RESEARCH

ENERGY CONSUMPTION, ENVIRONMENTAL IMPACTS AND EFFECTIVE MEASURES OF GREEN OFFICE BUILDINGS: A LIFE CYCLE APPROACH

Guozhu Mao[1,2], Hao Chen[1], Huibin Du[3,4]*, Jian Zuo[5], Stephen Pullen[6], Yuan Wang[1]

ABSTRACT

The last few decades have witnessed a rapid development of green buildings in China especially the office sector. The life cycle assessment (LCA) approach has potential to weigh the benefits and costs associated with green building developments. Essentially, the LCA method evaluates the costs and benefits across a building's life cycle with a system approach. In this study, a green office building in Beijing, China, was analyzed by life cycle assessment to quantify its energy use and evaluate the environmental impacts in each life cycle stage. The environmental impacts can be reduced by 7.3%, 1.6% and 0.8% by using 30% gas-fired electricity generation, increasing the summer indoor temperature by 1°C, and switching off office equipment and lighting during lunchtime, respectively. Similarly, by reusing 80% of the selected materials when the building is finally demolished, the three major adverse environmental impacts on human health, ecosystem quality, and resource depletion can be reduced by 11.3% 12.7%, and 7.1% respectively. Sensitivity analysis shows that electricity conservation is more effective than materials efficiency in terms of a reduction in environmental impacts. These findings are useful to inform decision makers in different stages of the green building life cycle.

KEYWORDS:

green office building; life cycle assessment; energy consumption; environmental impacts

1. School of Environmental Science and Engineering, Tianjin University, Tianjin 300072, China
2. Tianjin Key Laboratory of Indoor Air Environmental Quality Control, School of Environmental Science and Engineering, Tianjin University, Tianjin 300072, China
3. College of Management and Economics, Tianjin University, Tianjin 300072, China
4. Center for Energy & Environmental Policy Research, Institute of Policy and Management, Chinese Academy of Sciences, Beijing 100190, China
5. School of Architecture & Built Environment; Entrepreneurship, Commercialisation and Innovation Centre (ECIC), The University of Adelaide, Adelaide 5005, Australia
6. School of Natural and Built Environments, University of South Australia, Adelaide 5001, Australia
* Corresponding author. Tel.: +86-22-27404446 (H. Du); Fax: +86-22-27404446 (H. Du); E-mail addresses: duhuibin@tju.edu.cn (H. Du)

INTRODUCTION

Compared with other manufactured products, buildings have a much longer life expectancy and continuously consume natural resources for decades after construction [1]. This means that they significantly affect the consumption of natural resources, the environment and ecosystems [2, 3]. Thus, buildings have long-term impacts on energy consumption and environmental contamination. As one of the largest energy consumers in any industrialized country, buildings, especially office buildings within the commercial sector, have substantial impacts on our environment [4, 5]. In China, the building sector alone accounts for about 1/3 of the energy demand by 2020 and will have significant environmental implications [6]. It has been pointed out that China took only 20 years to double its energy consumption with an average growth rate of 3.7% [5], and office buildings, as an important part of the urban environment, consume the largest amount of electricity in construction [7].

It has been highlighted that life cycle assessment is an appropriate method to analyze the energy used and the use of other natural resources, as well as the impact on the environment in the building sector [8]. Life cycle energy analysis is a feasible approach to assess the energy use in various stages. The pre-use stage includes the manufacturing of building materials, transportation to the site, and construction. The energy required in this stage is called the *initial embodied energy*. Different material composition, manufacturing techniques/processes, mix design of the building materials, or different building structures can result in different embodied energies that change a building's energy requirements over its entire life span [9-11]. By improving the manufacturing technologies of the material used, or a more robust building structure, the initial embodied energy will be reduced. The energy conservation during the manufacturing of a building helps to reduce the acquisition of natural resources.

The operational stage encompasses all the activities that are related to the use of buildings and the energy consumed for these activities is defined as *operational energy*. As buildings are often used for a long time, the operational energy use of buildings has attracted numerous research studies. One of the ways to conserve energy in the operational stage requires changes of the building use [12] such as operation patterns [13] or seasonal operation strategies [14], which have considerable potential in energy saving.

Finally, the energy required in building demolition and transportation of dismantled building materials to a landfill site and/or recycling plant at the end of its life stage is called *demolition energy*. Even though demolition energy is less than 1% of the life cycle energy [15], some of the previous research focuses on dismantled building materials. For instance, Saghafi and Blengini assess energy savings and environmental benefits by recycling building materials [16, 17]. Furthermore, Amponsah et. al. provided relevant information in prioritizing the selection of materials for recycling or reuse and the optimum number of reuse or recycle times of a specific material [18].

In China, LCA studies on buildings mainly focused on energy consumption, carbon emissions, and environmental impacts of both residential [19] and public buildings [7, 20]. In these studies, the end of a building's life cycle is usually overlooked in the existing LCA studies due to its relative low impact. Similarly, previous LCA studies in China often ignored the effective measures to achieve environmental benefits during building operation.

The Green Building Label (GBL) is a green building rating tool initiated by the China Green Building Council (CGBC) in 2007 [21]. The Green Building Assessment Standard (GBT 50378-2006) is used to evaluate residential buildings and public buildings that include office buildings, shopping malls, and hotels, etc. The evaluation index system includes the following six items: outdoor environment; energy saving and energy use; water saving and water resource utilization; material efficiency; indoor environmental quality; operation management (residential buildings), and comprehensive performance (public buildings). Specific indicators of the six items are divided into three classes, i.e. the control items, the general items and the preferences. According to the satisfaction level of the general items and the preferences, each green building is classified into three levels. Green buildings have been rapidly introduced in China despite a late start as compared to the West [22]. According to the Automotive Engineering R & D Center of Shenzhen, 1,014 buildings were awarded the GBL by June 8, 2013, and 45% of these were public buildings [23]. 996 of these buildings obtained the Green Building Design Label, whereas only 55 buildings obtained the Green Building Operation Label. This demonstrated that close attention should be paid to the operation stage. The research of green buildings in China has been mainly focused on the development of green buildings [24-29], advanced technologies [30-32], and relative evaluation systems of construction, e.g. a voluntary building environmental assessment scheme to encourage good environmental practice [33] or a green residential building evaluation system involving structural design for evaluating green level [34]. In essence, green building studies in China is scarce. A recent systematic review revealed that the vast majority of green building studies focus on the comparisons between green and conventional buildings in areas such as energy efficiency, water efficiency, indoor environmental quality, thermal comfort, and health and productivity [35]. This is essentially a horizontal approach as these studies compare the performance of green buildings with that of conventional buildings. A vertical approach, i.e. comparing a green building with itself will be even more beneficial to realize the benefits of green building development, such as energy savings and pollutants emission reduction.

Therefore, the aim of this paper is to quantify the energy use and to evaluate the environmental impacts in each stage of a green building's life cycle. Consequently, practical measures are proposed in both the operational stage and the end of the green office building's life cycle. Sensitivity analyses were conducted in order to investigate the impacts of the application amount of building materials, electricity consumption, and the length of the building's life time to the environmental impacts in the LCA model.

METHOD

LCA considers the entire life cycle of a product, from raw material extraction and acquisition, through energy and material production and manufacturing, to use at the end of life for treatment and final disposal [36].

According to ISO 14040, an LCA includes four major steps: goal and scope definition, life cycle inventory, life cycle impact analysis and interpretation of the results [37].

Step 1: Defining the goal and scope of the study, the goal and scope defines the boundaries of the building system, the sources of data, the functional unit, the environmental impacts categories and impact methods selected in the LCA model.

Step 2: Developing a model of the product life cycle with all the environmental inputs and outputs. This data collection effort is usually referred to as life cycle inventory (LCI).

Step 3: Understanding the environmental relevance of all the inputs and outputs. This is referred to as life cycle impact assessment (LCIA). As the most important stage in the process, the life cycle impact analysis includes all the energy use and pollution emissions at each stage of life cycle.

Step 4: The interpretation of case study data for conclusions and implications. The life cycle assessment of a building can be performed using general LCA software such as Gabi and Simapro [38]. A life cycle approach is adopted to analyze the energy consumption and the environmental impacts of the office building case study.

2.1 Description of the case study buildings

The building that was chosen for this study was awarded the GBL Three-Star Label. The building is located in Beijing, China, which has a mean daily maximum temperature of 35 to 40°C and -14 to -20°C in the summer and winter respectively, and an annual mean daily maximum of temperature ranging from 11 to 13°C. The case study building is based on a frame shear wall structure system and the total floor area is 30,191m^2. This includes the steel superstructure of nine floors with a total area of 22, 468 m2 and the substructure made of reinforced concrete with an area of 7,723 m^2. The basement storey of the building is used for storage, garage and the relevant equipment room. The first and second floors are public areas with the same storey height of 4.8 meters and are used as service areas for reception, meetings and technical presentations. The third floor to the eighth floor are used as general offices with each having a storey height of 3.67 meters. The ninth floor with a storey height of 3.58 meters is used as general offices, a gymnasium, and a reading room.

2.2 System boundaries

The case study includes three life cycle stages of a building: the pre-use stage, which is the manufacturing process of building materials and transporting the materials to the site; the operational stage consisting of heating, ventilating and air conditioning system (HVAC), network computer room, public area (e.g. water supply, public area lighting, electric elevator etc.) and the use of office equipment, which is powered by electric power, and a central heating system which is powered by natural gas. This excludes the maintenance, repair, replacement and refurbishment of the building, as the case study is a new building and the collection of related data would be fairly difficult. The end of life stage includes the transportation of construction waste to a landfill for disposal or re-use/recycling. The demolition process and the construction stage was not considered in the whole building life cycle as it accounts for a minor proportion of the life cycle energy as 1.41% [7]. Energy consumed during materials production and building services is accounted in the primary energy (MJ). According to the regulations issued by the state, Unified Standard for Reliability Design of Building Structures (GB50068-2001), the designed working life of commemorative architecture and particularly important building structures is 100 years, while the working life of ordinary buildings and structures is 50 years [39]. In this research, the building life span is assumed to be 50 years.

2.3 Functional unit

LCA is a relative approach which is structured around a functional unit [36]. In LCAs of whole buildings, the functional unit should be defined so that the different buildings can be compared based on the assumption of similar services for a similar duration [40]. In this study, the functional unit is defined as "one square meter of floor area per year" with a 50 year life cycle's axiom.

2.4 Data source and life cycle inventory (LCI) analysis

The main source of information, such as the types and quantities of the building materials and the building system components were obtained from the bills of quantity, technical specifications, and other relevant documents obtained from the building contractor.

2.4.1 Building materials manufacture

The materials embodied energy coefficients were obtained from various references [19, 41, 42] (Table 1).

TABLE 1. Embodied energy coefficients of the building materials used in the analysis.

Materials	Embodied energy per unit (MJ/kg)	Reference source
Concrete	1.3	[42]
Steel	29	[19]
Block	2.235	[41]
Cement	5.5	[19]
Gypsum	3.31	[42]
Glass	16	[19]
Stone	2	[19]
Aluminum	180	[19]
Wood	1.8	[19]
Bitumen	158	[41]
Copper	70	[19]
Paint	81.5	[42]

The material production data was retrieved from the SimaPro 7 software. Production data of a material includes its input (energy and resource) and output (emissions to air, water, land) from cradle to gate. We obtained the related information about one material, for instance, the density of concrete from the building contractor. Therefore, we choose the concrete with the nearest density in the database of Simapro. Other materials were chosen in a similar way, and finally the case study building was assembled as one industrial goods.

2.4.2 Building operation

The operational consumption was mainly the electricity from the grid which was recorded by using electricity meters, and the heating from city heating net, details of which were obtained from property management. The statistics of central heating consumption were calculated monthly, and the heating time was January, February, March, November, and December. The statistics of electricity consumption were calculated monthly and also sub-metered for explicating the power consumption of different systems. The related data sources and the conversion process are shown in the Appendix.

2.4.3 Building end of life

The last stage of a building's life is demolition. The conventional disposal method results in landfill for the majority of material wastes in China. Previous studies pointed out that the demolition stage consumed less than 1% of the total energy use in a building's life cycle time, and due to the lack of data on the energy requirement of demolition machinery, we only consider the energy requirements for the transportation of demolition waste to landfill/recycling site.

2.4.4 Transportation

The transportation is divided into two parts: the transportation of building materials products from plant to on-site, and the transportation of building materials wastes to the landfill/recycling site. The parameters of transportation are shown in Table 2. The specific calculated data of transportation are shown in the Appendix.

TABLE 2. Parameters of transportation.

Parameters	Values
the distance between the factory of concrete, cement, steel and the building	500km
the distance between the factory of other materials and the building	800km
the distance between the building and landfill/recycling site	500km
loads of heavy truck	20t
fuel consumption of every hundred kilometers	25L/100km

2.5 The Eco-Indicator 99

In order to obtain a more comprehensive assessment on environmental aspects of the building life cycle, Eco-Indicator 99 was also used as an environmental impact assessment method based on an expert panel approach. In order to reconcile the different perspectives of the seriousness of environmental effects, the Eco-indicator 99 used a three "archetype" of perspectives approach: the egalitarian perspective, the hierarchism perspective, and the individualist perspective. The H/A methodological option of EI99, where "H" refers to the hierarchist version for characterization, and "A" refers to the average weighting set [43].

The environmental impacts of the pollutant emissions of the building system have been divided into three damage categories: Human Health (HH, unit: DALY= Disability adjusted life years; this means different disability caused by diseases are weighted), Ecosystem Quality (EQ, unit: PDF*m2yr; PDF= Potentially Disappeared Fraction of plant species), and Resource Depletion (RD, unit: MJ surplus energy Additional energy requirement to compensate lower future ore grade). Eco-Indicator 99 converts the inventory results into a single score and the environmental damage level can then be assessed.

SimaPro 7 software application was used as a supporting tool in order to establish the LCA model and carry out the assessment.

RESULTS

The results of energy consumption and environmental impacts of the whole building life cycle including the buildings pre-use stage, operational stage, and end of life stage are presented in this section.

3.1 Pre-use stage

Embodied energy coefficients of the building materials are taken from the literature [19, 41, 42] and for a more consistent analysis, most of the data was adopted from the research of Gu et al [19]. The quantities of the materials were obtained from the bills of quantity. The embodied energy of the building is calculated by adding the quantity of construction materials multiplied by their corresponding embodied energy per unit quantity. The embodied energy coefficients of the building materials are shown in Table 1.

The major building material used was concrete as demonstrated by the material mass in the pre-use stage of the green office building (Fig.1). Figure 1 shows the amount of concrete used accounted for more than 80% of the total mass of the construction materials. The total amount of the other materials accounted for less than 20%. Steel (4.9%), block (4.6%), and cement (4.2%) are also significant components of the total material mass.

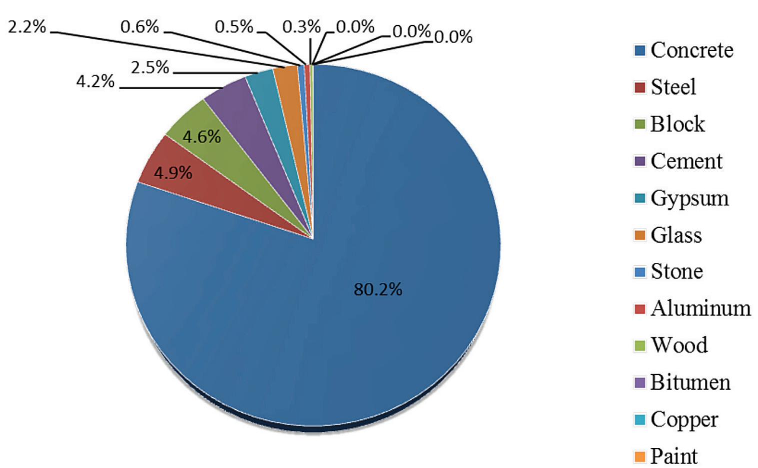


FIGURE 1: Material percentage contribution by material mass in pre-use stage of the office building.

The energy of building materials production is 120.5 MJ/m^2 per year. The energy of building materials transportation to on-site is 13.3 MJ/m^2 per year. The initial embodied energy is 133.8 MJ/m^2 per year. The material percentage contribution by energy consumption in the pre-use stage of the office building is shown in Figure 2. Analysis of the pre-use stage indicates that steel, concrete and aluminum are the most significant materials in terms of their associated energy consumptions as they account for about 33.5% (2018.1 MJ/m^2), 24.7% (1485.4MJ/m^2) and 21.5% (1295.6MJ/m^2), respectively. Steel is the largest contributor to embodied energy, despite its usage being less than 5%. Other materials including glass, cement, block, gypsum, etc only contribute up to 20.4% (1226.9MJ/m2) of the total embodied energy.

The life cycle assessments have also studied the environmental impact of the office building. Figure 3 indicates the environmental impact of each of the building materials according to three environmental indicators. The environmental score attributed by the total building was 0.664. The largest contributor of energy consumption was steel, which also had the

FIGURE 2: Percentage of material share in energy consumption in the pre-use stage of the office building.

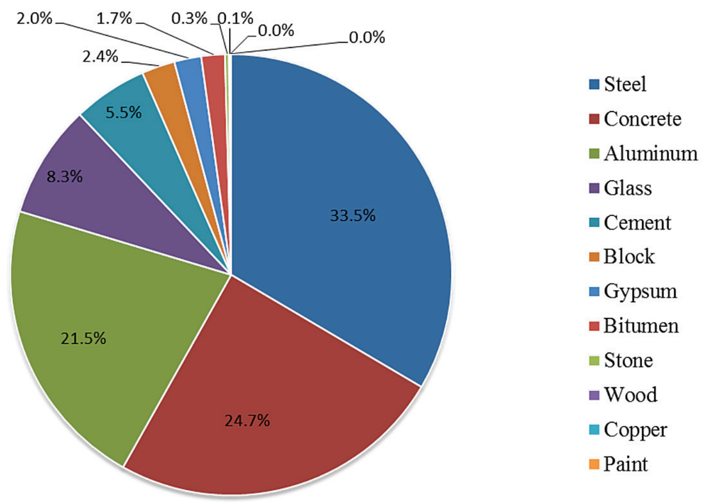
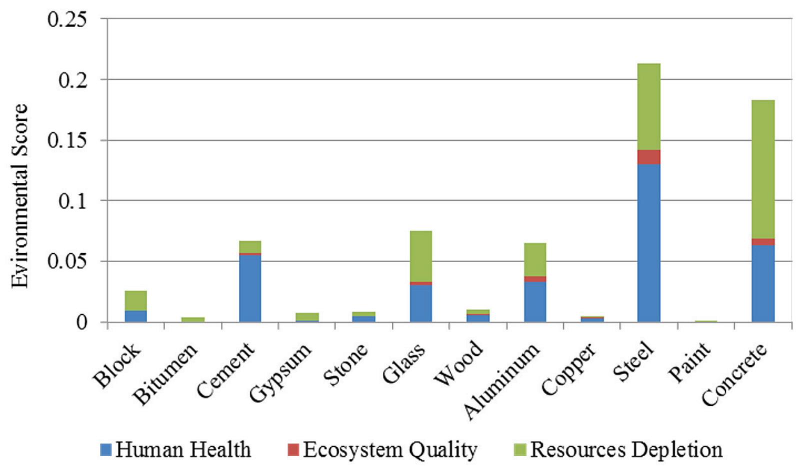


FIGURE 3: Environmental impacts of each building material in the pre-use stage.



biggest environmental damage, and its environmental score was 0.214, followed by concrete (0.183), glass (0,075), cement (0.067), and aluminum (0.065). Each building material had a relatively low adverse effect on the ecosystem quality (the total EQ was 0.029), as compared with human health and resources depletion (the total HH and RD were 0.335 and 0.300, respectively). Compared with the score of EQ and RD, steel (0.130), cement (0.055) and aluminum (0.033) had the largest impact on human health during their production processes. The comparison of HH and EQ shows that concrete (0.114) and glass (0.0423) had a higher level impact on resource depletion.

Figure 4 shows the contribution of building materials from the three environmental indicators. Concerning human health, steel has the most adverse impact (38.8%), followed by concrete (18.8%), cement (16.4%) and aluminum (10.0%). Concerning the ecosystem quality, steel (42.7%) was also the biggest contributor, followed by concrete (18.9%), aluminum (14.5%), and glass (10.0%). Whilst for resource depletion, concrete (38.16%)

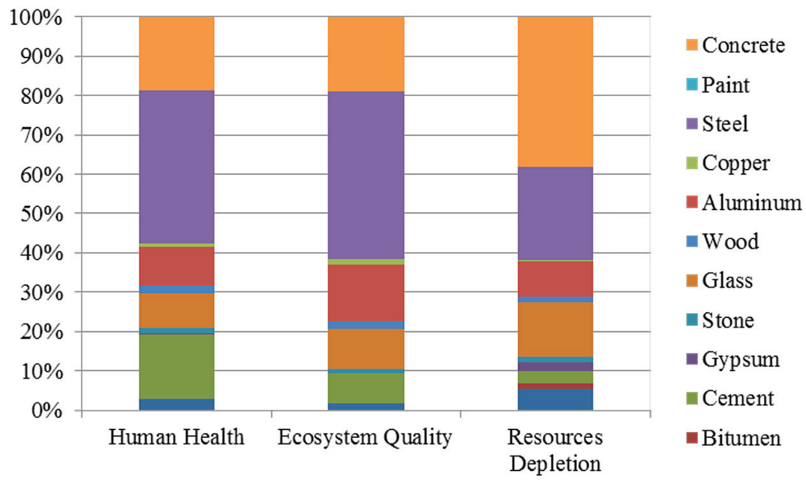


FIGURE 4: Material percentage share of each environmental impact of the office building.

contributed the most, followed by steel (23.8%), glass (14.1%), and aluminum (9.0%). The analysis of energy consumption and environmental impacts of the production of these building materials showed that steel and concrete were always the largest contributors.

3.2 Operational stage

The operational stage of a building includes heating, cooling, ventilation, lighting, equipment operation, and public area supply (e.g. elevator, illumination, etc.). Only actual use of electricity and central heating were considered in this case study. The electricity consumption records of the office building in 2013 were used as the building was still new at the time of this study. The records were measured in kWh. The central heating consumption records of the study in 2013 were measured in GJ. These data were all converted into primary energy in MJ to make it consistent with the energy consumed in the pre-use stage. The relative referring factors are shown in the Appendix. It was also assumed that the electricity use and central heating of the building will remain constant in the future. The energy used in the operational stage was mainly available from the China national grid and the city heating net. The total amount of central heat supply was 187.5 MJ/m^2 per year, and Table 3 shows the percentage of electricity distribution by end use in the operational stage. The electricity consumption during the building operational stage was 492.1 MJ/m^2 per year. The total amount of energy used in the operational stage of the green office building was 679.6 MJ/m^2 per year.

TABLE 3. Distribution of electricity consumption by end use during operational stage.

Network Computer Room	HVAC	Office Equipment	Public Electricity	Others
386776 kWh (24%)	430720 kWh (27%)	182107 kWh (12%)	166069 kWh (11%)	415585 kWh (26%)

TABLE 4. Total environmental impacts of the pre-use and operational stage.

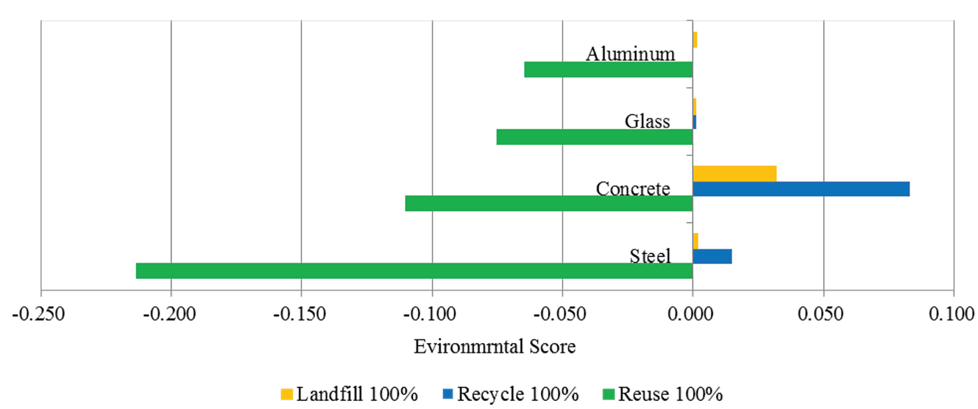
Environmental indicator	Pre-use stage	Operating stage
Human Health	0.335	1.262
Ecosystem Quality	0.029	0.121
Resources Depletion	0.300	2.104
Total	0.664	3.487

The total environmental impacts of the pre-use and operational stage are compared in Table 4. The total environmental score of the two stages of life cycle before demolition were 4.151, and the operational stage contributed 84% of the environmental hazards. The environmental scores show that operation of the building had little impact on the ecosystem quality. The EQ environmental score was 0.121, about 4.2 times that of the pre-use stage. While the HH accounted for 1.262 which was about 3.8 times that of the pre-use stage. The resource depletion caused by the operational stage was much larger than the pre-use stage which was 2.104 or about 3.2 times.

3. 3 End of life stage

The energy of material wastes transportation to a landfill/recycling site is 11.5 MJ/m^2 per year, which demonstrated the total energy demand at the end of the building's life stage. Recycling/reusing is considered to be a more sustainable option as compared with traditional demolition and landfill disposal because it reduces the cost and energy use incurred by landfilling and reduces the demand for extraction of new materials by making use of the recycled/reused materials [44]. Four materials were considered that had the most significant energy consumption (embodied energy) and environmental impacts. 100% landfill, recycle, and reuse was an extreme approach for contrasting profit and loss clearly. Glass, concrete and steel can be categorized as inert material landfill. No direct emissions from inert material landfill were inventoried as they were deemed negligible. By contrast, aluminum can be considered as sanitary landfill, with long-term emissions from landfill to groundwater. Recycle has significant implications on the energy used for dismantling, transport to dismantling facilities, and final disposal of waste material. The greater application amount of material, the greater energy and

FIGURE 5: Environmental impacts of waste materials under different disposal methods.



environmental impacts are. Reuse helps to use these wastes in another building, and the saved energy and resource defined as environmental benefits produced by the case study building.

Figure 5 presents environmental impacts of aluminum, glass, steel and concrete under three different waste disposal methods: 100% landfill, recycle, and reuse. It indicates that both recycle and landfill had harmful impacts on the environment, while reusing resulted in a negative environmental score, which means reuse is beneficial to our environment. Reuse steel from the building had the greatest environmental benefit. The environmental score was -0.214, followed by concrete (-0.110), glass (-0.075) and aluminum (-0.065). The environmental benefits obtained from reusing can completely neutralize the negative impacts caused by landfill/recycle.

DISCUSSION

The total energy consumption in the life span of the green office building is 824.9 MJ/m2 per year. The initial embodied energy corresponds to 16.2% of the total primary energy consumption, while the energy during the building's operational stage accounts for 82.4%, and the end of life stage contributes 1.4%. It is clear that the building's operational stage contributes the greatest energy loading and environmental impacts. The green office building has a more reasonable structure, more friendly building materials chosen when compared with more traditional buildings, and it caused a low improvement potential during the pre-use stage. The operational stage had relative greater savings potential. As shown in Table 4, the network computer room consumes the largest proportion of the operational energy (25%), arguably due to its 24 hours per day of operating time, and the energy saving potential is comparatively small from the energy performance management point of view. Similarly, the HVAC, office equipment and public areas (e.g. water supply, public area lighting, electric elevator etc.) have the highest potential to save energy.

4.1 Environmental benefits under different measures

To reduce the green building's life cycle energy consumption, various measures were considered in both the operational stage and end-of-life stage of the case study.

4.1.1 Operational stage

There are generally two ways of electricity saving and pollutants reduction. First, even though natural gas accounts for more than 50% of energy consumption in China, it is mainly used in the chemical industry and residential sector. In developed countries, power generation from natural gas accounts for 28% in Japan, more than 20% in USA, and more than 30% in Europe. By improving the utilization efficiency of natural gas and full implementation of clean energy power generation, 30% of the initial electricity can be obtained from gas-fired sources [45]. Second, it is imperative to enhance the energy saving behavior from an operation management point of view when dealing with office equipment and lighting systems that remained on outside of the normal working hours. Modifying the design criteria enables air conditioning systems to work more efficiently without imposing additional costs. This includes modifying the set point of air-conditioning during the period in which the building is unoccupied or when its temperature is less than the desired unoccupied indoor temperature [46]. The set point temperature of the building could be as low as 20-25°C according to the outdoor temperature in summer which is lower than the standard indoor air set-point temperature of 26°C [42].

TABLE 5. Environmental benefits at the operational stage.

Electricity saving under measures	Using 30% gas-fired sources	Increasing the indoor air set point temperature by 1°C	Switching off office equipment and lightening of 1 h
Total	-0.254	-0.057	-0.027
HH	-0.198	-0.022	-0.010
EQ	-0.008	-0.001	-0.000
RD	-0.047	-0.034	-0.016

Each of the environmental scores of the building has been calculated according to the various measures as shown in Table 5.

These negative environmental scores present each of the environmental benefit under different measures. By using 30% of the gas-fired electricity, increasing the indoor air set point temperature by 1°C, switching off office equipment and lighting for 1 hour during lunch breaks, the environmental score at the operational stage can be reduced by 7.3%, 1.6%, and 0.8%, respectively. The improvement in environmental benefits demonstrates that innovative power generation technologies and the utilization of clean energy sources are much more beneficial than the other two measures. Nevertheless, as there are significant costs required for the research and development of new technologies and deployment of clean energies, a focus on building management and users' behaviour is beneficial as no extra cost is required.

4.1.2 End of life stage

Based on the actual recovery outcome and the optimization of environmental benefits, it is assumed that 80% of the initial mass of these four materials (steel, concrete, glass and aluminium) will be reused when the building is finally demolished. The remaining materials will be sent to a landfill. Table 6 presents the improvement of the three environmental indicators. It resulted in the total human health score of -0.181, ecosystem quality was -0.019, and resource depletion was -0.171. This resulted in the three environmental indicators being decreased by11.3% 12.7% and 7.1% during the building life cycle. The re-utilization of building material wastes brings numerous benefits to the ecosystem, and the performance of steel is particularly important. Compared to results shown in Table 3, the total environmental score gained by re-using these chosen materials is -0.371, while by using 30% gas-fired electricity can provide -0.254 of the environmental score. It can be concluded that the end of life stage of a building has a greater potential to create environmental benefits than the operational stage.

TABLE 6. Environmental benefits at the end of life stage.

Environmental impacts	Steel 80% reuse	Concrete 80% reuse	Glass 80% reuse	Aluminum 80% reuse
HH	-0.104	-0.053	-0.024	-0.028
EQ	-0.010	-0.004	-0.002	-0.003
RD	-0.058	0.057	-0.034	-0.022

4.2 Sensitivity analyses

Several sensitivity analyses were conducted to explore the environmental impacts of various factors. The results are presented in the Figure 6, where for brevity the energy consumption and each environmental impact are focused on. The sensitivity coefficient SPR is defined as the extent of the change in results due to the change of parameters. The formula is expressed where Δx, Δy is the variable quantity relative to the initial value x, y respectively:

Six of the building materials, i.e. concrete, steel, block, cement, glass and aluminum were selected as their total contribution was 95.8%. The consumption of these six materials is varied to allow a sensitivity analyses. The allowable variation range of usage amount of steel and concrete were defined in the Construction Engineering Technology and Measurement [47]. Accordingly, the variation rate of steel and concrete was set as 7%. It is assumed that the various rates of the other four materials (block, cement, glass and aluminum) are the same due to the comparative low amount of consumption. The sensitivity analyses of the building materials showed that the energy consumption of the building is the most sensitive to the changes in the amount of steel (the sensitivity coefficient is 0.131), concrete (0.096) and aluminum (0.084), which is shown in Figure 6. EC and TS are the total energy consumption and total environmental score per square meter per year, respectively. The figure demonstrates that the total environmental impact is most sensitive to steel (0.073), concrete (0.062) and cement (0.023). For steel, ecosystem quality is the most sensitive indicator to material usage. For cement, the impact of human health is highlighted as important.

The sensitivity analyses were also conducted on electricity consumption. Based on the electricity-saving situation after buildup, it is assumed the amplitude of variation is 4% in the electricity consumption of the studied building. The sensitivity coefficients of the electricity consumption are much bigger than those of the application amount of the chosen materials. For instance, the sensitivity coefficient of EQ of electricity consumption is 0.563, while it is 0.171 for the consumed amount of steel. This reveals that taking measures to reduce electricity consumption is more effective than saving materials for total energy consumption and environmental impacts. The results also show that resource depletion is the most sensitive in the sensitivity analysis of electricity consumption.

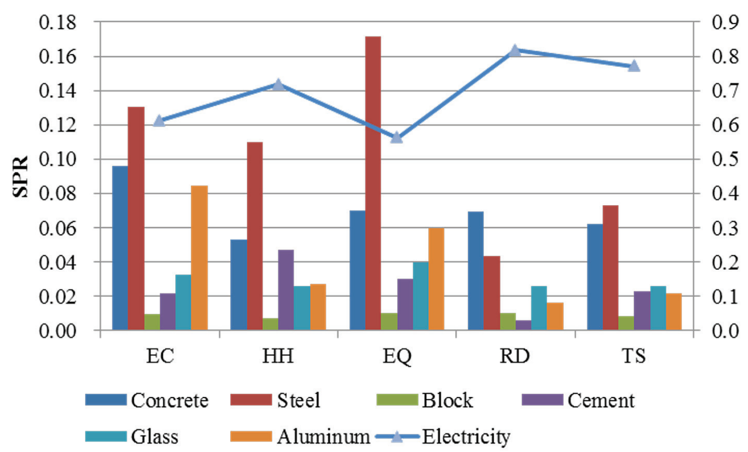
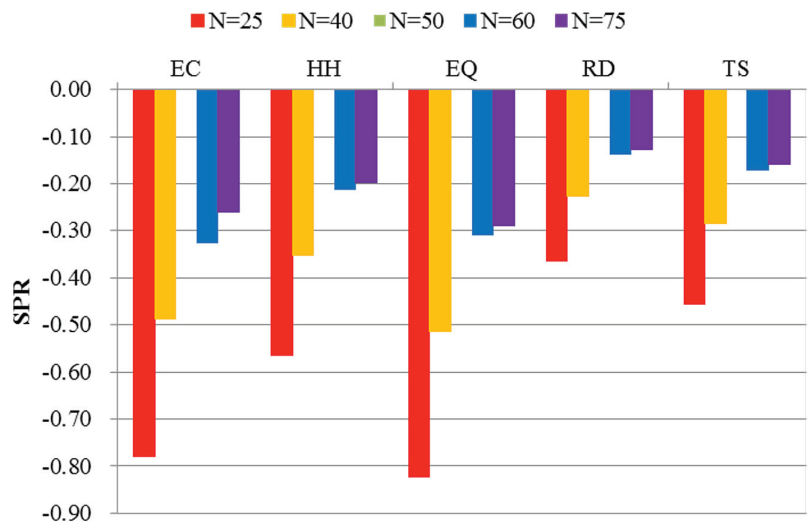


FIGURE 6: Sensitivity analysis of the amounts of the selected materials and electricity consumption.

The effect of changing the length of the building's life time was evaluated where the varied service life span is from 25 to 75 years. According to the negative value of the sensitivity coefficient, the energy consumption and environmental impacts of the case building

FIGURE 7: Sensitivity analysis of building's life span.



decrease with an increase in of the building's life cycle. The sensitivity coefficient is negatively correlated with the building's service life, which shows a diminution of the level of sensitivity. This demonstrates that the longer the service time of the building, the smaller the total energy consumption, and the environmental impact are shown in Figure 7.

CONCLUSION

The essence of the LCA approach is taking a system view to assess both the energy consumption and environmental impacts associated with buildings and consequently take the appropriate measures to reduce energy use and alleviate the negative environmental impacts. The vast majority of previous LCA studies focus on technological aspects, such as building material (e.g. the manufacturing of steel), structure (e.g. steel, concrete or timber), and air conditioning systems (e.g. improved HVAC system during the operational stage). These studies focus on the technological improvements in one particular stage of a building's life cycle. To compare the green building from a vertical perspective, energy use and evaluation of the environmental impacts were quantified in each life cycle stage of the green office building. Practical measures are recommended in both the operational and end of life stage of the green office building. For the case study, the total energy consumption of the office building in its life cycle is 824.9 MJ/m^2 per year. The initial embodied energy is 133.8 MJ/m^2 per year, which corresponds to 16.2% of the total primary energy consumption during its 50 year life time. Its operational energy is 679.6 MJ/m^2 per year, accounting for 82.4% of the total primary energy consumption. Steel, concrete, glass and aluminum are the major contributors to both energy consumption and environmental impacts of the office building. Thus, these four building materials were selected for reuse after the building is demolished. From the operational management point of view, some feasible measures were proposed, such as using 30% gas-fired electricity, increasing the indoor air set point temperature by 1°C in summer, and switching off office equipment and lighting for 1 hour during lunch time. These measures reduce the environmental damage by 7.3%, 1.6% and 0.8%, respectively. If 80% of these four materials were reused, it can reduce the HH, EQ and RD of environmental impacts by 11.3% 12.7% and 7.1% in the whole life cycle respectively. These results revealed that there is a huge potential to create environmental benefits at the end of a building's life cycle as compared to the operational stage. When sensitivity analyses of the application amount of building materials are considered, the electricity consumption and the life cycle time are more sensitive to total energy consumption and environmental impacts. It demonstrates that steel, concrete, cement and aluminum consumption are more influential than other types of building materials in terms of reducing environmental impacts. Therefore, priorities should be placed on reducing these building materials. Similarly, a longer life cycle and reduction of electricity consumption benefit the environment as shown in the sensitivity analysis results. Results also show that electrical energy savings that extend the green building's lifespan bring more environmental benefits as compared with other measures such as improving material efficiency. As a result, the full benefit of a green building development will be achieved.

Future research opportunities exist to conduct more case studies to validate the findings of this research. Similarly, the contextual factors could be taken into consideration when comparing cases in different contexts.

ACKNOWLEDGEMENTS

This study was supported by the National Natural Sciences Foundation of China under Grant 71273185 and 41201591, Post-doctor Sciences Foundation of China under Grant 2013M540145, and The Key project of the National Social Science Fund under Grant 13AZD011.

REFERENCE

[1] P. Yang, G. He, G. Mao, Y. Liu, M. Xu, H. Guo, X. Liu, Sustainability needs and practices assessment in the building industry of China, Energy Policy 57 (2013) 212-220.

[2] J.D. Silvestre, J. de Brito, M.D. Pinheiro, Environmental impacts and benefits of the end-of-life of building materials – calculation rules, results and contribution to a "cradle to cradle" life cycle, Journal of Cleaner Production 66 (2014) 37-45.

[3] S.V. Russell-Smith, M.D. Lepech, R. Fruchter, Y. B. Meyer, Sustainable target value design: integrating life cycle assessment and target value design to improve building energy and environmental performance, Journal of Cleaner Production, In Press, Corrected Proof, Available online 20 March 2014

[4] S. Junnila, A. Horvath, A.A. Guggemos, Life-cycle assessment of office buildings in Europe and the United States, Journal of Infrastructure Systems 12 (1) (2006) 10-17.

[5] L. Pérez-Lombard, J. Ortiz, C. Pout, A review on buildings energy consumption information, Energy and buildings 40 (2008) 394-398.

[6] J. Li, Towards a low-carbon future in China's building sector—A review of energy and climate models forecast, Energy Policy 36 (5) (2008)1736-1747.

[7] H. Wu, Z. Yuan, L. Zhang, J. Bi, Life cycle energy consumption and CO2 emission of an office building in China, The international journal of life cycle assessment 17 (2) (2012) 105-118.

[8] P.C.F. Bekker, A life-cycle approach in building, Building and Environment 17 (1982) 55-61.

[9] N. Huberman, D. Pearlmutter, A life-cycle energy analysis of building materials in the Negev desert, Energy and Buildings 40 (2008) 837-848.

[10] G. Jamie, T. Keane, A. Kelly, The assessment of embodied energy in typical reinforced concrete building structures in Ireland, Energy and Buildings 42 (2010) 735-744.

[11] S. Xing, Z. Xu, G. Jun, Inventory analysis of LCA on steel-and concrete-construction office buildings, Energy and Buildings 40 (7) (2008) 1188-1193.

[12] M.F. Haniff, H. Selamat, R. Yusof, S. Buyamin, F.S. Ismail, Review of HVAC scheduling techniques for buildings towards energy-efficient and cost-effective operations, Renewable and Sustainable Energy Reviews 27 (2013) 94-103.

[13] E. Azar, C.C. Menassa, A comprehensive framework to quantify energy savings potential from improved operations of commercial building stocks, Energy Policy 67 (2014) 459–472.

[14] J. Joe, W. Choi, H. Kwon, J. Huh, Load characteristics and operation strategies of building integrated with multi-story double skin façade, Energy and Buildings 60 (2013) 185-198.
[15] T. Ramesh, R. Prakash, K.K. Shukla, Life cycle approach in evaluating energy performance of residential buildings in Indian context, Energy and Buildings 54 (2012) 259-265.
[16] M.D. Saghafi, Z.S.H. Teshnizi, Recycling value of building materials in building assessment systems, Energy and Buildings 43 (2011) 3181-3188.
[17] G.A. Blengini, E. Garbarino, Resources and waste management in Turin (Italy): the role of recycled aggregates in the sustainable supply mix, Journal of Cleaner Production 18 (10–11) (2010) 1021-1030.
[18] N.Y. Amponsah, Impact of building material recycle or reuse on selected emergy ratios, Resources, Conservation and Recycling 67 (2012) 9-17.
[19] D. Gu, Y. Zhu, L. Gu, Life cycle assessment for China building environment impacts, Journal-Tsinghua University 46 (12) (2006) 1953.
[20] S. Xing, Z. Xu, G. Jun, Inventory analysis of LCA on steel-and concrete-construction office buildings, Energy and Buildings, 40 (7) (2008) 1188-1193.
[21] Z. Gou, S.S.Y. Lau, F. Chen, Subjective and objective evaluation of the thermal environment in a three-star green office building in China, Indoor and Built Environment 21 (2012) 412-422.
[22] Y. Li, L. Yang, B. He, D. Zhao, Green building in China: Needs great promotion, Sustainable Cities and Society 11 (2014) 1-6.
[23] Updated statistical report of the amount of green buildings in China, Industry News, Automatic Technology R&D Center in Shenzhen, 2013. http://www.gb-cabr.com/index.asp?page=details&id=4408&categoryid=260
[24] B. Qiu, From Green Building to Low Carbon Eco-City, Urban Studies 7 (2009) 1-11.
[25] H. Liang, F. Zhang, J. Liang, An Important Model of New-type Urbanization: New City of Green Building Industry, Urban Development 7 (2013) 022.
[26] H. Tan, S. Chen, Q. Shi, L. Wang, Development of green campus in China, Journal of Cleaner Production 64 (2014) 646-653.
[27] Y. Qin, Chinese Condition Must be Considered on Developing Green Building in China, LTLGB 2012, Springer Berlin Heidelberg, (2013) 19-19.
[28] J. Li, C. Wu, W. Qu, F. Wang, W. Li, Study on the Implementation and Development of the Green Building in China, Applied Mechanics and Materials 438 (2013) 1662-1665.
[29] L. Ye, Z. Cheng, Q. Wang, W. Lin, F. Ren, Overview on green building label in China, Renewable Energy 53 (2013) 220-229.
[30] Y, Wu, R. Xu, Green building development in China-based on heat pump demonstration projects, Renewable Energy 53 (2013) 211-219.
[31] X. Zhai, R. Wang, Y. Dai, J. Wu, Q. Ma, Experience on integration of solar thermal technologies with green buildings, Renewable Energy 33(8) (2008) 1904-1910.
[32] X. Liu, X. Duan, M. Shen, J. Chen, Application of Attapulgite Clay Mineral Modified by Flame Retarder in Green Building Materials, Advanced Materials Research 298 (2011) 226-242.
[33] W.L. Lee, C.K. Chau, F.W.H. Yik, J. Burnett, M.S. Tse, On the study of the credit-weighting scale in a building environmental assessment scheme, Building and Environment 37(12) (2002) 1385-1396.
[34] X. Bao, X. Duan, Q. Wang, The Green Residential Building Evaluation Structural System Based on Gray Clustering, Applied Mechanics and Materials 368 (2013) 1183-1188.
[35] J. Zuo, Z. Zhao, Green building research-current status and future agenda: A review, Renewable and Sustainable Energy Reviews 30 (2014) 271-281.
[36] M. Finkbeiner, A. Inaba, R.B.H. Tan, The new international standards for life cycle assessment: ISO 14040 and ISO 14044, The international journal of life cycle assessment 11 (2006) 80-85.
[37] ISO, ISO 14040, Environmental Management-Life Cycle Assessment-Principles and Framework, International Organization for Standardization, 1997.
[38] I. Zabalza Bribián, A. Aranda Usón, S. Scarpellini, Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification, Building and Environment 44(12) (2009) 2510-2520.
[39] M. Li, D. Hu, Z. Shi, Technical Retionality and Background on the Unified Standard for Reliability Design of Building Structures (GB50068-2001), Building Structure, 2002.
[40] G.A. Blengini, T. Di Carlo, The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings, Energy and Buildings 42 (2010) 869-880.

[41] T. Ramesh, R. Prakash, K.K. Shukla, Life cycle approach in evaluating energy performance of residential buildings in Indian context, Energy and Buildings 54 (2012) 259-265.
[42] O.F. Kofoworola, S.H. Gheewala, Life cycle energy assessment of a typical office building in Thailand, Energy and Buildings 41(10) (2009) 1076-1083.
[43] M. Goedkoop, R. Spriensma, The eco-indicator99: A damage oriented method for life cycle impact assessment: Methodology report (2001) 1-144.
[44] A. Akbarnezhad, K.C.G. Ong, L.R. Chandra, Economic and environmental assessment of deconstruction strategies using building information modeling, Automation in Construction 37 (2014) 131–144.
[45] Energy conservation information, http://www.chinameer.com/
[46] V. Vakiloroaya, B. Samali, A. Fakhar, K. Pishghadam, A review of different strategies for HVAC energy saving, Energy Conversion and Management 77 (2014) 738-754.
[47] Y.L. Yi, Construction Engineering Technology and Measurement, China Planning Press, 2010.