalized indicator scores were 195 and 242 Pt/m^2, respectively. It resulted less impact caused by the selected SC building than that of the selected RC building. The Eco-indicator 99 method was established by European region. In the lack of the localized impact method, the adaptation of Eco-indicator 99 method should be very carefully. The difference between local environment and European conditions should be recognized.

6. Conclusions

In this study, we introduced the LCA concept into environmental and energy considerations of two selected school buildings. There are some findings summarized in the followings:

- For both buildings, it is found that the most energy consumption occurs in the occupation stage, i.e. 95.8 % for the SC building and 87.2% for the RC building, respectively. This result is consistent with the previous studies, although they are dominant.

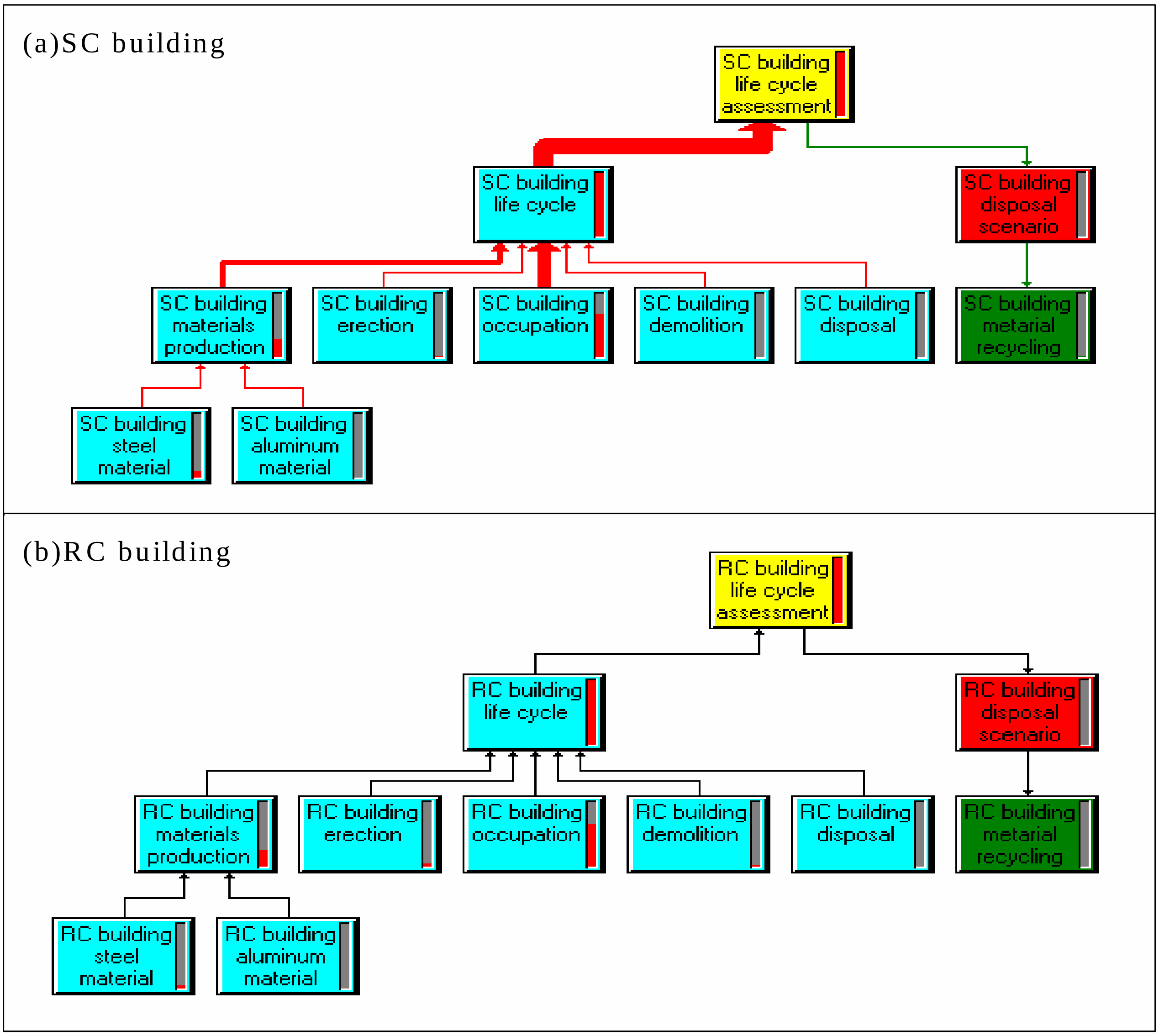

Figure 4. Tree diagrams adapted in this simulation: (a) for SC buildings and (b) for RC buildings

- Due to the different construction processes, the RC building consumes higher energy than that of the SC buildings, whereas the energy consumption in the material production stage for the SC building is higher.
- The service time of selected buildings will influence the energy consumption especially in the first 30 years.
- The environmental impacts caused by the selected SC building were less than that of the RC building based on the Eco-indicator 99 method.
- LCA model can be used in the simulation of local school buildings in their energy and environmental considerations.

Due to the lack of data, the developed LCA-based energy evaluating model has some limitations. The application of this model should be careful. More local data are necessary to develop the model.

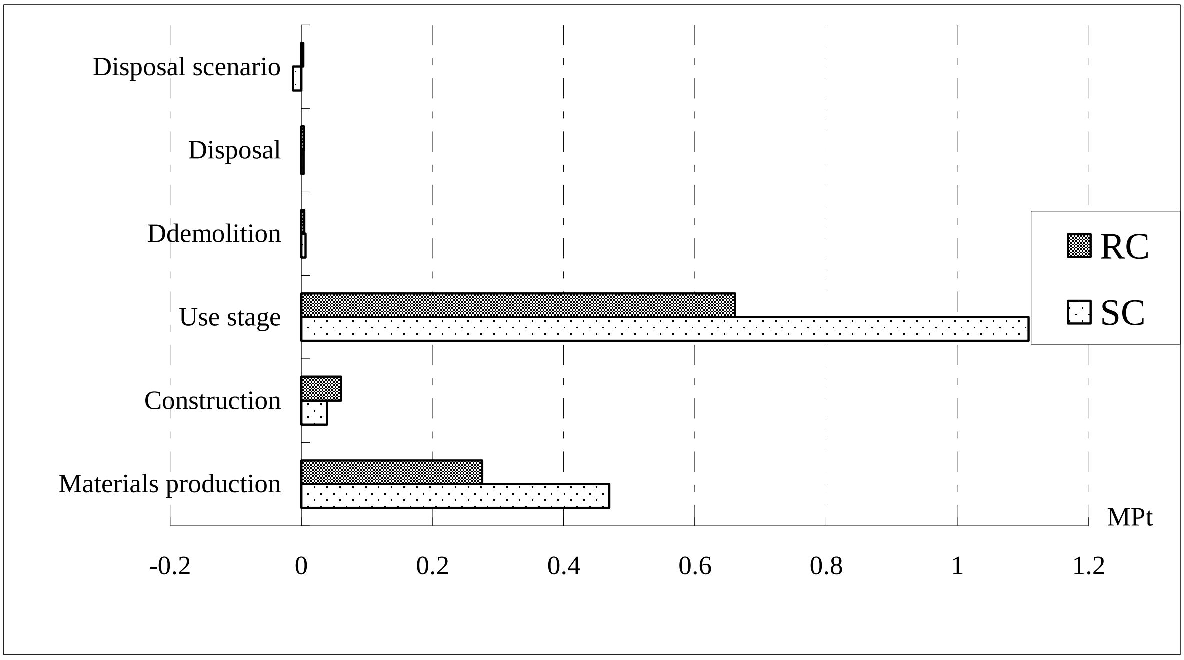

Figure 5. The results of LCA simulation in each stage

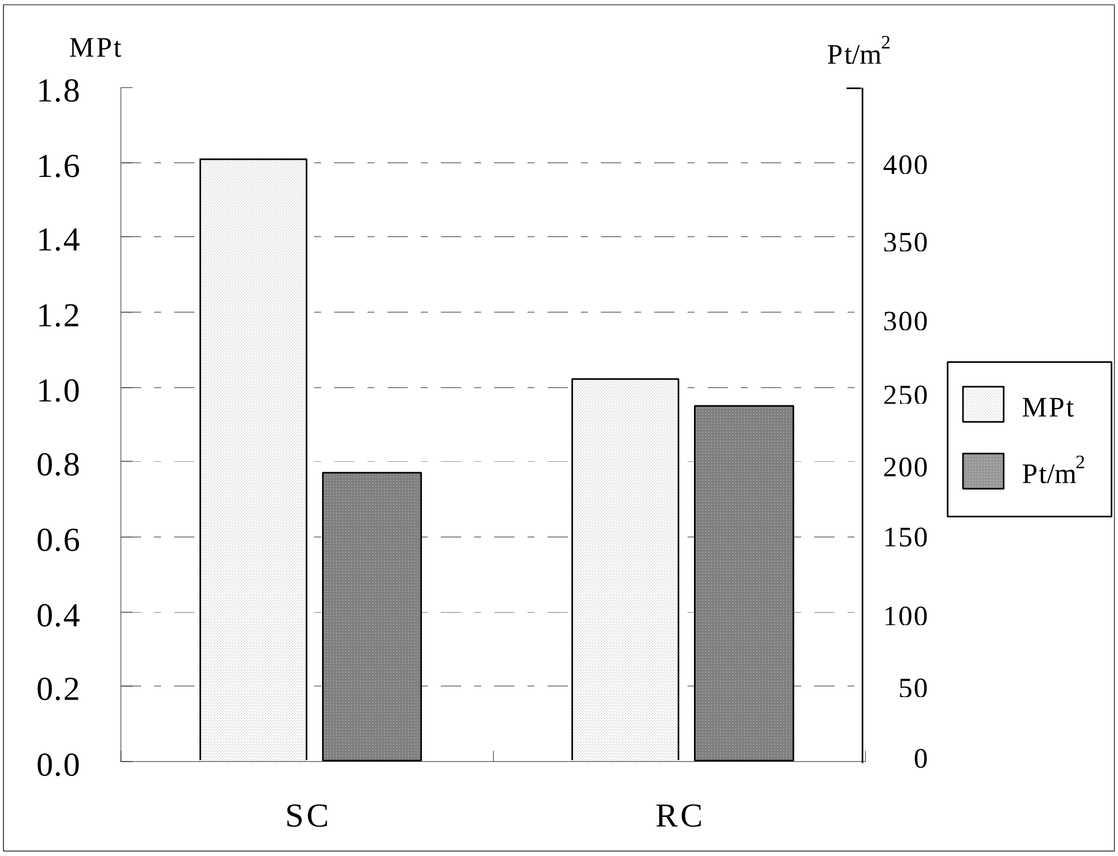

Figure 6. The comparison of simulated environmental impacts between the selected SC and RC school buildings

References

[1] Adalberth, K. 1997. Energy use during the life cycle of buildings: a method. *Building and Environment*, 32: 317-329.

[2] Khanduri, A. C., C. Bedard, and S. Alkass. 1996. Assessing office building life cycle costs at preliminary design stage. *Structural Engineering Review*, 8: 105-114.

[3] Kua, H. W. and S. E. Lee. 2002. Demonstration intelligent building—a methodology for the promotion of total sustainability in the built environment. *Building and Environment*, 37: 231-240.

[4] Peuportier, B. L. P. 2001. Life cycle assessment applied to the comparative evaluation of single family houses in the French context. *Energy and Buildings*, 33: 443-450.

[5] Cole, R. J. and P. C. Kernan. 1996. Life cycle energy use in office buildings. *Building and Environment*, 31: 307-317.

[6] Federspiel, C., Q. Zhang, and E. Arens. 2002. Model-based benchmarking with application to laboratory buildings. *Energy and Buildings*, 34: 203-214.

[7] Filippin, C. 2000. Benchmarking the energy efficiency and greenhouse gases emissions of school buildings in central Argentina. *Building and Environment*, 35: 407-414.

[8] Ameziane, F. 2000. An information system for building production management. *International Journal of Production Economics*, 64: 345-358.

[9] Jonsson, A., T. Bjoklund, and A. Tillman. 1998. LCA of concrete and steel building frames. *International Journal of Life Cycle Assessment*, 3: 216-224.

[10] Gunther, A. and H-C Langowski. 1997. Life cycle assessment study on resilient floor coverings. *International Journal of Life Cycle Assessment*, 2: 73-80.

[11] Zmeureanu, R. and C. Peragine. 1999. Evaluation of interactions between lighting and HVAC systems in a large commercial building. *Energy Conversion & Management*, 40: 1229-1236.

[12] Rabie, N. and G. J. Delport. 2002. Energy management in a telecommunications environment with specific reference to HVAC. *Building and Environment*, 37: 333-338.

[13] Jenning, A. A. 1995. Automating probabilistic environmental decision analysis. *Environmental Software*, 10: 251-262.