The Environmental Impact of Expositions:

A Study of Some Contributing Factors

By

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Abstract

Since the Great Exhibition of 1851, the exhibition industry has grown steadily in significance. As a result, this thesis argues that associated large environmental impacts have emerged invisibly. Because they are invisible, these impacts have not been paid adequate attention. Few relevant studies have attempted to investigate the consequence of the impacts of expositions and especially current “sustainable” expositions.

This thesis investigates the whole life cycle energy use, carbon footprint and ecological footprint of large-scale exhibitions in terms of the contributing factors, including exhibition buildings, visitor-related transportation, and exhibition-related economic aspects. The aim of this research is to determine, within this scope, the environmental impact of large-scale exhibitions and define what a real sustainable exposition and sustainable exhibition building might be. More specially, it creates an appropriate and specific methodology for assessing the environmental impacts generated from exhibition-related factors.

A mixed methods research approach through integration of Life Cycle Analysis and Ecological Footprint Analysis is used. This is to account for whole life cycle energy and resource use and the resulting environmental impacts generated from exhibition buildings (over the construction, operation, maintenance, and demolition phases), different transport modes for visitor travel, and the exhibition-related economic aspect of four case studies. These are the Great Exhibition of 1851 in London, the National Exhibition in Shanghai, Expo 2000 in Hannover, and Expo 2010 in Shanghai.

The results of comparative analysis confirm that the total energy and resource consumption of large-scale exhibitions is increasing. The exhibition-related economic aspects consumed most energy and resources, and these rise in relation to the number of visitors, especially visitors from outside the host city. For visitor travel, the choice of visitor transport modes can significantly affect the overall environmental impact. Foreign visitors going to expos by airplane lead to more energy usage than the average travel energy consumption for an expo. For local travelling, using public transport modes can effectively help to reduce energy and resource usage in host cities. For buildings, using the high-tech approach currently does little to mitigate the energy and resource usage of large expo pavilions. Due to the short useful life, current sustainable exhibition buildings do not perform as well as their designers imagined. Therefore, the energy flow of sustainable exhibition buildings as influenced by actual useful life needs to be paid more attention in the process of environmental assessment.

Furthermore, it is proposed that the assessment method developed in this research can be used to evaluate the impacts of large-scale events, similar to expositions, on the environment in terms of their energy and resource consumption. The results suggest that the analysis boundary for assessment of event-related environmental impacts needs to be the “whole life cycle” and it needs to be broadened for the environmental assessment of large-scale exhibitions to include not just exhibition buildings, but visitor travel (local and international travel), and event-related economic aspects.

Key words: Sustainable exposition, Sustainable exhibition building, Visitor travel, Exhibition-related economic aspects, Energy consumption, Carbon Dioxide emissions, Ecological footprint

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Chapter 1 Introduction

1.1 Introduction

The exhibition industry not only promotes the local tourism industry and economic development, but also speeds up development through the design and construction of cutting edge exhibition buildings. Much literature has demonstrated the remarkable exhibition-related economic growth generated by exhibition activities (Netzer, 1978; Kirkwood, 2002; Skinner, 2006; Kim et al, 2009). At the beginning of the 21st century the percentage of economic income from the modern exhibition industry accounted for 0.74~1.8% of total GDP in Hong Kong, the UK, and Canada (McCann et al, 2005; Joppe et al, 2006; HKECIA, 2007). In terms of exhibition space, 1,062 venues with a minimum size of 5,000 m^2 have been identified and the total indoor exhibition space reached 27.6 million m^2 in 2006 (UFI, 2007).

However, exhibition-related environmental impacts have not been paid adequate attention. There is little relevant study found in terms of assessing specifically the impact of expositions and especially expositions promoted as sustainable. Although some assessments of the economic benefits and associated environmental impacts of large-scale events have been done (Hiller, 1998; Barker et al, 2002; Collins et al, 2007; Collins et al, 2009), the sustainability indicators created for these have not been applied for evaluation of expositions up to now.

In the field of the sustainable design of exhibition buildings, much effort has been put into detailed aspects (for example materials choices, passive design, and the use of building-integrated renewable energy systems), thus attempting to make buildings more sustainable. However, this research has found the largest part of the environmental impact of expositions is related to the building's location and exhibition-related economic aspects. There thus needs to be a greater understanding of the broader environmental assessment of expositions.

Based on this need, the aim of this research is to create an appropriate and specific methodology for assessing the environmental impacts generated from large-scale exhibitions; to define what is a real sustainable exposition and sustainable exhibition building; and to help policy-makers to measure the environmental impact in terms of sustainability of exposition activities and give them recommendations for the design principles of exhibitions and their associated buildings.

To reach the aim, a study related to both the environmental and economic sustainability aspects of large-scale expositions was undertaken. How this study was accomplished is outlined in the following paragraphs.

Chapter 2 reviews the existing practice and studies of whole life-cycle assessment for sustainable large-scale events such as the Olympic Games and World Expos in terms of the environmental impacts. These mainly focus on a working definition of sustainable development, sustainable expositions (or exhibitions), and assessment systems for sustainable expositions. It attempts to explore the gap between theoretical studies and practical achievements in the process of establishing sustainable expositions at both national and international levels.

Chapter 3 defines the detailed problems involved in exposition activities and assessment of expositions and demonstrates the need to investigate the environmental impacts of expositions. The main issues are determined; these are the fact that “sustainable” expositions do not appear to have reached any real level of sustainability in recent years and the fact the environmental impact of expositions lacks attention from researchers and policy makers. The chapter finds there is a lack of study of the considerable environmental impacts generated from human-related exhibition activities; a lack of systemic assessment of the sustainability theme and technologies before these have been implemented for expositions; and a lack of indicators within appropriate boundaries for evaluation of exposition activities which are intended to be sustainable.

Chapter 4 outlines the research questions, scope, and objectives of this study. The objects of this research are defined as world expositions and large-scale national exhibitions that are set up with a total number of visitors above 5,000,000 per year.

The spatial scale is limited to the main countries that hold most world expositions or have regular large-scale national exhibitions and the time scale is from 1851 to 2010. It is hypothesised that the exhibition industry does have large environmental impacts and requires concern in terms of infrastructure construction, transport modes, and exhibition-related economic aspects, the latter being the dominant factor. It is further hypothesised that the environmental impact of national and international exhibitions can be measured by a method which integrates Life Cycle Analysis and Ecological Footprint Analysis.

Chapter 5 outlines the development of the mixed research methods (including Life Cycle Analysis and Ecological Footprint Analysis for measuring the environmental impacts of expositions activities over their whole life cycle) in order to overcome the limitations and systematic biases of using a single method. The system boundary and research phases for quantitative evaluation are described. Four typical exhibition events, the Great Exhibition of 1851, Shanghai National Exhibitions, Expo 2000, and Expo 2010 are introduced for comparative study in the following chapters.

Chapters 6~9 quantify and estimate the energy and resource consumption of four selected large-scale exhibitions over their whole life cycle in the UK, Germany, and China from 1851 to 2011 (Table 1.1). They are evaluated in terms of energy flows and resource consumption for exhibition buildings, visitor travel by different transport modes, nationally and internationally, and direct and indirect exhibition-related economic aspects. The results are given in the chapters and appendices.

Chapter 10 brings the calculated results from the case studies together to provide a comparative analysis of large-scale exhibitions and the three related factors. The comparisons show that the total energy and resource consumption of large-scale exhibitions is increasing. The exhibition-related economic aspects consumed most energy and resources, which were much more than both the building consumption and visitor-related transportation. In detail, energy and resource consumption of buildings was greatest in their operating phase. The matter of short useful life resulted in the sustainable design buildings performing worse than normal exhibition buildings. The choice of visitor transport mode can affect the environment more than the factor of building location. In addition, the ecological footprint of international exhibition activities is increasing together with the increase in number of visitors.

Chapter 11 provides further discussions on how to make more sustainable expositions and how to measure appropriately large-scale expositions. The main finding for making a sustainable exposition is that using the high-tech approach does little to mitigate the energy and resource usage of a large expo pavilion, and that the sustainable design of large-scale exhibition buildings needs to focus more on reducing total energy consumption in the operating phase. In addition, international travel by flying is causing increasing energy and resource consumption and the number of visitors from outside the host city is one of the significant influential factors on exhibition-related economic aspects. A further issue for measuring expositions is that the analysis boundary for event-related environmental assessment needs to be broadened. By combining the factors of exhibition buildings, international visitor travel, and event-related economic aspects, an integrated and customised assessment tool is developed for measurement.

Chapter 12 provides a review of how each chapter has contributed to achieving the aim of this study and makes the conclusions from this study on the basis of comparative analysis and related further considerations in Chapters 10 and 11. Limitations of the research and opportunities for further research are then discussed.

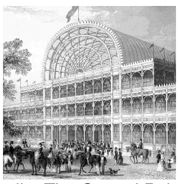
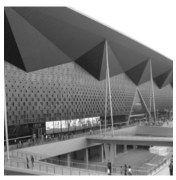
Buildings	Crystal Palace	Shanghai Exhibition Centre	Dutch Pavilion	Theme Pavilion
Useful life	1 May-15 Oct 1851 1854-1936 (rebuilt)	1955-ongoing	1 June-31 Oct, 2000	1 May-31 Oct, 2010 March - Sept, 2011
Floor area (m^2)	Hyde Crystal Place: 92,000 Sydenham Crystal Palace: 138,000	Original: 54,108 Extension: 25,892 Total: 80,000	6,144	143,000
Number of visitors	6,039,195 (1 May~15 Oct, 1851)	7,500,000/year	4,060,000 (1 Jun~31 Oct, 2000)	23,000,000 (1 May-31 Oct, 2010)
Number of floors	Hyde Crystal Place: 3 Sydenham Crystal Palace: 6	5	6	2
Photo graphs	 Wikipedia, The Crystal Palace, from http://en.wikipedia.org/wiki/The_Crystal_Palace		 Dutch Pavilion, from http://www.archreh.com/ecotarium-research.html	

Table 1.1 Four Case Study Buildings

Chapter 2 Assessing the Sustainability of Expositions

Many previous studies have explained the concept of sustainable development at both global and national level (WCED, 1987; LGMB, 1993; Wackernagel and Rees, 1996; US Department of Energy, 2001) and have introduced assessment tools for measuring the environmental impacts of the building stock, for example LEED, BREEAM, GREEN STAR (Attmann, 2009, p.58-65; Roderick et al, 2009). Although the literature covers a wide variety of theories, this review focuses on existing research on whole life-cycle sustainability assessment for large-scale events such as the Olympic Games and World Expos. (The definition of a large-scale event is given in Section 2.2.) Three themes are the main concern of this part of the research: a working definition of sustainable development; sustainable expositions (or exhibitions); and assessment systems for sustainable expositions. Although the literature presents these themes in a variety of contexts, this research primarily focuses on the environmental impacts of large-scale expositions within the context of strong sustainability. A detailed explanation of the scope of this investigation is given in Chapter 4.

The purpose of this chapter is to describe briefly the relevant research that has been reported in terms of the sustainability and environmental assessment of large-scale events. It aims to explore the gap between theoretical studies and practical achievements in the process of establishing sustainable expositions at both national and international levels. It also aims to identify the problems involved in estimating the sustainability of exhibition buildings, and exhibition-related transportation and economic impacts. The detailed reasons for selecting these three aspects are given in Chapter 5. This review helps to define the research scope and set out the central components of the research.

2.1 Sustainability and sustainable development

This section describes the concept of sustainable development and discusses the relationship between the environmental, social, and economic dimensions that have been thought to influence sustainability and sustainable development.

2.1.1 Defining sustainable development

The concept of "development" basically means socio-economic development. Most economists are agreed that "development is closely bound up with the evolution of capitalism" (Sklair, 1994; Conteras, 1997). In fact, the concept of development mainly implies "economic growth".

As explained below, some experts have pointed out that classical economics, which only considers economic growth, will result in the collapse of natural systems. As early as 1798, Malthus (1798), an economist and a country pastor in England, set out the relationship between population growth and economic development in ***An Essay on the Principle of Population***, which demonstrated that growing population rates would lead to a rise in consumption of natural resources (Rogers, 2008, p.20). Meadows et al (1972) developed a model for simulating the consequences of rapid population growth and finite resource supplies, in the book ***Limits to Growth***, again showing that collapse was inevitable unless population growth was curbed. Later the World Watch Institute provided "much-appreciated summaries of the global use of natural resources and the environment, usually accompanied by warnings of imminent collapse" (Brown et al, 1992; Rogers, 2008, p.20). The concept of "sustainable development" as a new development model to avoid such collapse was thus the subject of attention for both economists and environmentalists from the 1970s onwards.

After the 1970s energy crises and the environmental problems that emerged globally in the late 20th century (Carson, 1962; Meadows et al, 1972; Brown et al, 1984), the significance of sustainable development was gradually taken up as an idea, if not an outcome, by most stakeholders in Europe and the USA (Giddings et al, 2002). "Sustainable" as a major theme first appeared in "Blueprint for Survival" in the *Ecologist*, which was "an influential environmentalist text" that focused on environmental issues (Goldsmith et al, 1972; Kidd, 1992, p.12-13).

Although there are many accepted or acceptable definitions of sustainable development (Mawhinney, 2002, p.2), the most widely quoted definition is that of the

World Commission on Environment and Development, which came from the Brundtland report in the 1980s. It is given below.

> *Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs* (WCED, 1987; UNGA, 1987).

The key sections of this definition that are related to the subject of this research are: development and needs, present and future. Development can be interpreted generally as economic growth, social progress, and environmental protection (Munier, 2005, p. 10) and the concept of “needs” means the essential needs provided by development, particularly to the poor (WCED, 1987, p. 43). In addition, the present and future represents the time scale of sustainable development, which refers to the need to provide development in the present and also in the long-term future.

However, to some extent, this definition is ambiguous and questionable when it comes to putting it into reality. Firstly, at present there is no definite answer to the question of whether economic growth and environmental protection can be integrated in terms of human development. There exist many related debates in the field of academia. For example, the debate about Malthusian limits (that rapid population growth will cause a crisis) has been raging over the centuries (Rogers et al, 2008, p.20) and the global population is still increasing. Secondly, whether the needs for future environmental, social, and economic development can be predicted completely or not is uncertain. Rogers et al (2008, p.21) have argued that “it is impossible for the present generation to foresee descendants’ needs, because of the advancement of science, and consequently, establishing a time-frame for the achievement is impossible”.

In addition, there are many definitions proposed by other researchers, which are closely relevant to particular groups. For instance, the World Wildlife Fund stated that “Sustainable development means improving the quality of life while living within the carrying capacity of supporting systems” (IUCN et al, 1991). Wackernagel and Rees (1996) believed that sustainable development is “The need for humanity to live equitably within the means of nature”. More loosely, the US Department of Energy (2001) stated that “Sustainable development is a strategy by which communities seek economic development approaches that also benefit the local environment and quality of life." The accurate implication of what "Sustainable development" means, however, is difficult to define. This is because "Sustainable development" has been given a wide range of interpretation as it is defined by people from many different fields using their own criteria (Pearce et al, 1989).

Even though sustainable development does not have a definition accepted by all, it can be seen that sustainable development is a process of change. Such changes are mainly linked with behaviour, consumption patterns, spending and purchasing habits and evaluation of the environment (Munier, 2005, p.13) and not just the development of sustainable technologies (the detailed reasons for this will be demonstrated in Chapters 6~9). The argument below perhaps best describes the main point in reaching sustainability, which is the view taken by this thesis:

> *The challenge of sustainability is neither wholly technical nor rational. It is one of change in attitude and behaviour. Sustainability therefore must include the social discourse where the fundamental issues are explored collaboratively within the groups or community concerned. We do not do that very well, partly because of increasing populations, complexity, distractions, and mobility, but more because of certain characteristics of the dominant paradigm that are seen as desirable* (Fricker, 1998).

It is believed that changing the attitudes of human beings needs to be started by this generation. Reaching sustainability needs changes to actions.

2.1.2 Environmental protection versus economic growth

Sustainable development is perceived as a continuing process, which integrally consists of the three essential aspects of environment, economy, and society, named the "three pillars" of the 2005 World Summit (UNGA, 2005). This section discusses two different models in terms of the three pillars of development. These models are used to show the different relationships and connections between the environmental, social, and economic dimensions in the sustainable development model in detail.

- Triple Bottom Line model

The “Triple Bottom Line” model was presented by the Brundtland Commission in ***Our Common Future*** in the 1980s (WCED, 1987). Vanclaren (2008) claims the triple bottom line approach has been in common use for the past several years. In the model, the dimensions of environment, society, and economy are formed by three overlapping circles (Figure 2.1), which have the same magnitude and equal relationships to each other. The model thus appears as three interconnected rings (ICLEI, 1996; Barton, 2000).

The triple bottom line approach believes that environmental, societal, and economic dimensions can be developed and integrated, and are mutually influenced and reinforced in sustainable development. In addition, this model implies that the approach for reaching sustainable development is to explore how to keep a good balance between environment, society, and economy. In the triple bottom line approach it is essential to consider the three dimensions as interconnected and develop them as part of the same goal. This model is also called the ‘weak sustainability’ model, as will be discussed below.

However, the triple bottom line approach does not truly solve current problems. There are major weaknesses and limitations to this model. Firstly, this model is difficult to demonstrate. Giddings et al (2002) indicated that there are no convincing reasons why the model should use equal sized rings in a symmetrical interconnection. The possible permutations when changing these variables are endless. Secondly, environment, society, and economy, as three different entities, can be established or developed separately, although the three dimensions are concerned integrally in the triple bottom line model. In fact, some theories for reaching sustainability, such as assessment indicators for each of these three factors, are being formed and applied independently at present. For example, Life Cycle Analysis (LCA) for the environment (Mithraratne et al, 2007, p.34); Social Impact Assessment (SIA) for social sustainability (Hernandez et al, 2010, p. 189); and Global Reporting Initiative (GRI) G3 Core Indicators for economic sustainability (Philips, 2007). This means the three dimensions can be measured by different tools without an appropriate integration system. Thirdly, at present the economic dimension is still a dominant factor in decision making. This skewed relationship between environment, society, and economy can be clearly illustrated by the Mickey Mouse model (Figure 2.2). It shows the development of the three dimensions is not equal. The economy is the most important and social and environmental aspects are separated and minor. In addition, the idea of environmental protection is normally seen as an issue apart from the social lives of human beings.

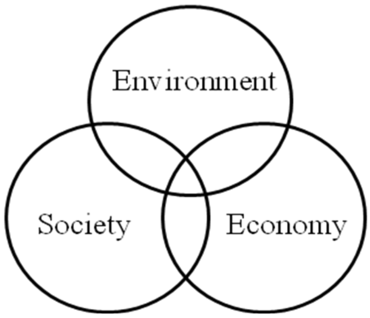


Figure 2.1 Triple Bottom Line model

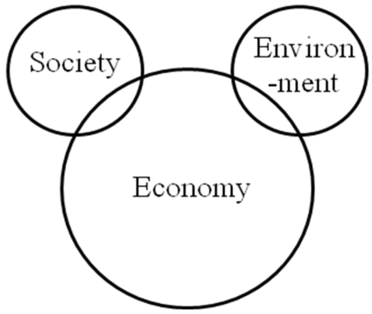


Figure 2.2 Mickey Mouse model

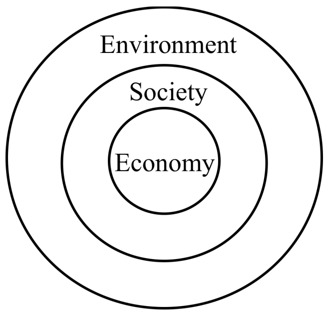


Figure 2.3 Three Concentric Circles model

There is a further concern that regarding environment, society and economy as separate entities could lead to a narrow techno-scientific approach (Giddings et al, 2002).

- Three Concentric Circles model

Although the economy has priority in the political reality, in the material reality the economy is, in fact, dependent on society and the environment (Daly, 1992; Rees, 1995). Based on this consideration, the Three Concentric Circles model was established to present a different relationship between the three dimensions of sustainable development. It can be seen, perhaps, as the ideal development model of “Strong Sustainability” (its definition will be described in the next section), and this is the concept accepted and adopted by this research.

The Three Concentric Circles model is depicted in Figure 2.3 and shows the circle of the economy nested within that of society, and economy and society are both inside the circle of the environment. This approach highlights the fact that the existence of society and the economy are basically dependent on the environment, rather than being at the same level with it.

Adopting this development model is a more sensible route to sustainable development for several reasons. Firstly, the environment as the fundament of material existence provides all the resources for human life such as energy and food. There is an important notion worth remembering, which is that human beings are a part of the biosphere, rather than separate from the whole ecosystem (Levins and Lewontin, 1994). This notion is concealed by many modern monetary and social activities of people. Secondly, it cannot be denied that the economy is a subsystem of human society, which is a subset of the biosphere (Porritt, 2006). Economic growth cannot be continued if the natural environment has totally collapsed. The Three Concentric Circles model shows an understanding that the environmental dimension, as the biggest circle in the model of sustainable development, needs to be the first to be given consideration.

Economic growth, therefore, is dependent on the environment. Sustainable development should be concerned with and assessed on the environmental impact generated by all human activities, including the associated societal and economic aspects.

2.1.3 Weak and strong sustainability

The sustainability debate has been divided into two different streams, known as “Weak Sustainability and Strong Sustainability”, and these derive from starkly contrasting assumptions about the sustainability of natural capital (Neumayer, 2010, p.20). This division shows the two different starting points for viewing sustainable development: the anthropocentric view and the physiocentric view. The anthropocentric view came from the notion that “human beings are at the centre of concerns for sustainable development” (NUCED, 1992). The physiocentric view is focused on the conservation of the natural environment, rather than human beings (GACGC, 1999; Statistics New Zealand, 2008).

Although some descriptions differ in detail, the most accepted descriptions of weak and strong sustainability are set out below.

> *Weak sustainability is built upon the assumption that natural capital is either abundant or substitutable both as an input into the production of consumption goods and as provider of direct utility. It means that natural capital can be safely run down as long as enough man-made and human capital is built up in exchange* (Neumayer, 2010, p.21-22).

> *Strong sustainability sees sustainability as non-diminishing life opportunities (Daly and Cobb 1989, p. 72). This should be achieved by conserving the stock of human capital, technological capability, natural resources and environmental quality* (Brekke, 1997, p. 91).

Weak sustainability focuses on the rule of keeping total net investment, encompassing all relevant forms of capital above zero (Neumayer, 2010, p.21). The central point of weak sustainability asserts that both the economy and society have a value equal to that of the environment, as found in the Triple Bottom Line model and the Mickey Mouse model (Figures 2.1 and 2.2). In fact, weak sustainability does not take into account the fact that keeping monetary flow is fundamentally dependent on consuming natural resources.

In contrast, strong sustainability believes that natural capital cannot be duplicated by manufactured capital. There is no need to describe the concept of strong sustainability in detail in this thesis, as many previous writings have explained and demonstrated it (Daly and Cobb 1989; Brekke, 1997; Neumayer, 2010).

In addition, a further consideration of strong sustainability is that the environment and natural resources have already been overshot, as demonstrated by the Ecological Footprint method of analysis (Wackernagel and Rees, 1996). (Detailed information on this will be given in Chapter 5.) It shows the urgency for all human beings to pay more attention to the consumption of natural capital rather than a rapid development of national economies. It should be noted that this research follows the concept of strong sustainability, using the Ecological Footprint (EF) as an indicator to assess the whole life cycle environmental impact of sustainable expositions.

2.2 Sustainability of expositions

This section aims to define the research subject in terms of exposition (exhibition) activities and their three associated aspects that lead to environmental impacts. The current practices with relation to "sustainable expositions" are reviewed and discussed. Sections 2.2.1 and 2.2.2 describe the origin of present expositions and demonstrate both the constructive and the associated negative impacts generated by large-scale expositions at both international and national levels. Section 2.2.3 discusses how world expositions are related to the concept of sustainability and how sustainable technologies have been used in expo-related infrastructure and transportation. From the review, the problems inherent in the present concept of "sustainable expositions" are propounded briefly at the end of this section. (The detailed description of the problems will be given in Chapter 3.)

2.2.1 Expositions and world affairs

The definition of an exposition (used equally with the word "exhibition", when it appears as a name of an exposition throughout the whole thesis) used in this research is an interpretation given in the context of modern industry. Briefly, an exposition is defined as an event at which products and services are displayed (CIC, 2003).

In the literature review, "exposition" (indicated as a World Fair or World Exposition) is mainly classified as a typical category of hallmark events (Ritchie, 1984) or mega-events (Ley and Olds, 1988; Hall, 1989; Hall and Hodges, 1996; Shoval, 2002).
Ritchie (1984) clarified "World fairs/Expositions" as one of seven categories of hallmark events, which are listed in Table 2.1. The definition of hallmark events was "Major one-time or recurring events of limited duration, developed primarily to enhance the awareness, appeal and profitability of a tourism destination in the short

and/or long term" (Ritchie, 1984). Ritchie (1984) stated that world fairs or expositions represent one of the first forms of events which are particularly focused on urban destinations by means of a theme having significance at a given point in time.

Category	Examples
World fairs/ expositions	Vancouver 86
Unique carnivals and festivals	Mardi Gras
Major sports events	Olympics; World Cup Soccer
Significant cultural and religious events	Papal Coronation
Historical milestones	Los Angeles Bicentennial
Classical commercial and agricultural events	Wine Purchasing
Major political personage events	Major political leadership conventions

Table 2.1 Classification of hallmark events (Ritchie, 1984)

After Ritchie's definition, a series of modified definitions of events were given by different researchers (for example, Jafari, 1988; Marris, 1988; Hall, 1989; Hiller, 1990; Roche, 2000). In their studies, expositions, together with the Olympics, were mostly classified into the category of "mega-events", which is a component of "hallmark events" (The classification of events is shown in Figure 2.4). Law (1993) defined the term "mega-event" as the largest category of events and that the international profile is the distinguishing feature. The Olympics and the Expositions are seen as the two most important events in this category of mega-events because of their huge number of visitors and long lasting impacts upon the host cities and the environment (Shoval, 2002).

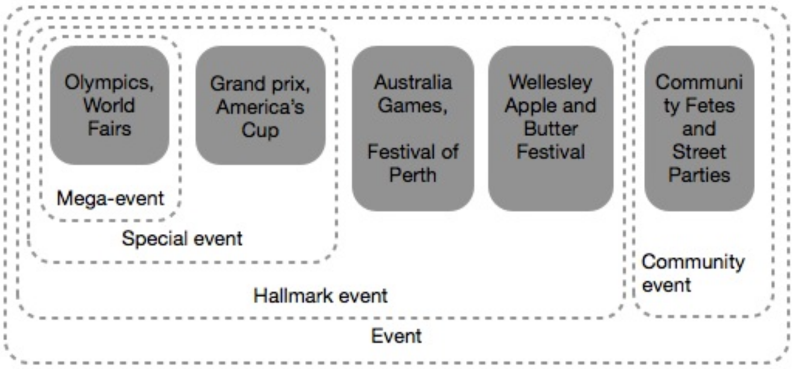


Figure 2.4 Classification of events (Hall, 1989)

As "substantial difficulties in the definition of mega-events still remain" (Jafari, 1988; Hall, 1989), exposition is classified as one category of "large-scale events" that are held at the international level in this thesis, because relevant studies have tended to view hallmark events as major, large scale events (Hall, 1989).

Over the past 16 decades, world fairs, a form of international exposition exhibiting products from many participating countries, have become relatively common and large scale in the global community since the Great Exhibition of 1851. In the 21st century international expositions, and particularly the regular World Expos, continue to display an impressive power of attraction for both visitors and participating countries (Findling and Pelle, 2000, p.1). Comparing the number of visitors between the 2004 Athens Olympic Games and Expo 2000 (Hannover), " The athens welcomed more than 20,000 journalists, 10,500 athletes and hundreds of thousands of officials and visitors" (Palli-Petralia, 2009), while 25 million visitors attended the World Exposition (EXPO2000, 2000). World Expos have had a tremendous impact on their host cities, and even on whole countries.

For national exhibitions, the number of exhibitions, exhibition buildings and visitors are continuously increasing (UFI, 2007). The Global Association of the Exhibition Industry has demonstrated that the exhibition space of the entire world is expanding (UFI, 2007). In 2006 there were 1,062 venues (with a minimum size of 5,000 m^2) identified and the total indoor exhibition space reached 27.6 million m^2 (UFI, 2007). Europe and North America had the highest number and capacity when it comes to exhibition spaces, being 44% and 34% of the total respectively. Asia was listed third, with 14% of total global indoor exhibition space. It is predicted that the total indoor exhibition space will reach 31.1 million m^2 by 2010. The US, Germany and China are dominating the exhibition industry in the Americas, Europe and Asia.

In this research, the defined scope of "exposition" (exhibition) includes international expositions (World Expositions) and large-scale national exhibitions that are set up in a specific place with a total number of visitors normally above 5,000,000 per year. The large scale of these activities suggests that the impacts generated from international and national exhibition activities are both significant and essential to consider in terms of the environmental degradation that they may cause.

The origin and evolution of expositions has a long history related to the national political and economic development of some countries. Findling and Pelle (2000, p.1) have stated that no other human event has the same force of involvement and the history of World Expos is longer than either the modern Olympic Games or the football World Cup.

The origin of large-scale exhibitions developed from the first national industrial exhibition, the French National Exhibition in 1798, which included a ceremony of state (the main activity, together with a competition and exhibition) (Wesemael, 2001, p.63). The purpose of these activities was to "imprint both the population and the entrepreneurs with new ideas, values and morals regarding the economics and ordering of society" (Wesemael, 2001, p.64). The first French National Exhibition was held during the Second Coalition of the Revolutionary Wars. The country suffered both a financial crisis and economic devastation because of the wars. Prior to this, "Louis XVI ascended to the throne amidst a financial crisis; the nation was nearing bankruptcy and outlays outpaced income" (Frey, 2004, p.3). Thus, exhibitions as a policy instrument were used to stimulate economic development and increase technological and manufacturing experiment through communication of ideas.

From 1798 to 1849, there were more than nine exhibitions held by France with the main exhibitions in 1798, 1801, 1802, 1806, 1819, 1823, 1824, 1834, and 1849 (Wesemael, 2001, p.63-113). People gave more attention to the competitions and exhibition of products. The Industrial Exposition of 1806 reflected the new context of state inspired economic growth (Heller, 2006, p.136). As a result there was an "emphasis on the competition: it was a means of obtaining a representative statistical overview of the continental economy, of creating a continental trademark, and of stimulating technological progress" (Wesemael, 2001, p.69). From then on, the scale of exhibitions of products was greatly increased in French national exhibitions.

In 1851 the first international exhibition was held by the UK government in London. The idea of organizing such an international exhibition resulted from the French national exhibitions. This new venture was to become the true meaning of an exhibition at the world scale. The scale of this international exhibition was much greater than that of the French national exhibitions. The organizers enlarged the scale of the whole enterprise and the exhibition layouts and in so doing produced a new sort of exhibition building (Wesemael, 2001, p.63-113). The government believed such an exhibition would be likely to improve both the economy and industrial innovation, and thus help government to build a broader industrial policy (Wesemael, 2001, p.119).

The aim of modern international expositions is to stimulate economies (Bachman, 2003, p.246). As such, they have considerable influence on the development of the local economy where the exhibition occurs (Findling and Pelle, 2000, p.1-2). However, the booming development of the exhibition industry is also part of the environmental deterioration that has occurred during the last hundred years. For example, exhibition buildings, which tend to have large numbers of end-users, have not attracted the same attention as other building types when it comes to environmental matters, even though the construction industry is currently concerned with improving performance with regard to sustainability in most countries (Luff, 2008, p. 190; Neuhoff, 2009, p. 456; Oritz, 2009).The detailed description of the problems will be given in Chapter 3.

2.2.2 Positive and negative impacts of expositions

The impact of expositions is firstly reviewed from the impact of general large scale events in this section. An analytical framework made by Ritchie in 1984 demonstrated the types of impact of hallmark events, which included economic, tourism/commercial, physical, socio-cultural, psychological, and political impacts.

On a comprehensive basis, the boarder impact of events focused on by researchers at present consists of the impact of the following (Higher Education Academy, 2007). This list is accepted by this thesis and part is used to form the research scope:

- Physical infrastructure;
- Environmental impacts;
- Economic impacts;
- Tourism and image impacts;
- Social impacts;
- Cultural impacts;
- Political impacts;
- Urban renewal

It is commonly recognized that mega-events, for example International Expositions, have the potential to help transform a city (Hiller, 1990; Hiller and Moylan, 1999; Hughes, 1993) or a country (Bhardwaj, 1997) into a major, legitimate tourism destination (Ritchie, 2000). Current studies have focussed on and highlighted the potential economic effect of events, which is shown as a significant positive aspect (Crompton and McKay 1994; Jones, 2001; Barker et al, 2002; Chhabra et al, 2003). For instance, the total expenditure at the World Rowing Championships (20-27 August, 2006, Eton) was £3,268,703 or £408,588 per day, which is much higher than the pre-event forecast (£2,841,866 in total) (UK Sport, 2007).

However, there is little systematic research found regarding impact assessment of large scale events (Faulkner et al, 2003). There is shortage of a comprehensive analysis system for assessing large-scale events (Hiller, 1998). Some previous studies (for example Hiller, 1998; Carlsen and Taylor, 2003; Fredline et al, 2003) recommended that the social, physical, environmental and tourism impacts of events and their interrelationships need to be taken into account in the research into events. This implies that the negative impacts generated from the development of the exhibition industry are currently being hidden.

Positive and negative impacts of exhibitions are discussed below.

- Positive impact

It appears that the exhibition industry not only promotes the local tourism industry and economic development, but also speeds up development through the design and construction of cutting edge exhibition buildings. The exhibition-related economic benefit (direct or potential benefit), seen as the most significant positive impact, is discussed below.

Much literature has reviewed and demonstrated the remarkable exhibition-related economic growth generated following exhibition activities. Netzer (1978) concludes that an exhibition (such as an art exhibition) has a positive impact on the local economy resulting in outcomes such as economic growth, growth in local tax revenues, and increased tourist-type revenues. Recent after the event econometric studies using intervention analysis have demonstrated the short term increase in economic growth from exhibitions in Jackson, Mississippi (Skinner, 2006). Kirkwood (2002) illustrates the multiplier effect derived from the exhibition industry, which includes output, employment, income, value-added, tax and imports. The multiplier effect, sometimes seen as the indirect effect, is bigger than before imagined. According to Kim and Partners' analysis for the Korean Exhibition Industry, the total exhibition receipts of US$645.7 million produced US$1.2 billion in output; 21692 full-time equivalent jobs; US$260 million in personal income for residents; US$ 577.4 million in value-added; US$ 54.2 million in indirect tax; and US$ 104.3 million in imports (Kim et al, 2009).

In addition, as part of GDP, the percentage of income from the modern exhibition industry for different countries is significant. In 2004 and 2006 in Hong Kong, HK$19 billion (US$ 2.4 billion) and HK$26.5 billion (US$3.38 billion) came from the exhibition industry, accounting for 1.5% and 1.8% of GDP (HKECIA, 2006; HKECIA, 2007). For the UK, £9.3 billion was generated by the exhibition industry in 2005 (McCann et al, 2005), accounting for 0.74% of GDP. In Toronto (Canada), income from the exhibition industry in 2006 was C$ 1.1 billion, equivalent to 0.87% of the regional GDP (Joppe et al, 2006).

World Expos, the biggest international exhibitions, have even more potential to stimulate local economic growth. Hahn (2006, p.30) states that the 1958 World Expo in Belgium was the first exposition held after World War II to promote economic growth. Another example is Expo 1970 held in Japan, which was the first world's fair held in an Asian country. Expo 1970 had a great impact on the national economy, particularly on the transportation infrastructure. This event helped Japan to reach a peak of high-level economic growth in the 1970s (Lvy, 1995, p.36).

Thus, the function of promoting national and international trade and potentially increasing national revenues makes expositions of more concern to policy-makers. The associated environmental problems resulting from exhibition activities, until now largely ignored, are considered in this research.

- Negative impact

Although several negative impacts of events, such as social issues (drunkenness, and disorderly behaviour), have been mentioned in previous research (Beke and Elands, 1995, p. 285-301; Hall et al, 1995; Allen, 1999), the environmental impact (Barker et al, 2002), as the most significant effect, is reviewed in this section. Expositions as a type of large-scale event affect the natural environment invisibly, which brings large negative impacts to the planet, although the environmental impact of large-scale events is to a limited extent increasingly a concern for researchers and policy-makers (Hiller, 1998; Higher Education Academy, 2007). In addition, exhibitions increase resource consumption and carbon emissions are generated from infrastructure construction, visitor travel, food consumption and other relevant industries.

The impact of environmental deterioration can be separated into two principal parts – one is the direct effect from the exhibition activities (e.g. building construction and visitor travel), the other part is the indirect impacts, which means the additional effect on the environment generated from the increasing production of manufacturers or the consumption of goods stimulated by exhibitions. The second part, which can have extremely large potential economic profits, can be assumed to be the much more significant factor in terms of consuming resources and reducing environmental quality. The indirect exhibition-related economic impact cannot be measured by one criterion, because the effect derived from exhibitions is integrated and compounded. The most significant function of holding an exhibition is to stimulate local and international consumption of products manufactured by exhibitors. It means the additional effect on the environment may be increased invisibly and sustained in the long run.

It seems the economic benefit (positive impact) and the environmental impact (negative impact) generated by the exhibition industry cannot reach a balance point at present (the reason for this is discussed in Section 2.1). Since increasing economic and political benefits were obtained by the UK government through the Great Exhibition of 1851, the question of whether the exhibition-related economy degrades the environmental quality is actually a part of the larger question of whether national economic growth in general obstructs sustainable development of the environment.

In consideration of the above, this study focuses on three aspects of large-scale events (physical infrastructure, environment, and economy) by analysing and estimating the environmental impact of buildings, transportation, and the exhibition-related economic aspect (the detailed research boundary will be given in Chapter 5). This research follows the concept of "strong sustainability", which is based on the principle that the functions that the existing stocks of natural capital perform cannot be duplicated by manufactured capital (Brekke, 1997, p. 91).

2.2.3 Sustainability of expositions

This section explores the relationship between expositions and the concept of sustainable development. It reviews the theme of some world expositions (relevant to the concept of sustainability) and the related sustainable technologies used in "sustainable expositions", such as sustainable exhibition halls and transportation. The review aims to discuss the question of whether modern sustainable expos truly reach sustainability by using modern technologies.

- The theme of sustainability

The concept of sustainability in terms of expositions is firstly shown by the number of world expositions taking it as a theme. They not only show technological innovations, but increasingly also show concern for the sustainable development of the human community (Findling and Pelle, 2000, p.2).

The concept of "Sustainable development" has gradually become the main theme for recent World Expositions (see Table 2.2). Expo 1974 was the first exposition to have an environmental theme (Expo Museum, 2008), probably resulting from the 1970s energy crisis which drew attention to the whole issue of sustainable development. The themes of both Expo 1975 and Expo 1982 referred to the environmental issue. For Expo 2000 in Hannover it was stated, "technology and nature should be combined to be a whole ecosystem in a building" (McDonough et al, 1992). In Expo 2005 in Aichi, Japan, the theme of the exposition was "the use of cutting-edge science and technology for the future, along with new lifestyles and social systems" (EXPO2005, 2005). For Expo 2010, sustainability as the main theme was applied in many aspects (e.g. in pavilions and the master plan of the whole exposition area) (EXPO2010, 2010). Expos can, therefore, be a platform on which to implement and enact sustainability measures (Findling and Pelle, 2000, p.2).

Date	Place	Name	Theme
1974	Spokane, USA	Expo'74-World's Fair	Celebrating Tomorrow's Fresh Environment
1975	Okinawa, Japan	International Ocean Exposition Okinawa	Ocean, the Future Hope
1982	Knoxville, USA	1982 Knoxville International Energy Exposition	Energy Turns the World
2000	Hannover, Germany	Universal Exhibition Hannover 2000	Humankind, Nature, Technology
2005	Aichi Prefecture, Japan	Aichi World Exposition	Nature's Wisdom
2010	Shanghai, China	Expo 2010 Shanghai Expo	Better City, Better Life

Table 2.2 Expos with the theme of sustainability (Expo Museum, 2010)

However, at the start, as an exposition theme, the concept of sustainability was not given serious attention. In Expo 74 fair officials did not really take up the theme of ecology as most environmental groups were not encouraged into full-scale participation, while big companies, who invested money in the fair, were welcomed (CSPN, 2008). Currently, guidelines for sustainable expositions have been used as part of the process of their operation. For example, the guidelines for building World Expo 2000 in Germany set up by McDonough became known as the Hannover Principles. In the principles, sustainability as the main guideline informed the design theme of the expo (McDonough et al, 1992).

- Application of sustainable technologies

Many exhibition halls for World Expositions, especially in recent and current expositions, have been described as sustainable buildings. For instance, the Expo Centre in Expo 2010 reached an international standard (LEED Gold rating) for green buildings (EXPO2010, 2010). However, there is still no real measure of the environmental impact of large buildings over their whole useful life. Studies have shown that reduction in the operating energy for commercial buildings is more significant in terms of total environmental impact than a decrease in building embodied energy (Winther and Hestnes, 1999; Sartori and Hestnes, 2007). Much research has been focussed on optimising energy efficiency technologies and exploring how to ensure the modelled results become a reality once the building is in use (Figueres and Philips 2007). The results from building modelling simulations show that energy efficiency improvement has helped offset energy demand from growth in the building sector (Dimoudi and Tompa, 2008; EECA, 2008; Kneifel, 2010). For example, Torcellini et al (2006) found that high-performance commercial buildings can help to decrease energy use by 25-70% below code.

However, there are several factors relating to this conclusion that make it an uncertain measure of sustainability, such as the years of useful life, and the real performance of exhibition buildings when used by visitors and exhibiters. The Dutch Pavilion in Expo 2000 (held in Hannover, Germany) is a typical example. Located in the south east area of the exposition, this building had six storeys. Each storey had a different character or theme, such as a grotto, agriculture, container gardens, forest, rain and ponds. The designer MVRDV stated that this building was “a mix of technology and nature, emphasizing nature’s make-ability and artificiality” (MVRDV, 2005, p.1120). MVRDV also suggested that this building showed that high population density could coexist with an increase in the quality of life because it demonstrated that a natural environment could be created along with the built environment. It also demonstrated that a natural environment could be made mutually with a building. MVRDV concluded that this building not only saved space, but also saved energy, time, water and infrastructure. The useful life of this building was just 5 months and it was not reused after the World Exposition. The reason for this is possibly because of the high maintenance cost and impractical design for function. MVRDV focused on saving the operating energy of the building, but without considering unseen energy consumption, such as the initial and recurring embodied energy, which were exaggerated by the very short life.

As discussed above, the answer to the question of whether the modern “sustainable” expos truly reach sustainability by using modern technologies is uncertain. The problem embodied in the “sustainable buildings” of expositions is whether they are sustainable over their whole life cycle. Some misunderstanding of sustainable expositions is visibly generated through the economic development strategies made by exhibition sponsors. For instance, the implementation of environmental protection techniques for exhibition buildings, such as solar water heating and low energy lighting, seems to be an attractive selling point for expositions in some countries, of which however the principal purpose is to attract more visitors and promote the products. However this invisible and potentially more significant factor (the economic aspect) can cause much more environmental damage. This will be discussed in later chapters.

2.3 Assessment systems for sustainability of expositions

The section briefly reviews the characteristics and categories of traditional indicators in general and sustainability indicators in particular, as many previous studies have covered this area in depth (Hart, 1999; Munier, 2005). The sustainability indicators for estimating sustainable expositions (represented by indicators for sustainable large-scale events) are discussed in Section 2.3.3. This section points out some common problems in the existing indicators from the literature (the detailed problems will be discussed in Chapter 3).

2.3.1 Indicators and traditional indicators

The answer to the question of what an indicator is needs to be settled before deliberating over the suitability of traditional indicators. Munier (2005, p. 265) states that “Indicators are qualitative or quantitative measures signalling for some condition, for a decision to be taken, to give an early warning, and to show the results of a certain action or process”. The International Institute for Sustainable Development gives the more tangible definition that “An indicator quantifies and simplifies phenomena and helps us understand complex realities. Indicators are aggregates of raw and processed data but they can be further aggregated to form complex indices (IISD, 2008)”. This definition definitely indicates the physical function of an indicator.

Indicators provide basic guidance for decision-making, and they translate physical and social science knowledge into manageable units of information that help to facilitate the decision-making process (SCOPE, 2006). It can be seen that an indicator as an assessment tool can assist users to make decisions by clarifying certain criteria at the global and national level. Good indicators need to be scientifically sound, understandable, and sensitive to change (Custance and Hilary, 1998). The certain characteristics of effective indicators in general are listed below (Zachary, 1995, p.12-13; Hart, 1999, p.26):

- Relevant, which means effective indicators can show the part of the system that need to be known;
- Easy to understand, even by people who are not experts;
- Reliable, so the user can trust the information that the indicator is providing;
- Accessible, so the information is timely;
- Actionable, so as to measure conditions or activities that can be changed in a positive direction by local actions.

As economy, society, and environment are seen as the three dominant dimensions in the process of development (discussed in Section 2.1.2), indicators are classified as economic indicators, social indicators, and environmental indicators by researchers (Hart, 1999, p.53; Vera and Langlois, 2007), and these are what are called traditional indicators. The detailed content of traditional indicators is shown in Table 2.3.

Category	Content
Economic indicators	General business (jobs and income); Industry (manufacturing, services, renewable and non-renewable extraction); Energy; Transportation
Social indicators	Education; Government, Participation, Volunteerism, Cooperation; Health; Housing; Public safety; Recreation, Culture
Environmental indicators	Ecosystem; Population; Land use; Resource use

Table 2.3 Traditional indicators (Hart, 1999, p.53)

Traditional indicators, consisting of economic, social, and environmental indicators, seem to involve comprehensively the three main dominant areas of development. However, the problem is that each traditional indicator is specifically focused on one dimension, without interconnection with the other areas (Atkinson, 1997; Munier, 2005, p.268). The traditional indicators can be seen as isolated indicators.

For example, the profit of stockholders is a traditional economic indicator under the heading of “Industry” (see Table 2.1); quality of water is a traditional ecological indicator under the heading of “Ecosystem” (Golusin and Ivanovic´, 2009). If the economic and environmental aspects are assessed separately for the fresh water fishing industry for instance, through the hunting of fish from rivers, the estimated result cannot show the true condition in terms of sustainable development. It is because the indicators measure the economic effect in terms of profits without considering the associated environmental impacts, such as over fishing which affects long term availability of product (and, incidentally, long term profits).

2.3.2 Sustainability indicators

In Chapter 40 of Agenda 21 (United Nations, 1992), the Earth Summit recognized that indicators can have an important role in helping countries to make informed decisions concerning sustainable development. A range of environmental, social and economic Sustainable Development Indicator (SDI) methodologies regarding human activities have been proposed (Bell and Morse, 2004; Heuting and Reijnders, 2004; Wilson et al, 2007). In addition, it has been suggested sustainability indicators should be developed at both international and national levels (Daly and Cobb, 1989; Pearce and Atkinson, 1992, 1993; Pearce, 1994). SCOPE (2006) stated that a first compilation of 134 sustainability indicators in 1996 developed by the UN Commission on Sustainable Development (CSD) was tested by over 20 countries. A revised set of 58 core indicators was published in 2001.

Noticing the problems of traditional indicators, discussed in 2.3.1, some time ago, Hart (1995, p.9) compared the traditional indicators to sustainability indicators in economic, social, and environmental aspects. Table 2.4 shows part of Hart's assumptions about sustainability indicators. It can be seen that traditional indicators measure changes in one part of a community, while sustainability indicators reflect the tight interconnection between the three different areas (Hart, 1995, p.9).

	Traditional Indicators	Sustainability Indicators
Economic Indicators	Unemployment rate; Number of companies; Number of jobs	Diversity and vitality of local job base; Number and variability in size of companies; Number and variability of industry types; Variability of skill levels required for jobs
	Size of the economy as measured by GNP & GDP	Wages paid in the local economy that are spent in the local economy; Dollars spent in the local economy which pay for local labour and local natural resources; Percent of local economy based on renewable local resources
Social Indicators	SAT and other standardized test scores	Number of students trained for jobs that are available in the local economy; Number of students who go to college and come back to the community
	Number of registered voters	Number of voters who vote in elections; Number of voters who attend town meetings
Environmental Indicators	Ambient levels of pollution in air and water	Use and generation of toxic materials (both in production and by end user); Vehicle miles travelled
	Tons of solid waste generated	Percent of products produced which are durable, repairable, or readily recyclable or compostable

Table 2.4 Traditional versus sustainability indicators (Hart, 1995, p.9)

It is essential to have integral indicators, which are as simple as possible but that give a value relating to all the areas from the point of view of sustainability (Munier, 2005, p.275). For example, social-economic sustainability indicators would not just measure the number of positions, but also consider the associated income with the living cost (Golusin and Ivanovic, 2009). The linkage between economy, society, and environment is necessary for an appropriate indicator of sustainability. The reason given for this is that all existing economic and ecological approaches have weaknesses (Rennings and Wiggering, 1997).

Categories of sustainability indicators are classified as several different types by different researchers (Rennings and Wiggering, 1997; Hanley et al, 1999; Patterson, 2002), according to their different viewpoints regarding the understanding of sustainable development, growth, and sustainability (Ramos and Caeiro, 2010). For example, Rennings and Wiggering (1997) categorised sustainability indicators into two types in the context of the concept of weak and strong sustainability. Patterson (2002) categorised sustainability indicators into five different types, which are "Ecological indicators, Policy Performance Indicators, Macro Economic Indicators, Eco-efficiency and Lifecycle Assessment Indicators, and Composite Index Indicators".

Category	Assumption	Typical indicators
Weak sustainability indicators	Assume perfect substitutability between produced and natural capital	Green GDP; Index of Sustainable Economic Welfare (ISEW) (Daly and Cobb, 1989); Sustainable income (Hueting and Bosch, 1991)
Strong sustainability indicators	Assumes no substitutability	AMOEBA; Pressure-state-Response; Ecological Footprint (Wackernagel and Rees, 1996)

Table 2.5 Weak and strong sustainability indicators (Rennings and Wiggering, 1997; Ayres, 2008; Ramos and Caeiro, 2010)

In this research, Rennings and Wiggering's category, which defined sustainability measurement into two directions, weak and strong sustainability (detailed discussion in Section 2.1.3) is followed. The reason is that it well illustrates the integration of the three dimensions, and at the same time, it clearly distinguishes the two methods for measuring sustainability from its different interpretation. Two categories of indicators were given under the different assumptions of sustainability as shown in Table 2.5. For this research, a strong sustainability indicator, the Ecological Footprint, has been selected to be the assessment tool following the bottom-up method, which aims to evaluate the impacts of sustainable expositions. The detailed explanation for selecting the theories and applying the methodology will be given in Chapter 5.

Although the interpretation of the three areas of development (economy, society, and environment) has been given attention in the development of sustainability indicators, there is no clear best approach at present, because there has only been a little success in linking these concepts or drawing their boundaries (Rennings and Wiggering, 1997; Wilson et al, 2007). Heuting and Reijnders (2004) point out that economic measures and standard sustainability measures are unable to deal with global ecological problems. Wilson et al (2007) stated that since the concept first appeared sustainable development indicators have not yet fully matured. This means that there are still some problems in existing sustainability indicators, which aim to guide humanity to reach sustainability. The detailed explanation of the problems faced will be given in Chapter 3.

2.3.3 Indicators for sustainable expositions

At present, there is little relevant study found in terms of assessing specifically the impact of expositions and sustainable expositions. This means that up to now existing sustainability indicators have not been applied for the evaluation of expositions. For this reason, the literature for this section mainly reviews the existing research related to the assessment and assessment tools for similar large-scale events, such as the Rugby World Cup and the Football World Cup. The condition and problems of indicators for the exhibition industry can be derived from the relevant studies.

As the large economic benefits and associated environmental degradation of large-scale events have been given attention (the detailed impacts have been discussed in Section 2.2), assessment of the impacts of large-scale events has been done by some researchers (Hiller, 1998; Barker et al, 2002; Collins et al, 2007; Collins et al, 2009). In the literature review, it is noticed that most research, although asserted to be impact assessment, has not been made in terms of quantitative measures.

It has been found that the majority of impact estimation for large-scale events is focused on the economic benefits generated from the event-related activities. Most of the studies evaluated the events by the use of traditional indicators. For example, Kirkwood (2002) estimated the output, employment, income, value-added, tax and imports influenced by large-scale exhibitions. Thornton et al (2006) estimated the potential economic effects of the 2012 Olympic Games in London, by looking at the total receipts, income from tourism, number of jobs, etc. Kim (et al, 2009) analysed the Korean Exhibition Industry using traditional economic indicators, which meant mainly assessing the total exhibition receipts, the number of jobs exhibitions created, personal income for residents, the indirect tax, and amount of imports. Currently, there is little balance between these studies of economic assessment and environmental assessment.

In terms of the impacts of a large-scale event, there have been a number of studies investigating the social impacts (for example Arcodia and Whitford, 2002; Fredline et al, 2002; Jago et al, 2002) and the economic impacts of events (Dwyer et al, 2000a, b; Lee and Taylor, 2005; Lee, 2006). Nevertheless, environmental impacts have been rarely explored (Carlsen et al, 2001; Dickson and Arcodia, 2010).

For the environmental assessment of large-scale events, the environmental consequences of sporting events have been the main focus of research. A typical example is from Collins et al (2007). They assessed the environmental impact of transport, food and drink consumption, stadium construction, and waste, for the FA Cup Final by using the methods of Environmental Input-Output Analysis and Ecological Footprint Analysis. Collins et al (2007) compared and analysed the results made by using the two different methods. However, the results from the quantitative study cannot be checked, as there is no relevant data provided.

In the limited existing studies, the Ecological Footprint is used as a common method to assess the impacts of large events (examples from Collins et al, 2007 and Collins et al, 2009). In addition, as part of the lack of consideration of the impacts of large events, other problems are referred to by some researchers. Barker et al (2002) found a notable lack of available data that document the impacts of events. It is noted that "more research attention needs to be directed towards understanding the social, physical, and environmental impacts associated with hosting events in their local context" (Barker et al, 2002).

Consideration of the above shows that how to assess the impacts of events has become an essential issue for analysis. These questions will be addressed in this research by analysis of several case studies in Chapters 6~9.

2.4 Chapter conclusion

This chapter reviews the existing investigation of whole life-cycle assessment for sustainable large-scale exhibitions in terms of their environmental impacts. Three aspects of a working definition of sustainable development, sustainable expositions (or exhibitions), and assessment systems for sustainable expositions have been its focus. The review begins to reveal the problems occurring in the current exhibition industry at both national and international levels.

Based on this, Chapter 3 will discuss in more detailed the further problems of the issues of sustainable expositions.

Chapter 3 The problems

This chapter defines and summarises the problems involved in exposition activities and the assessment of sustainable expositions. The purpose of this chapter is to explore further the need and motivation for this research which stemmed from two issues which are discussed below. The first is that recent “sustainable” expositions do not appear to reach any real level of sustainability and the second is that the environmental impact of expositions lacks attention from researchers and policy makers. The nature and urgency of this study are demonstrated through discussing the special problems from existing expositions, sustainable world expositions, and exposition assessment tools.

3.1 The problems of conventional expositions

3.1.1 Exposition-related environmental issues

The booming development of expositions has become a significant factor which has affected the natural environment. Expositions increase resource consumption for infrastructure construction and operation, emit carbon dioxide generated from visitor travel, and increase local food consumption and waste.

In some countries exhibition buildings currently have large operating energy consumptions. Teheran’s International Flower Building (TIFB) (9,500 m^2) was an extreme example studied by Karbassi et al (2008). Karbassi et al (2008) calculated the energy consumption of this exhibition building using TABESH software. The overall cooling and heating loads of this building are 19.9 GJ/hour, and the annual energy consumption of the building is equal to 39,615GJ/year or 4,150 MJ/m^2/year. The heat loss from the TIFB envelope is more than twice as high as the standard (Karbassi et al, 2008). Another example is that the Perth Convention and Exhibition Centre (16,650 m^2) had an operation energy consumption of 29,629 GJ/year, which was equal to 1,780 MJ/m^2/year (Australian Government, 2009). Pullen (2000) found that the average operating energy consumption of commercial buildings in Australia was around 500 to

1,000MJ/m^2/year. The Queensland Government (2009) reported that operating energy of office buildings had a range from 630 ~ 1,100 MJ/m^2/year. Comparing the operating energy between these exhibition building and a commercial or office building, they consumed more energy than the latter in their operating phase. This suggests that the sustainable consideration for the design of exhibition buildings is both essential and urgent.

In addition, expositions create a large amount of waste after the activities are over. According to a survey in 2001, which formed part of the workshop of the Sustainable Exhibition Industries (SEXI) project (commissioned by the Association of Exhibition Organisers, the British Exhibition Contractors Association and the Exhibition Venues Association), the exhibition industry in the UK produces more than 60,000 tonnes of waste each year including brochures, show literature and carpets (Reynolds, 2002b). The solid waste generated by the Olympic Games, using the 2006 Torino Olympic Winter Games as an example, was 1,213 tonnes in total for the 16 days the games were held (12-28th February). This equates to 76 tonnes/day, and the waste included paper, plastic, organic material, glass and metal cans, wood, and waste that was burned to produce energy (Crawford, 2007). If the waste of the exhibition industry is compared to that of the Olympic Games, to some extent the environmental impact of expositions is likely to be more serious than the Olympics, because expositions are held over a longer period (6 months or more), and because, as explained in Section 2.2.1, expositions typically attract many more visitors than the Olympic Games.

In fact, there is little research that considers the environmental effect and environmental assessment of large-scale expositions or international exhibitions over their whole life cycle (the definition of whole life cycle assessment will be given in Chapter 5). To date most research regarding the environmental impact of the exhibition industry is just focused on the relatively narrow topic of reducing the waste generated by exhibitions (Reynolds, 2002a; Reynolds, 2002b). This former research cannot account for all the natural resources consumed by the exhibition industry in terms of a reasonable research boundary.

3.1.2 Imbalance between exhibition-related economic growth and environmental protection

The question of whether exhibition-related economic growth degrades environmental quality, which is a part of the larger question of whether economic growth obstructs sustainable development of the environment, still remains unanswered at present.

Some idealistic economists have argued that economic growth did not and will not damage the environment. Their reasoning is based on an econometric estimation using the method of "the inverted-U relation", called an environmental Kuznets curve (EKC), which was hypothesised by Kuznets in the 1950s (Kuznets, 1955). The hypothesis states that:

> *At low levels of development both the quantity and intensity of environmental degradation is limited to the impacts of subsistence economic activity on the resource base and to limited quantities of biodegradable wastes. However, at higher levels of development, structural change towards information-intensive industries and services, coupled with increased environmental awareness, enforcement of environmental regulations, better technology and higher environmental expenditures, result in levelling off and gradual decline of environmental degradation (Panayotou, 1993; Stern et al, 1996).*

This hypothesis obviously implies that economic growth does not threaten the sustainability of the human community and that so-called advanced industrialization will be able to grow without facing environmental limits. The research of Grossman and Krueger (1991) estimated the environmental impacts of a North American Free Trade Agreement. It measured three air pollutants in urban areas of 42 countries. They finally found sulphur dioxide and "smoke" increased, together with the GDP per capita, at lower levels of national development, while they decreased at higher levels of national income. Panayotou (1993) also demonstrated the U-shape curve's relationship between SO_2 emissions per capita and income per capita.

In contrast, an increasing relationship between economic growth and environmental damage is shown from current research (Arrow et al, 1995; Ekins, 1997; Gale and

Mendez, 1998). Gale and Mendez (1998) explore the idea that “Increases in economic activity have a negative effect on the environment separate from changes in per capita income, whose relation to the environment is now positive and linear not inverted U-shaped.” Arrow et al (1995) demonstrate that the inverted-U curve was just applied to a selected set of pollutants only, such as SO_2, NO_X, and CO and that it might not apply to all pollutants The reason that the two approaches have come to different conclusions is probably because while Grossman and Kruger looked at classic pollutants, in the sense of things that were toxic or physically harmful to health, the later studies have considered carbon dioxide, which in itself appears harmless, but which is now accepted as the main agent of widespread climate change.

There are a large number of studies focusing on exhibition performance (Kerin and Cron, 1987, p.87; Gopalakrishna and Lilien, 1995; Hansen, 2004, p.1), such as individual selling and promotional objectives and the overall performance of the entire exhibition. In recent literature, the economic related environmental impact of these large-scale events (most literature has focused on the Olympics) is becoming a concern. Holden et al (2008) stress that the meaning of “Sustainable Olympic Games” can be interpreted in different ways, which is like playing language games, suiting the result to the scale of operation and the particular agenda. In the Sydney Olympics 2000, the concept of the “Green Games” was part of the promise (Cashman and Hughes, 1999, p.82). However, whether “sustainable events” are being “green washed” or whether they have truly achieved sustainability over their whole life cycle can be re-considered.

Many sustainable practices for expositions focus solely on the building construction and renewable materials (for example MVRDV, 2005, p.1120; Expo 2010, 2010), without considering the invisible and potentially more significant factors, such as the exhibition-related economic factor, which it seems could cause much more environmental damage (this statement will be demonstrated by several case studies in Chapter 6~9).

3.2 The problems of sustainable expositions

3.2.1 Sustainability as a theme

In the 1970s, the concept of sustainability was not given any serious attention by the global exposition industry (discussed in Section 2.2.3). The construction and utilisation of exposition pavilions in Expo 74, which was the first world exposition to use the theme of sustainability, were good examples. The main pavilions, such as the Energy Pavilion and the Agriculture Pavilion, were sponsored by high energy-consuming and highly polluting companies, including oil, electricity, nuclear power companies, and agribusiness, chemical, petroleum, and food-processing firms. In fact, these companies were seldom concerned about saving energy or the effect of modern agriculture on ecosystems and public health (CSPN, 2008). The Ford Motor Company stated that environmental protection must not raise the cost of living (CSPN, 2008). These findings reflect the fact that sponsors and policy makers did not truly realise the urgency of environmental issues and as a result it was not possible to truly implement the theme of sustainability in the operation of the exposition.

In the 21st Century, some organisers of expositions have brought the sustainability concept into the exhibition design principles. For example, the guidelines for building World Expo 2000 in Germany set up by William McDonough became known as the Hannover Principles. In the principles, sustainability as the main guideline informed the design theme of the expo (McDonough et al, 1992). This principle was interpreted in various ways by designers based on their own understanding. In the Dutch Pavilion, the concept of sustainability was interpreted as a mix of technology and nature, mixing several natural elements (such as forest and rain) with high technology (wind turbines), by MVRDV (MVRDV, 2005, p.1120). Using renewable material (recycled paper) for constructing the Japan Pavilion (Davey, 2009, p.80) can be seen as another interpretation from Japanese designers. The Swiss Sound Box, the Swiss Pavilion in Expo 2000, was constructed with a timber structure as the solution to sustainability (Zumthor, 2000). The designer Peter Zumthor explained that “Taking the Expo theme of sustainability seriously, we constructed the pavilion out of 144 km of lumber with a cross-section of 20 × 10 cm, totalling 2,800 cubic metres of larch and Douglas pine from Swiss forests, assembled without glue, bolts or nails, only braced with steel cables, and with each beam being pressed down on the one below" (Zumthor, 2000). The question of whether transporting the construction material from Switzerland to Germany is a sustainable way to proceed or not was uncertain.

As the consideration above demonstrates, the theme of sustainability for expositions needs to be further explicitly defined and assessed.

3.2.2 Sustainable technologies

Sustainable technologies have been utilised in both the exhibition buildings and in exhibition-related transportation in some world expositions (discussed in Section 2.2.3). Although some researchers have proposed that improving energy efficiency in commercial buildings (and exhibition buildings fall into this category) is one of the easiest and lowest cost ways to mitigate the environmental problems associated with buildings, and observing that lowering carbon footprint has become a key target globally (Figueres and Philips, 2007; Kneifel, 2010), some problems associated with the application of sustainable technologies in terms of reducing the embodied and operating energy of pavilions and the CO_2 emissions of transportation still remain. The data in support of this statement will be demonstrated by the four case studies in Chapter 6~9.

For buildings, although some studies show that reduction in the operating energy is more significant than an increase in building embodied energy (Winther and Hestnes, 1999; Sartori and Hestnes, 2007), there are several factors relating to this conclusion that make it uncertain. Firstly, it is based on the assumption that buildings have a long and useful life (at least 50 years). However, the useful life of exhibition pavilions is often short, and this means that the even the supposedly sustainable building will end up consuming a large amount of embodied energy. The useful life of the Dutch Pavilion at Expo 2000 was just 5 months and it was not reused after the exposition. Most of the pavilions built for Expo 2010 in Shanghai have been demolished after the event (EXPO, 2010). This phenomenon raises the problem of the embodied energy in the "sustainable buildings" of expositions, which is whether "sustainable exhibition buildings" are truly creating a sustainable environment and saving natural resources over their whole life cycle. Although it is simplistic, unless a building has the useful life for which it was designed, it will never be sustainable, and extending building life is one way to reduce total environmental impact. Sartori and Hestnes (2007) concluded that a solar house required an approximate doubling of embodied energy (in terms of the need for increased insulation etc.) to halve the total energy needed when the lifetime was 50 years (compared to an equivalent conventional building). The same authors also found that a slight increase in the embodied energy of the same passive solar house reduced total energy threefold when the lifetime was 80 years. Winther and Hestnes (1999) demonstrate that as the operating energy of buildings is reduced, the use of materials, especially of energy intensive materials, is increased. Much research shows that increasing the use of technical equipment contributes to an increase in the total energy used for construction and maintenance (Kohler, 1991; Feist, 1996; Adalberth, 1996). Secondly, there is a lack of data for the energy used in building demolition, especially in finding energy equivalents for the pollution produced. It is probable that the energy used for the demolition of buildings with a lot of high technology equipment might be significantly higher than that for low-tech buildings. The third uncertainty comes from real building performance. Analysis has shown that many low energy buildings have performed worse than predicted and that the designers are overly optimistic about the behaviour of the occupants (Torcellini et al, 2004). Moreover, Newsham et al. (2009) have determined that 28~35% of monitored LEED certified buildings consume more unit energy than conventional buildings. Whether buildings designed to be sustainable remain so once the end users are in control is another uncertainty.

For visitor travel, although much of the current research focuses on sustainability of transportation (Amekudzi et al, 2009; Shore, 2006; Federici et al, 2003), application of sustainable technologies for transportation is still an unsolved issue. A good example is the World Expo 2005 held in Japan (Expo2005, 2005). The concern for sustainability was demonstrated by the establishment of an advanced-technology eco-community, a recycling system, and sustainable transportation. For example, there were eight Toyota fuel cell hybrid vehicles (FCHV) (hybrid buses) used for on-site transportation at Expo 2005 (Büchi et al, 2009, p. 490-491). The FCHV is a hybrid with a fuel cell instead of an engine, using hydrogen as the fuel and emitting no CO_2 (Friedrichs et al, 2009, p.9). Friedrichs et al (2009, p.9-10) stated that there are a large number of issues, including the high cost (which must be reduced to approximately 1/1000 of the current level), cruising distance, and energy consumption for the creation of a hydrogen supply infrastructure, that must be resolved before there is full-scale use of FCHVs in the market.

Another problem is that the choice of transport modes of the visitors attending exhibitions is an important issue that needs to be considered. In Melbourne, every day 14% of people take public transport and 82% use private automotive vehicles (Urban Planning Program, 2005). With this sort of transport mix the environmental impact (CO_2 emissions) of private automotive transport for visitor travel to attend exhibitions is several times greater than that of public transport (Shen et al, 2009). This means that the types of transport infrastructure that are put in place when exposition venues are built may have a great effect on the overall impact of the exposition, depending on the types of transport they encourage visitors to use.

3.3 The problems of sustainability indicators for expositions

3.3.1 Assessment of large-scale events

As existing sustainability indicators have not been used for the evaluation of expositions up to now (discussed in Chapter 2, Section 2.3), the issues from the use of assessment indicators for large-scale events are discussed in this section.

Firstly, to date no single best measuring system for assessing sustainability has been evolved (Wilson et al, 2007). Because of the complex nature of ecosystems, it is difficult to measure sustainability at present and sustainable development varies according to needs, priorities, and values (Wilson et al, 2007). As a result, the definition of sustainability and the solution to what sustainable development means are still under debate (explained in Section 2.1). Under this situation, assessment indicators for large-scale events have not been completely established.

Secondly, there has only been very little success in drawing appropriate evaluation boundaries. The analysis boundary is used to define the space and time scale for achieving the sustainability of a subject. Bell and Morse (2008, p.15) believed that the spatial scale (a farm, village, town or city, region, country, or the whole planet) is important when putting sustainability into practice or when determining the level of sustainability of an existing system. “However, even if individuals can clearly define the boundary, there are problems in implementing sustainability.” This is because in a sustainable project, “project boundaries may well have to work within political borders, rather than with more reasonably formulated system boundaries” (Bell and Morse, 2008, p.15). On the other hand, due to the difference of time scale, the system boundary varies, because “Different components of sustainability in the same system may best be measured in different time frames” (Bell and Morse, 2008, p.15). Uncertainty of spatial and time scales makes the evaluation boundaries ambiguous.

In addition, the environmental measures become obscure, as all data are subject to errors and biases (Barnett and O’Hagan, 1997). Custance and Hillier (1998) explain that the reliability of assessment of impact on the environment mainly depends on what is being sampled, the sampling methods, and how to aggregate the results into the national scale. Some estimation is given by using complex models, which also depend on various assumptions and some degrees of uncertainty (Custance and Hillier, 1998), but a widely agreed standard definition of sustainability does not exist.

As the discussion above makes clear, it seems that a sustainability indicator for large-scale events, particularly for expositions, needs to be built on a carefully defined assessment scale, as certain measures may be more suitable for certain contexts (Wilson et al, 2007).

3.3.2 Policy bias

Both sustainable development indicators and economic indicators are used to monitor government policy - its making and its performance (Custance and Hillier, 1998). As mentioned in Section 3.3.1, in the implementation of sustainability, project boundaries have to work within political borders (Bell and Morse, 2008, p.15). This means that policy bias can sometimes influence the setting of assessment boundaries and the results from the estimation.

Some studies have used existing sustainability indicators to assess the environmental impact of large-scale events at the international level. For example, Collins et al (2007) state that policy-makers are increasingly concerned with the environmental impacts of major events in the regions. In their study, the result from the assessment of the FA Cup Final (2003-2004) shows that 3,051gha of resources was consumed by visitor-related activities (including transport, food, and infrastructure) in a day, which was equivalent to the land usage for 3,800 people living in India in a year (0.8gha/person/year) (Vale and Vale, 2009, p.38). However, the environmental impact and associated environmental assessment systems for expositions are not something with which organisers bother or of which they are commonly aware.

It is essential that policy makers have a comprehensive understanding of using different sustainable development indicator metrics, which are following the different conceptualizations and definitions of sustainability (Custance and Hillier, 1998). It is necessary that policy makers have some basic knowledge in terms of the philosophy, biases, and limitations of sustainability indicators.

3.4 Summarising the problems

This Chapter points out several issues arising from environmental degradation, modern sustainable expositions, and sustainability indicators for expositions. The problems are summarised as follows:

(a) Development of the exhibition industry can lead to a number of typical environmental issues, such as resource consumption for building construction, carbon emissions for transportation, large amounts of waste generated from the activities, and the potential exhibition-related economic effect. However, there is a shortage of studies of the large potential environmental impacts generated from human-related exhibition activities.

(b) Whether any "sustainable" world exposition at present has achieved sustainability is questionable. There is a lack of systemic assessment of the sustainable theme or its principles, and sustainable technologies, utilised in the pavilions and transport systems, before these have been implemented.

(c) To date there is a lack of indicators within reasonable analysis boundaries for evaluating the environmental impact of expositions.

Chapter 4 Research Focus

The previous chapter presented some of the specific problems involved in the current form of sustainable expositions, development of the exhibition industry, and sustainability indicators for gauging the environmental impact of expositions. Although Chapter 2 reviews the concept of sustainability, impacts of expositions, and associated sustainability indicators in a variety of contexts, this research is primarily concerned with the environmental impact of large-scale exhibitions within the context of strong sustainability.

The purpose of this chapter is to identify the tangible research questions and to delimit the scope of this research. This chapter determines the objectives and hypothesis of this study. It also further explores the need and motivation for this research which stemmed from the three issues summarised in Section 3.4. The careful definition of the research parameters is to help identify reliably the intended outputs of this thesis.

4.1 Research questions

This thesis attempts to seek the answer to the simplified question of how the environmental impact generated by the contemporary exhibition industry can be measured within certain research boundaries at national and international levels.

Based on this fundamental question, two relevant questions are proposed for further analysis. These are "What is the environmental impact generated from a large-scale international exhibition or exposition over its whole life cycle?" and "Is it possible that this mixed methods approach can be developed as a framework for gauging the environmental impact of large-scale events at the international level?"

The specific research questions are outlined below:

The first main research question is:

How can the environmental impact generated by the contemporary exhibition industry be measured at both the national and international level?

(a) How can the system boundaries of measurement be set up and appropriate methods for assessment applied?

(b) Do the analysis boundaries of Life Cycle Assessment need to be broadened for the environmental assessment of expositions and if so what should these be?

The second research question (based on the results from the assessment of the four selected case studies) is:

What is the environmental impact (comprised of energy consumption, carbon footprint, and ecological footprint in this thesis, defined by the analysis boundary in Section 5.1.1) generated by a large-scale international exhibition or exposition over its whole life cycle (considering exhibition buildings, transportation for visitor travel, and exhibition-related economic aspects)?

(a) What is the average initial and recurring embodied energy and operating energy of an exhibition building?

(b) Are buildings getting better? Given current improvements in energy efficiency is there a significant difference between modern and historic large single space exhibition buildings in terms of the embodied and operating energy in the construction and operating phases?

(c) What is the energy consumption and associated CO_2 emissions of visitor travel for attending expositions or exhibitions?

(d) Has the environmental impact of visitor travel to exhibitions increased or decreased over time? Does the location of buildings influence the energy consumption and carbon emissions of visitor travel?

(e) What is the most significant factor in the process of exposition activities, in terms of the whole life cycle environmental assessment?

4.2 Research scope

It is important to identify the scope of this study prior to gathering initial information. The scope helps to form the analysis boundary of environmental assessment for the research objects. The objects of this research are defined as world expositions and large-scale national exhibitions that are set up at a specific place with a total number of visitors above 5,000,000 per year. Impacts generated from international and national exhibition activities are both significant and essential to consider regarding the environmental issues discussed in detail in Chapter 2. In addition, world expositions and large-scale national exhibitions are both typical activities in the general category of large-scale events (the definition of which is explained in Section 2.2.1), which means that the research results may be applicable to this wider category.

Before sustainability can be achieved, the three aspects of spatial scale, time scale, and interpretation of life quality have to be defined, because they provide the context within which the process takes place (Bell and Morse, 1999, p.14). Bell and Morse (1999, p.17) state that spatial and time scales are key components of achieving sustainability and that they need to be carefully selected.

First of all, the spatial scale of this research is limited to two of the main continents that hold world expositions or have regular large-scale national exhibitions, these being Europe and Asia. This is because most national and international exhibitions and exhibition-related venues are organised and built in European and Asian cities (this has been reviewed in Section 2.2.1). This study was limited to places where data could be accessed.

Figure 4.1 shows the percentage of exhibition venues distributed in different areas in the world. Europe has the highest number and capacity of exhibition spaces (44%), and 14% of total global indoor exhibition space is in Asia. For national exhibitions, Germany and China are both the largest countries and dominate the exhibition industry in Europe and Asia (CEIR, 2009). For international exhibitions (which mainly means World Expos), five expos - 1851 (UK), 1925 (France), 2000 (Germany), 2005 (Japan), 2010 (China) - are considered here as examples of the main significant expos in the history of World Expositions.

As explained above, the study of national and international exhibitions in this research focuses primarily on three chosen countries, which are the UK, Germany, and China. The exhibition industry of these three countries is used to represent and reflect the developing condition of expositions, starting from the Great Exhibition in London in 1851.

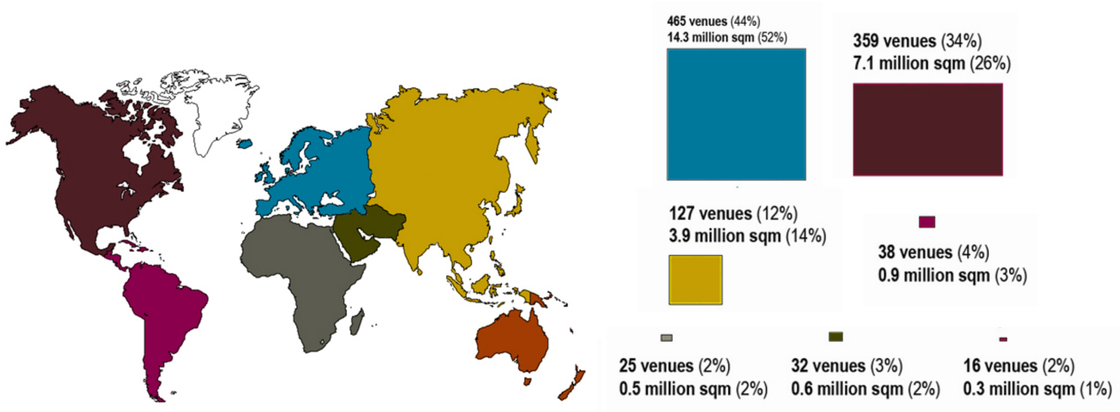


Figure 4.1 Percentage of venues in different areas of the world (CEIR, 2009)

Secondly, the time scale of this research is delimited from 1851 (the first World Exposition, the Great Exhibition in London) to 2010 (World Expo 2010 in Shanghai).

A simplified diagram of the research scope of this thesis is given below in Figure 4.2. The output of this thesis research is reflected in the environmental index of sustainability (energy flow, CO_2 emissions, and ecological footprint), and it is simultaneously considered both in exhibition-related environmental and economic aspects (e.g. income from exhibitions and exhibition-related industries). It is noted that the social or 'quality of life' assessment of the sustainability of exhibition activities is not included in this thesis, as its content is highly complex (Bell and Morse, 1999, p.17). This will be an area for further research as the meaning of quality of life as the main element of system quality is difficult to define, because this element as a key component of the concept of sustainability has many different definitions (Bell and Morse, 1999, p.17). From later considerations of sustainability, whether human quality of life should be included as a component within system quality is questionable (Jeffrey, 1996; Bell and Morse, 1999, p.17; Phillipps, 2006).

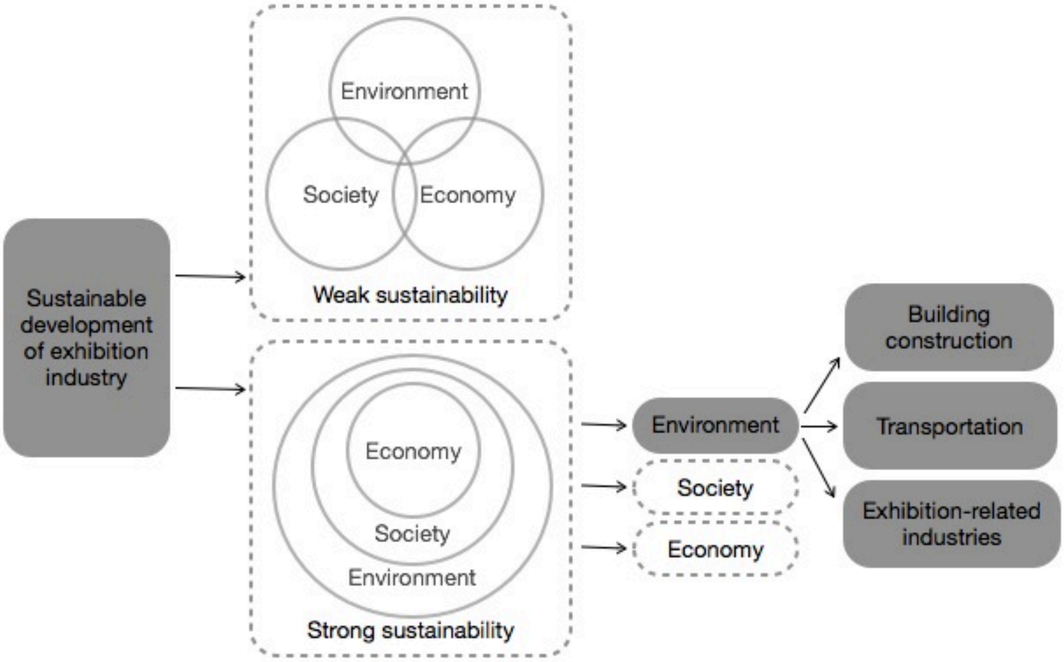


Figure 4.2 Diagram of the research scope

The concept of strong, as opposed to weak, sustainability puts the environment first, as without a functioning environment there can be no human society and no economy (discussed in Chapter 2). Therefore, the analysis and discussion of this thesis is established under the concept of strong sustainability. It means that minimising resource consumption for expositions is the first goal for reaching sustainability in this thesis, rather than the quality of life condition.

4.3 Objectives and hypothesis

In order to provide a greater understanding of the motivation behind assessment activities, the overall objectives of this research are to:

(a) Create an appropriate and specific methodology for assessing the environmental impacts generated from large-scale exhibitions at the national and international level, and fill the information gap found in environmental assessment study.

(b) Explore the real problems existing in the exhibition industry in terms of the environmental aspect and define what a real sustainable exposition and sustainable exhibition building are by comparing the environmental impact of different phases for building construction, different modes of transport, and exhibition-related industries.

(c) Seek the possibility of devising a sustainability indicator for the sustainable development of the exhibition industry, based on LCA and Ecological Footprint analysis. Help policy-makers and sponsors to understand the sustainability of exposition activities and measure their environmental impact, and give them suggestions or recommendations for the design principles of exhibitions and their associated buildings, and for reduction of the impacts from exhibition activities. Advise users how their life habits and choices impact on the natural environment.

More specifically, as discussed in the material reviewed and in previous chapters of this thesis, this research hypothesises that:

(a) The environmental impact of national and international exhibitions can be measured by a method integrating Life Cycle Analysis and Ecological Footprint Analysis.

(b) The exhibition industry does have large environmental impacts and these require concern in terms of infrastructure construction, transport modes, and exhibition-related economic benefits. The exhibition-related economic factor dominates, with the greatest impact on the environment, compared to the other factors.

4.4 Chapter conclusion

This chapter describes the focus of this research in terms of the three main research questions, research scope, and objectives and hypotheses. According to the research questions and research scope, the relevant research methodology and analysis boundary for specific assessment are explained in the next chapter. The objectives and hypotheses are given in Section 4.3. They will be demonstrated through four case studies as described in Chapters 6, 7, 8 and 9. This thesis establishes an analysis of four specific exhibition activities in different countries. The first case study is the Great Exhibition held in London, the UK, in 1851 (case study 1); the second case study is Expo 2000 in Hannover, Germany (case study 2); the other two of these four case studies are national exhibitions and Expo 2010, both located in Shanghai, China (case studies 3 and 4). They will be introduced in detailed in Section 5.2.3.

This thesis can be seen as the starting point for setting up a specific sustainability indicator and the conceptual system framework for sustainable exhibition management. It turns out that this sustainability indicator should be a simple and easily understood indicator to assess sustainability, which will have good acceptance from a wide range of stakeholders. This study makes a contribution as a reliable reference for setting up an indicator for events within reasonable boundaries.

Chapter 5 Methodology

This chapter describes the research methodology in three parts. Firstly, the system boundary and research phases for quantifying and evaluating the environmental impact of expositions are described and delimited in Section 5.1. Section 5.2 explains a mixed methods research approach (including Life Cycle Analysis and Ecological Footprint Analysis for the environmental assessment), which is used for achieving the research objectives and overcoming the limitations and systematic biases of one single method. The strengths and inadequacies of Life Cycle Analysis and Ecological Footprint Analysis are identified in this section. Furthermore, four selected case studies are introduced for the quantitative research in Section 5.3.

5.1 System boundary and research phases

It is vital to explain the system boundary for evaluation in this chapter, as the results and conclusions of the environmental assessment of expositions must be reliably drawn within the specific boundary. In addition, the three phases of the study are briefly described in Section 5.1.2.

5.1.1 System boundaries

1. Need for setting up the system boundary

A system boundary is usually applied to simplify the evaluation process, because all the inputs and outputs of an object to be assessed cannot be completely traced (Mithraratne et al, 2007, p. 24). This means that the system boundary of sustainability investigations serves to restrict the research content to what is relevant and significant and what is not, and the explicit system boundary can "tell us what is included and what is excluded and under what assumptions" (Maru and Woodford, 2007).

For this thesis, the development of the global exhibition industry does have direct and indirect environmental impacts (identified in Chapter 2). As a result, the environmental impact of expositions and international exhibitions needs to be accounted for within a reasonable research system boundary. The explicit boundary of this study provides an opportunity for exhibition organisers and a wider audience to judge or learn about the sustainability of expositions from specific perspectives. It can be seen that defining the boundaries for the collection of quantitative data is an important aspect in terms of whole life cycle environmental assessment. The reason for this is because the system boundary may influence data collection activities in all the categories.

2. Boundary for assessing the impacts generated by expositions

Although there are three dimensions of sustainability (environment, social, and economy), this thesis focuses on the environmental aspect in terms of the impact generated by expositions. This is partly because of the limited time for a PhD study, and more important is the fact the environmental dimension is the most significant and fundamental aspect among the three dimensions, as discussed in Chapter 2.

From the literature review, the common impacts of large-scale events (and expositions fall into this category) currently being studied include the impact of physical infrastructure, environment, economy, tourism and image, society, culture, policy, and urban renewal (Higher Education Academy, 2007). However, it needs to be noted that the boundary of this study is formed with the specific aim of analysing the most significant aspects of impacts in order to simplify the quantitative and evaluation process. It is impossible to estimate all the impacts from the events, as impacts will be quite possibly generated by some factors which cannot be quantified directly.

Generally, there are three main components which form the exhibition activities in expositions; these are physical infrastructure, visitors, and exhibitors (Figure 5.1). According to the characteristics of the three components, the impact on the environment from physical infrastructure comes particularly from energy and resource consumption, and the carbon footprint of the construction of exhibition buildings in their initial and recurring phases; the impact from visitors is mainly from resource usage of the exhibition including the buildings and the carbon emissions of people using these (operating energy for indoor heating, cooling, ventilating, and water usage), travel-related transportation, and waste; the environmental impact from exhibitors is generated from exhibition-related waste and increased production manufacture stemming from attending the exhibition activities.

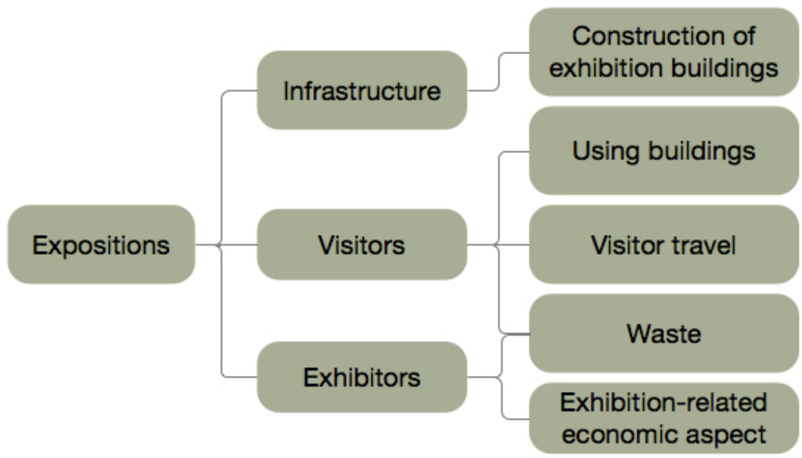


Figure 5.1 Diagram of the three main components of expositions

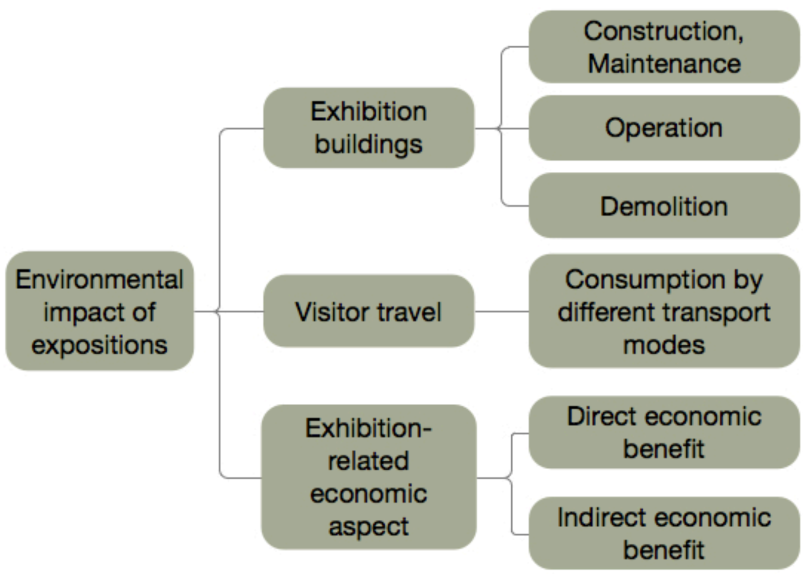


Figure 5.2 Diagram of system boundaries for the study in this thesis

Based on these components, the impacts estimated in this study are those which are generated from exhibition buildings, visitor related transportation, and more importantly the effect of the exhibition-related economic activity. The explicit system boundaries are illustrated in Figure 5.2. The boundary is defined more broadly than in conventional research of environmental assessment in terms of building construction, transportation, or events. For buildings, the boundary limits research to estimates of the energy and resource consumption in the construction, maintenance, operation, and demolition phases; for transportation, it means measure of the energy, carbon and ecological footprint generated from different modes of transportation used for visitor travel; the analysis of exhibition-related economic aspects is limited to the resource consumption of direct and indirect economic benefits from exhibition-related industries. Because of time limitations, the analysis of carbon footprint is just focused on visitor-related transportation to investigate and compare the effects of different transport modes using different types of fuel.

It is noted that the assessment of water consumption and the environmental impact from human waste or other exhibition-related wastes are not included in this research, as these will be likely to have a fairly small effect in the whole environmental impact of exposition activities, compared to the other aspects. Collins et al (2007) found that the total ecological footprint of waste (including the waste collected from the event venue, food and drink businesses, licensed mobile food operators, coach and car parks) generated from the FA Cup Final 2003/04 was 146 global hectares or 0.02gha/visitor. It accounted for approximately 4.8% of the total footprint for the whole event. From their study, the majority of waste came from food waste and food and drink packaging. Because of the difficulty of data collection as identified by Collins et al (2007) and the small environmental effect of water consumption at a major event, visitor water usage is excluded from the quantitative study in this thesis, but would be a topic for further investigation.

The system boundary of Life Cycle Analysis (its assessment method is introduced in detail in Section 5.2.1) has two possible scopes. One is “cradle to grave analysis”, which analyses the life cycle of a material or product from construction to disposal, including material extraction and processing, manufacture, transportation, product use, maintenance, disposal (Moore and Brunner, 1996; Mithraratne et al, 2007, p. 23). The other one is “cradle to cradle analysis”. This evaluates the whole life cycle impact of a material from construction to recycling process (as the source of a new product) (Mithraratne et al, 2007, p. 25). “Cradle to cradle analysis” is adopted in this research, as it covers most impacts. In particular it includes the process for the recycling of construction components, which is a necessary part of the investigation of the environmental impact of temporary exhibition buildings (McDonough and Braungart, 2003).

5.1.2 Research phases

The quantitative study for this thesis is divided into three phases (Table 5.1).

Phase 1 is to set up a target for each impact category for environmental weighting and data collection. For the chosen case studies, some of the relevant parameters, such as the size or weight of building components and distances of visitor travel using different transport modes, are measured from drawings or maps; the other data are sourced from literature although some reasonable assumptions have to be made. Assumptions, and the reasons for using them, are always fully explained.

Phase 2 is data classification, characterisation, and calculation. According to the inventory categories in terms of environmental implications, bills of quantity for building construction, transport modes, and exhibition-related industries are established and evaluated. The categories, data needed, and methods of calculation are shown in Table 5.1.

Phase 3 is data analysis and comparison. The results from the calculations of the four case studies will be analysed and compared. For example, the percentage of embodied energy of different materials will be analysed to evaluate the environmental impact of choosing different building materials for exhibition buildings. The average embodied energy per square metre of an exhibition building will be compared with other commercial buildings and other historic exhibition buildings. Further comparisons will be made between CO_2 emissions generated by visitor travel. Most importantly the calculation results will be compared to see which of the categories investigated has the largest environmental impact.

Three factors	Assessment items	Data needed	Method of calculation
Buildings	Initial embodied energy/m^2	Volume or weight of construction materials Embodied energy coefficients	Volume of different materials (m^3) × Embodied energy coefficient (GJ/m^3)
	Recurring embodied energy/m^2	Initial embodied energy Durability of construction materials	Initial embodied energy (GJ) of different materials × number of replacements
	Operating energy/m^2	Total construction area Energy consumption/m^2	Construction area (m^2) × Energy consumption/m^2 (kWh/m^2)
	Life-cycle energy/m^2	-	Embodied energy (GJ) + Operating energy (GJ)
	Ecological Footprint	Land energy conversion factor	Land equivalent environmental impact
Visitor travel	Embodied energy of infrastructure	Volume or weight of materials Embodied energy coefficients	Volume of different materials (m^3) × Embodied energy coefficient (GJ/m^3)
	CO_2 emissions for travel/ visitor	Number of visitors Distance of travel CO_2 emissions factor of various transport modes	Number of visitors × Distance of travel (km) × CO_2 emissions factor of various transport modes (t CO_2/ km)
	Ecological Footprint	Land energy conversion factor	Land equivalent environmental impact
Economy	Ecological Footprint of exhibits / visitor	Ecological Footprint factors Lists of exhibits, etc.	Types of exhibitors × Ecological Footprint factors
	Effects on local economy	Local GDP growth, Housing growth, Infrastructure creation	Converting monetary costs to Ecological Footprint
	Effects on international economy	GDP Forecasts + projections	Converting GDP growth to Ecological footprint

Table 5.1 Data collection and calculation

5.2 Mixed methods approach

A large number of methods and tools for the environmental assessment of the built environment have been exploited (Forsberg and Malmborg, 2004), such as energy use labelling or construction materials selection. Reijnders and van Roekel (1999) classify the current assessment tools into two groups: one group is qualitative tools based on scores and criteria, for example, LEED, BREEAM, and GBTool; the other is quantitative tools based on a physical life cycle consideration within material and energy accounting techniques (life cycle inventories or production data based on material or energy flows), such as Life Cycle Analysis, Ecological Footprint Analysis, and Material Flux Analysis.

Qualitative tools, such as LEED, are currently the most widespread tools used for environmental assessment (Lutzkendorf and Lorenz, 2006; Cole, 2010, p. 274). The main reason for this is because their assessment results can be easily obtained and applied for marketing purposes (Lutzkendorf and Lorenz, 2006). However, results assessed by these tools do not necessarily reflect the real resource flows and the actual environmental outputs (Lutzkendorf and Lorenz, 2006). For this reason, quantitative assessment tools have been increasingly given attention, although they have not been extensively applied to various objects (Forsberg and Malmborg, 2004). These tools quantify and evaluate energy or material flows of a production or development process in terms of environmental impact (Moore and Brunner, 1996). Kohler (2007, p. 348) explained that values of material and energy flows in terms of environmental impacts that can be represented in physical units by the quantitative approach, for example, GJ is the unit for energy consumption.

The quantitative method, therefore, is selected to evaluate the environmental impact of expositions in this thesis. This is because qualitatively based rating tools hide the real mass flows which have the greatest effect on the environment and "the specific environmental impact of one human being can enormously vary according to the society in which he lives" (Kohler, 1999). Kohler (1999) stressed that environmental assessment should be based on energy or material flows, so that the results assessed for buildings in different contexts can be compared during their life cycle.

Furthermore, empirical analysis is adopted by applying a mixed quantitative methods approach, including Life Cycle Analysis and Ecological Footprint Analysis, to four case studies in the thesis. The reason for adopting a mixed methods approach is given in Section 5.2.3. The detailed explanation of these two methods appears in the sections below.

5.2.1 Life Cycle Analysis

Life Cycle Analysis (LCA) (ISO 14040, 1997) is the quantitative assessment of materials, energy flows and waste discharges for every step of the life of a product, service or technology (Krozer and Vis, 1998, p.53; Chevalier and Le Teno, 1996, p. 488; Mithraratne et al, 2007, p. 23; Jurasovich, 2003, p.279). LCA as one of the most developed material accounting techniques has been generally adopted for research and practice purposes (Moore and Brunner, 1996). Normally, it can be used to quantify and evaluate all material, energy and related impacts (including ecological, human health, resource depletion, and social and aesthetic issues) of a large range of products and activities (Moore and Brunner, 1996; Blair et al, 2003; Mithraratne et al, 2007, p. 23).

Hobbs (1996) and Jaques (1998) state the four main objectives of the Life Cycle Analysis method as listed below:

- Compare alternative processes;
- Assess environmental impact;
- Improve resource efficiency and identify methods of reducing the impact;
- Be a source of information on resource use and emissions into the environment.

Life Cycle Analysis can identify the most significant aspects in the environmental impacts over the life cycle. In this research, LCA is applied to quantify and estimate the energy flows of exhibition buildings in case study events over their whole life cycle and compare the energy consumption of buildings in different phases of their lives. By these evaluations and comparisons, the most significant aspects of the impact generated from buildings can be identified and this can help policy-makers to reduce the related impacts.

The methodology of Life Cycle Analysis is composed of four steps, which are definition of goal and scope, inventory, impact assessment, and interpretation (Jönsson et al, 1996). “Definition of goal and scope” is used to determine the objectives of the analysis and the system boundaries. For this research, the need is to establish the simplified models of case study buildings by defining the system boundary, which is given in Section 5.1.2. In the “Inventory” step, the relevant data needs to be gathered, such as resource and energy use, so that the inputs and outputs of the research objects can be quantified and estimated over their life cycle. Relevant generic published data on materials and energy are used in this thesis. Even though generic data could change over time, using these data does not influence a comparative study (Mithraratne et al, 2007, p. 26). “Impact assessment” is the most complicated step, which consists of four stages, including classification, characterisation, weighting, and valuation. This step is to quantify the effects of the environmental burdens in terms of physical units, according to the built inventory. The last step of “Interpretation” tends to explain and evaluate assessment results for reducing the environmental impact. The diagram of the phases of Life Cycle Analysis is shown in Figure 5.3.

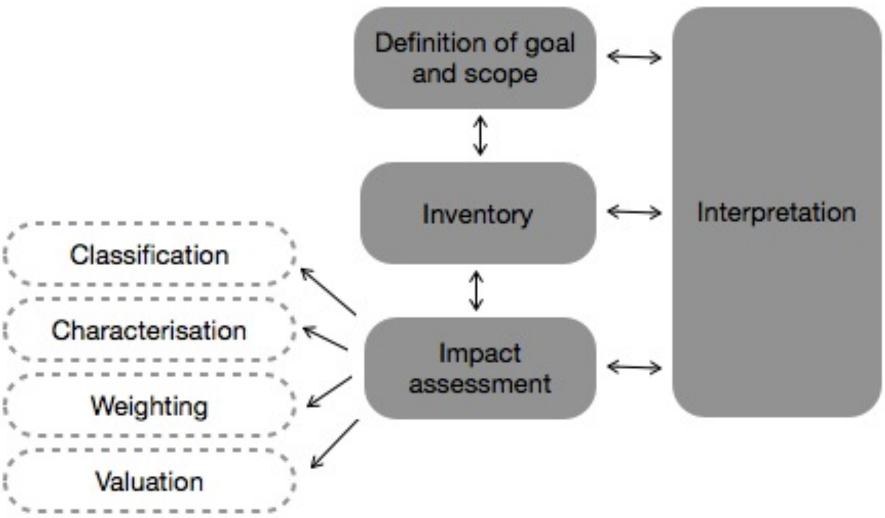


Figure 5.3 Phases of Life Cycle Analysis

The strength of Life Cycle Analysis is that it gives a comprehensive overview regarding the complex interactions between different processes within ecosystems and over extended timescales over the whole life cycle (Moore and Brunner, 1996; Blair et al, 2003).

In this thesis, Life Cycle Analysis is used to evaluate the energy consumption of exhibition buildings over their whole life cycle, which includes embodied energy, operating energy, and building demolition-related energy. Embodied energy is defined as “the total energy used to create a product including all the processes involved in harvesting, production, transportation and construction” (Mithraratne and Vale, 2007). In detail, the embodied energy of the building includes the energy consumed by the initial and recurring building processes. The operating energy is defined as the energy usage for the case study building in its operation phase, such as the electricity consumption for lighting, cooling and ventilation. The energy consumption from building demolition is assumed to be negligible in this study. The reason is because the demolition-related energy resulting from general public buildings is too small to be of significance (Camilleri *et al*. 2001.p.41). Thus, demolition-related energy and resource consumption is calculated as zero in this comparative study.

However, the results from LCA always involve data, model accuracy and completeness issues (Mithraratne et al, 2007, p. 28). These arise because of the often huge data collection requirements, possibly arbitrary methods for setting research scope, and because the ways of evaluating environmental impacts are frequently uncertain (Guinee et al, 1993). Although the results of LCA are not absolutely accurate because of the assumptions made, it is noted that this method, which performs as an assessment tool for quantifying the environmental impacts through the whole life cycle of objects based on comparative analysis, effectively helps in reducing the environmental burden and, by providing a tangible guideline, leads to more sustainable practices.

5.2.2 Ecological Footprint Analysis

Ecological Footprint Analysis is “an accounting tool that enables us to estimate the resource consumption and waste assimilation requirements of a defined human population or economy in terms of a corresponding productive land area” (Wackernagel and Rees, 1996, p.9). The method of Ecological Footprint Analysis originally proposed in the 1990s can be seen as a useful tool to assess the environmental impact of human behaviour and commercial events.

The ecological footprint is an aggregated indicator, which is similar to the method of using GDP to present the financial dimensions of the economy (Collins et al, 2007). In addition, the ecological footprint as an area-based (land or water) indicator is used to quantify the intensity of resource use and waste discharge activity related to ecological carrying capacity. In this thesis, the theory of Ecological Footprint Analysis is adopted to calculate the land area required for constructing and operating buildings, transportation, and exhibition-related economic aspects. The material accounting technique is applied to the calculations for different parts of the environmental impact of expositions. The energy value is converted to ecological footprint by using the factor of 100 GJ/gha (Vale and Vale, 2009).

The bottom-up approach to data collection for ecological footprint calculation, which is also called the “Component Model method” (Simmons and Chamber, 1998; Simmons et al, 2000), is selected for use in this thesis. The first reason for this is that this approach has been commonly accepted by researchers (Barrett, 2001; Chi and Brain, 2005). The second reason is because “the bottom-up” approach demonstrates considerable flexibility in its application (Moore et al, 2007) and is relatively easily used for environmental assessment of expositions.

The strength of Ecological Footprint Analysis is that it is conceptually related to the embodied energy analysis and corresponds closely to the definition of human impact on the environment (Blair et al, 2003, quoted in Rees, 2000). For this thesis, Ecological Footprint Analysis as a common assessment tool can simply and intuitively identify the impact of exhibition activities by means of quantifying land consumption. Ecological Footprint can also be seen as an excellent communication tool, because it is easily understood by different groups (Deutsch et al, 2000; Costanza, 2000; Blair et al, 2003). In addition, Ecological Footprint Analysis is useful in that it considers the principle of economics simultaneously with the carrying capacity (Rees, 2000). Although this land consumption method has received some criticisms, such as inaccurately demonstrating the impacts of human consumption (Ferng, 2002; Collins et al, 2007), it has become a common tool to help users understand the environmental impacts of human behaviour.

5.2.3 Mixed methods approach

In order to account for resource use and the resulting environmental impacts generated from exhibition buildings (over the construction, use, and demolition phases), different transport modes for visitor travel, and the exhibition-related economic aspect, the assessment method is required to cover all these aspects over the whole life cycle and needs to be able to quantify various resource and energy uses at different times.

Due to this consideration, a mixed methods approach is applied in this research. The mixed assessment methods approach includes the Life Cycle Analysis and the Ecological Footprint Analysis for evaluating energy consumption, carbon footprint and ecological footprint of buildings, visitor travel, and exhibition-related economic aspect. Use of the mixed methods approach is because single indicators lack a means of integration (discussed in Chapter 2). These two methods are chosen because the limitations inherent in each could be compensated by the other. For example, the Ecological Footprint indicator suffers from lack of a research scope for determining flows of specific products or processes (Ayres, 2001). This problem can be supplemented by Life Cycle Analysis. Secondly, the macro-economic effect generated from expositions cannot be directly measured by Life Cycle Analysis, but it can be done by using the Ecological Footprint indicator. These two methods also have compatibility in that they are both based on the concept of strong sustainability. The detailed benefits of using these two methods are described below.

The LCA method is the broadest indicator, as it provides a comprehensive assessment over the whole life cycle of a product. The flows of energy and materials in Life Cycle Analysis are accounted for at each stage in the whole life cycle (IEA, 2001). The IEA (2001) identified that “LCA as a rigorous accounting tool reconciles physical interactions between buildings and other elements of the environmental framework”. Life Cycle Analysis therefore helps to determine the importance of life cycle stages for buildings, transportation, and exhibition-related industries and may avoid unnecessary data collection activities.

Ecological Footprint Analysis does not require extensive data (Blair et al, 2003) and it is good at establishing a first approximation of the resource consumption of a product. The exhibition-related economic aspect can be measured as an approximate value by using generic data in a comparative analysis.

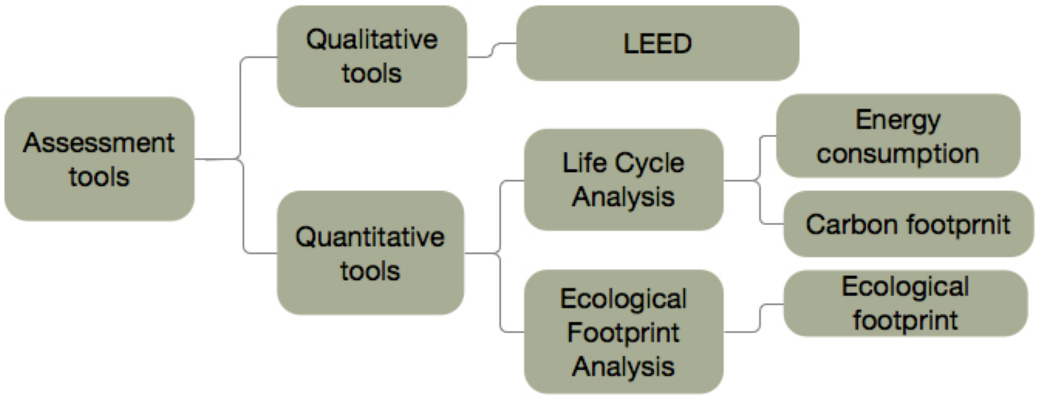


Figure 5.4 Diagram of the method used in this thesis

However, there are limitations with applying these two methods. The material evaluation accounting methods require huge data for their support (Blair et al, 2003). As a result, many assumptions or large scale surveys may be involved in the estimation. The need for a lot of data and hence assumptions is also the typical weakness in Life Cycle Analysis, which means “the result may be heavily dependent on particular assumptions used” (Mithraratne et al, 2007, p. 28). The evaluated results can be discussed however by using sensitivity analysis.

5.3 Selection of case studies

As the greatest number of exhibition activities are held in Germany, China, and European countries, four case study events and related exhibition buildings are selected from London (the UK), Hannover (Germany), and Shanghai (China). Appendix E lists some example exhibition buildings located in different countries from 1851 to 2010. It shows the similarity of design concept, structure, and materials of exhibition building construction relative to the four selected case study buildings from 1851 to 2010. It is impossible to put all examples studied to ensure the case studies are representative in this appendix.

The selected case studies are the Great Exhibition of 1851 (Crystal Palace, 1851~1936), Shanghai National Exhibitions (Shanghai Exhibition Centre, 1955~2011), Expo 2000 (Dutch Pavilion, 2000), and Expo 2010 (Theme Pavilion, 2010~2011). The results from assessment will be analysed by comparative study and the reasons for selection of these case studies are explained below.

These case studies, events and related buildings, are typical and representative (as described in sections 5.3.1~5.3.4). They are delimited by using the criteria of large-scale exhibitions and the research boundary. In this section, the main similarities and differences of the chosen four case studies are summarised, in order to generalise the findings for designing sustainable expositions. The different aspects are used as points of comparison and to form the conclusions.

First of all, these four events can be classified as large-scale exhibitions, because they have reached the two main factors of the criteria (Figure 5.5). One is the number of visitors attending was more than 5,000,000, and secondly, the floor areas of the main exhibition buildings were larger than 5,000 m^2 (CAST, 2007).

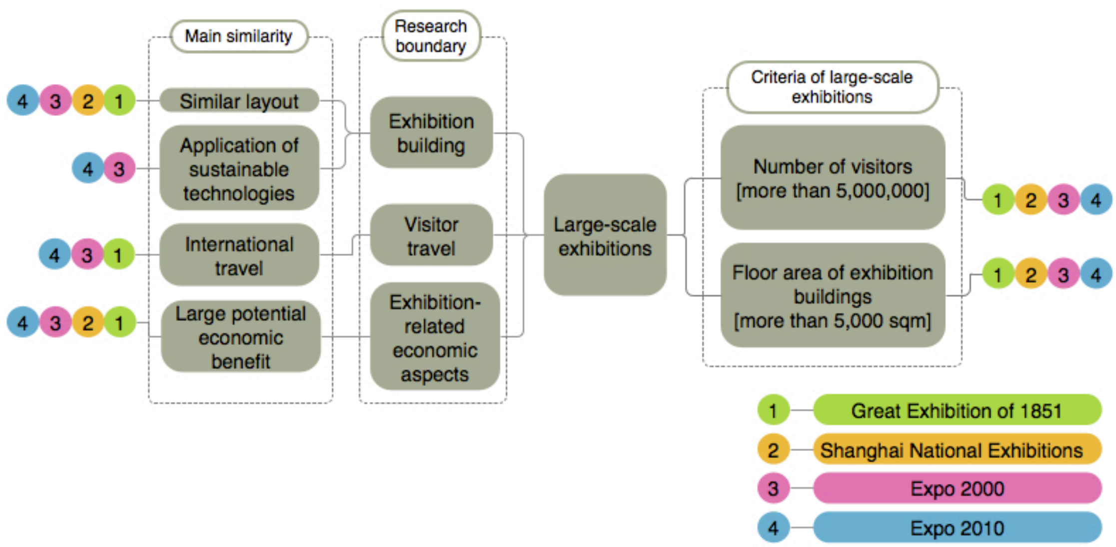


Figure 5.5 Diagram of main similarities of four case studies

Furthermore, the four case studies are selected in terms of buildings, visitor travel, and exhibition-related economic aspects, which are the main factors for environmental assessment focused on in this research.

The four case study buildings were designed with a similar layout (large column-free spaces linked by service spaces). Although the detailed design of the layouts of these buildings were different, this will not obstruct comparative analysis, as the calculated results will be compared by the units of average energy and resource consumption. The four buildings were constructed at different times and with different structures (Table 5.2). This choice is to allow exploration of the development of energy efficient building construction and operation and the difference between a heavy weight building and a light weight one. The useful life of the four buildings is estimated both over their actual life and over an assumed useful life of 50 years. Two modern exhibition buildings were designed with the application of similar sustainable technologies (using renewable energy), and their results can be compared to the other two case study buildings without sustainable considerations.

Case study buildings	**Construction (year)**	**Useful life**		**Structure**
		Actual	Assumed	
Crystal Palace	1851	82.5 years	50 years	Metal
Shanghai Exhibition Centre	1955	56 years	50 years	Concrete
Dutch Pavilion	2000	5 months	50 years	Hybrid (metal and concrete)
Theme Pavilion	2010	13 months	50 years	Metal

Table 5.2 Case study buildings

In terms of energy consumption as part of the building performance of the four selected cases, the heating and cooling degree days (at 18 degrees Celsius for heating degree days and 24 degrees Celsius for cooling degree days) for the three cities of London, Shanghai, and Hannover, in 2010, are shown in Table 5.3. This shows that the results of the energy analysis of these four exhibition buildings can be considered as comparable, because they were constructed and operated under roughly similar climatic conditions, assuming they were heated and cooled to achieve similar internal conditions.

2010	London	Shanghai	Hannover
Heating degree days	2,710	1,807	3,340
Cooling degree days	8	407	16
Degree days	2,718	2,214	3,356

Table 5.3 Heating and cooling degree days for three cities (BizEE, 2010)

For visitor travel, three international events will be investigated. This is to compare the average energy and resource consumption of visitors from the local area to that of visitors from overseas. In addition, different levels of operating energy consumption generated from different transport modes, which is related to passenger travel opportunities in different cities and countries, will be the focus.

For exhibition-related economic aspects, four case studies are investigated that have generated great economic benefits for the host cities. The average resource consumption per visitor of each case study will be compared.

Thus, these case studies will be analysed in terms of energy flows and resource consumption for buildings, visitor travel, and exhibition-related economic effect. The following sections give a brief description of each selected case study and the reasons behind each selection. One important reason for all selections is the availability of appropriate data.

5.3.1 Historic case study: the Great Exhibition, 1851~1936

The Great Exhibition of 1851 is selected, as it was the first world exposition and had a great influence at the international level. From the end of the 18th Century, a series of Industrial Exhibitions at national level had become popular in France (Wesemael, 2001, p.63). The increasing economic and political profits generated from these exhibitions soon became the focus of attention for many other European countries. The UK government was aware of the phenomenon and was keen to take advantage of it. The government sponsored and organised the Great Exhibition in London in1851, drawing products from all over the world.

The Crystal Palace was the first large glass and iron pre-fabricated building of ‘modular’ form to be moved to a different site (Bird, 1976). The building process of the

Crystal Palace included conception, fabrication, shipment, assembly, dismantling, and reuse (McKean, 1994, p.22). The detailed environmental design of the Crystal Palace was considered by Joseph Paxton and the industrial designer Henry Cole (Bonython and Burton, 2003). For the 1851 building they considered lighting, solar control, ventilation, and cooling. Heating was only incorporated when the Crystal Palace was dismantled and moved to Sydenham following the closing of the Great Exhibition, which ran in summer only, in Hyde Park (Schoenefeldt, 2008b). This building effectively represented the earliest attempt to design an interior environment for a major exhibition building.

For this case study, energy and resource consumption of the historic building, transportation modes, and exhibition-related economic effect will be quantified by their footprints during the whole of their life cycle. This is to see how they performed in terms of sustainable design and to estimate whether, in comparison with this nineteenth century example, modern technologies really achieve ecological improvement.

5.3.2 Conventional case study: Exhibition activities at the Shanghai Exhibition Centre between 1955~2011

The second case study, the Shanghai Exhibition Centre, is chosen as being typical of buildings for conventional exhibitions. The main reason for choosing this exhibition building is that it represents well the characteristics of an exhibition building which has been used continually for holding a series of popular national exhibitions.

The Shanghai Exhibition Centre was built in 1955 to Russian design and renovated in 2001. Although it was built half a century ago, its structure and materials can serve as a typical example representing this type of public building in a humid subtropical climate in Eastern Asia. On average, this building hosts 7,500,000 visitors annually (see section 7.1), which is more than for most other exhibition buildings in western countries. It can be assumed therefore that this case study building might consume more energy for visitor travel at the city scale than other examples with fewer visitors and this can help in investigating the environmental impact generated by human behaviour. The large-scale national exhibition activities have also potentially increased total GDP in 2008 (detailed calculation in Chapter 7). The quantitative research will be given in terms of the building, visitor travel, and economic effect.

5.3.3 Modern sustainable case study 1: Dutch participation at Expo 2000

World Expo 2000 in Germany is selected as the first modern event case study in this thesis. Due to the lack of data for estimating energy and resource consumption of all the paticipating countries and visitors, The Netherlands, as a typical participating country, is selected for study in detail.

The first reason for the selection is because the Dutch Pavilion, as one of the most popular pavilions in Expo 2000, was a showcase for its sustainable design and construction. It was designed as the exhibition hall of The Netherlands for World Expo 2000 in Germany. The design concept followed the EXPO 2000 theme of Humanity – Nature – Technique. In addition, initial research undertaken for the thesis shows that the exhibition-related economic effect for The Netherlands from the Dutch Pavilion in Expo 2000 in Germany is extremely positive. It has been estimated there was € 350 million in revenue for the Dutch economy generated from the Dutch Pavilion at Expo 2000 (Walvis, 2009). Since the total revenue of The Netherlands in 2000 was € 173 billion, the Expo revenue accounted for approximately 0.2% of total national revenue in 2000. This shows that The Netherlands gained significant economic profit from this exhibition. All this additional economic activity leads to national growth, which in turn impacts on the environment because of the resources consumed.

This case study is mainly concerned with the energy intensity and ecological footprint of a sustainable exhibition building (the Dutch Pavilion), visitor travel, and exhibition-related economic effect.

5.3.4 Modern sustainable case study 2: The Theme Pavilion and Expo 2010 in Shanghai

For study of a modern sustainable event and exhibition building, World Exposition 2010 and the Theme Pavilion, as the biggest and main exhibition hall in this exposition, are selected and quantified in this thesis in Chapter 9. This world exposition closed in

Shanghai, China, on October 31, 2010. It generated a very large number of visitors who travelled from local and international origins to the site of the exposition and who also potentially increased the income of exhibition-related industries.

The theme pavilion was built as a permenent exhibition building in the central area of the exposition, using many high-tech sustainable technologies, such as solar panels. The western hall (Hall 1) of the Theme Pavilion is built as a column-free space of 22,680 m^2, which has been described as the biggest column-free hall in the Asian area built so far (BCSWE, 2011). For this case study, energy consumption and ecological footprint of the sustainable building, transportation, and exhibition-related economic aspect will be quantified and analysed, as shown in Chapter 9.

5.4 Chapter conclusion

This chapter describes the two assessment methods of Life Cycle Analysis and Ecological Footprint and the need in this study for mixing these methods in order to overcome the limitations of both. The system boundary and research phases for quantitative assessment and subsequent evaluation are described and together form the research scope. In addition, the chapter introduces the four selected exhibition events, the Great Exhibition of 1851, Shanghai National Exhibitions, Expo 2000, and Expo 2010 and explains the reasons for selection.

Chapter 6 Historic case study: the Great Exhibition; the Crystal Palace, 1851~1936

6.1 Introduction

The energy and resource consumption of the Great Exhibition of 1851, held in the Crystal Place, London, UK, are quantified as a historic case study in this chapter. Quantification includes the energy and resource consumption of the Crystal Palace, visitor travel to the Great Exhibition, and exhibition-related economic aspects (the research boundary has been explained in section 5.1). The reason for selecting this particular world exposition for investigation was provided in section 5.3.

For the international activity of the Great Exhibition, an amazing and innovative glass and iron exhibition building, the Crystal Palace (Figure 6.1), was constructed in Hyde Park in 1851 and re-erected in Sydenham in 1854. The total usable floor area after the move was 138,000 square metres on three storeys. Transportation for visitor travel included walking, riding horses, taking streamships, and taking steam trains, so it was very different from modern travelling. Railways and steam trains were the new technologies that had been introduced into London and that were vital for holding the Great Exhibition. The railways were also one of the main factors that led to stimulation of the local economy in the 1850s (explained in detail in section 6.2.3).

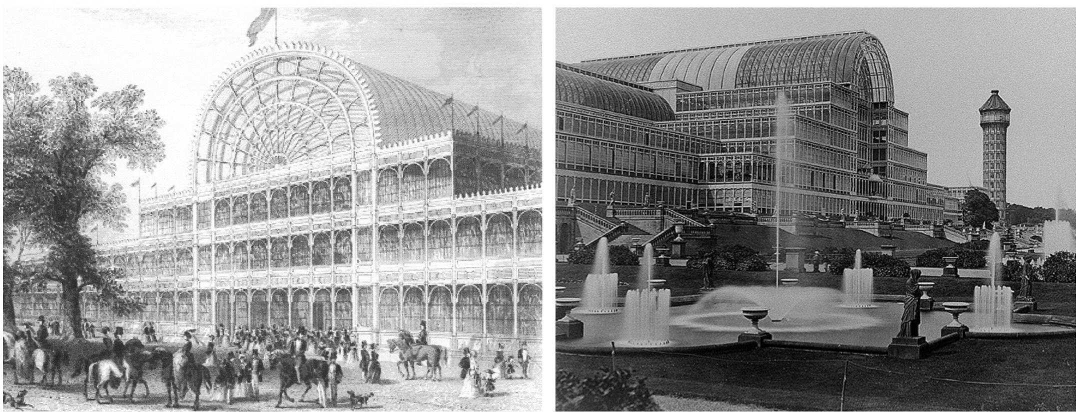


Figure 6.1 Crystal Palace at Hyde Park and Sydenham (Lienhard, 1997; Burck, 2010)

The method of quantitative work, results, and related analysis of this historic case study are described and demonstrated in the following sections.

6.2 Method

This section explains the detailed methods for quantifying the whole life cycle energy and resource consumption of the historic case study, consisting of the Crystal Palace itself (6.2.1), visitor travel (6.2.2), and exhibition-related economic aspects (6.2.3).

6.2.1 Building

Energy consumption of the Crystal Palace comprises the embodied energy (6.2.1.1), operating energy (6.2.1.2), and building demolition-related energy (6.2.1.3). The definition of these types of energy usage has been outlined in Chapter 5.

6.2.1.1 Embodied energy

The Hyde Park Crystal Palace was finished in 1851, and had a total usable floor area of 92,000 m^2 on three storeys. After the Great Exhibition, it had to be moved from Hyde Park and was rebuilt in a modified form in Sydenham in 1852. Musgrave (1995, p.11) states that in the move "the simple three-storied building grew into a complex five-storied one with a total floor area of nearly half as much again as the original", which means the total floor area of the Sydenham Crystal Palace was increased to 138,000 m^2 by 1854. The original building components were reused in the construction of the Sydenham Crystal Palace (Phillips et al, 1860).

Furthermore, all the elements of this original building were produced using the four basic materials of glass, iron, wood and concrete (detailed information for the Hyde Park and the Sydenham Crystal Palace is shown in Table 6.1).

1. Glass

Glass was used for the skin of the building. Information from ***1851 and the Crystal Palace*** and ***The glass house*** show that Charles Fox and his subcontractors required 900,000 ft^2 (83,612 m^2) of glass for the original building (Hobhouse, 1950, p39; Hix, 1974, p135). The total weight of glass in the Hyde Park Crystal Palace was 408 t[1].

2. Iron

Iron was used for columns, girders, underground pipes, roof trusses, metal louvres and the connection collars on each column. Hobhouse (1950, p 39) states that "There were 3,300 iron columns and 2,224 girders in all". It has been assumed for this research that all the iron elements were reused in the Sydenham Crystal Palace.

Each column was inserted into a "vase" as it was erected, which connected it with a pipe in the base. There were 1,060 columns in each tier, at intervals of 24 ft (7.5 m) each way (Hobhouse, 1950, p44). For this analysis, each column has been assumed to be 0.3m in diameter, with a wall thickness of 0.05 m, and to be 4.4 ~ 6 m in height. The total weight of the 3300 iron columns was 2,669 t. The micro-constituents present, the composition, and temperature determine the density values for the various types of cast iron. For example, the densities of gray iron castings are from 7.0 g/cm^3 (high-carbon irons) to 7.3 g/cm^3 (low-carbon irons). Ductile iron's density changes from 7.1 g/cm^3 to 7.4 g/cm^3 according to its carbon content. Thus, it can be assumed that the average density of cast iron is 7.2g/cm^3 (=7,200 kg/m^3) (Davis, 1996). The underground pipes, with a total length of thirty-four miles (55 km), were to carry the rain-water away from the columns (Hobhouse, 1950, p43-44). The pipes were 6 inch (0.15 m) diameter (McKean, 1994, p23) with an assumed wall thickness of 0.01 m. Their total weight of 906 t can be calculated on the same basis as the assumptions for the density of cast iron. All the girders were prefabricated before delivery and installation. Girders were a standardized length because all the columns had the same outer diameter (Hix, 1974, p136). Hix (1974, p139) also states that the largest 24 ft girder weighed under a tonne. The depth of the majority of the spanning girders was a consistent 3 ft (0.9 m). However, the depth was increased to 6 ft (1.8 m) where they

[1] Metric tonnes have been used throughout the thesis.

crossed the nave (Hix, 1974, p137). The weights of the two types of girders are assumed here to be 500 kg and 1,000 kg (based on the assumptions of volume and density of iron). Furthermore, Hix (1974, p139) states that "A 3 ft (0.9 m) band of louvred ventilation ran around each tier at the top of the wall." There are 5 separate louvres in one band (0.9 m height in all). Thus, it is assumed that the size of each louvre, which was made from galvanized sheet iron, is 0.2 m high, 2.4 m long and 0.001 m thick. The total circumference over three levels is calculated as 4,104 m. Therefore, the total weight of these metal louvres running round the building at each of three levels is 30t. Moreover, there was also a band of louvred ventilation at ground level on the ground floor. The whole system on the ground floor level was operated by a series of wheels, rods and gears, enabling an operator to open or close a 108 ft (33 m) length of metal louvres on each side of the mechanism (Hix, 1974, p139). Each item is assumed to be 0.2 m high and 0.001m wide giving a weight for the ground floor louvres of 10 t. The total weight of all the louvres is 40 t.

Another metal element was the tension reinforcement of the composite roof trusses. Generally there were 3 such trusses installed in each bay. The assumed sizes for each principal truss tension member are 30mm diameter and 7.5m long. Based on this, the roof trusses contain 565 t of iron. The other main metal elements were the cast iron connection collars. A 3 ft (0.9 m) connection collar with its cast-iron connecting-lip was bolted on top of columns at each floor level and at roof level (Hix, 1974, p136). The number of connection collars is, therefore, 3,300 (the same as the number of columns) and the diameter and thickness of the collars are assumed to be the same as for the columns. Thus, the total weight of the connection collars is 469 t.

3. Wood

Wood was mainly utilised for interior walls, beams, floor, "Paxton gutter" and sash-bars. Some of the timbers used in the beams and floors came from the site fencing during the construction phase (Hobhouse, 1950, p43). Hix (1974, p135) states that the building had 372 roof trusses, 24 miles (38.6 km) of Paxton gutter, 205 miles (330 km) of sash bar and 600,000 ft^3 (16,990 m^3) of timber in total. The total weight of timber used in the building is assumed as 8,495 t, which is calculated by multiplying the total volume by the average density of pine which is 500 kg/m^3 (Simetric, 2009).

In detail, the timber used for the main elements, such as floors, interior walls, beams, roof trusses, Paxton gutters, sash-bars and barrel vault segments can be calculated in a different way. Each structural bay on the exterior walls uses 2 timber columns with light cast iron bases and 33 wooden floorboards for the floor. Each bay, therefore, consumed 2.86 m^3 of timber which is equal to 1,430 kg. There are 1,256 bays in the ground level, 626 in the first floor level and 146 bays in the second level. The total weight of wood used, based on the bays, is, therefore, 2,900 t. Furthermore, each Paxton gutter is 5 inches (0.13 m) wide and 6 inches (0.15 m) high. Therefore, 24 miles (38.6 m) represents 449 t of timber. To calculate the volume of the sash bars, their assumed cross section is 0.01m^2. This means the 205 miles (330 km) of sash bars amount to 1,650 t. The barrel vault segments made from laminated timber that sat over the nave are assumed to have had a height of 0.3 m and a thickness of 0.45m. These timber arches crossed a 72 ft column-free space giving them a diameter at the base of 22 m. Each arch is 900 mm deep and 450 mm thick. The total length of each arch is 35 m, (based on half a circle of 22 m diameter) so the volume of one arch is 35 x 0.9 x .0.45 = 14.2 m^3. If the density of timber is 500 kg/m^3, the weight of one arch will be 7.1 tonnes. If there are 18 arches, total weight will be 128 tonnes. These known components add up to a combined weight of 5127 t, which is less than the first estimation. However, the rest of the timbers were used for making internal walls, roof trusses and enclosure, for which the size and weight of each element are unknown. In this study, the total weight (8,495 t) is, therefore, applied to the calculation of timber components, which accounts for timber lost during the machining of the components, and avoids an underestimate.

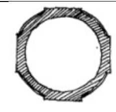
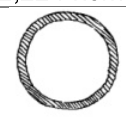
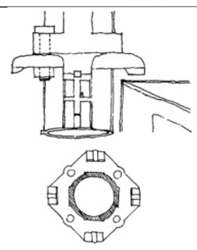
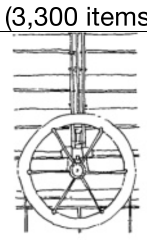
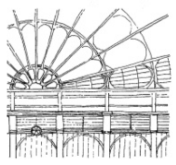
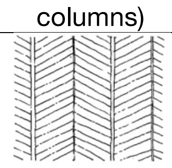
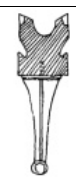
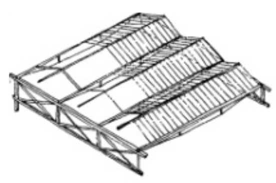
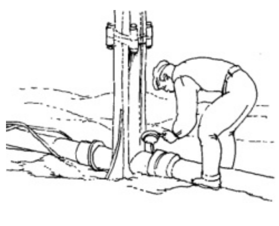
Furthermore, the amount of wood used in the structure of the Sydenham Crystal Palace decreased (Hix, 1974, p142 -144). Most of the arches there were of lattice iron work, not of laminated wood, as at Hyde Park. Many of the wood infill panels had been replaced with glass on the lower floors. For simplification, here it is assumed all the original wooden elements were reused in the Sydenham Crystal Palace and the additional materials for the expanded building were of iron and glass.

4. Concrete

Concrete was used for the foundations. The footing for each column has been taken as 3 ft (0.9 m) high, and 2 ft (0.6 m) square (Hix, 1974, p137). The volume of each footing was therefore 0.32 m^3. There were 702 columns on the ground floor for the Crystal Palace in Hyde Park. The density of concrete is 2400 kg/m^3 (Glenn, 1999). Thus, the total weight of concrete used was 539 t.

For the Crystal Palace, its embodied energy (initial and recurring embodied energy) relates to the fuel used by the manufacturing industry of the time, such as the coal used in the process of manufacturing iron. The useful life of the Crystal Palace was from 1851-1852 and 1854-1936, making 82.5 years in total.

To simplify the process of calculation, the total embodied energy of the Crystal Palace will not include the energy embodied in the interior and exterior decoration, except the painting of construction materials. Paint is a very high embodied energy material, and presumably the Crystal Palace structure had to be painted externally on a fairly regular basis (every five years) to keep corrosion away from the iron and to protect the wood. Therefore the embodied energy of the paint could be quite important over the life of the building. For example, the total volume of timber used in the Hyde Park Crystal Palace is 16,990 m^3. It is assumed that the average volume of each element is 1 m^3, and its surface area will be 6 m^2, which means the total surface area for painting of timber elements is 101,940 m^2. For the Sydenham Crystal Palace, the reused wooden elements from the Hyde Park Crystal Palace are assumed to be repainted 16 times (see Appendix A) in the 82 years of its useful life. The total lifetime equivalent area (inside and out) for painting of the timber elements of the Sydenham Crystal Palace is therefore 1,631,040 m^2. The detailed surface areas for painting and repainting the reused and new iron elements in the two Crystal Palaces are shown in Table 6.23.

Materials and Building elements		Size ($_A$=assumption)	The Hyde Park Crystal Palace (1851)		The Sydenham Crystal Palace (1854-1936)			Total weight (t)
			Weight (t)		Additional weight (t)			
GLASS	Main building		16 oz/piece	408	Partly reused	21 oz/ piece (6.3 kg/ m^2 (Varghese, 2005, p.140)) New structure nearly doubled the glass area of the original	527	935
GLASS	Colonnade	-	From the end of the south wing to the Railway station	-	New	30,000 superficial feet (Phillips et al, 1860).	18	18
IRON	Column	Height: 4.4-6m, Diameter: 0.3m $_A$ Thickness: 0.05 m $_A$	 (3,300 items)	2,669	Reused	The total weight of iron used in the main building and wings amounts to 9641 tonnes, 17 cwts., 1 quarter (Phillips et al, 1860). The hot water systems combined with the special boilers for the plants had nearly fifty miles of pipe. This extra heating added greatly to the operational cost when compared to the unheated Hyde Park palace (Hix, 1974, p.142 -144). The boiler-houses erected in the basement story contain 22 boilers, each holding 11,000 gallons of water (Crystal Palace, 2009).	3,324	9,641
IRON	Girders	Total height: 7.3 m Total length: 0.91 m Total width: 0.1 m	 (2,224 items)	1,668				
IRON	Pipes (underground)	Length: 54,718m Diameter: 0.15m $_A$ Thickness: 0.01m $_A$		906				
IRON	Connection collar	Height: 1m Diameter: 0.3m $_A$ Thickness: 0.05m $_A$	 (3,300 items)	469				
IRON	Metal louvres	Each louvre: Length: 2.4m Height: 0.2m Width: 0.001m $_A$	  (15 items between two columns)	40				
IRON	Tension reinforcement of composite roof trusses	Length: 7.3m, Diameter: 30mm *	 (4,290 items)	565				
IRON	Boilers	-	-	-	New			
IRON	Colonnade	-	-	-	New	The quantity of iron employed in this covered passage is 60 tonnes (Phillips et al, 1860)	60	60
WOOD	Floors, interior walls, beams, roof trusses, Paxton gutter, sash bars and barrel vault segments	16,990 m^3	 	8,495	Reused	The amount of wood used in the structure had been decreased (Hix, 1974, p.142 -144). Most of the arches were of lattice iron work, not of laminated wood, as at Hyde Park. Many of the wood infill panels had been replaced with glass on the lower floors.	0	8,495
CONCRETE	Foundations (footing)	Length, width: 0.6 m Height: 0.9 m		539	New	15,391 cubic yards (Phillips et al, 1860)	719	1,258
BRICK	Foundations	-	-	-	New	The amount of brick-work in the main building and wings is 15,391 cubic yards (= 11,767 m^3) (Brick=1.3t/m^3)	15,297	15,297

*This figure comes from two types of trusses

Table 6.1 Generated quantities of materials in building from literature

The assessment of initial and recurring embodied energy for building materials is taken from the quantities of construction materials (the amount of volume or weight of materials discussed in the last section). Some relevant parameters, such as the size or weight of components, are sourced from literature. The total embodied energy is calculated by multiplying the embodied energy coefficients with the weight of materials respectively. The energy intensities used are UK data from Hammond and Jones's research (Hammond et al., 2008). This was a meta study, and included all available data, so does not just represent the most modern coefficients. Although the embodied energy coefficients applied to the calculation of the case study building are from recent research in the UK, the factors have not changed very much, at least not recently, according to study and comparisons of the energy intensity from the UK and other countries in the last two decades (Table 6.2), despite the fact that the energy mix of the countries is different.

	Australia (MJ/kg) (Lawson, 1996)	**New Zealand (MJ/kg) (Alcorn, 2003)**	**UK(MJ/kg) (Hammond, 2008)**	**Germany (MJ/kg) (Anon, 1994)**
Kiln dried sawn softwood	**3.4**	**2.5**	**1.6**	**1.5**
Particleboard	**8.0**	**8.0**	**9.5**	**5.7**
MDF	**11.3**	**11.9**	**11**	**10.5**
Gypsum plaster	**2.9**	**4.5**	**1.8**	**2.5**
Plasterboard	**4.4**	**6.1**	**6.8**	**3.4~8.5**
Fibre cement	**4.8**	**9.5**	**10.9**	**5.3**
Cement	**5.6**	**7.8**	**4.6**	**4.4**
Precast steam-cured concrete	**2.0**	**2.0**	**2.0**	**2.5**
Clay bricks	**2.5**	**0.1**	**3.0**	**2.2**
Concrete blocks	**1.5**	**0.9**	**0.6***	**0.6~0.8**
Glass	**12.7**	**15.9**	**15.0**	**15.0**

*8MPa concrete block

Table 6.2 Embodied energy coefficients of selected materials in different countries

For example New Zealand has a much higher percentage of renewable energy in total energy mix than the UK (see Table 7.2 in Chapter 7). The other reason for using modern embodied energy data is because many industrial goods were made by hand during the mid-nineteenth century meaning that energy consumption should be lower than now. However, much of the energy for most industries depended on coal at that time, which might result in higher values than those for modern manufacturing. These factors are assumed to balance each other, meaning that the assumption of the energy coefficients for the case study building is reasonable as a starting point.

6.2.1.2 Operating energy

Operating energy for buildings normally includes the energy usage for lighting, heating, cooling, ventilation and air conditioning systems. However, the Hyde Park Crystal Palace achieved almost zero energy consumption in its operating phase. There was no artificial lighting, heating, cooling and ventilation in the building. The internal lighting entirely depended on the natural light through the wholly transparent external materials. The exhibition opened only during the hours of day light. Using glass was satisfactory for the main function of the building, and shows an alternative way to physically reduce energy usage through design and timetabling. Furthermore, the cooling and ventilation systems were elaborately designed to work on the natural buoyancy of air, and they were operated mechanically by hand. To reduce the anticipated high interior temperatures, Paxton designed a series of metal ventilation louvres, installed in every storey. Moreover, there were no heating appliances for the building, because the Great Exhibition was held during the warmer season from May to October.

The Sydenham Crystal Palace was intended to be open all year round, so the designer, Paxton, added a heating system in the basement which was composed of pipes and coal-fired boilers. It was made up from 22 boilers and associated pipe work, each boiler holding 11,000 gallons (42m^3) of water (Crystal Palace, 2009). This extra heating added greatly to the operational cost when compared to the unheated Hyde Park building (Hix, 1974, p142 ~ 144). To estimate the likely energy consumption the use of energy for heating commercial glasshouses was examined. Cock and Lierde (1997) report that the total primary energy usage (including electricity) of heating winter glasshouses was 22,990 PJ in Belgium in 1997, which equals 1.12 GJ/m^2/year. Another study shows that the average annual energy required to maintain 20 degrees Celsius by day and 16 degrees Celsius by night for a glasshouse in London was 2.2 ~ 2.4 GJ GJ/m^2/year from 1961 to 1980 (Wass and Barrie, 1984). In addition, Nederhoff and Houter (2007) reported that a glasshouse needs 1.077 GJ/m^2/year in the Auckland region of New Zealand, and 1.573 GJ/m^2/year in

Christchurch for temperature control (20 degrees Celsius at day and 18 degrees Celsius at night). They also found adding additional energy for aspects such as humidity control, CO_2 enrichment and a coal boiler, the total energy consumption would come to 1.3~1.4 GJ/m^2/year for the greenhouse in Auckland, and 2.0 ~2.1 GJ/m^2/year for Christchurch. It is assumed that there was no energy used for humidity control, and CO_2 enrichment at the Sydenham Crystal Palace. The selected unit energy usage is that of the Belgium study (1.12 GJ/m^2/year) because of its wide scope and similar climate, and this is applied when calculating the operating energy of the case study building after its removal to Sydenham.

6.2.1.3 Building demolition-related energy

The assessment of energy usage for building demolition is commonly ignored, because it accounts for a very small percentage of the total energy consumption in a building's whole life cycle (Camilleri and Jaques, 2001, p.41). For the case study building, the Hyde Park Crystal Palace was dismantled and reassembled by hand. The Sydenham Crystal Palace was lost in 1936. A fire destroyed all the elements. As a result the demolition phase has been ignored in this assessment.

6.2.2 Visitor travel

In this section, energy consumption and carbon emissions for visitor transportation to the Great Exhibition in 1851 were determined by the visitor numbers, the fuel consumed by the transport mode, the distance travelled and the relevant energy intensity and carbon emission coefficients. The details of these parameters are explained below.

6.2.2.1 Number of visitors

There were a total of 6,039,195 visitors to the Great Exhibition in 1851 (Bird, 1976, p.112) and 58,427 of these were from foreign countries (Moser, 2002 p.48). What is not known is where all these visitors came from in the UK, so some estimates have to be made. It is assumed here that half of all visitors from the UK (i.e. 2,990,384) were equally split between those from Inner and Outer London. There were a limited range of available transport modes in 1851. It is assumed here that those coming from the Inner London Boroughs walked or used horse-powered transport, while those who lived in Outer London would, where possible, use the railway (i.e. steam trains) or else use horse powered transport. Table 6.3 shows the estimated number of visitors to the Crystal Palace in London in 1851 and their different transportation methods. They have been divided into three groups, those from London, those from other cities in the UK and those from other countries in the world.

Assumptions have been made in order to perform the calculations. The possible transport modes are assumed to be walking, horses (riding), horses (cabs and horse buses), steam trains, steamships or sailing ships. Most of the visitors living in Inner London are assumed to have walked to the Great Exhibition and people from the Outer London Boroughs used steam trains as their transportation, then walked or took cabs (Hackney carriages) from the railway station to the Crystal Palace. Most of the visitors who came from other parts of the UK took steam trains from their main centres to London, then walked, or took cabs/horse buses to Hyde Park. Moreover, visitors from overseas had to take steam trains or horse transport to the main port cities in their own country, and then transfer to ships. It is assumed that most American customers started their travel from the port of New York and thence to Southampton in the UK and the majority of visitors from Oceania and Asia would be from Australia and India. However there were no trains in Australia in 1851 (the first railway was completed and opened in 1854 (NZETC, 1929)) and India's first steam train was in December 1851 (IRFCA, 2009). At that time, African countries had not introduced steam trains and steamships. Thus, visitors from these countries might have ridden horses and used sailing ships driven by the wind to travel to the UK (Timeline of railway history, 2010; Lynn, 2002, p.105).

Visitors		Number of people	Area	Transportation mode	Number of people	
UK (5,980, 768)	From London (50%)	2,990,384	Inner London Boroughs (50%) (1,495,192)	walking (50% of visitors living in Inner London Boroughs)	747,596	
				horse/ cab/ horse bus (50%)	747,596	
			Outer London Boroughs (50%) (1,495,192)	horse/ cab/ horse bus (50%) (living in Outer London Boroughs)	747,596	
				steam trains (50%)→ walking/ horse/ cab/ horse bus	747,596	
	From UK but living out of London (50%)	2,990,384	England (2,000,000)	cab/horse bus (25% of visitors living in England)	500,000	
				steam trains (75%) → walking/ horse/ cab/ horse bus	1,500,000	
			Wales (330,128)	steam trains → walking/ horse/ cab/ horse bus	330,128	
			Scotland (330,128)	steam trains → walking/ horse/ cab/ horse bus	330,128	
			Ireland (330,128)	steamships → steam trains → walking/ horse/ cab/ horse bus	330,128	
From foreign countries (Moser, 2002, p.48)		58,427	Europe (Austria:672; Belgium:3,796; France:27,236; Germany:10,440; Greece:94; Holland:2952; Italy:1,489; Norway, Sweden, and Denmark:648; Prussia:1,489; Russia and Poland:854; Spain and Portugal:1,774; Switzerland:734; Turkey and Egypt:86)	steam trains → steamships→ steam trains → walking/ horse/ cab/ horse bus	52,264	
			Americas (5,048)	steamships→ steam trains → walking/ horse/ cab/ horse bus	2,524 (from New York)	
				steam trains → steamships→ steam trains → walking/ horse/ cab/ horse bus	2,524	
			Oceania	steamships→ steam trains → walking/ horse/ cab/ horse bus	1,115	372
			Asia	steamships → steam trains → walking/ horse/ cab/ horse bus		372 (China:8)
			Africa	sailing ships → steam trains → walking/ horse/ cab/ horse bus		371
Total		6,039,195	-	-	-	

Table 6.3 Number of visitors from different areas and their transportation modes

6.2.2.2 Distances of visitor travel

1. Visitor travel from London

Visitors living in London probably took cabs (the London Hackney Carriage Act was passed in 1831 (BBC, 2002)), rode horses or in carriages or used horse buses or walked to the Crystal Palace. These modes of travel are assumed here to have no carbon-related environmental impact. However, they have a land related area for their food, and these areas have been included in the overall impact (see section 6.3.2). The method of accounting for the ecological footprint of horse-related visitor travel is explained in section 6.2.2.5.

Some 747,596 people are assumed to have travelled within London to the exhibition by steam train. According to the London map of 1851 (Figure 6.2), there were seven railways into central London. They were the Great Western Railway (built in 1838 (Great Western Railway, 2010), North Western Railway (Reed, 1996), Great Northern Railway (Simkin, 2003), Eastern Counties Railway (built in 1839), Blackwall Railway (Blackwall, 2002), London and Greenwich Railway (London and Greenwich Railway, 2010) and South Western Railway (London and South Western Railway, 2010). In 2009 London had the following surface railways, some of which use the track of the railways of 1851 (First Great Western, London Overground, Northern Line, National Express East Anglia, South Eastern and South West Trains and Docklands Light Railway) and some lines have been increased in length.

The seven railway lines inside London today are as shown in Figure 6.3. The visitor distance has been measured from the middle station in each line to the central London terminus and back (Table 6.4).

Thus, the assumed distances by railway for visitor travel are from the middle stations (by number rather than by distance, and only within the London area) to the terminus of each railway line. The driving distance (by car) between these two railway stations can be measured by using Google Maps. Putting the map into AutoCAD, the rail distances were measured by the relative proportions according to the known distance (car) from the map, and are shown in Table 6.4. The length of all the railways was 119 km and average half distance is 60 km. The average distance per passenger per line is defined to be the half distance divided by the seven lines (9 km).

2. Visitors from other regions

Apart from London, in 1851 there were visitors from the four countries of the UK (England, Wales, Scotland and Ireland). This section will analyse the different transportation modes visitors are assumed to have chosen and their travel distances from each of the regions.

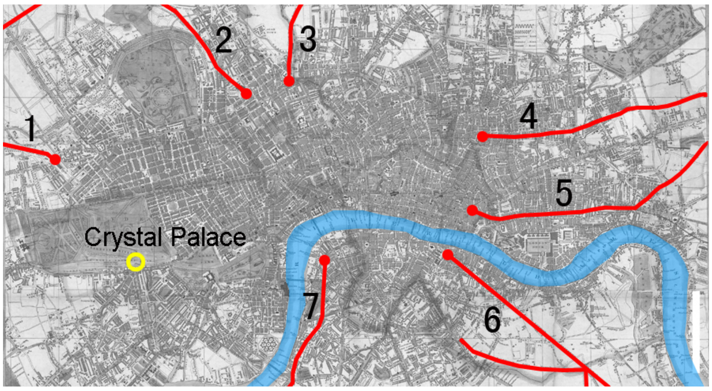


Figure 6.2 Map of London in 1851 (Redrawn from MAPCO. (2007). Map of London - Cross's London Guide 1851, Commercial Docks, Limehouse Hole, Isle Of Dogs, The Kings Dock Yard, & Deptford, from http://archivemaps.com/mapco/cross1851/cross24.htm)

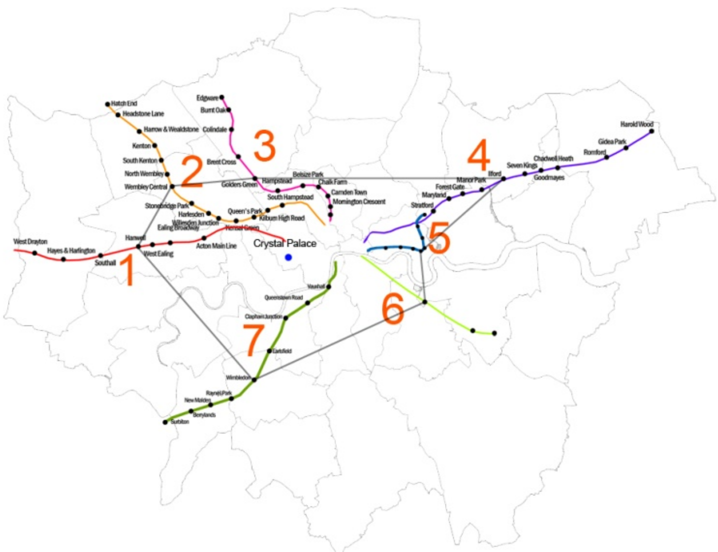


Figure 6.3 Stations of London railways in 1851 (Redrawn from Map of the London Boroughs. This map is based upon Ordnance Survey material with the permission of Ordnance Survey on behalf of the Controllor of Her Majesty's Stationery Office. Unauthorised reproduction infringes Crown copyright and may lead to prosecution or civil proceedings. (ONS. GD272183. 2003))

	Name of Railway in 1851 *	Name of Railway in 2009	Type in 1851	Route	Terminus in London	Total Distances (km) **	Average half distances (km)
1	Great Western Railway (built in 1838)	First Great Western	National railway	London→ Bristol	Paddingt on	23.89	11.9
2	North Western Railway (built in 1846)	London Overground	National railway	-	Euston	20.56	10.3
3	Great Northern Railway (built in 1846)	Northern Line	National railway	-	Euston	19.2	9.6
4	Eastern Counties Railway (built in 1839)	National Express East Anglia	National railway	London→ Colchester	Liverpool Street	21.9	11.0
5	Blackwall Railway (built in 1836)	Docklands Light Railway	Local railway	-	Fenchurc h Street	7.22	3.6
6	London and Greenwich Railway (built in 1836-1838)	South Eastern	Local railway	-	London Bridge	6	3.0
7	South Western Railway (built in 1838)	South West Trains	National railway	London→ Weymouth	Waterloo	19.5	9.8
Total distance of the seven railways						119	60
Average distance per passenger per line (km)						9	
* Wikipedia. (2009). List of early British railway companies, retrieved 5th April 2009, from http://en.wikipedia.org/wiki/List_of_early_British_railway_companies ** Google Map, retrieved 10th April 2009, from http://maps.google.co.nz/maps?hl=en&tab=wl							

Table 6.4 Average half distances of the railways in the outer London boroughs

- People from England

Within England, there are eight regions, the North East, North West, Yorkshire and Humberside, East Midlands, West Midlands, East of England, South West and the South East except London. The results for fuel consumption and CO_2 emissions will be calculated from the emission factors for coal, the assumed number of visitors from the different regions and the distances from the different places to the Great Exhibition. This study will use the population density of main centres to represent the whole regions, because it was difficult to find accurate and detailed data about population distribution in the regions in the 1850s. The chosen main centres of each region are, respectively, Newcastle Upon Tyne, Manchester, Leeds, Nottingham, Birmingham, Cambridge, Bristol, and Canterbury (Table 6.5, Figure 6.4). Because it was not possible to find figures for the distance by train from each of these cities to the appropriate London terminus, an average was taken of the straight-line distance, and the distance by road (calculated from Google Maps).

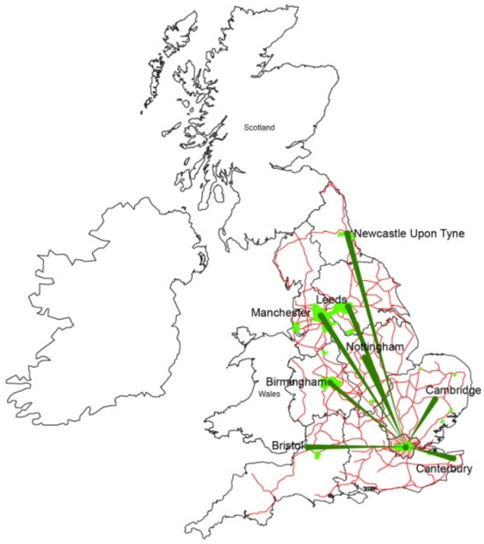


Figure 6.4 Assumed railway lines and main centres in England, UK in the 1850s
(Redrawn from 1998, United Kingdom: Government Office Regions, Produced by ONS Geography GIS & Mapping Unit (2003))

Visitors	Regions	Main centres	The percentage of population	Number of people visiting the Great Exhibition	Distances from cities to London (km) (direct/car)	Average distances from cities to London by train (km)
From England (except London) (1,500,000)	North East	Newcastle Upon Tyne	6.0%	90,000	396/457	427
	North West	Manchester	21.6%	324,000	264/323	294
	Yorkshire and the Humber	Leeds	11.8%	177,000	273/315	294
	East Midlands	Nottingham	20.2%	303,000	178/207	193
	West Midlands	Birmingham	16.0%	240,000	155/194	175
	East of England	Cambridge	13.1%	196,500	80/94.7	87
	South West	Bristol	9.4%	141,000	172/196	184
	South East	Canterbury	1.9%	28,500	84/95	90
Number of people visiting the Great Exhibition was calculated by the percentage of population in each region in England. The population of cities in 1850s: Newcastle Upon Tyne: 87,784 ;Manchester: 316,213; Leeds: 172,270; Nottingham: 294,380; Birmingham: 232,84; Cambridge: 191,894; Bristol: 137,328; Canterbury: 28,000						

Table 6.5 Average distances from main centres to London by train

- People from Wales, Scotland and Ireland

The assumed number of visitors from Wales was 330,128 (Table 6.1). The capital, Cardiff, was chosen as the main centre and the average distance from Cardiff to London is assumed to be 230 km (calculated the same way as above) (Table 6.6).

Similarly, in Scotland, it was estimated that there were 330,128 visitors who participated in the Great Exhibition. As Glasgow was then the biggest city in Scotland, the distance used to calculate the energy consumption was Glasgow to London, which was 607 km.

Visitor origins	Number of passengers	Distances (km)	Average distance to London (km)
Wales	330,128	212/247 (direct/car)	230 (train)
Scotland	330,128	562/651 (direct/car)	607 (train)
Ireland	330,128	100 (from Dublin to Holyhead) (ship) 364/462 (from Holyhead to London) (direct/car)	100 (from Dublin to Holyhead) (ship) 413 (from Holyhead to London) (train)

Table 6.6 Average distances from Wales, Scotland and Ireland to London by train

Figure 6.5 Assumed railway lines and main centres in Wales, Scotland and Ireland, UK in the 1850s

Unlike visitors from England, Wales and Scotland, visitors from Ireland would have to take a steamship to cross the Irish Sea and then a steam train. Dublin was the biggest city in Ireland (Figure 6.5). The route assumed for visitors from Ireland is steamship from Dublin to Holyhead, and then steam train to London. The shipping line from

Dublin to Holyhead was 100 km (Portworld, 2010) and it is 413 km from Holyhead to London.

3. Visitors from foreign counties

Most of the foreign visitors are assumed to be from Europe, the Americas, Oceania, Asia and Africa. In Europe, the main countries close to the UK are Germany and France, and for the purposes of these calculations it is assumed that European visitors came from these two countries.

In Germany, visitor travel was calculated on the basis that people took steam trains first, then steamships (from Germany to UK), and finally steam trains to London. One of the largest port cities in Germany is Hamburg. The distance of the shipping line from Hamburg (Germany) to Southampton (UK) was 926 km (Table 6.7). In respect of steam trains in Germany, there were more than 2,000 km of railway by 1845 (History of rail transport in Germany, 2010). It is assumed here that most visitors were starting their journey in Berlin. The distance by road from Berlin to Hamburg is 280 km, as shown in Figure 6.6 (The red line represents the route by road and the green one shows the railway line). It is seen that the railway line is longer than the road. Thus, the assumed distance of train travel is 290 km. However, when visitors arrived at Southampton, they would take trains again (from Southampton to London). The direct distance and road distances measured by Google Maps were 113 and 117 km respectively. Thus, the average travel distance for this journey by steam train is 115 km.

Compared with Germany, French railways developed more slowly, but France had well-developed canal systems. The first railway built in France, which was from Saint-Étienne to Andrézieux, started operation in 1832. It is assumed that most visitors started their sea journey from Le Havre. It is likely that they took steam trains from Paris to Le Havre, which was a distance of 204 km (Figure 6.7, red line), then took ships from Le Havre to Southampton (202km), and finally went to London the same way as other European foreign visitors (115 km by steam trains). In order to simplify the calculation, the distances for steam trains and steamships will be taken as the average distance for France and Germany combined (Table 6.7).

Figure 6.6 Railway map of Germany in 1851(Redrawn from IEG-MAPS · Server für digitale historische Karten / Server for digital historical maps, retrieved 13rd April 2009, from http://www.ieg-maps.uni-mainz.de/mapsp/mape851d.htm)

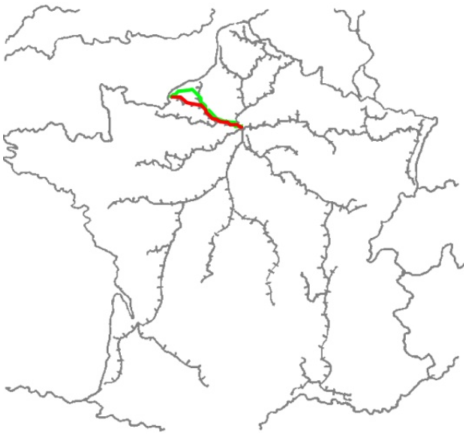


Figure 6.7 French railways in 1856 (Redrawn from Wikipedia, Histoire des chemins de fer français, from http://fr.wikipedia.org/wiki/Histoire_des_chemins_de_fer_fran%C3%A7ais)

For the Americas, the assumption was made that visitors were all from North America (Figure 6.8). One group of visitors was assumed to set out from New York by ship directly; others were from other east coast cities, taking trains from Boston or Washington, D.C. to New York (because the railways in the 1850s were mainly located in the coastal area of eastern America), then using ships. Total railroad mileage in the USA in 1850 was 9,021 km (Rail transport in the United States, 2010). The road distance from Boston to New York and from Washington, D.C. is 343 km and 365 km respectively. Thus, the average distance of railway travel is assumed to be 355 km. New York's population was 3,097,394 in 1850 (New York, 2010) which accounted for 13.36% of the total population of the USA (23,191,892 people (Haines and Steckel, 2000)). It has therefore been assumed that 2,524 visitors from New York directly took steamships to go to the Great Exhibition in London. After they arrived at Southampton, they took steam trains like the visitors from Europe.

Figure 6.8 American railways in 1850 (Redrawn from Perry-Castañeda Library, Map Collection, from http://www.lib.utexas.edu/maps/historical/ward_1912/us_population_railways_1850.jpg)

In Oceania, the first railway was completed and opened for traffic on 13th September, 1854 in Australia (NZETC, 1929). Thus, there was no steam train during the Great Exhibition in London. Visitors might take ships from Australia to India first, then from India to the UK because of the long travelling distance. Then they took steam trains in the UK for attending the exhibition (travel distances are shown in Table 6.7).

In Asia, railways were first introduced to India in December 1851 (IRFCA. 2009). However, the first steamship in Asia seems to have been the Nawab of Oude's steam yacht. It was built at Lucknow in 1819, and equipped with an eight horse-power engine sent out from England (Blue, 2009). The first steamships in India operated on the Hoogly in the early 1820s, mainly as tug boats (Blue, 2009). Thus, it can be assumed most Asian visitors, the majority of whom were governmental officers and merchants, rode horses, took carriages or walked to Cochin (India), and then took steamships to Southampton. The measured distance of shipping was 19,070 km (Calculation results, 2009). They took steam trains in the UK after they arrived at Southampton.

In Africa, the first railway was built in 1852 (Timeline of railway history, 2010). As there was no steamship service operating in 1851(during the Great Exhibition) in Africa (Lynn, 2002), visitors from Africa would have had to use sailing ships navigating the Atlantic Ocean with their luggage and products. They then took steam trains which might be the first time they had seen and used steam trains. Sailing ships are assumed here to have no environmental impact, being powered by the wind.

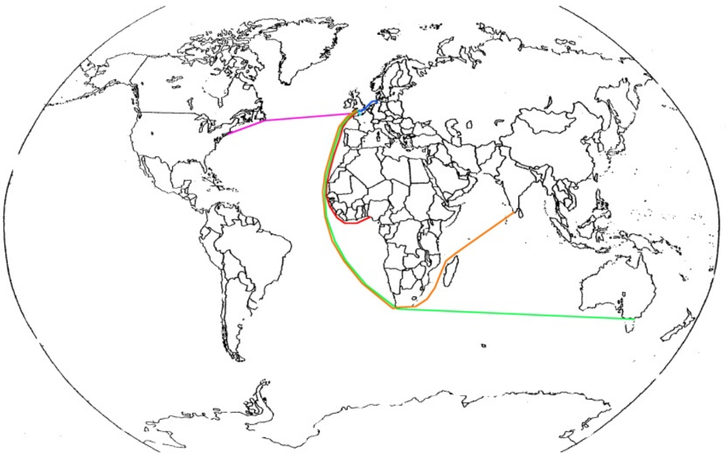


Figure 6.9 Shipping lines visitors took from overseas (Redrawn from Calculation results, Global Shipping Platform, from http://www.searates.com/reference/portdistance)

Figure 6.9 shows the shipping lines used by ships (steam and sail) from Europe, the Americas, Oceania, Asia and Africa to the UK. Table 6.7 sets out the assumptions made about modes and distances of visitor travel from foreign counties.

6.2.2.3 Energy intensity of the different transport modes

The fuel consumption of the different visitor transportation modes in London in 1851 was found by multiplying the fuel consumption per passenger-km for each mode with the number of passengers and the return distances from the original place where visitors lived to London.

Visitors	Counties	Transport	Distance on Steam train (km)		Distance on Steamships (km) *		Distance on Steam train (km)
From foreign countries	Europe	steam trains→ steamships→ steam trains→ walking/ horse/ cab/ horse bus	290 (Berlin→ Hamburg)	247 (average distance)	926 (Hamburg, Germany)	564 (average distance)	115 (direct distance =113; car=117) (Southampton→ London)
			204 (Paris→ Le Havre)		202 (Le Havre, France)		
	Americas	steam trains→ steamships→ steam trains→ walking/ horse/ cab/ horse bus	343 (Boston→ New York)	355 (average distance)	5,700 (New York, USA)		115 (direct distance =113; car=117) (Southampton→ London)
			365 (Washington, D.C.→ New York)				
	Oceania	steamships→ steam trains→ walking/ horse/ cab/ horse bus	-		21,580 (Melbourne, Australia→ Cape Town, South Africa: 10,580; Cape Town, South Africa → Southampton, UK: 11,000)		115 (direct distance =113; car=117) (Southampton→ London)
	Asia	steamships→ steam trains→ walking/ horse/ cab/ horse bus	-		19,070 (Cochin, India → Cape Town, South Africa: 8,070; Cape Town, South Africa → Southampton, UK: 11,000)		115 (direct distance =113; car=117) (Southampton→ London)

* Ship Voyage Distance Calculator, http://www.portworld.com/map/

Table 6.7 Assumptions made about visitor numbers and modes of travel from overseas

At this stage this research has not included the footprint of food which people and horses need for the extra activity associated with travel. Normally these modes of travel are thought of as environmentally neutral (Lopez, 2008, p. 244). It is possible to show that in modern times the impact of the food consumption for “non-powered” forms of travel can be significant (Vale and Vale, 2009, p.29–71). However, in 1851 it is assumed that the input of non-renewable energy to the agriculture and food system was low, and that therefore this was not an important issue. The fuel consumption of steam trains and steamships is discussed below. The locomotives of steam trains in the UK used coal as the fuel, while in America engines burned both wood and coal (White, 1980, p.88). Steamships are assumed to use coal.

1. Steam trains

- Coal as the fuel

In 1851, steam trains in the UK burned coal, and they continued to do so until the 1960s. The total energy consumption for a steam hauled rail trip is estimated to be 0.42 GJ per km (1.1 MJ/passenger-km) in the 1950s (Vale and Vale, 2009, p.117). However, in 1851 the locomotives of trains were probably less efficient than those of a hundred years later. An existing example of an “old” railway, which might be comparable with mid-nineteenth century technology, is the 2ft narrow gauge Darjeeling Himalayan Railway in India. Its B Class 0-4-0ST are small two-axle tank locomotives which carry their water tanks on the boiler (a saddle tank) and are fitted with large lateral coal bunkers (IRFCA, 2009b). The towed load, in view of the very severe profile of the line, which climbs up into the mountains, is only 28 tonnes. The oldest B Class working loco still climbing the mountains today was built in 1889 (IRFCA, 2009b). The B Class 0-4-0ST was a development of the simple 0-4-0 type of wheel arrangement which was used in Richard Trevithick’s 1804 pioneering locomotive (0-4-0, 2009). In 1832 an 0-4-0 was built for the Baltimore and Ohio Railroad in the U.S. (0-4-0, 2009). Thus, it is possible to assume that locomotives roughly comparable to the B Class 0-4-0ST were built and used in the 1830s-1860s in the UK, albeit designed for standard gauge track. The average coal consumption per mile on the Darjeeling railway is 39 lbs (IRFCA, 2009b). The seating capacity of the coaches varies between 12 and 33 passengers (Singh, 2007), so a train on the

Darjeeling Himalayan line might have 78 passengers in total. Converted to SI units the coal consumption is 11 kg per km and the calorific value of coal is around 30 MJ/kg (Allen, 1953). So the train uses around 4.2 MJ/passenger-km (Table 6.8).

Type of Locomotive	Date	Seats	Average coal consumption	Energy consumption per km (MJ/km)	Energy consumption per passenger km (fully occupied) (MJ/passenger-km)	Other
British Railways passenger express	1950s	384	9 tonnes for 400 mile trip	420	1.1	Standard gauge main line
B Class 0-4-0ST	Assume similar to 1830s~1860s	78	39 lbs/mile	330	4.2	Narrow gauge mountain railway

Table 6.8 Comparison of two steam trains

Therefore, if a 1950s steam express passenger train (better technology than in 1851) used 1.1 MJ/passenger-km, and a narrow-gauge steam mountain railway (similar technology to 1851, but a more demanding route) uses 4.2 MJ/passenger-km, it might be reasonable to assume that a train in 1851 might have a coal consumption of 3.0 MJ/passenger-km.

- Wood as the fuel

Unlike the UK situation, the locomotives used in some parts of the USA consumed wood as their fuel, as the price of wood at that time was cheaper than that of coal (White, 1973, p. 84). As late as 1851 the Philadephia and Reading Railroad used more than 61,000 cords of wood, although it was also operating some coal-burning engines (White, 1973, p. 84). It can be assumed that in 1851, steam trains consumed both coal and wood on the US railways. In the nineteenth century one tonne of soft coal was considered equal to 1.75 cords of wood (wood: 3,000 pounds per cord, so 2,000 pounds of coal equaled 5,250 pounds of wood) (White, 1973, p. 86). The cost of wood fuel for an American passenger locomotive in 1851 is given as 18 cents per mile, with the cost of wood being $4.50 per cord (Illinois Central Railway, 1857). These figures mean that the locomotive used 0.04 cords per mile, and if a cord is 3,000 lb, the locomotive consumed 120 lb of wood per mile, or roughly 34 kg of wood per km. The energy content of wood fuel (air dry, 20% moisture) is about 15 GJ/t (BFIN, 2009), so 34 kg of wood per km is 510 MJ per km. Although railways in Britain and Europe used four and six wheeled carriages until the 1860s, railroads in the United States began quite early in their development to use longer, eight-wheel cars riding on two four-wheel trucks (Railroad track, 2007). Bianculli shows a number of eight-wheeled American passenger cars from the period 1840 – 1850, all with seats for about forty passengers (Bianculli, 2001, p. 18-20). Assuming a three to five car train, with forty passengers per car, the energy consumption of a wood-burning American passenger train would be between 4.3 and 2.6 MJ per passenger-km, giving an average of 3.5 MJ/passenger-km. This is quite similar to the figure derived for coal-burning locomotives above.

However, the performance of coal-fired locomotives in the USA appears to be different from that of the UK locomotive. The Illinois Central Railroad, as an example, began to experiment with coal-burning locomotives in 1855 due to the cheap price of coal from the southern Illinois coal fields. Wood fuel cost 18 cents per mile at that time while coal cost only 12 cents per mile (White, 1973, p.78) and by the mid-1850s coal was about $3.00 per tonne (White, 1973, p.87). If these figures are used the same way as above to calculate the coal consumption of the locomotive, it can be seen that it burned 0.04 tonnes of coal per mile, which was equal to 36.6kg per mile (22.7 kg/km). Depending on the type of coal used the energy content might lie between the better quality coal with an energy content of about 30 GJ/t and the poorest quality, black coal, whose energy content varies between 27 – 13 GJ/t (Australian Government, 2008, p.2). The average figure of 20 GJ/t was chosen here. Thus, owing to the different type of coal and the likely number of passengers, the total coal consumption for a trip in terms of American steam trains in the 1850s was between 454 and 681 MJ per km, and the average coal consumption per passenger (fully occupied) was 4.1 MJ per passenger-km. These results are summarised in Table 6.9.

Country	USA			UK
Fuel	Wood	Coal		Coal
Seats	120-200	120-200		78 - 384
Energy content of fuel	15 GJ/t	30 GJ/t	20 GJ/t	30 GJ/t
Fuel consumption per km (MJ/km)	510	681	454	330 - 420
Fuel consumption per passenger (MJ/passenger-km)	3.5 (4.3 and 2.6 MJ per passenger-km)	5.1 (6.3 and 3.8 MJ per passenger-km)	3.1 (3.8 and 2.3 MJ per passenger-km)	1.1 and 4.2 MJ/passenger-km
Assumed average fuel consumption per passenger	3.5 MJ/passenger-km	4.1 MJ/passenger-km		3.0 MJ/passenger-km

Table 6.9 Assumed fuel consumptions of passenger trains in the 1850s

2. Steamships

Craig mentions in his book published in 1980 that the steamship presented no real competition to the sailing vessel during the period 1815 to 1865 (Craig, 1980, p.3-4). However "She provided entirely new services on short-range high-density passenger routes…and as a heavily subsidized mail and passenger carrier on the Atlantic and eastern routes she provided a service which did not exist before" (Craig, 1980, p.3-4). In 1854, the Scottish engineers John Elder and Charles Randolph designed and built the first ocean-going compound engines for the steamship *Brandon* (764 tonnes gross) (Craig, 1980, p.11). So at the time of the Great Exhibition there were only the less efficient single-expansion steam engines in ships.

The *Brandon* used 3.25 lbs of coal per HP per hour, whereas the previous most economical ships used between 4.0 and 4.50 lbs per HP per hour (Craig, 1980, p.11). The improvement over time, from 1850s to 1901, in performance of coal consumption of steam engines is shown in Table 6.10 below.

Steam engines	1850s	1854	1872	1881	1891	1901
Coal consumption (lbs per HP per hour)	4.50	3.25	2.11	1.83	1.52	1.48

Table 6.10 Coal consumption of steam engines for steamships from 1850-1901 (Craig, 1980, p.14)

Unfortunately, the engine size in HP and the duration of the voyage are not known and the overall fuel consumption of any ship from this period could not be found in Craig's book. However the ratio of the different fuel consumptions at different dates from Table 6.10 could be used to establish some idea of the fuel consumption for other dates. The steamer *Oscar II*, built in 1891, could carry 4600 tonnes deadweight of cargo at 9 knots using 14 tonnes of coal a day. This is 400 km a day on 14.22 tonnes of coal, with a cargo of 4674 tonnes or 1,869,600 tonne-km (Craig, 1980, p.14). This works out to 0.0076 kg of coal per tonne-km (0.274 MJ/tonne-km (NPL, 2008)). From the table above, the coal consumption of a ship in the 1890s was around 1.5 lbs per HP per hour and in the 1850s it was 4.5 lbs per HP per hour, three times greater, so it could be assumed that the energy consumption of a ship in the 1850s was three times that of the *Oscar II*, or around 0.82 MJ/tonne-km.

However, all the ships in Table 6.10 are freighters. An example of a passenger ship is the steamship *Atlantic* (1851), which was built as the pioneer steamer of the American Collins Line (Robert and Thurston, 1878). The state-rooms were arranged on each side of the dining saloon, and accommodated 150 passengers (Robert and Thurston, 1878). Another example from the period is the Cunard Line's *America*, built in 1847, which carried 140 first class passengers and 450 tons of cargo. This ship is stated to have had a coal consumption of one ton per 7.3 km, or roughly 0.14 tons per km (Cunard Steamship Fleet, 1849). At an energy density of 30 GJ/ton (steamships are presumed here to have used the best quality of coal, because they could carry only a fixed quantity in their bunkers, and they did not have anywhere en route from the USA to England where they could stop to refuel), this means the total coal consumption represented 0.14 tons x 30 = 4.2 GJ per km. This can then be divided by the 140 passengers to give a figure of 30 MJ/passenger-km. If all the fuel consumption is assumed to relate to the transportation of the passengers, this figure is reasonable. However, the *America* carried 450 tons of cargo as well as her 140 passengers. Not knowing if the quoted figure is in US tons or Imperial tons, and taking an assumed cargo capacity of 420 tonnes, the ship's coal consumption represents 10 MJ per tonne-km.

The 140 passengers with their baggage will each weigh 120 kg, and of the 90 crew of the *America*, 70 are assumed to be there to look after the passengers, and they will also have baggage, making a total weight of 210 people x 120 kg = approx 25 tonnes.

Each of these people will need perhaps 3 kg of food and other supplies each day for a two week passage, making a further, say, 50 kg per person, or an additional 10 tonnes.

The proportion of the fuel consumption attributable to the passenger-carrying aspect of the ship's crossing of the Atlantic is therefore 35 tonnes of passengers, luggage, stores and crew divided by 420 tonnes of freight multiplied by the fuel consumption in tonne-kilometers; 35/420 x 10 = 0.8 MJ/passenger-km. To allow for the weight of the fit-out of the ship for passenger carrying (the state-rooms, dining saloon, and other luxuries) this figure will be increased to 1 MJ/passenger-km.

Table 6.11 lists the assumed energy consumption for people taking steam trains and steamships in the 1850s. Using the available statistics, it has been possible to calculate how much coal was consumed and calculate the coal consumption per person in order to calculate the total usage of coal by people travelling to the Great Exhibition.

	UK	USA	
	Coal consumption per person	Coal consumption per person	Wood consumption per person
Walking	-	-	-
Horses	-	-	-
Carriages	-	-	-
Steam trains	3.0 MJ/ passenger-km	4.1 MJ/passenger-km	3.5 MJ/passenger-km
Steamships	1.0 MJ/ passenger-km	1.0 MJ/passenger-km	-

Table 6.11 Assumed energy consumption in MJ per passenger-km for various transport modes

6.2.2.4 CO_2 emissions coefficients

The total fuel consumption for steam trains and steamships can be calculated by multiplying the number of visitors, distance that people travelled and fuel consumption factor (per km per person). The CO_2 emission factor of coal is 0.093 kg CO_2/MJ (OEE, 2008). Wood and wood waste's emission coefficients are 195.0 Pounds CO_2 per Million Btu (EIA, 2009). So the CO_2 emission factor of wood is 0.08384 kg CO_2/MJ (88.45kg CO_2 /Million Btu $\times 10^{-3} \div 1.055$), which is not much lower than the figure for coal. However, wood is a renewable resource. In the process of growing, trees absorb

CO_2 and release oxygen as well. Whether wood can be considered to be a carbon neutral fuel depends on whether people continue to plant trees and the number of new trees. In Table 6.12 the CO_2 emissions of wood-burning trains in the USA are assumed to be zero. In addition, this table does not include the CO_2 emissions of horse transport or walking as these did not consume any fuel (although in a more detailed calculation, the non-renewable energy for producing, and particularly for transporting, food could be considered).

	CO_2 emission factor of coal	**CO_2 emission factor of wood**
Steam trains	0.093 kg CO_2/MJ	0 kg CO_2/MJ
Steamships	0.093 kg CO_2/MJ	-

Table 6.12 CO_2 emission factors of coal and wood

6.2.2.5 Horse-related visitor travel

Although there was no carbon footprint of horse-related visitor travel, land-related consumption cannot be neglected. The evaluation of the ecological footprint generated from horse-related transport to go to the Crystal Palace includes visitors who travelled from local and foreign countries.

1. Visitors from London

Total number of local visitors from London taking horse-related transport to go to the Crystal Palace was 2,242,788 (2,990,384-747,596) (Table 6.3).

In this study, the horse-related transport modes include riding a horse (single rider), taking cabs (2 passengers), and taking a horse bus (17~20 passengers) (Perdue, 2007) in 1851. Perdue (2007) stated that there were about 621 horse buses operating in 1851. If they all were used for visitors travelling to the Crystal Palace (6 months), the total days of travelling by horse buses were 111,780 (621 horse buses ×180days). To make an estimate on the high side, to avoid underestimating the impact, it is assumed that the average horse made one trip in one day). This means the horse buses can carry about 1,117,800 visitors maximum during the Great Exhibition (111,780×10 passengers/horse bus).

Table 6.13 shows the number of visitors who travelled by different horse-related transport modes in 1851. It is assumed that number of visitor taking cabs was twice the horse riders. The total journeys by horse were 973,552, which were 374,996 for riding horses, 374,996 for taking cabs, and 223,560 for horse buses, as shown in Table 6.13.

Transportation mode	Number of visitors	Days of travel by a horse
Horse (1visitor/horse)	374,996	374,996
Cabs (2 visitors/horse)	749,992	374,996
Horse bus (9~10 visitors/horse)	1,117,800	223,560
Total	2,242,788	973,552

Table 6.13 Number of visitors who travelled by horses to go to the Crystal Palace in 1851

Vale and Vale (2009, p.86) give the average energy consumption of keeping a horse for moderate and intense work at 103~137 MJ/day (average 120 MJ/day). Therefore total energy consumption of visitors from London who travelled by horses was 116,826 GJ, or 52 MJ/visitor. The ecological footprint of local visitors travelling by horse to the Crystal Palace was 1,168 gha, or 0.0005gha/visitor (Table 6.14).

Transportation mode	Energy consumption (GJ)	Ecological footprint (gha)
Riding horse	45,000	450
Taking cab	45,000	450
Taking horse bus	26,827	268
Total	116,826	1,168

Table 6.14 Energy consumption and ecological footprint of visitors from London who travelled by horses to go to the Crystal Palace in 1851

Given that a horse may well have made more than one trip per day, the figures in Table 6.14 represent a likely maximum value.

2. Visitors from outside of London

The visitors from outside of London took steam trains or steamships to go to the Great Exhibition and the total number of these visitors was 3,048,811 (Table 6.3). As the average consumption of visitors who travelled by horse-related transport was accounted above (52 MJ/visitor), the total horse-related energy and resource consumption of visitors who travelled from other cities and other countries were 158,538 GJ and 1,585 gha respectively.

3. Total energy and resource consumption of horse-related visitor travel

Total energy and resource consumption of horse-related visitor travel was 275,364 GJ and 2,753 gha, as shown in Table 6.15.

Visitors	Energy consumption (GJ)	Ecological footprint (gha)
From London	116,826	1,168
From UK (apart from London)	155,500	1,555
From overseas	3,038	30
Total	275,364	2,753

Table 6.15 Total energy consumption and ecological footprint of visitors who travelled by horses to go to the Crystal Palace in 1851

6.2.3 Exhibition-related economic aspects

Resource consumption of exhibition-related economic aspects of this case study is converted from the monetary value of economic income from the events. The methods of quantifying economic income and related impacts are indicated in this section.

6.2.3.1 Exhibition-related economic income

The Great Exhibition contributed to the national economic growth of the UK during the 1850s. The concept of exhibition-related economic benefit used in this study is considered differently from the conventional approach, which includes only the direct benefits from the income of exhibitions.

To clarify, the exhibition-related economic contribution is split into two parts in this study; one is the direct effect; the other is the indirect effect. Direct economic benefit is defined as the immediate monetary income from the Great Exhibition in the UK in 1851. The indirect economic benefit from the Great Exhibition is here defined as the part of economic growth stimulated by the Great Exhibition at a national level in the UK. It is reflected by the amount of GDP growth from the exhibition-related industries that are selected from the related categories of the exhibits displayed in the Great Exhibition in this study (the detailed categories are stated in the following section). The reason for analysing this is that, normally, the purpose of holding an exhibition is to increase the sale of products exhibited. In the Great Exhibition, many new technologies and machines were displayed and introduced to the public (for example, the ice maker), which potentially enlarged the market of these new manufactures and consequently brought increased income.

1. Direct economic benefit

Direct economic benefit in this study includes the revenue input from the tickets, and food and drink sold to visitors during the 144 days of the Great Exhibition (the exhibition was open for six months, from Monday to Saturday). The calculations of direct economic benefits are based on the relevant written historical sources.

- Income from tickets sold at the Great Exhibition of 1851

Gibbs-Smith (1950, p.34) reported that receipts from the Great Exhibition were £522,179 in total, and the net profit was £186,437. If it is assumed that the total receipts were from the ticket sales and the total number of visitors was 6,039,195 (Gold, 2005, p.67), the average cost of a ticket per visitor was £0.09 (1.7 shillings). The actual costs of a ticket were 1 shilling, half-a-crown and five shillings according to which days the visitors came (Gibbs-Smith, 1950, p.33). The average daily wage of a worker around this time was just over two shillings (Clark and Werf, 1998, p.832).

- Income from food and drink sold at the Great Exhibition in 1851

Peskett (2006) stated that Messrs Schweppes were contracted by the Commissioners for the Great Exhibition to undertake the catering arrangements. Schweppes paid the Commissioners £5,000 for this privilege and made a total profit of £45,000 from the refreshments sold (including 1,804,718 buns) (Peskett, 2006). The breakdown of the refreshments and drink sold is sourced from Clowes (1852) and Peskett (2006) (Table 6.16). It is noted that bath buns, milk, biscuits, potted meats, rough ice and Schweppes soda water, lemonade, and ginger beer sold well during the Great Exhibition. Interestingly, the ices, made on the spot by a patent freezing machine run by steam, sold more than other types of food (Peskett, 2006; Phillips and Phillips, 1978, p.26). Attending the Great Exhibition thus was a good opportunity for Messrs Schweppes to create a fortune from marketing their new soft drinks in the 1850s

(Auerbach, 1999). In this they were helped by the fact that no alcoholic drinks were sold at the Great Exhibition (Gibbs-Smith, 1950, p.34).

Types	Amount of goods sold	Types	Amount of goods sold
Bread, quarters	52,094	Savoury Patties	23,040 lbs
Bread, Cottage loaves	60,698	Macaroons	1,500 lbs
Bread, French rolls	7,617	Biscuits	37,300 lbs
Pound cakes	68,428	Preserved fruits	4,840 lbs
3d cakes	36,950	Savoury pies	33,456 lbs
Savoury cakes	20,415	Rich cakes	2,280 lbs
Italian cakes	11,797	Potted meats / tongues	36,130 lbs
Victoria biscuits	73,280	Mustard	1,120 lbs
Bath buns	934,691	Coffee	14,299 lbs
Plain buns	870,027	Tea	1,015 lbs
2d pastries	36,000	Chocolate	4,836 lbs
School cakes	4,800	Meat	113 tonnes
Banbury cakes	34,070	Potatoes	36 tonnes
Pineapples	2,000	Rough Ice	363 tonnes
Sausage rolls	28,046	Salt	37 tonnes
Milk	33,432 quarts	Hams	33 tonnes
Cream	32,049 quarts	Pear syrup	5,350 bottles
Jelly	2,400 quarts	Schweppes soda water, lemonade, and ginger beer	1,092,337 bottles
Pickles	1,046 gallons		

Table 6.16 Types of refreshment and amounts sold at the Great Exhibition of 1851

- Total direct economic benefit from the Great Exhibition in 1851

Gibbs-Smith (1950, p.39) states that total expenditure for the Great Exhibition was £335,742, of which the building and fittings were approx. £170,000. The building was sold for £70,000 on moving to Sydenham after the event. The total net profit (direct income) from the Great Exhibition in 1851was £256,437, including the net income from tickets of £186,437 and profit from building sold of £70,000 (Gibbs-Smith, 1950, p.39; Gibbs-Smith and Victoria and Albert Museum, 1981, p.24).

2. Indirect economic benefit

The indirect economic benefit defined as the economic (GDP) growth stimulated by the Great Exhibition, is quantified by the amount of GDP growth from the exhibition-related industries. Hudson (2009) states the Great Exhibition of 1851 marked the peak of British economic dominance. The Great Exhibition of 1851 in London was conceived to symbolize this industrial, military and economic superiority of Great Britain (Victorian Station, 2001). The “Great Exhibition of the Industry of All Nations” was described as a huge and monumental enterprise, of importance in art, science and technology, and of political, economic and social significance. It had involved not only a huge swathe of British society, but also the whole world (Davis, 2000).

Although the macro-economic profit generated from the Great Exhibition cannot be assessed accurately, Fay (1951a, b, p. 91) asserts that in both large and small matters, the Great Exhibition has had its effect on British economic history, as on other aspects of British life. The Great Exhibition and the other twenty-three world fairs held in the 19th century illustrate the social changes of an era and can be seen as showcases of the economic performance of the participating countries. Starting with the Great Exhibition, with the increasing economic growth of the nineteenth century, the fairs took on greater international significance (Dahmen-Ingenhoven and Feireiss, 2004, p.113).

For the purpose of quantification and analysis of the exhibition-related economic effect, an average percentage increase in GDP is applied in this research. As part of GDP, the percentage of income from the modern exhibition industry for different countries is similar. In 2004 and 2006 in Hong Kong, HK$19 billion (US$ 2.4 billion) and HK$26.5 billion (US$3.38 billion) came from the exhibition industry, accounting for 1.5% and 1.8% of GDP (HKECIA, 2006; HKECIA, 2007). For the UK, £9.3 billion was generated by the exhibition industry in 2005 (McCann et al, 2005), accounting for 0.74% of GDP. In Toronto (Canada), income from the exhibition industry in 2006 was C$ 1.1 billion, equivalent to 0.87% of the regional GDP (Joppe et al, 2006). From the literature, the average proportion (0.8%) is used, as the data for the historic exhibition industry cannot be found.

For an exposition, the economic effect is normally taken as having an effect over a period of ten years by most researchers. For example, the forecast of expenditure from tourists in Shanghai after Expo 2010 is made by the Expo Economic Research Institute based on 10 years (CREN, 2010). In the study of the economic impact of the Sunbelt Agricultural Exposition, the potential economic effect on the Moultrie region is estimated over the next ten years after the Exposition (Flanders et al, 2006). In this study, the analysis of the potential economic effect after the Great Exhibition is estimated over a period of ten years. The average GDP of the UK from 1851 to 1860 was £724,900,000/year (Chantrill, 2010). As a result, the annual income arising from the exhibition was £6,161,650 (£724,900,000×0.85%). By subtracting the direct economic profits, the total indirect economic benefit from the Great Exhibition from 1851 to 1860 was £6,136,006/year.

At the micro-economic level, the Great Exhibition appeared to affect the income of "local trade and transport" and "income from abroad" from 1851 to 1871 in the total national revenues, which are taken from Deane and Cole's study (1962, p.106) (Table 6.17). Extracting from the figures the percentage increase, it is apparent that the increase in rate of total national income (37.2%) in the UK reached a peak in the period 1801-1901.

	1831	1841		1851		1861		1871	
	Income (£m.)	Income (£m.)	Increase	Income (£m.)	Increase	Income (£m.)	Increase	Income (£m.)	Increase
Agriculture, forestry, fishing	79.5	99.9	25.7%	106.5	6.6%	118.8	11.5%	130.4	9.8%
Manufacture mining, building	117.1	155.5	32.8%	179.5	15.4%	243.6	35.7%	348.9	43.2%
Trade and transport	59.0	83.3	41.2%	97.8	17.4%	130.7	33.6%	201.6	54.2%
Domestic and personal	19.2	26.9	40.1%	27.4	1.8%	35.0	27.7%	45.5	30%
Housing	22.0	37.0	68.2%	42.6	15.1%	50.3	18.1%	69.4	38.0%
Income from abroad	3.9	6.2	59.0%	10.4	67.7%	19.9	91.3%	39.5	98.5%
Government, professional and all other	39.3	43.6	10.9%	59.0	35.3%	69.7	18.1%	81.3	16.6%
Total national income	340.0	452.3	33.0%	523.3	15.7%	668.0	27.7%	916.6	37.2%

Table 6.17 The industrial distribution of the national income of Great Britain, 1831-1871 (Deane and Cole, 1962, p.106)

Looking at the period from 1851 to 1871, which could be considered the years most likely to be immediately affected by the Great Exhibition, the categories of "Trade and transport" and "Income from abroad" had higher rates of increase than most other categories, as show in Figure 6.10 ("Income from abroad" in orange, "Trade and transport" in green). The income from trade and transport in the UK increased significantly, going from £97.8 million to £201.6 million (an increase of 54.2% between the years of 1851-1871). However, the rate of increase from 1851 to 1871 was the highest during the period studied. Meanwhile, income from abroad also experienced the highest rate of increase during these 20 years, 98.5% in 1851-1871, which shows that increase in goods for export reached a peak after the Great Exhibition.

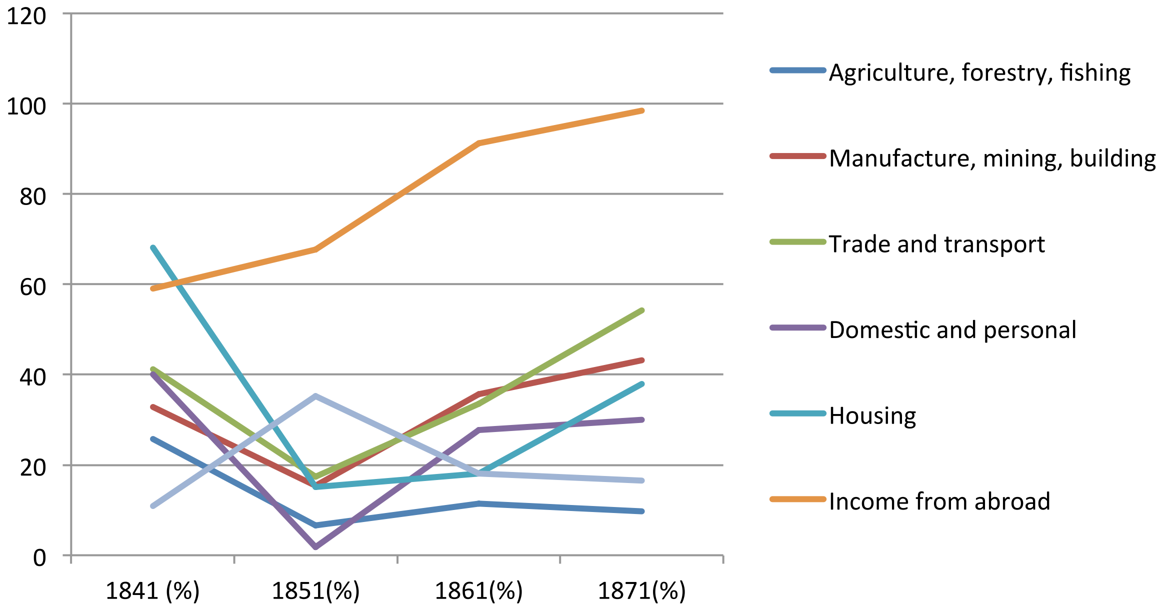


Figure 6.10 Distribution of national income of Great Britain between sectors, 1841-1871 (Deane and Cole, 1962, p.106)

Secondly, the other factor related to the potential economic benefit is the distribution of exhibits displayed in the Great Exhibition. Moser (2002, p.57) reported that 8,903 exhibits from the UK (in 30 classes) were displayed in the Great Exhibition out of the total exhibits (13,876 items). The detailed categories of exhibits are listed in Table 6.18. It shows that the category of “Machines for direct use, including horse drawn carriages, railway and marine mechanism” accounted for the largest percentage (11.2%) of the total number of exhibits. The exhibition-related indirect economic benefit from this category of exhibits is assumed to be £687,233 (11.2% of total income) (6,136,006 × 11.2% = 687,233), because the contribution for economic growth from exhibitions can be said to be directly or indirectly affected by the categories and quantity of exhibits displayed to visitors. The income for different categories of industries is calculated following the corresponding percentage.

Sections	No	Different categories	Number of exhibits	Percentage (%)	Income/ year (£)
Raw materials	1	Mining and mineral products	531	6.0	368,160
	2	Chemical and pharmaceutical products	118	1.3	79,768
	3	Substances used as food	162	1.8	110,448
	4	Vegetable and animal substances used in manufactures	138	1.6	98,176
Machinery	5	Machines for direct use, including carriages, railway and marine mechanism	998	11.2	687,233
	6	Manufacturing machines and tools	631	7.1	435,656
	7	Engineering, Architecture, and Building contrivances	224	2.5	153,400
	8	Naval Architecture, military engineering, &c.	337	3.8	233,168
	9	Agricultural and horticultural machines and implements	291	3.3	202,488
	10	Philosophical, musical, horological, and surgical instruments	739	8.3	509,289
Manufactures	11	Cotton	65	0.7	42,952
	12 & 15	Woollen and Worsted	501	5.6	343,616
	13	Silk and Velvet	80	0.9	55,224
	14	Flax and Hemp	96	1.1	67,496
	16	Leather, Saddlery and Harness, Boots and Shoes, Skins, Fur, and Hair	335	3.8	233,168
	17	Paper, Printing, and Bookbinding	212	2.4	147,264
	18	Woven, Felted, and Laid Fabrics, Dyed and Printed (including Designs)	94	1.1	67,496
	19	Tapestry, Carpets, Floor-cloths, Lace, and Embroidery	403	4.5	276,120
	20	Articles of Clothing for immediate, personal, or domestic use	218	2.5	153,400
	21	Cutlery, Edge and Hand Tools	50	0.6	36,816
	22	General Hardware, including Locks and Grates	810	9.1	558,377
	23	Works in Precious Metals, Jewellery, &c.	140	1.6	98,176
	24	Glass	100	1.1	67,496
	25	China, Porcelain, Earthenware, &c.	61	0.7	42,952
	26	Furniture, Upholstery, Paper Hangings, Decorative Ceilings, Papier Mache, and Japanned Goods	536	6.0	368,160
	27	Manufactures in Mineral Substances, for Building or Decoration	145	1.6	98,176
	28	Manufactures from Animal and Vegetable Substances, not being Woven or Felted	201	2.3	141,128
	29	Miscellaneous Manufactures and Small Wares	320	3.6	220,896
Fine Arts	30	Sculpture, Models, and Plastic Art, Mosaics, Enamels, &c	367	4.1	251,576
Total	-	-	8,903	100	6,136,006

Table 6.18 Number of exhibits in different categories (Great Exhibition, 1851)

Because this research focuses on the national economic benefit and relevant environmental impact from the Great Exhibition and there is great difficulty in discovering exactly what these are, two factors in terms of the total number of exhibits and the number of patents are combined here, and the category of transport (represented by the railway industry, because it was the main energy-consuming industry for transportation in the 1850s), is selected to be representative of the exhibition-related effect for estimating economic and associated environmental impact (assessed by ecological footprint). Secondly, the railway was an important transportation means for visitor travel to the exhibition and also a necessary tool for helping the construction of the Crystal Palace (Moser, 2002. p.25). Trains brought the prefabricated parts from factories and brought the heavy exhibits and provincial people who would not otherwise have come (Moser, 2002. p.25). In addition, the technological development of the railway also played a major part in the industrial revolution for local economic development (Deane and Cole, 1962, p.182).

6.2.3.2 Economic-related ecological footprint

The economic-related environmental impact is quantified here using the Ecological Footprint (EF) method (Wackernagel and Rees, 1996). The direct and indirect environmental impact caused by the event is translated first into energy consumption (GJ) and then to land area (gha) and the results comprehensively demonstrate the potential impact generated by visitors, exhibits and exhibitors.

In order to work out the ecological footprint of the indirect impacts of the Great Exhibition the money has to be turned into 'land'. Currently this is usually done by using a dollar/energy unit value. For example, EPA Victoria (2005, p.11) produced an input-output calculation model by translating 1996-1997 economic tables provided by the Australian Bureau of Statistics to the environmental footprints, and then were able to get footprint values per dollar of expenditure. Plan Bleu (2011) discussed the question of what is the impact of human activities on the environment by comparing the ecological footprint per unit of GDP of the Mediterranean countries. No such units were available for 1851. Section 6.2.3.2 sets out in detail how a land value was calculated for the part of the indirect economic benefit related to all categories in Table 6.18 that could be said to come under the umbrella of manufacturing and manufactured products, termed 'mineral' (as opposed to 'animal' or 'vegetable'). To simplify the process the assumption is made that the detailed calculations of land footprint related to the railways under the heading 'machinery' can be applied to all other entries in the overall category 'mineral'. A similar method is applied to the animal and vegetable categories where the land to money transfer is based on the ecological footprint of the food sold at the 1851 exhibition.

1. Economic-related direct environmental impact

- EF from tickets sold by the Great Exhibition in 1851

The environmental impact from tickets sold was mainly attributed to visitor travel. The method of input-output analysis was applied to calculate its ecological footprint.

- EF from food and drink sold at the Great Exhibition in 1851

The total ecological footprint of food and drink is found by multiplying the total weight of food sold and the average EF of each type of food. The average ecological footprint of conventional food used for the calculation is from UK data based on research into the ecological footprint of Cardiff (Cardiff Council, 2005). Food produced in the 1850s can be seen as organic food as it was grown with minimal, or without, synthetic chemical fertilizers and pesticides. Organic crops tend to give lower yields, however, there was no reliable data available for this study in terms of land requirements for organic agriculture in the UK in 1851 (Barrett et al, 2005; Collins, 2007). In this study it is assumed that production of organic and conventional food has similar land requirements.

2. Economic-related indirect environmental impact

The potential exhibition-related environmental impact from the Great Exhibition was quantified by looking at the ecological footprint of the railway industry (the reason has been described in section 6.2.3.1). The total ecological footprint of the railway industry stimulated by the Great Exhibition in the UK (1851-1860) includes the EF of land, construction of trains and railway tracks, construction of railway stations and operation of the railways (the reason for selecting the railway industry as the main and representative calculated model is stated in section 6.2.3.1).

- Land

By the end of 1851, there were 6,696 miles of railway line open to traffic and 10,201 miles of railway were opened to the public by 1860 (Deane and Cole, 1962, p232-233). The increase in opened railway line in 10 years was 3,505 miles (5,641,000m). In addition, the absolute minimum width of land needed for an English double track railway line is 30 feet (9.14 metres) (Greenleaf and Tyers, 1948, p.23). The width for a double track railway line is assumed here to be 10 metres. Because the type of rail tracks (single or double) built between 1851 and 1860 has not been found, the width for all rail lines is assumed here to be 10 metres.

The area occupied by all new railway lines in UK 1851-1860 was 56,410,000 m^2 (5,641 hectares). To change this into global hectares a calculation method from McLaren et al (1998, p.337) and Monfreda et al (2004) was used.

- Construction of trains and railway tracks

1) Construction of trains

The ecological footprint of the construction of trains is found by converting the embodied energy of new trains built from 1851 to 1860 in the UK, including the embodied energy of locomotives and wagons into land (the embodied energy of new trains means the total energy consumed for manufacturing the trains). The embodied energy of locomotives and wagons is multiplied by the number of products, weight of different types of products, and average embodied energy per tonne.

The dominant builders of locomotives during the ten years under consideration are sourced from literature. By 1850 the industry contained approximately 20 specialist builders with Stephensons, Sharp Brothers (Manchester), E.B. Wilson (Leeds), Bury, Curtis and Kennedy (Liverpool), R. and W. Hawthorn (Newcastle Upon Tyne), William Fairbairn (Manchester) and Rothwell & Co. (Bolton) as the market leaders (Kirby, 1988). In this research, these seven leading builders are studied as the representative companies for estimating the embodied energy and ecological footprint of locomotives built from 1851 to 1860. The numbers and types of locomotives produced by these seven builders from 1851 to 1860 (Lowe, 1975) are listed in Table 6.19. The total number of locomotives manufactured in the 1850s was 1,190. According to the literature, the types of locomotive for passenger trains were 0-4-0, 0-4-2, 2-2-2, 2-4-0 and 4-2-0; and the locomotive type for freight trains was 0-6-0 (Table 6.19).

Company	Number of locomotives produced	Types of locomotive
Robert Stephenson and Company	300 (assumed)	4-2-0
Sharp and Brothers	300 (max)	2-2-2, 0-4-2
E.B. Wilson and Company	350 (max)	2-2-2, 2-4-0, 0-6-0
Bury, Curtis, and Kennedy	0	Closed down in 1851
R and W Hawthorn	80 (assumed)	2-2-2, 0-4-0
William Fairbairn & Sons	80 (min)	0-4-0, 2-2-2, 2-4-0, 0-4-2
Rothwell and Company	80 (assumed)	2-2-2, 4-2-0
Total	1,190	Passenger trains: 0-4-0, 0-4-2, 2-2-2, 2-4-0, 4-2-0 Freight trains: 0-6-0

Table 6.19 Number of locomotives produced by leading companies from 1851 to 1860 in the UK (Lowe, 1989)

Although no literature shows the unit weight of the different types of locomotive produced by these seven companies in the 1850s, the relevant weights of typical types of locomotive are listed in Table 6.20. The average weights for different types of locomotive used in the study are shown in Table 6.21.

The total weight of the different types of locomotive manufactured by the different companies is 25,020 tonnes (21,229 tonnes for passenger and 3,791 tonnes for freight locomotives) (Table 6.22).

Date	Name	Company	Type	Size	Weight
1837	Vulcan *	Charles Tayleur & Co., Vulcan Foundry, Newton-le-Willows	2-2-2	8ft (2.46 metre) driving wheels and 4ft 6ins (1.38 metre) carrying wheels	18¼ tonnes
1838	Thunderer *	R & W Hawthorn & Co., Newcastle	0-4-0	6ft (1.85 metre) coupled driving wheels	12 or 12½ tonnes
1838	Hurricane *	R & W Hawthorn & Co., Newcastle	2-2-2	10ft (3.08 metre) driving wheels and (probably) 4ft 6ins (1.38 metre) carrying wheels	11 tonnes 10 cwt
1848	largest Crampton type engine **	-	-	Two cylinders 18 in. diameter by 24 in. stroke, and the driving wheels were 8 ft. diameter	35 tonnes
1851	Folkstone ***	Robert Stephenson and Company	4-2-0	Wheels 3 feet 6 inches (1.07 m) diameter, driving wheels 6 feet (1.83 m) diameter. Cylinders 15"x 22" (380mmx560mm)	26¼ Tonnes
1880	- ****	Dubs & Co., Glasgow, Scotland, Neilson & Co., Glasgow, Scotland	0-4-2 ST	Total Wheelbase: 13' 0" Cylinders HP: Two - 9 x 18"	15.7 tonnes
1870	I.E. James *****	Baldwin	2-4-0	48 in.	55,000 lbs = 25 tonnes
1875	J. W. Bowker *****	Baldwin	2-4-0	48 1/4 in.	65,000 lbs = 30 tonnes
1868	William Bouch ******	North Road Works	0-6-0	4ft 11½in coupled wheels and the boiler was pressed to 130psi	32 tons 8 cwt (=32.4 tonnes)

* Marshall, R. (2004). A history of Britain's broad gauge railways, retrieved 18 July 2010, from http://laluciole.net/gwr/gwr01a-earlylocos.html
** Mike. (2007). The Story Of The Locomotive – 2, The Development of the Railway Engine after the Rainhill Trials, from http://mikes.railhistory.railfan.net/r114.html
*** Wikipedia. (2010). Crampton locomotive, retrieved 18 July 2010, from http://en.wikipedia.org/wiki/Crampton_locomotive
**** CLASS C 0-4-2 ST. (2010). Locomotive Specifications, retrieved 18 July 2010, from http://www.trainweb.org/nzsteam/c_0-4-2.html
***** Nevada State Railroad Museum. (2008). V & T Locomotive Roster. Retrieved 18 July 2010, from http://www.nsrm-friends.org/nsrm09.html
****** MacLean, J.S. (1923). *The locomotives of the North Eastern Railway, 1841-1922*. Newcastle, R. Robinson & Co., p.50. from http://www.steamindex.com/locotype/nerloco.htm

Table 6.20 Weight of different types of locomotive

Train	Type	Weight (tonne/item)
Passenger trains	2-2-2	15.0
	0-4-0	12.0
	0-4-2	15.7
	2-4-0	25.0
	4-2-0	26.3
Freight trains	0-6-0	32.4

Table 6.21 Unit weight of different types of locomotive used in the research

Company	Number of locomotives produced	Type of locomotives	Number	Weight (tonnes)	Total weight (tonnes)
Robert Stephenson and Company	300 (assumed)	4-2-0	300	26.25	7,875
Sharp and Brothers	300 (max)	2-2-2	150	15	2,250
		0-4-2	150	15.7	2,355
E.B. Wilson and Company	350 (max)	2-2-2	116	15	1,740
		2-4-0	117	25	2,925
		0-6-0	117	32.4	3,791
Bury, Curtis, and Kennedy	0	Closed down in 1851	-	-	-
R and W Hawthorn	80 (assumed)	2-2-2	40	15	600
		0-4-0	40	12	480
William Fairbairn & Sons	80 (Min)	0-4-0	20	12	240
		2-2-2	20	15	300
		2-4-0	20	25	500
		0-4-2	20	15.7	314
Rothwell and Company	80 (assumed)	2-2-2	40	15	600
		4-2-0	40	26.25	1,050
Total	1,190	-	1,190	-	25,020
* Values in imperial tons (1,016 kg) have been taken as tonnes (1,000 kg) for the sake of simplifying calculations.					

Table 6.22 Total weight of locomotives produced in the UK from 1851 to 1860

In addition, most passenger carriages were constructed of wood in the 19th century (Passenger car (rail), 2010). In 1836 in America it was reported that the weight of a double car for a train was 4.17 tonnes (2.1tonnes/car) (Minor and Schaeffer, 1836, p. 149). The weight for wagons for freight is assumed to be 2 tonnes per wagon, as these are lighter than passenger carriages. A passenger train is assumed to have had four carriages and the seating capacity of the carriages might vary between 12 and 33 passengers (Darjeeling Himalayan Railway, 2009). Eight wagons are assumed for freight trains.

2) Construction of railway tracks

For a traditional railway, the dominant railway track form worldwide consists of steel rails supported on timber or pre-stressed concrete sleepers (ties) (Rail tracks, 2010). In this study, the embodied energy of railway tracks thus includes the energy embodied in the steel rails and timber sleepers. This is multiplied by the weight of materials, the embodied energy coefficients of different materials and the total new mileage opened from 1851 to 1860.

In the nineteenth century bullhead rails were used in the UK. Typical weights per rail are 40 to 50 kg/m (Mike, 2007). The volume of a timber sleeper is assumed to be 0.04 m^3 (2.5 long, 0.2 wide and 0.08 high). As there are assumed to be 3 timber sleepers supporting the rail per metre (Greenleaf and Tyers, 1948, p.11), the volume of timber sleepers is 0.12 m^3 per metre.

- Construction of railway stations

According to the statistics, 718 stations were opened from 1851 to 1860 all over the world (List of railway stations, 2010), and 282 railway stations opened in the UK during the decade (Railway stations opened in 1851, 2010). The figure of 282 railway stations opened is used to calculate the embodied energy of stations in this research.

- Operation of the railways

The ecological footprint of railways also relates to the operating energy of railways opened from 1851 to 1860 in the UK. The operating energy of the railways is found by multiplying the energy intensity, number of trains, average distance of each trip and the average number of trips during the ten years.

The energy intensity of steam trains was about 4.2 MJ/passenger-km for the calculation (this has been discussed in section 6.2.2.3).

The average number of trips for railways (1851~1860) is referenced from the railway timetable on 50 selected important routes in 1850 and 1870 (Leunig, 2005). The average number of trips for the 50 important routes is 16 trips/route/day. The average distance of each trip is 143 km (measured by using Google Maps). If an average train travels at 50 km/h, and can operate for twelve hours a day, allowing for maintenance and for taking on coal and water, each train can make two return trips, or four trips in a day. The total number of locomotives manufactured from 1851 to 1860 was 1,190. Because all locomotives are regularly maintained, it is assumed only 1,000 new locomotives are operating at any one time, which is an additional 100 in each year.

- Ecological footprint of exhibition-related industries from 1851 to 1860 in the UK

Based on the results of the EF of the railway industry, the total ecological footprint of the exhibition-related industries can be estimated by using the percentage distribution of exhibits among the different industries in the Great Exhibition. To simplify the calculation, the 30 classes of exhibits classified by the committee of the Great Exhibition (listed in Table 6.18) are divided into two main categories, of "Animal/vegetable" and "Mineral". The ecological footprint of each category is converted from monetary value (income) to land usage.

6.3 Results and analysis

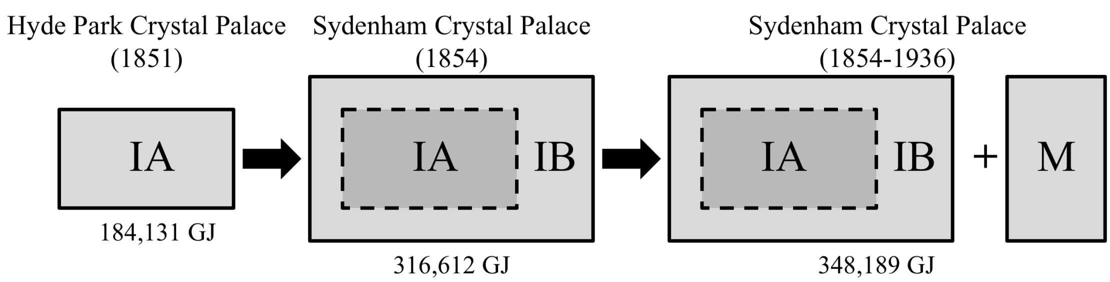
6.3.1 Building

The results of quantification of energy consumption of the Crystal Palace, in its construction, operating phases are demonstrated in the sections below.

6.3.1.1 Embodied energy

This section provides the detailed results of calculation through the whole life cycle (including the construction, maintenance, and operation phases) of the Crystal Palace and compares its unit energy intensity to those of modern buildings.

The total embodied energy of the Crystal Palace from 1851 to 1936, including the initial and recurring embodied energy (both at Hyde Park and the revised Sydenham version), is estimated to be 348,189 GJ (31 MJ/m^2/year).



IA=Initial embodied energy of Hyde Park Crystal Palace
IB=Initial embodied energy for new components of Sydenham Crystal Palace
M= Recurring embodied energy over 82 years

Figure 6.11 Schematic diagram showing the recycling of components from the Hyde Park Crystal Palace to Sydenham Crystal Palace

Materials	Building elements	Embodied energy of Original (1851) (GJ)	Embodied energy of rebuild and maintenance (1854-1936) (GJ)
Glass	Main building, Colonnade	6,120	8,175
Iron	Columns, Girders, Pipes, Connection collars, Metal louvres, Roof trusses, Boilers, Colonnade	157,925	84,625
Wood	-	13,592	0
Concrete	Foundations (footing)	1,078	1,438
Brickwork	Foundations	-	38,243
Paint (Durability: 5 years)	Columns, Girders, Pipes, Connection collars, Metal louvers, Roof trusses, New iron elements built for Sydenham Crystal Palace, Boilers, Colonnade, Wood	5,416	31,577
Total	-	184,131	164,058
In all	**348,189 GJ** (31 MJ/m^2/year)		

Table 6.23 Embodied energy of the Crystal Palace in Hyde Park and Sydenham (1851-1936)

In this research, the energy used for manufacturing the building elements of the Hyde Park Crystal Palace is defined as the initial embodied energy. The energy for new building elements and maintenance of original elements, which were used to construct the enlarged Sydenham Crystal Palace, is defined as the recurring embodied energy (Figure 6.11). The respective total embodied energy figures for the Hyde Park Crystal Palace (1851) and the additional materials and their maintenance for the Sydenham Crystal Palace (1854-1936) are 184,131 GJ and 164,058 GJ (Table 6.23). The increase from the move to Sydenham was mainly generated by the additional metal elements and maintenance (painting) of the iron and timber elements.

6.3.1.2 Operating energy

The total operating energy, which was only from the boilers of the Sydenham Crystal Palace, is estimated by the floor area and energy intensity for heating a normal greenhouse, to give 12,673,920 GJ (1.12 GJ/m^2/year) , as shown in Table 6.24.

	Area	Energy intensity (GJ/m^2/year)	Useful life (years)	Operating energy (GJ)	Total
Hyde Park Crystal Palace	92,000	0	<1	0	**12,673,920 GJ**
Sydenham Crystal Palace	138,000	1.12	82	12,673,920	

Table 6.24 Operating energy of the Crystal Palace in Hyde Park and Sydenham (1851-1936)

Visitors from	Regions	Number of visitors (thousand)	Distances travelled (km)	Coal consumption (3.0 MJ/Passenger/ km, UK) (4.1 MJ/passenger /km, USA) (GJ)	Wood consumption (3.5 MJ/passenger/km) (GJ)
Outer London boroughs	-	747.6	9	20,185	-
England (Expect London)	North East	90	427	115,290	-
	North West	324	294	285,768	-
	Yorkshire and the Humber	177	294	156,114	-
	East Midlands	303	193	175,437	-
	West Midlands	240	175	126,000	-
	East of England	196.5	87	51,287	-
	South West	141	184	77,832	-
	South East	28.5	90	7,695	-
Wales	-	330	230	227,700	-
Scotland	-	330	607	600,930	-
Ireland	-	330	413	408,870	-
Europe	*	26	247 (Berlin→Hamburg) (Paris→Le Havre)	19,266	-
	**	26	115 (Southampton→ London)	8,970	-
Americas	***	1.3	355 (coal) (Boston→NY) (Washington→NY)	1,892	-
		1.3	355 (wood) ((Boston→NY) (Washington→NY)	-	1,615
	****	5	115 (Southampton→London)	1,725	-
Oceania	-	0.4	115 (Southampton→London)	138	-
Asia	-	0.4	115 (Southampton→London)	138	-
Africa	-	0.4	115 (Southampton→London)	138	-
Total	-	-	-	2,285,375	1,615
In all	Fuel consumption of steam trains: 4,573,980 GJ (one way = 2,286,990 GJ)				

* European visitors took steam trains to the main ports. They are assumed to come from Germany and France.
**European visitors took steam trains to go to London when they arrived in the UK.
***American visitors who did not live in New York (assumed to come from Boston and Washington, D.C.) took steam trains (coal or wood as the fuel) to go to New York.
**** All American visitors took steam trains to go to London, after arriving in the UK.

Table 6.25 Energy consumption of visitors taking steam trains in 1851

Visitors	Number of visitors (thousand)	Distances travelled (km)	Coal consumption of steamships (1.0 MJ/passenger/km) (GJ)
Ireland	330	100	33,000
Europe	52	564	29,328
Americas	5	5,700	28,500
Oceania	0.4	21,580	8,632
Asia	0.4	19,070	7,628
Total	-	-	107,088
In all	Fuel consumption of steamships: 214,176 GJ (one way = 107,088 GJ)		

Table 6.26 Energy consumption of visitors taking steamships in 1851

6.3.2 Visitor travel

The total energy consumption as a result of using horses, steam trains and steamships was 5,063,520 GJ. The energy consumed by horse-related transport was 275,364 GJ (see section 6.2.2.5). The total energy consumed by steam trains was 4,573,980 GJ, as shown in Table 6.25. Furthermore, the energy used by steamships was 214,176 GJ (Table 6.26).

In addition, their CO_2 emissions were 425,080 tonnes for travel by steam trains and 19,918 tonnes by steamships (Table 6.27).

Visitors from	**Steam train**		**Steamship**
	CO_2 emissions by burning coal (0.093 kg CO_2/MJ) (tonnes)	**CO_2 emissions by burning wood (0 kg CO_2/MJ)**	**CO_2 emissions by burning coal (0.093 kg CO_2/MJ) (tonnes)**
Outer London boroughs	1,877	-	-
England (Expect London)	92575	-	-
Wales	21,176	-	-
Scotland	55,886	-	-
Ireland	38,025	-	3,069
Europe	2626	-	2,728
Americas	336	0	2,651
Oceania	13	-	803
Asia	13	-	709
Africa	13	-	-
Total	212,540	0	9,959
In all	CO_2 emissions of steam trains: 425,080 tonnes (one way= 212,540 tonnes)		CO_2 emissions of steamships: 19,918 tonnes (one way = 9,959 tonnes)

Table 6.27 CO_2 emissions of visitors taking steam trains and steamships in 1851

The total energy consumption and CO_2 emissions of visitor travel (return) were 5,063,520 GJ and 444,998 tonnes during the six months of the exhibition (Table 6.28).

	Fuel consumption (GJ)	CO_2 emissions (tonnes)	Average CO_2 emissions (g CO_2/pass-km)	Average CO_2 emissions (g CO_2/passenger)
Horse	275,364	0	0	0
Steam trains	4,573,980	425,080	280	64
Steamships	214,176	19,918	93*	51
Total	5,063,520	444,998	-	-
* The emission per passenger-km for ships is low because it is assumed that they are also carrying cargo.				

Table 6.28 Energy consumption and average carbon emissions of transport in 1851

6.3.3 Exhibition-related economic aspects

The direct economic benefits were £256,437 and the indirect benefits were £61,360,060 (£6,136,006/year over 10 years) (this has been discussed in section 6.2.3.1). The total exhibition-related economic profits contributed by the Great Exhibition from 1851 to 1860, thus, were calculated as £61,616,497 (£256,437+£61,360,060). The economic-related direct and indirect environmental impacts are demonstrated below.

1. Economic-related direct environmental impact

The ecological footprint from direct economic income (the food and drink sold in the Great Exhibition) is calculated as 1,221 gha from May to Oct 1851 (Table 6.29), as the environmental impact from tickets sold was attributed to visitor travel.

Types	EF (gha)	Types	EF(gha)
Bread	5.3	Savoury Patties	10.2
Cakes	291	Macaroons	0.7
Victoria biscuits	4.7	Preserved fruits	1.0
Sausage rolls	7.5	Savoury pies	24.1
Milk	43.7	Rich cakes	1.6
Cream	185	Mustard	0.3
Jelly	3	Meat	287
Pickles	2	Potatoes	10.8
Pineapples	0.1	Rough Ice	36.3
Biscuits	23.8	Salt	32.6
Coffee	28.7	Hams	62
Tea	1.6	Pear syrup	1.4
Chocolate	12.1	Schweppes soda water, lemonade, and ginger beer	144.2
Total	1,221 gha (0.000202gha/visitor)		

Table 6.29 EF of refreshments sold (Peskett, 2006; Cardiff Council, 2005)

2. Economic-related indirect environmental impact

- Land

The area occupied by all new railway lines in UK 1851-1860 was 56,410,000 m^2 (5,641 hectares). The land area occupied by new railways 1851-1860 was 12,467gha (Table 6.30).

Total length of increase in opened railway line from 1850 to 1860	3,505 miles (=5,641,000m)
Assumed width	10 m (Greenleaf and Tyers, 1948, p.23)
Land occupied by railway line	56,410,000m^2 (5,641,000×10)
Ecological footprint of railway line	12,467gha

Table 6.30 Calculation of the ecological footprint of railway lines

- Construction of trains and railway tracks

1) Construction of trains

The ecological footprint of the construction of trains is found by converting the embodied energy of new trains built from 1851 to 1860 in the UK, including the embodied energy of locomotives and wagons into land. Table 6.31 shows the total embodied energy and ecological footprint of passenger and freight trains produced from 1851 to 1860 (40,788gha).

Passenger trains	Embodied energy per tonne for train manufacture and service	113,600MJ/t (CarbonNeutral, 2008)
	Weight of locomotives	21,229 tonnes (1,073 items)
	Weight of carriages	9,013 tonnes (2.1t/each×4 carriages=8.4tonnes)
	Total weight of passenger trains	30,242 tonnes
	Total embodied energy	3,435,491,200 MJ
	Ecological footprint	34,355gha
Freight trains	Embodied energy per tonne for train manufacture and service	113,600MJ (CarbonNeutral, 2008)
	Weight of locomotives	3,791 tonnes (117 items)
	Weight of wagons	1,872 tonnes (2t/each×8 wagons=16tonnes)
	Total weight of freight trains	5,663 tonnes
	Embodied energy of wagons	643,316,800 MJ
	Ecological footprint	6,433gha
Total	Total ecological footprint	40,788gha

Table 6.31 Calculation of embodied energy of trains

2) Construction of railway tracks

The total embodied energy of new railway tracks opened from 1851 to 1860 is 13,887,529 GJ (Table 6.32). The total ecological footprint of railway tracks is 138,875gha.

Elements of railway tracks	**Volume/m**	**Weight/m**	**Embodied energy coefficient**	**Total embodied energy/m**	**New mileage opened**	**Total embodied energy**
Steel rails	0.01 m^3/m	80 kg/m (two rails per m) (Density: 7,700kg/m^3)*	24.40 MJ/kg**	1,952 MJ/m	5,640,751 m (3,505 miles)	11,010,746 GJ
Timber sleepers	0.12 m^3/m	60 kg/m (average density of pine: 500 kg/m^3)***	8.50 MJ/kg**	510 MJ/m	5,640,751 m (3,505 miles)	2,876,783 GJ
Total	-	-	-	2,462 MJ/m	-	13,887,529 GJ

*Elert, G. (2005). Density of steel. The Physics Factbook™. Retrieved August 2, 2010, from http://hypertextbook.com/facts/2004/KarenSutherland.shtml
** Hammond, G., & Jones, C. (2008). *Inventory of carbon & energy (ICE), Version 1.6a*. Sustainable Energy Research Team (SERT), Department of Mechanical Engineering, University of Bath, UK.
*** Simetric. (2009). Weight of various types of wood. Retrieved July 10, 2010, from http://www.simetric.co.uk/si_wood.htm

Table 6.32 Embodied energy of new railway tracks opened from 1851 to 1860

- Construction of railway stations

Most of the railway stations built in the UK during the decade in question were constructed of wood or brick. The average floor area of the station buildings was around 470 m^2 (135m^2-810m^2). If construction of railway stations was similar to conventional houses in the UK, the average embodied energy per square metre of railway stations could be assumed to be 5 GJ/m^2 as the embodied energy of load-bearing masonry houses ranges from 4.5GJ/m^2 to 5.5 GJ/m^2 (Balderstone, 2004). The total embodied energy for railway stations built from 1851 to 1860 in the UK is calculated as 11,750 GJ (5GJ/m^2×470m^2×282), giving an EF of 118 gha.

- Operation of the railways

The total operating energy for new passenger railways in the UK from 1851 to 1860 would be 39,100,000 GJ (4 trips/train/day × 365 days × 143 km/train/trip × 0.375 GJ/km × 500 locomotives (average new available over ten years)). The freight trains are assumed to have run at night and assumed to consume the same energy for operation as the passenger trains, as although there are fewer locomotives, they are likely to be pulling much greater loads. The total operation energy for trains was 78,300,000 GJ and the total EF for operation is 783,000 gha.

The total ecological footprint generated from the railway industry during 10 years was 975,248 gha, including the EF of land, construction of trains, railway tracks, stations, and operation of the railways, as shown in Table 6.33. Operating the railways consumed most of the energy and resources.

Factor	EF (gha)
Land	12,467
Construction of trains and railway tracks	179,663
Construction of railway stations	118
Operation of the railways	783,000
Total for 10 years	975,248

Table 6.33 Ecological footprint of exhibition-related railway industry from 1851 to 1860 in the UK

- Ecological footprint of exhibition-related industries from 1851 to 1860 in the UK

The annual exhibition-related income of the railway industry from 1851 to 1860 was £687,233 (shown in Table 6.18) and the annual EF for railway industry was 97,525 gha (Table 6.33). This means 1gha resource consumption relates to £7.0 of income for the railway industry every year (Table 6.34). This railway footprint is used to represent the footprint of all "Mineral" exhibit categories. The income of the "Mineral" category was £4,043,627/year, which equates to an ecological footprint of 577,661gha per annum.

For the category of "Animal/vegetable", a similar method is used and the result is converted from the EF of refreshments sold at the Great Exhibition. The income from refreshments sold was £45,000 and their total EF was 1,221gha (Table 6.29), which means 1gha of resource consumption generated £36.86 in income for food sold. The ecological footprint for the "Animal/ vegetable" category is, therefore, 57,098gha/year.

Category	Income	Income/ EF	EF/year	Total EF (gha)
Mineral*	£4,043,627 /year	£7.0/gha/year (£687,233 /97,525gha)	577,661gha/year (£4,043,627/7.0)	5,776,610
Animal/ vegetable**	£2,104,648 /year	£36.86/gha/year (£45,000/1,221gha)	57,098gha/year (£2,104,648/36.86)	570,980
Total	£5,905,213 /year	-	-	6,347,590
*Including classes of 1,2,5,6,7,8,9,10,21,22,23,24,25,27,29,30 (in Table 6.18) **Including classes of 3,4,11,12,13,14,15,16,17,18,19,20,26,28 (in Table 6.18)				

Table 6.34 Ecological footprint of exhibition-related industries from 1851 to 1860 in the UK

6.4 Whole life-cycle impact

Total ecological footprint of this case study including three aspects was 686,973gha in a year. The average ecological footprint of each aspect is demonstrated in Table 6.35.

	Total ecological footprint in a year (gha/year)	Average ecological footprint (gha/visitor/year)	Average ecological footprint (gha/m^2/year)
Crystal Palace	1,579	0.0003	0.01
Visitor travel going to the building	50,635	0.0084	0.37
Exhibition-related economic aspects	634,759	0.1051	4.60
Total	686,973	0.1138	4.98

Table 6.35 Total ecological footprint of the case study

- Further comparisons

The further comparison is made between the ecological footprint of the 1851 international event and the 2003/04 FA Cup Final as studied by Collins et al (2007b) (Table 6.36).

Factors	Great Exhibition (6 months) (41,939 visitors/day) (Opened six days per week)		2003/04 FA Cup Final (1 day) (Collins et al, 2007) (73,069 visitors)	
	Total EF (gha)	Average	Total EF (gha)	Average
Food	1,221 (6 months)	0.0002 gha/visitor	1,381	0.189 gha/visitor
Building	130,221 (82 years)	0.0000008 gha/visitor/day	0.10	0.00001 gha/visitor/day
Travel	50,635 (6 months)	0.0084 gha/visitor	1,670	0.228 gha/visitor
Event-related economy	6,347,590 (10 years)	0.1051 gha/visitor	-	-

Table 6.36 Comparison of EF (four factors) between the Great Exhibition and 2003/04 FA Cup Final

Collins et al (2007b) calculated the ecological footprint of food consumption, infrastructure, visitor travel, and waste generated from the day of the FA Cup Final. The objective for the comparison here is to demonstrate whether the event-related environmental impact has been mitigated in the context of the development of sustainable technologies. Through the comparison, the results also assist researchers and policy-makers in exploring the problems embodied in the operation of large events.

Food. Food consumption for the day of the FA Cup Final was calculated as 0.189gha per visitor, which was much higher by 945 times than the average for the food consumed daily by a visitor to the Great Exhibition in 1851 (0.0002 gha). Although it is not clear whether people in the 19th century needed less food than now or whether people living in modern society waste more food than before, one factor is the fact that no alcohol, with its high EF (Cardiff Council, 2005) was served at the Great Exhibition (Gibbs-Smith, 1950, p.34).

Building. The average ecological footprints of the buildings for the Great Exhibition and the FA Cup Final are not directly comparable. The reason is that the average footprint of the stadium for the FA Cup Final was sourced from average data of general infrastructure in the UK, including schools and offices. Secondly, the FA Cup calculation is based on the assumption that the stadium has 100-year lifespan with an estimated 100 million visitors during that period (Collins et al, 2007). The assumption for this lifespan can be argued, because some buildings have not had the long useful life predicted, for example the Dutch Pavilion at the Hannover Expo (Ivar hagendoorn, 2000) was only used for 5 months. The Wembley Stadium was opened by King George on 23rd April 1924 (Wembley Stadium, 2010) and a new stadium was opened on the same site in 2007, an 82 year life. Stadia are also renovated during their lifetime, as has happened at Eden Park in New Zealand opened in 1914, which has been undergoing major renovation for the 2011 Rugby world Cup (EDEN PARK, 2010).

Travel. An average ecological footprint for visitor travel to the Great Exhibition and the FA Cup Final is found in both studies, although the transport modes were different. The travel footprint was 0.0084gha/visitor for the former event and 0.228gha/visitor for the latter.

Event-related economic stimulus. The average ecological footprint from economic factors was 0.11 gha per visitor for the Crystal Palace. However, there is no relevant study for the FA Cup Final because this was a different sort of event that did not set out to boost economic activity.

Waste. Collins et al (2007) indicated that the waste for the FA Cup Final was calculated for separate categories, including glass, food, paper and card, plastic, metals, and miscellaneous. The waste from a historic event, such as the Great Exhibition, is difficult to discover, so the factor of waste is not compared here, although this could be a subject of further research.

6.5 Chapter conclusion

The study has indicted that the total energy consumption and ecological footprint of a major event over the whole cycle has increased from the 1850s to the present. In addition, the event-related economic factor has a significant impact, which is usually ignored because it is invisible. The consumption patterns of visitors, such as transport modes used or types of food consumed, do impact on the ecological environment. The results also show that operating a large scale event can generate a correspondingly large ecological footprint irrespective of when the event occurred.

Chapter 7 Conventional case study: Exhibition activities at the Shanghai Exhibition Centre between 1955~2011

7.1 Introduction

This chapter looks at the energy and resource consumption of the national exhibitions held in the Shanghai Exhibition Centre, China, in a year, as a case study of a conventional exhibition venue. The energy and resource consumption of the Shanghai Exhibition Centre, visitor travel, and exhibition-related economic aspects will be quantified (the research boundary has been explained in section 5.1). The main reason for selection was explained in section 5.3. The method of quantitative work, results, and related analysis of this case study are described in the following sections.

The Shanghai Exhibition Centre holds exhibitions regularly at the national level (7,500,000 visitors annually[2]). It was designed by architects from the Soviet Union and built in 1955. Some structural elements were reinforced, and it was renovated, with the main elevation redecorated and two more exhibition halls added, in 2001. The total floor area of this building is 80,000 square metres. There are four Exhibition Halls together with one Convention Hall providing space for both display and convention activities. Although it was built half a century ago, its structure and materials can serve as a typical example representing this type of public building in a humid subtropical climate in Eastern Asia.

7.2 Method

This section aims to explain the detailed methods for quantifying the whole life cycle energy and resource consumption of the conventional exhibition venue case study, based on the Shanghai Exhibition Centre itself (7.2.1), annual visitor travel (7.2.2), and annual exhibition-related economic aspects (7.2.3).

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[2] This data was calculated from the average number of visitors attending an exhibition in a year in China. 7,500,000 is the average number of visitors to a national exhibition in China. Source from http://shbbs.soufun.com/1210195822~-1~3919/37355969-37355969.htm, retrieved on 5th November, 2008 (in Chinese).

7.2.1 The Building

Energy consumption of the building comprises the embodied energy (7.2.1.1), operating energy (7.2.1.2), and building demolition-related energy (7.2.1.3). The definition of these sorts of energy usage has been explained in Chapter 5.

7.2.1.1 Embodied energy

The embodied energy of the building includes the energy consumed by the initial and recurring building processes. In terms of the case study building, the initial energy was embodied in the original construction of the Exhibition Centre in 1955, and the recurring energy was generated by replacement of materials through maintenance, renovation and construction of the new parts of the building from 1956 to 2011 (the useful life is thus defined as 56 years).

The calculation of the initial embodied energy of the case study building uses the quantities of materials (volume, weight) and the relevant energy intensities. Relevant parameters, such as the size or weight of components, are sourced from literature and the official website of the Shanghai Exhibition Centre. The bills of quantity of construction materials and drawings of the detailed building plans were prepared and used for quantitative calculations in this research (SMTA, 2010).

The materials quantified for the Shanghai Exhibition Centre are shown in Table 7.1. The main structure of the building (foundations, columns, beams, floors, walls, staircases, and roof) was built of concrete. Cement mortar, granite, and paint were used for the finishes. Glass, steel, timber, and copper were used for windows and doors and for decoration. Other construction materials, such as plywood and plaster, were used to form the ceilings.

Materials	Components	Volume	Weight
Reinforced concrete	Foundations, Columns, Beams, Floors, Walls, Staircases, Roof	43,010 m^3	107,527 t
Damp proof membrane	Foundations	15,305 m^2	214 t
Cement mortar 1:3	Columns, Beams, Floors, Walls, Roof	1,813 m^3	3,265 t
Granite	Columns	3726 m^3	90 t
Paint	Columns, Walls, Ceiling, Roof	96,643 m^2	20 t
Terrazzo	Staircases, Floors	653 m^3	1502 t
Rockwool	Wall, Roof	726 m^3	18 t
Float glass	Windows, Doors	3,563 m^2	88 t
Steel	Windows	13.6 m^3	106 t
Timber	Windows, Doors	85 m^3	51 t
Copper	Doors	1.25 m^3	11 t
Plywood	Ceiling	8221 m^2	16 t
Plasterboard	Ceiling	4989 m^2	80 t
Plaster	Ceiling	293 m^3	381 t
Asphalt	Roof	18900 m^2	189 t
Stone	Staircases	17 m^3	44 t

Table 7.1 Material breakdown of the Shanghai Exhibition Centre (Appendix B)

A main factor in the analysis, the energy intensities of materials used for the calculation of the embodied energy of the case study building, are taken from typical Australian data (from Treloar, 1994). Owing to the fact that establishment of the Chinese embodied energy database (Sino Centre) is ongoing, values for Chinese energy intensities are substituted with Australian data for energy consumption because of the similar proportions of fuel mix for electricity generation compared to other countries, as shown in Table 7.2. Research which has applied the Australian data to similar calculations has demonstrated appropriate results in terms of the embodied energy of case studies in China (Chen et al, 2001; Wang and Cai, 2006).

In addition to the building fabric, the impact of the energy embodied in the building services needs to be considered in the calculation of this case study building. From a literature review, Cole concludes that the total initial embodied energy used in the building services for a general concrete office building (no underground parking) accounts for 24.5% of the total energy embodied in all the materials (Cole and Kernan, 1996). However, in Treloar's research (1996), the building services represent 19% of the embodied energy of a commercial building in Melbourne (Cole and Kernan, 1996). Pullen used 20% when calculating the embodied energy of building services for a campus building in Australia in 2000 (Pullen, 2000). Thus, in this study a proportion of 20% of the total embodied energy of the building has been used for calculating the extra embodied energy of the building services.

China (2007)				
Fuel mix	Coal	Hydro	Nuclear	Others
Percentage	87.38	7.11	1.72	3.79
CO_2 emissions factor	1 kg/kWh			

UK (2005) (Mithraratne et al., 2007)					
Fuel mix	Natural gas	Coal	Nuclear	Renewables	Others
Percentage	39.3	33.4	20.6	3.8	2.9
CO_2 emissions factor	0.46 kg/kWh				

Australia (2005) (Mithraratne et al., 2007)						
Fuel mix	Black coal	Brown coal	Gas	Hydro	Oil	Others
Percentage	54.8	21.9	14.2	6.8	1.3	1.0
CO_2 emissions factor	1.051 kg/kWh					

USA (2007) (EIA, 2009)							
Fuel mix	Coal	Nuclear	Natural gas	Hydro	Other renewables	Petroleum	Other gases
Percentage	48.5	19.4	21.6	5.8	2.5	1.6	0.3
CO_2 emissions factor	0.648 kg/kWh (EIA)						

NZ (2004) (Mithraratne et al., 2007)						
Fuel mix	Hydro	Gas	Coal	Wind	Geothermal	Others
Percentage	63.9	16.1	9.7	1.1	6.4	2.7
CO_2 emissions factor	0.1 kg/kWh					

Table 7.2 Fuel mix of electricity generation in different countries

Secondly, recurring embodied energy is calculated in terms of the energy required for repairs, maintenance, and refurbishment. This study looks at the life-cycle of the building over 56 years (1955-2011). Energy consumption for maintenance and replacement of construction materials is quantified, according to the useful life of different construction materials. The method of calculation for recurring embodied energy is the same as that for initial embodied energy.

7.2.1.2 Operating energy

The energy consumption of the Shanghai Exhibition Centre is found by multiplying the construction area and the value for electricity usage per square metre. Electricity consumption for the building is not known, but in Shanghai public buildings consume 150~300 DU (1DU=1000Wh) per square metre per year (Ren, 2007).

From 1955 to 2001, the Shanghai Exhibition Centre used diesel boilers as the building heating system. After the building renovation in 2001, air-conditioning was installed for heating and cooling. Figures are known for similar buildings, the Wu Han International Exhibition Centre, China; and the 21st Century Museum of Contemporary Art, Kanazawa, Japan. These are discussed below to allow comparison with the situation in Shanghai.

The gross construction area of Wu Han International Exhibition Centre is 126,000 m^2. According to published statistics, electricity consumption apart from air conditioning of this building is 36,280 kWh per day. If this building opens every day, its total consumption in a year will be 13,242,200 kWh (Zhang et al, 2004). This makes 105kWh/m^2/year for the electricity consumption apart from the air conditioning load.

The total internal floor area of the 21st Century Museum of Contemporary Art is 17,093 m^2 and it is circular in form, with a diameter of 112.5 m (Kanazawa, 2004). Its average electricity consumption (per month) is about 300,000 kWh (2007). Therefore, the total electricity use is about 3,600,000 kWh a year. This is 210kWh/m^2/year.

In addition, according to a speech made by the Vice Minister of Construction of China (2004), the average electricity consumption of a government office located in the western area of China (per square metre per year) is 132 kWh. Furthermore, the average electricity consumption if it were located in the eastern area of China (per square metre per year) would be 139 kWh (Xing, 2007).

Given the two values of 105kWh/m^2/year and 210kWh/m^2/year for two exhibition type buildings with and without air-conditioning, the figures quoted by the Vice Minister of Construction and an additional figure of 150kWh/m^2/year for all public buildings in Beijing (buildings over 20,000 m^2 with a centralized air-conditioning system) (Jiang and Xue, 2004), this research uses a average value of 124kWh/m^2/year (446 MJ/m^2/year) in the following calculations of energy use for the case study exhibition building ($(105 \times 46 + 210 \times 10) \div 56$).

The gross floor area of the Shanghai Exhibition Centre, which includes the first floor exhibition area and the outdoor exhibition venue, is 93,000 m^2 and the constructed area which means the whole footprint area of the exhibition building is 80,000 m^2. The electricity consumption of the Shanghai Exhibition Centre is assumed to be 9,920,000 kWh/year (35,712,000 MJ/year).

7.2.1.3 Building demolition-related energy

The energy consumption from building demolition is assumed to be negligible in this study. The reason for this has been explained in section 5.1.

7.2.2 Visitor travel

Both of the methods of calculating energy consumption and carbon emissions generated from transportation are described in this section. This was the case study for which the calculation method of visitor travel was first derived. The method was then used for the other case studies.

The energy consumption of visitor travel (transportation) can be quantified and demonstrated by the number of users, the distances of travel, and the energy intensity of different transportation modes.

7.2.2.1 Number of visitors

In Shanghai, the public transport modes include underground, taxi and bus. The official reporting category ‘private automotive vehicles’ consists of cars and motorcycles; whereas ‘non-motorized transport’ means bicycle, electric bike and scooter even though a scooter uses oil as its energy source.

According to an interview with the Party Committee Associate Secretary of Shanghai Transportation Bureau in 2007, transport usage in Shanghai shows 27% of people taking trips using public transport, and 4.86%, 6.21% and 15.93% of people choosing underground, taxi and bus respectively. Moreover, just over 17.5% of people use a private automotive vehicle, which includes 2.1% using a motorcycle (Wang, 2005) and 1.78%, 11.06%, 2.56% in three sizes of cars based on the market share for different cars in 2007 (Zhang, 2008; Chen et al, 2009). The percentage of people in the ‘non-motorized vehicle' category was 28.5%, the majority of which used bicycles (22.14%), with 5.53% using an electric bike and 0.83% a scooter (Liu et al, 2008). Finally, 27% opted to walk for their journey (Table 7.3).

Mode	Number of people per year	Mode (detail)	Percentage of people per year	Average Number of people per year
Public transport	2,025,000 (27%)	Underground	4.86%	364,500
		Taxi	6.21%	465,750
		Bus	15.93%	1,194,750
Private automotive vehicle	1,312,500 (17.5%)	Motorcycle	2.10%	157,500
		Car	1.78%(Small)	133,500
			11.06% (Medium)	829,500
			2.56%(Large)	192,000
Non-motorized vehicle	2,137,500 (28.5%)	Bike	22.14%	1,660,500
		Electric bike	5.53%	414,750
		Scooter	0.83%	62,250
Walk	2,025,000 (27%)	-	-	2,025,000
In all	7,500,000 people per year			

Small= Small petrol car (up to 1.4 litre engine) (Defra, 2007);
Medium= Medium petrol car (1.4-2.0 litres) (Defra, 2007);
Large= Large petrol car (above 2.0 litres) (Defra, 2007)
The percentage of people using the underground accounted for 18% of public transport use in 2007. This figure is expected to increase to 40% in 2012 when 12 new underground lines will be completed (Zhang, 2007).

Table 7.3 Average number of visitors going to Shanghai Exhibition Centre by different transport modes

The average number of visitors going to the Shanghai exhibition centre is about 7,500,000 each year. These numbers were generated from the number of visitors going to a major exhibition and the number of such exhibitions each year (Jiang, 2006). Assuming an average of 7.5 million visitors a year, the numbers of visitors using different modes of transport are shown in Table 7.3.

7.2.2.2 Distances of visitor travel

The number of visitors travelling with regard to taking different transport modes was recalculated from the percentage breakdown of the total Shanghai population living in different districts. There are 19 districts in Shanghai. However, the underground and bus routes are located in only 12 of the districts. Further data are shown in Tables 7.4, 7.5. Note that where transport modes are unavailable no people have been assigned to these in the tables. It is also assumed that cost means that people will not use a taxi if they live a long way from the centre in the outlying districts 13-19. Because of the number of different transport modes, these have been split between the two tables, starting with public transport and moving to private transport.

Another variable that needed consideration was the distance from the Shanghai Exhibition Centre to every district. The average point at which visitors can take the underground or buses to reach the destination was chosen by using the mid-point of access to public transport. Twelve spots located on the mid-points of access to public transport routes in the twelve districts were selected. The visitors from other districts which do not have public transport were assumed to use cars and the average distances they travelled were assumed to be from the mid-points of each district to the Shanghai Exhibition Centre.

Area	The percentage of population	The number of visitors (thousand)	The number of people taking various modes (thousand)				
			Underground (4.86%)	Taxi (6.21%)	Bus (15.93%)	Motorcycle (2.1%)	Small petrol car (1.78%)
1	6.3%	473	22.97	29.34	75.27	9.93	8.41
2	5.1%	383	18.59	23.75	60.94	8.04	6.81
3	5.7%	428	20.78	26.55	68.10	8.98	7.61
4	7.8%	585	28.43	36.33	93.19	12.29	10.42
5	4.4%	330	16.04	20.49	52.57	6.93	5.88
6	2.3%	173	8.39	10.71	27.48	3.625	3.07
7	4.4%	330	16.04	20.49	52.57	6.93	5.88
8	13.9%	1043	50.67	64.74	166.07	21.89	18.56
9	6.5%	488	23.69	30.28	77.66	10.24	8.68
10	2.3%	173	8.39	10.71	27.48	3.625	3.07
11	6%	450	21.87	27.95	71.69	9.45	8.01
12	6.4%	480	23.33	29.81	76.47	10.08	8.55
13	3.9%	293	-	-	-	35.10 (12.00%)	29.75 (10.17%)
14	5.3%	398	-	-	-	47.70 (12.00%)	40.43 (10.17%)
15	3.7%	278	-	-	-	33.30 (12.00%)	28.23 (10.17%)
16	3.8%	285	-	-	-	34.20 (12.00%)	28.99 (10.17%)
17	3.9%	293	-	-	-	35.10 (12.00%)	29.75 (10.17%)
18	3.3%	248	-	-	-	29.70 (12.00%)	25.17 (10.17%)
19	5.0%	375	-	-	-	45.00 (12.00%)	38.14 (10.17%)
In all	100%	7500	235.84	301.34	773.00	372.09	315.36

Table 7.4 The number of visitors taking different transport mode in 19 Districts (part 1)

Area	**The percentage of population**	**The number of visitors** (thousand)	**The number of people taking different transport modes (thousand)**					
			Medium petrol car (11.06%)	Large petrol car (2.56%)	Bike (22.14%)	Electric bike (5.53%)	Scooter (0.83%)	Walk (27%)
1	6.3%	473	52.26	12.10	104.61	26.13	0.39	127.58
2	5.1%	383	42.31	9.79	84.69	21.15	0.32	103.28
3	5.7%	428	47.29	10.95	94.65	23.64	0.36	115.43
4	7.8%	585	64.70	14.98	129.52	32.35	0.49	157.95
5	4.4%	330	36.50	8.45	73.06	18.25	0.28	89.10
6	2.3%	173	19.08	4.42	38.19	9.54	0.14	46.58
7	4.4%	330	36.50	8.45	73.06	18.25	0.28	89.10
8	13.9%	1043	115.30	26.69	230.81	57.65	0.87	281.48
9	6.5%	488	53.92	12.48	107.94	26.96	0.41	131.63
10	2.3%	173	19.08	4.42	38.19	9.54	0.14	46.58
11	6%	450	49.77	11.53	99.63	24.89	0.38	121.50
12	6.4%	480	53.09	12.29	1074.34	26.55	0.4	1310.18
13	3.9%	293	184.86 (63.2%)	42.79 (14.63%)	-	-	-	-
14	5.3%	398	251.22 (63.2%)	58.16 (14.63%)	-	-	-	-
15	3.7%	278	175.38 (63.2%)	40.60 (14.63%)	-	-	-	-
16	3.8%	285	180.12 (63.2%)	41.70 (14.63%)	-	-	-	-
17	3.9%	293	184.86 (63.2%)	42.79 (14.63%)	-	-	-	-
18	3.3%	248	156.42 (63.2%)	36.21 (14.63%)	-	-	-	-
19	5.0%	375	237 (63.2%)	54.86 (14.63%)	-	-	-	-
In all	100%	7500	1959.64	453.64	2148.69	268.34	8.06	2620.35

Table 7.5 The number of visitors taking different transport modes in 19 Districts (part 2)

7.2.2.3 Energy intensity of different transport modes

The energy intensity of each different transport mode, including underground, taxi, car, bus, motorcycle, electric bike, and scooter, in China is sourced from available literature and listed in Table 7.6.

Modes		Fuel	Energy intensity (MJ/passenger-km)	Reference
Underground		Electricity	0.071	Zhang, 2010, p.39
Taxi		Fossil fuel	2.494	Zhang, 2010, p.39
Car	Small	Fossil fuel	1.467	Zhang, 2010, p.39
	Medium	Fossil fuel	2.304	
	Large	Fossil fuel	3.133	
Bus		Fossil fuel	0.648	Xie, Huang and Ma, 2010; Li and Wu, 2008
Motorcycle		Fossil fuel	1.000	IFEU, 2008, p.32
Electric bike		Electricity	0.036	Li, 2005
Scooter		Fossil fuel	0.086	IFEU, 2008, p.32

Table 7.6 Energy intensity of different transport modes in China

7.2.2.4 CO_2 emissions coefficients

Carbon emissions generated from visitors going to the Shanghai Exhibition Centre are also calculated by combining the number of visitors, distance of travelling, and average emissions of different transport modes. The number of visitors taking different transport modes to go to the Shanghai Exhibition Centre and the distances of travelling are the same as the figures provided in the last section.

The CO_2 coefficients of different transport modes in Shanghai are converted by energy value to carbon dioxide equivalent value. Using 1 kWh of grid electricity can generate 0.839 kg CO_2 in China (U.S. Department of Energy, 2007). Burning 1 kWh of petrol emits 0.24176 kg CO_2 (Carbon Trust, 2011). The coefficients are listed in Table 7.7.

Modes		Fuel	CO_2 emissions coefficients (g/passenger-km)	Calculation
Underground		Electricity	16.6	0.071× 0.2778 × 0.839 × 1000
Taxi		Fossil fuel	167.5	2.494 × 0.2778 × 0.24176 × 1000
Car	Small	Fossil fuel	98.6	1.467× 0.2778 × 0.24176 × 1000
	Medium	Fossil fuel	155.0	2.304× 0.2778 × 0.24176 × 1000
	Large	Fossil fuel	210.0	3.133× 0.2778 × 0.24176 × 1000
Bus		Fossil fuel	43.5	0.648× 0.2778 × 0.24176 × 1000
Motorcycle		Fossil fuel	67.2	1.000 × 0.2778 × 0.24176 × 1000
Electric bike		Electricity	8.4	0.036× 0.2778 × 0.839 × 1000
Scooter		Fossil fuel	5.8	0.086 × 0.2778 × 0.24176 × 1000

Table 7.7 CO_2 emissions coefficients of different transport modes in China

7.2.3 Exhibition-related economic aspects

7.2.3.1 Exhibition-related economic income

The exhibition industry, as a service industry, generally consumes fewer natural resources than manufacturing industries. However, the exhibition-related indirect effect, which has extremely large potential economic profits, can be assumed to be the much more significant factor in terms of consuming resources and reducing environmental quality.

The exhibition-related economic impact and subsequent environmental deterioration of the Shanghai national exhibitions can be separated into two principal parts – one is the direct effect from the exhibition activities (e.g. the impact of exhibitions, such as the selling of tickets and related services), the other part is the indirect impacts, which means the additional effect on the environment generated from the increasing production of exhibiting manufacturers or the higher consumption of goods stimulated by the exhibitions.

The direct environmental effect from the exhibition activities is estimated by the level of activity of the local exhibitions industry, population, and the national Ecological Footprint intensity of China. From the literature review, the monetary output of the Shanghai exhibition industry was 1,800,000,000 RMB in 2001, which accounted for about 0.4% of total GDP in Shanghai (OLGMEDIA, 2002). Additionally, the Shanghai Bureau of Statistics reported the population of Shanghai in 2001was about 16,800,000.

7.2.3.2 Economic-related ecological footprint

In this section, resource consumption of exhibition-related economic aspects is quantified by the Ecological Footprint method. The Ecological Footprint intensity is defined as "the ratio of the EF and the real status of the economic output, which depicts the resource consumption intensity corresponding to unit economic output". The ratio of GDP to EF per capita directly shows the close relationship between the 'land demand' and economic output (Farber et al, 2002). For China, Qi (2008) concludes that the Ecological Footprint intensity decreased steadily over the period 1981–2001, from 429 RMB/gha in 1981 to 5,139 RMB/gha in 2001 (Figure 7.1)

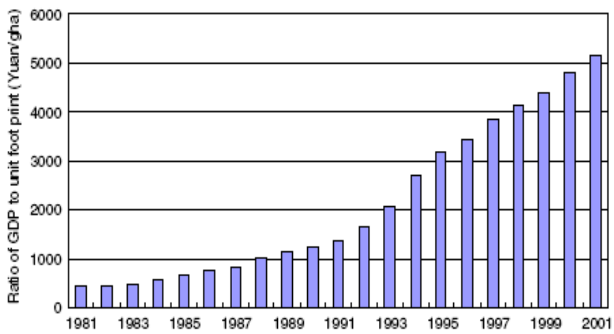


Figure 7.1 Time series of ratio of GDP to Ecological Footprint in China from 1981 to 2001(Qi, 2008)

The indirect exhibition-related economic impact cannot be measured by one criterion, because the effect derived from exhibitions is integrated and compounded. The most significant function of holding an exhibition is to stimulate local and international consumption of products manufactured by exhibitors. It means the additional effect on the environment may be increased invisibly and the environmental impact sustained in the long term.

In this research, the indirect economic impact is depicted and demonstrated by several typical categories of industries, which account for most exhibitions held in Shanghai. There were 167 and 211 exhibitions held in Shanghai in 2008 and 2009 respectively. The main categories of exhibitions were Clothing, Leather, Textiles; Machinery, Industry, Process; and Chemicals, Energy, Environmental protection. Figure 7.2 shows the number of exhibitions in the main categories from 2008 to 2009.

It can be seen that the category of clothing and textiles was the major focus of exhibitions in Shanghai in these two years.

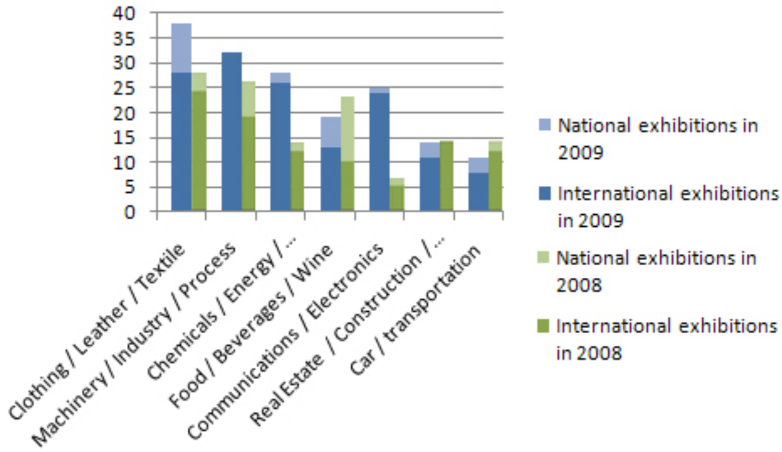


Figure 7.2 Number of exhibitions in main categories in Shanghai from 2008 to 2009

The ecological footprint of each category in 2008 is calculated from the Shanghai GDP of each industry, Shanghai population (19,000,000 people), and the 2001 national Ecological Footprint intensity of China (5,139 RMB/gha). The GDP of each category is found by multiplying the total GDP of Shanghai (1,370 billion RMB) in 2008 and the percentage of output of each industry.

7.3 Results and analysis

7.3.1 Building

The results of quantification of the energy consumption of the case study building, the Shanghai Exhibition Centre, in its construction, and operating phases are shown below.

7.3.1.1 Embodied energy

For the embodied energy of the case study building, the initial embodied energy of the Shanghai Exhibition Centre is estimated at 439,884 GJ or 11.2 GJ/m^2 (Table 7.8). The total recurring embodied energy (over a life of 56 years) of the Shanghai Exhibition Centre is estimated at 150,590 GJ or 3.8 GJ/m^2. In the initial construction phase, building foundations, building services facilities and exterior walls of the case study building account for a large proportion of the embodied energy (60%). For the recurring embodied energy, because the case study building received two new Exhibition Halls (around 40,000m^2) in 2001, the average embodied energy of the building (11.2 GJ/m^2) was used to calculate the embodied energy of these two Exhbition Halls. The recurring embodied energy for the extensions is 168,298 GJ. The total embodied energy is 758,772 GJ (Table 7.8).

The other analysis is focused on the weight and choice of construction materials of the case study building. The total weight of the Shanghai Exhibition Centre (excluding building services, which are unlikely to add much to the weight), is 112,420t or 2.9t/m^2 (Table 7.10).

Elements	Initial embodied (GJ)	Percentage (%)
Foundations	110,638	25.2
Columns	13,758	3.1
Beams	14,244	3.2
Floors	22,587	5.1
External walls	73,439	16.7
Internal walls	42,614	9.7
Windows	9,853	2.2
Doors	2,697	0.6
Ceiling	11,084	2.5
Staircases	2,926	0.7
Roof	20,594	4.7
Arch structure	5,022	1.1
Galleries	22,446	5.1
Services	87,977	20.0
Total	439,884	100

Table 7.8 Quantification of initial embodied energy of the Shanghai Exhibition Centre (Appendix B)

	Energy use
Initial embodied energy of the building (1955-2001)	439,884 GJ
Recurring embodied energy for maintenance (56 years)	150,590 GJ
Recurring embodied energy for extension	168,298 GJ
Total embodied energy	758,772 GJ

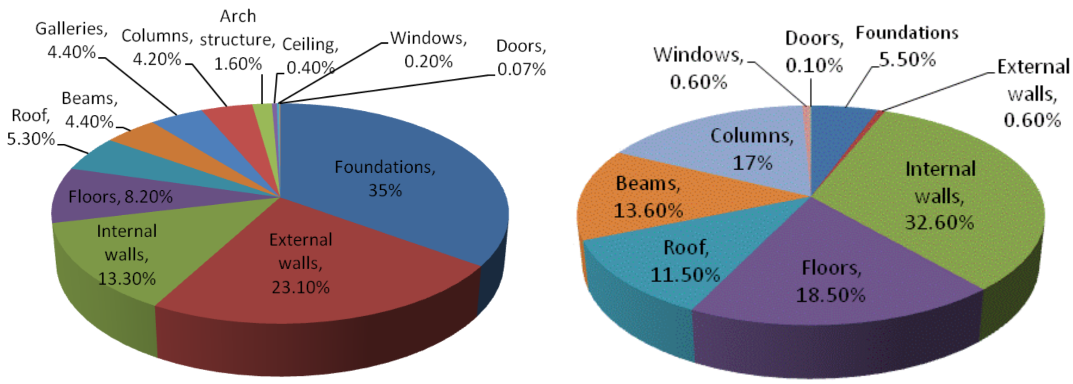
Table 7.9 Total embodied energy of the Shanghai Exhibition Centre (1955-2011)

Elements	Shanghai Exhibition Centre		
	Materials	Total weight (t)	Percentage (%)
Foundations	Reinforced concrete, Damp proof membrane	39,344	35.0
External walls	Reinforced concrete, Rockwool, Cement mortar, Paint	25,952	23.1
Internal walls	Reinforced concrete, Rockwool, Cement mortar, Paint	14,981	13.3
Floors	Reinforced concrete, Cement mortar, Terrazzo	9,191	8.2
Roof	Reinforced concrete, Rockwool, Asphalt, Cement mortar, Paint	5,943	5.3
Beams	Reinforced concrete, Cement mortar	4,942	4.4
Galleries	Reinforced concrete, Asphalt, Cement mortar, Paint	4,917	4.4
Columns	Reinforced concrete, Cement mortar, Granite, Paint	4,660	4.2
Arch structure	Reinforced concrete, Cement mortar, Paint	1,751	1.6
Ceiling	Plywood, Plaster, Plasterboard, Paint	484	0.4
Windows	Float glass, Steel, Timber	182	0.2
Doors	Timber, Glass, Copper	73	0.07
Total	-	112,420 (2.9t/m^2)	100

Table 7.10 Total weight of the Shanghai Exhibition Centre (1955-2001) (excluding services)

It is obvious that the Shanghai Exhibition Centre is much heavier than the Crystal Palace. Compared to other metal structure buildings, the Crystal Palace was a lightweight building (the main structural elements were made from iron). If comparisons are made in terms of the weight of each type of building component between the Shanghai Exhibition Centre (1955-2001) and the Crystal Palace (1851-1936), some new insights can be noted.

Figure 7.3 shows the weight of each element of the two buildings as a percentage of the total. It is interesting to find that the heaviest components of the Shanghai Exhibition Centre are the foundations and walls, which are built of reinforced concrete, and account for about 71.4% of the total weight. For the Crystal Palace, the timber walls and floors are heavier than the other building elements, being around 51.1% of the total.



Total weight of the Shanghai Exhibition Centre *Total weight of the Crystal Palace*

Figure 7.3 Comparison of the weight of the two case study buildings (excluding services)

It is worth noting that the average initial embodied energy (per square metre) of the conventional exhibition building is 4.1 times that of the historic building. It is evident that the old large single space building consumed much less energy than the Shanghai Exhibition Centre in the initial phase of building construction, although it was erected using a large amount of cast iron, which has a much higher embodied energy than concrete. The comparison regarding the initial embodied energy of elements of these two buildings is also revealing. For the conventional exhibition building, building foundations and exterior walls account for a large proportion of the embodied energy (52.3%); while in 1851 most initial embodied energy for the Crystal Palace was contained in the roof, beams, and columns (67%).

Furthermore, if the Crystal Palace is viewed as a large public building with a steel structure, because the embodied energy coefficient for iron is similar to that of steel, this case study suggests that large public buildings with steel structures could have a lower embodied energy, but this may only be true because of the Crystal Palace's greenhouse-like design.

7.3.1.2 Operating energy

The operating energy is determined by the electricity useage of the building per year. After calculation, the total operating energy of the Shanghai exhibition centre building was 1,999,872 GJ, or 35,712 GJ per year. This means the average operating energy consumption of this building is 5 MJ/visitor annually.

If this figure is compared with the average consumption of the ASB Showgrounds in Auckland, New Zealand, the issue of how energy was consumed becomes much more evident (Table 7.11). Owing to the lack of relevant data about the energy consumption of New Zealand exhibition buildings, consumption is assumed to be similar to the energy usage of NZ buildings in general and office buildings in particular. The average energy usage per building occupied in 2006 was 107kWh/m^2 per year in New Zealand (MED, 2007). However, for an office building, energy use was 269kWh/m^2 per year (Pink Panther, 2006). So the average energy usage per square metre of an exhibition building is assumed here to be 200kWh/ m^2 per year. Thus, the electricity consumption of the ASB Showgrounds building, 15,000 m^2 (ASB SHOWGROUNDS, 2010), will be 10,800 GJ/year. When this is translated to electricity use per visitor the figures become much closer in value (Table 7.11).

Buildings	Electricity consumption	Average electricity consumption
Shanghai Exhibition Centre	45,520 GJ/year	5 MJ/visitor/year
ASB Showgrounds (Aucland)	10,800 GJ/year	9 MJ/visitor/year

Table 7.11 Comparison between Shanghai Exhibition Centre and ASB Showgrounds

7.3.2 Visitor travel

Using the proportions in every district, the numbers of people choosing different transport modes in every district were calculated.

The total energy consumption of visitors travelling by different transport modes is 204,431 GJ, or 0.027GJ/visitor in a year. The energy usage of visitors taking different transport modes is listed in Table 7.12. The medium petrol car had the highest total consumption compared to the other transport modes (see Table 7.3).

It is noted that these average numbers for different modes of transport do not give a very accurate basis for calculation of consumption as they do not take into account how easy it is to access the building for the different transport modes, or the distance travelled. To avoid complication, this study will not take account of visitors who do not come from Shanghai. It should be noted that visitors from outside Shanghai are likely to have larger transport-related consumption because of their greater travel distance. This means that the figures given in this paper for transport consumption related to attending the exhibitions are likely to be a lowest possible estimate.

The CO_2 emissions of visitor travel by transport are given by multiplying the average distance from the Shanghai Exhibition Centre to the centre of every district in Shanghai by the number of people and appropriate CO_2 emissions factor. The total CO_2 emissions for each visitor to the exhibition, including the travel to the exhibition and back home, were twice this result. Therefore, the results for CO_2 emissions of people's travel are presented in Table 7.13, giving total emissions of 27,473 t per year.

Area	Average distance (km)	Energy consumption that people taking different transport generate (GJ)								
		Under Ground (0.071)	Taxi (2.494)	Bus (0.648)	Motor cycle (1.000)	Small petrol car (1.467)	Medium petrol car (2.304)	Large petrol car (3.133)	Electric bike (0.036)	Scooter (0.086)
1	6.05	10	442	295	60	75	728	229	23	14
2	7.20	9	426	284	58	72	701	221	22	13
3	8.35	12	552	368	75	93	909	286	28	17
4	11.31	23	1023	682	139	173	1683	530	53	31
5	7.2	8	368	245	50	62	605	191	19	11
6	0.79	0	21	14	3	4	35	11	1	1
7	5.15	6	263	175	36	44	433	136	14	8
8	11.2	40	1808	1205	245	305	2974	936	93	55
9	6.17	10	466	311	63	79	767	241	24	14
10	3.63	2	97	65	13	16	160	50	5	3
11	6.29	10	438	292	59	74	721	227	23	13
12	6.99	12	520	346	70	88	855	269	27	16
13	24.92	-	-	-	876	1089	10632	3347	-	-
14	39.23	-	-	-	1874	2330	22736	7157	-	-
15	36.74	-	-	-	1226	1524	14873	4681	-	-
16	47.98	-	-	-	1641	2040	19912	6268	-	-
17	31.67	-	-	-	1114	1385	13512	4254	-	-
18	36.80	-	-	-	1095	1362	13290	4183	-	-
19	42.50	-	-	-	1913	2378	23207	7305	-	-
Total		143	6425	4282	10609	13190	128732	40522	331	197
In all：204,431 GJ (0.027GJ/visitor)										

Table 7.12 Energy consumption of visitors who travelled by different transport modes

Area	Average distance (km)	CO_2 emissions that people taking different transport generate (t)								
		Under ground (0.0000166)	Taxi (0.0001675)	Bus (0.0000435)	Motor cycle (0.0000672)	Small petrol car (0.0000986)	Medium petrol car (0.000155)	Large petrol car (0.00021)	Electric bike (0.0000084)	Scooter (0.0000058)
1	6.05	2	30	20	4	5	49	15	1	0.01
2	7.20	2	29	19	4	5	47	15	1	0.01
3	8.35	3	37	25	5	6	61	19	2	0.02
4	11.31	5	69	46	9	12	113	36	3	0.03
5	7.2	2	25	16	3	4	41	13	1	0.01
6	0.79	0.11	1	1	0.19	0	2	1	0.06	0.00
7	5.15	1	18	12	2	3	29	9	1	0.01
8	11.2	9	121	81	16	20	200	63	5	0.06
9	6.17	2	31	21	4	5	52	16	1	0.01
10	3.63	0.51	7	4	1	1	11	3	0.29	0.00
11	6.29	2	29	20	4	5	49	15	1	0.01
12	6.99	3	35	23	5	6	58	18	2	0.02
13	24.92	-	-	-	59	73	714	224	-	-
14	39.23	-	-	-	126	156	1528	479	-	-
15	36.74	-	-	-	82	102	999	313	-	-
16	47.98	-	-	-	110	137	1340	420	-	-
17	31.67	-	-	-	75	93	907	285	-	-
18	36.80	-	-	-	73	91	892	280	-	-
19	42.50	-	-	-	129	160	1561	490	-	-
		33	432	288	712	886	8652	2714	19	0.20
In all：27,473 t (one way= 13,736 t)										

Table 7.13 Calculated CO_2 emissions of people's travel

7.3.3 Exhibition-related economic aspects

On the basis of the calculation method (explained in section 7.2.3), the total ecological footprint of exhibition-related industries of the selected five categories was 181,360,000gha, or 2.0gha/capita. As exhibition-related economic income was around 5% of total benefits (mentioned in section 7.2.3), the total ecological footprint of exhibition-related economic aspects was 9,068,000gha, or 1.21gha/capita (Table 7.14).

Categories	**Percentage of output in GDP (%)** (NBS, 2006)	**Output** (thousand RMB)	**Total EF of exhibition-related industries** (thousand gha)	**Total EF of exhibition-related economic aspects** (thousand gha)	**Average EF of exhibition-related economic aspects** (gha/capita)
Clothing / Leather / Textile	7.03 (A8M. 2009)	96,311,000	18,741	937	0.05
Machinery / Industry / Process	45.4	621,980,000	121,031	6052	0.32
Food / Beverages / Wine	1.9	26,030,000	5,065	253	0.01
Real Estate / Construction / Decoration	7.3	100,010,000	19,461	973	0.05
Car / transport	6.4	87,680,000	17,062	853	0.05
Total	-	932,011,000	181,360	9,068	1.21

Table 7.14 Ecological footprint of different categories of products held in Shanghai exhibitions in 2008

7.4 Whole life-cycle impact

The total ecological footprint of the case study building for holding Shanghai exhibitions for the three aspects considered was 9,070,537gha/year, or 1.2095 gha per visitor per year (Table 7.15).

	Total ecological footprint in a year (gha/year)	Average ecological footprint (gha/visitor/year)	Average ecological footprint (gha/m^2/year)
Shanghai Exhibition Centre	493	0.0001	0.01
Visitor travel going to the building	2,044	0.0003	0.03
Exhibition-related economic aspects	9,068,000	1.2091	113.35
Total	9,070,537	1.2095	113.39

Table 7.15 Total ecological footprint of the case study

The fact that the environmental effect of transportation is worse than that of building construction is perhaps entering the awareness of researches and users (Jurasovich, 2003). This study shows that the environmental impact of visitor travel has 4 times the effect than that of the building construction. (The results of the Ecological Footprint analysis for the Shanghai Exhibition Centre and Shanghai exhibition industry are shown in Table 7.15.)

However, the invisible impact generated from the economic growth, stimulated by the exhibitions, is huge and not something of which people are aware. The analysis in this study shows that the average ecological footprint of exhibition-related economic impact is much more than the impact of visitor travel to attend the exhibitions every year. The exhibition-related economic factor is the most significant aspect compared to the other two impacts in this case study. The results indicate that environmental impact measurements cannot just be focused on the energy consumption of building construction or infrastructure.

Comparing the ecological footprint of the exhibition industry and other exhibition-related industries, it is interesting to find that the exhibition industry itself is generally one of the lowest resource-dependent industries and the input of the exhibition industry is much lower than that of other industries. Many national governments have held, and apply to hold, international exhibitions (World Expo) every year, although the direct profit of some international exhibitions is negative (e.g. EXPO 2000 in Germany). This phenomenon not only shows the close relationship between exhibitions and economic growth, but also reveals how economic benefits connect to government policy and public awareness.

On the other hand, people are not yet aware of the findings of environmental research. For example, the current global average footprint demand is 2.7 global hectares (WWF, 2008). The average footprint of China was 2.1gha in 2008 and 2.5gha in 2010 (WWF, 2008; WWF, 2010). Although this figure is nearly equal to the average demand, the ecological footprint is dramatically increasing every year in China corresponding to the increase in national GDP. The exhibition-related economic stimulus directly and indirectly enhances national input and may also lead to an overshoot in resource consumption, which will directly influence the living environment. It is possible for China to reduce the ecological footprint but perhaps only if there are no more exhibitions.

7.5 Chapter conclusion

This chapter describes the energy and resource consumption of the case study building and the events held there and demonstrates what the most significant factor is that directly and indirectly degrades environmental quality as a result of holding exhibitions in Shanghai. The case study shows that the environmental measurement boundaries should be broader and capable of considering the economic aspect, when exhibition activities are studied. At this moment, for some developing countries such as China and India, the percentage of exports (e.g. clothing and textile industry) in the total national GDP is dramatically increasing from year to year. The international exhibitions held in these countries give them good opportunities to enlarge the national trade and increase the rate of employment, resident income and revenue, but at the same time, it should be noticed that exhibitions indirectly increase the local resource consumption and bring more environmental pollution to the countries. The questions of how to measure accurately the real environmental impact and how to balance an increasing economic perspective for every country with less effect on the environment need to be considered further by environmental researchers and policymakers. On this can then be based the development of energy efficiency techniques and the design of sustainable buildings, as well as the planning of more sustainable societies.

Chapter 8 Modern sustainable exhibition case study 1: Dutch participation at Expo 2000

8.1 Introduction

This case study is mainly concerned with the energy intensity and ecological footprint of a sustainable exhibition building, specifically the Dutch Pavilion, visitor travel, and an element of the exhibition-related economic effect at Expo 2000 (the reason for the selection has been provided in section 5.3).

The Dutch Pavilion (6,144 m^2), as one of the most popular pavilions in Expo 2000, was attractive to visitors because of its sustainable design and construction. It was designed as the exhibition hall of The Netherlands for World Expo 2000 in Germany by MVRDV. It mixed natural elements (agriculture and flowers, container gardens, forest, rain and sand dunes) and exhibition activities in a six storey building. The actual useful life was 5 months, during the time of the expo.

8.2 Method

This section provides the detailed methods for quantifying the whole life cycle energy and resource consumption of the modern sustainable building case study, the Dutch Pavilion (8.2.1), visitor travel (8.2.2), and exhibition-related economic aspects (8.2.3).

8.2.1 Building

The quantification of construction materials and energy use generally includes an estimation of embodied energy (initial and recurring), operating energy and demolition-related energy use. This study looks at both the energy and resource consumption of the Dutch Pavilion over its actual 5 month life and an assumed 50 year life.

8.2.1.1 Embodied energy

The assessment of embodied energy in this case study building mainly includes the initial and recurring energy consumed by the building's construction and maintenance. The recurring energy appears when a 50 year life is assumed for the Dutch Pavilion in order to look at the effect of short building life in a whole life-cycle assessment.

1. Initial embodied energy

The calculation of the initial embodied energy of the case study building uses the quantities of materials (volume, weight) and the relevant energy intensities as found in German data (explained below). Relevant parameters, such as the size or weight of components and structural elements, are sourced from the literature about the building (Martina, 2000; Cecilia and Levene, 2002; MVRDV, 2005). A list of the quantities of construction materials and drawings of building floor plans were prepared and used for the quantitative calculations in this research (see Appendix C).

The energy intensities of materials used for the calculation of the embodied energy mainly come from German data (Anon, 1994; Eyerer et al, 2000; Pohlmann, 2002), because the construction of the Dutch Pavilion was based on local German building technology. In addition, owing to the lack of referenced energy intensities for some materials, UK data (Hammond and Jones, 2008) were also used in the quantification of energy used in making the case study building. The reason for using UK data is because the UK energy intensity factor is similar to that of Germany (Anon, 1994; Hammond and Jones, 2008) (see Table 6.2). It shows the match between UK and German data is reasonable.

Moreover, as a result of the special sustainable design approach of the Dutch Pavilion, the impact of the energy embodied in the building services needs to be considered separately from the quantification of other building elements in the calculation. The detailed data for building services used in each floor is unknown. An average proportion (20%) of the embodied energy is applied to the six levels in this calculation due to the variety of service systems in the case study building. The reason for using the average energy intensity to calculate the embodied energy of building services is because on the water and windmill floors, the application of technologies such as the water pond and water reclamation systems, involves a greater level of energy for producing the equipment. On the other hand, the other floors (the forest floor, dunes floor, pot floor and glass floor) have less energy embodied in the manufacture of the services systems, because of using natural ventilation. The average energy intensity is used for the calculation to balance the two levels of energy use. Some special aspects of the building have their embodied and recurring energies calculated separately, as detailed below.

Special sustainable design features of the Dutch Pavilion were the installation of wind turbines on its top floor and its green roof. The types of materials utilised during the wind generator manufacturing are steel, cast iron, glass reinforced plastic, copper, paints, lubricant oils, aluminium, PVC, and bronze (Ardente et al, 2008). The initial embodied energy of wind turbines (six on the building) is quantified by using the weight and energy coefficients of the different materials (Table 8.1). In addition, detailed information on the green roof and roof pond are taken from the literature (Herbert et al, 2001; David, 2002; Pledge, 2005), and used to quantify their initial embodied energy (Table 8.2).

Materials	**Weight (kg)** (Ardente et al, 2008)	**Factors (MJ/kg)** (Anon, 1994; Eyerer et al, 2000; Pohlmann, 2002; Hammond and Jones, 2008)	**Embodied energy (MJ)**
Steel	6,643	15	99,645
Cast iron	600	25	15,000
Glass reinforced plastic (76% of glass fibres, 24% of epoxy resin)	495	100	49,500
Copper	92	50	4,600
Paint	39	68	2,652
Aluminium	9	155	1,395
PVC	7	77.2	540
Bronze	0.5	77	39
Total initial embodied energy: 173,371 MJ			

Table 8.1 Initial embodied energy of six wind turbines

	Materials	**Weight (kg)**	**Factors (MJ/kg)** (Anon, 1994; Eyerer et al, 2000; Pohlmann, 2002; Hammond and Jones, 2008)	**Embodied energy (MJ)**
Green roof	Waterproofing PVC	138	77.2	10654
	Asphalt (Waterproofing layer)	25000	2.6	65000
	Mineral wool (Insulation)	50	5	250
	PVC (Drainage layer)	138	77.2	10653
	PVC (Substrate)	138	77.2	10653
Roof pond	Reinforced concrete (Structure)	512500	2.54	1301750
	Mineral wool (Thermal insulation layer)	620	5	3100
	Asphalt (Waterproof layer)	30000	2.6	78000

Table 8.2 Initial embodied energy of green roof and roof pond

2. Recurring embodied energy

Recurring embodied energy is defined as the energy required for repairs, maintenance, and refurbishment of buildings in their useful life. The Dutch pavilion had a useful life of only 5 months although it was designed for a longer life. To reveal the impact of creating exhibition buildings that are not recycled a comparison is made here between the actual life of the building and an assumed life of 50 years (2000-2050) in the calculation of energy use for maintenance and replacement. The 50 year life was taken because the pavilion was comparable in structure and construction to a normal commercial building. Energy consumption for maintenance and replacement of construction materials is quantified according to the useful life of different construction materials in Germany. The method of calculation for recurring embodied energy is the same as that for initial embodied energy.

The analysis shows the energy consumed by maintenance of the six wind turbines (Table 8.3) on the top floor is much more than for the other construction elements or materials. Ardente *et al* demonstrate that usually the useful life of a wind farm is 20 years, which means most of the wind turbines will be replaced at the end of this period. In their investigation the electrical company concerned had specific scheduled maintenance and control cycles. These involved a daily inspection during the first operation period and, successively, one inspection every 2 ~ 3 weeks. If the inspection personnel choose to use diesel cars the overall energy consumption for related transportation would be about 7,000 kg of diesel during the 20 years of useful life. Cycles of ordinary maintenance occur 2 ~ 3 times per year, and these involve lubrication, painting and substitution of necessary spare parts (Ardente et al, 2008).

	Embodied energy (MJ)	Useful life (years)	Recurring embodied energy (MJ)
Wind turbines	4,038,048	20	8,076,096
Transportation of personnel undertaking inspection	317,100 (45.3 MJ/kg)	20	792,750
Maintenance spare parts	605,707 (15% of embodied energy of wind turbines)	20	1,514,268
Total recurring embodied energy: 10,383,114 MJ			

Table 8.3 Recurring embodied energy of six wind turbines

8.2.1.2 Operating energy

The operating energy is defined as the energy used for a building in its operation phase, such as the electricity consumption for lighting, cooling and ventilation. As the case study building has a special construction and different functions for each floor, the operating energy (mainly electricity) is not as much as found in conventional commercial buildings. In addition the electricity consumption of the whole building is less because some electricity comes from the wind turbines on the roof.

The steel tower of a wind turbine with nominal power rating of 660 kW as found in Ardente's study was 55m high and the rotor diameter was about 50m (Ardente et al, 2008). However, the output from the six windmills around 15m high and with a 5m rotor diameter as installed on the Dutch Pavilion will be small compared to the demands of the whole building. It can be assumed that the generation of a small windmill of this type (10 kW) is around 10,000kWh/year (Jimenez, 2010), making the total amount of energy generated 60,000kWh/year. The distance between two small turbines for maximum effectiveness is usually 20 ~ 30m (CANWEA, 2009; Migliore, 2009). However, the distance between the small wind turbines installed on the Dutch Pavilion is less than 15m. This will reduce the generating capacity of the turbines (Herbert et al, 2001). Overall, the total maximum possible electricity production of the windmills of the Dutch Pavilion is 20,000 ~30,000 kWh per year, but this is assumed to be halved because of their less than optimal installation. In a UK study (Encraft, 2009) building mounted wind turbines were found to be far less effective than predicted.

The operating energy for each level is significantly different due to the different functions. The office level is assumed to be the level with the highest energy consumption. There are no heating, cooling and ventilation systems in some levels, such as the forest floor and dunes floor, which are built as covered external open space. Because of the complex operational performance and use of strategies such as natural ventilation, the case study building has been assumed to act overall as an efficient office building in terms of its energy use. Generally a conventional air-conditioned office uses 200 ~ 400kWh/m^2/year (IEA PVPS, 1999). In this study, the energy intensity of the office floor and windmill floor (VIP room), which have installed heating, cooling, ventilation and lighting systems, is assumed to be 300kWh/m^2/year. Moreover, about 30kWh/m^2/year is used for lighting for a typical German house (Gauzin-Müller, 2002). In the absence of better data, this value has been used for the lighting intensity of the floors without HVAC installed. The operating energy of each floor is found by multiplying the floor area and the appropriate value for electricity usage per square metre.

8.2.1.3 Building demolition-related energy

The energy consumption from building demolition is assumed to be negligible in this study. The reason for this assumption has been explained in Chapters 5 and 7.

8.2.2 Visitor travel

With the same methodology as used in the case studies presented in Chapters 6 and 7, the energy consumption of visitor travel can be quantified and demonstrated by using the number of visitors, the distances of travel, and the energy intensity of different transportation modes.

8.2.2.1 Number of visitors

The average number of people who visited an independent pavilion at Expo 2000 was 2.72 million over five months (Walvis, 2003). Walvis (2003) also reported that the

German Pavilion as the most visited pavilion received 5,400,000 visitors. Therefore, the total number of visitors going to the Dutch Pavilion (the second most popular pavilion) was assumed to be 4,060,000 ((5,400,000+2,720,000) ÷2).

Althues and Maier (2002) stated that at Expo 2000, 93% visitors were from Germany, which means 3,775,800 visitors were German and the number of foreign visitors was 284,200 (Table 8.4).

Visitors	Percentage	Number of visitors
From Germany	93%	3,775,800
From foreign countries	7%	284,200
Total	100%	4,060,000

Table 8.4 Number of visitors from different countries (Althues and Maier, 2002)

1. Visitors from Germany (3,775,800)

- Visitors from Hannover (416,773)

Some of the German visitors came from the host city, Hannover. The total population of Hannover is about 520,966. If it is assumed that 80% of the population visited the Expo, the number of visitors from Hannover would be 416,773. How the split was derived is shown in Figure 8.1 and Table 8.5. Table 8.5 shows the population of 33 different districts in Hannover.

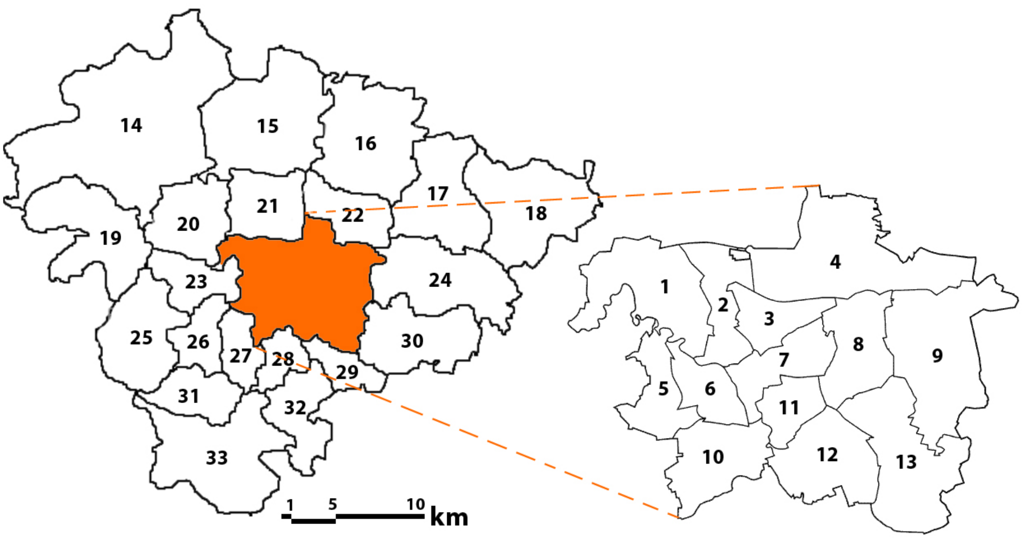


Figure 8.1 Districts in Hannover, Germany

1	2	3	4	5	6	7
Herrenhausen-Stöcken	Nord	Vahrenwald-List	Bothfeld-Vahrenheide	Ahlem-Badenstedt-Davenstedt	Linden-Limmer	Mitte
34,664	16,501	67,620	47,534	31,626	43,164	332,919
2.49%	1.18%	4.85%	3.41%	2.27%	3.10%	23.88%
8	9	10	11	12	13	14
Buchholz-Kleefeld	Misburg-Anderten	Ricklingen	Südstadt-Bult	Döhren-Wülfel	Kirchrode-Bemerode-Wülferode	Neustadt a. Rbge
43,386	31,774	43,422	41,575	33,593	29,728	45,237
3.11%	2.28%	3.12%	2.98%	2.41%	2.13%	3.25%
15	16	17	18	19	20	21
Wedemark	Burgwedel	Burgdorf	Uetze	Wunstorf	Garbsen	Langenhagen
29,108	20,432	29,951	20,247	41,134	61,818	51,982
2.09%	1.47%	2.15%	1.45%	2.95%	4.43%	3.73%
22	23	24	25	26	27	28
Isernhagen	Seelze	Lehrte	Barsinghausen	Gehrden	Ronnenberg	Hemmingen
22,882	32,683	43,339	33,667	14,588	23,109	18,606
1.64%	2.34%	3.11%	2.42%	1.05%	1.66%	1.33%
29	30	31	32	33		
Laatzen	Sehnde	Wennigsen	Pattensen	Springe		
40,237	22,862	1,190	13,946	29,356		
2.89%	1.64%	0.09%	1.00%	2.10%		

Table 8.5 Percentage of population of different districts in Hannover, Germany

Table 8.6 lists the number of visitors and their different transport modes. According to the population density, the proportional number of visitors from the different districts taking car, light rail, and bus can be derived as listed in Table 8.7.

Modes	-	Percentage	Number of visitors
Car (1.3 passengers/car)	Car driver	30%	125,032
	Car passenger	9%	37,510
Public transport (22%)	Light rail	11% (assumed)	45.845
	bus	11% (assumed)	45.845
Walking	-	23%	95.858
Bicycle	-	16%	66.684
Total	-	100%	416,773

Table 8.6 Percentage of using different transport modes in Hannover going to the Dutch pavilion (Johannsmeier et al, 2003)

	District	Percentage of population	Number of visitors	Car (39%)	Light rail (11%)	Bus (11%)
1	Herrenhausen-Stöcken	2.49%	10378	4047	1142	1142
2	Nord	1.18%	4918	1918	541	541
3	Vahrenwald-List	4.85%	20213	7883	2223	2223
4	Bothfeld-Vahrenheide	3.41%	14212	5543	1563	1563
5	Ahlem-Badenstedt-Davenstedt	2.27%	9461	3690	1041	1041
6	Linden-Limmer	3.10%	12920	5039	1421	1421
7	Mitte	23.88%	99525	38815	10948	10948
8	Buchholz-Kleefeld	3.11%	12962	5055	1426	1426
9	Misburg-Anderten	2.28%	9502	3706	1045	1045
10	Ricklingen	3.12%	13003	5071	1430	1430
11	Südstadt-Bult	2.98%	12420	4844	1366	1366
12	Döhren-Wülfel	2.41%	10044	3917	1105	1105
13	Kirchrode-Bemerode-Wülferode	2.13%	8877	3462	976	976
14	Neustadt a. Rbge	3.25%	13545	5283	1490	1490
15	Wedemark	2.09%	8711	3397	958	958
16	Burgwedel	1.47%	6127	2389	674	674
17	Burgdorf	2.15%	8961	3495	986	986
18	Uetze	1.45%	6043	2357	665	665
19	Wunstorf	2.95%	12295	4795	1352	1352
20	Garbsen	4.43%	18463	7201	2031	2031
21	Langenhagen	3.73%	15546	6063	1710	1710
22	Isernhagen	1.64%	6835	2666	752	752
23	Seelze	2.34%	9752	3803	1073	1073
24	Lehrte	3.11%	12962	5055	1426	1426
25	Barsinghausen	2.42%	10086	3934	1109	1109
26	Gehrden	1.05%	4376	1707	481	481
27	Ronnenberg	1.66%	6918	2698	761	761
28	Hemmingen	1.33%	5543	2162	610	610
29	Laatzen	2.89%	12045	4697	1325	1325
30	Sehnde	1.64%	6835	2666	752	752
31	Wennigsen	0.09%	375	146	41	41
32	Pattensen	1.00%	4168	1625	458	458
33	Springe	2.10%	8752	3413	963	963
	Total	-	-	162541	45845	45845

Table 8.7 Number of visitors from different districts in Hannover

	State	Capital	City population	Percentage (%)
1	Berlin	Berlin	3,450,889	33.2
2	Hamburg	Hamburg	1,783,975	17.2
3	Bavaria	Munich	1,330,440	12.8
4	Baden-Wurttemberg	Stuttgart	601,646	5.8
5	North Rhine-Westphalia	Dusseldorf	586,217	5.6
6	Bremen	Bremen	547,535	5.3
8	Saxony	Dresden	517,052	5.0
9	Hessen	Wiesbaden	277,493	2.7
10	Schleswig-Holstein	Kiel	238,049	2.3
11	Saxony-Anhalt	Magdeburg	230,456	2.2
12	Thuringia	Erfurt	203,830	2.0
13	Rhineland-Palatinate	Mainz	197,778	1.9
14	Saarland	Saarbrucken	175,810	1.7
15	Brandenburg	Potsdam	154,606	1.5
16	Mecklenburg-Western Pomerania	Schwerin	95,041	0.9

Table 8.8 Population distribution of Germany

	State	Capital	Percentage (%)	Number of visitors
1	Berlin	Berlin	33.2	1115565
2	Hamburg	Hamburg	17.2	576704
3	Bavaria	Munich	12.8	430090
4	Baden-Wurttemberg	Stuttgart	5.8	194493
5	North Rhine-Westphalia	Dusseldorf	5.6	189506
6	Bremen	Bremen	5.3	177001
8	Saxony	Dresden	5.0	167147
9	Hessen	Wiesbaden	2.7	89705
10	Schleswig-Holstein	Kiel	2.3	76954
11	Saxony-Anhalt	Magdeburg	2.2	74499
12	Thuringia	Erfurt	2.0	65892
13	Rhineland-Palatinate	Mainz	1.9	63936
14	Saarland	Saarbrucken	1.7	56834
15	Brandenburg	Potsdam	1.5	49979
16	Mecklenburg-Western Pomerania	Schwerin	0.9	30724
	Total	-	-	3,359,027

Table 8.9 Number of visitors from different States in Germany going to the Dutch Pavilion

- Visitors from other cities in Germany (3,359,027)

The total number of visitors from other cities in Germany going to the Dutch Pavilion at Expo 2000 was 3,359,027. Table 8.8 shows the population of 16 capital cities in Germany. Based on this population density, the number of visitors from cities can be calculated as a proportion (Table 8.9).

The percentage of visitors from other cities to Hannover taking different transport modes (figures from Kuhnimhof et al, 2009) is shown in Table 8.10. Thus, the number of visitors coming from other cities and taking different transport modes can be calculated (Table 8.11).

Car	Bus	Train	Air	Ship
71%	5%	12%	11%	1%

Table 8.10 Main mode shares in German long distance travel (Kuhnimhof et al, 2009)

	Capital	Number of visitors	Car (71.25%)	Bus (5.25%)	Train (12.25%)	Air (11.25%)
1	Berlin	1115565	794840	58567	136657	125501
2	Hamburg	576704	410902	30277	70646	64879
3	Munich	430090	306439	22580	52686	48385
4	Stuttgart	194493	138576	10211	23825	21880
5	Dusseldorf	189506	135023	9949	23214	21319
6	Bremen	177001	126113	9293	21683	19913
8	Dresden	167147	119092	8775	20476	18804
9	Wiesbaden	89705	63915	4710	10989	10092
10	Kiel	76954	54830	4040	9427	8657
11	Magdeburg	74499	53081	3911	9126	8381
12	Erfurt	65892	46948	3459	8072	7413
13	Mainz	63936	45554	3357	7832	7193
14	Saarbrucken	56834	40494	2984	6962	6394
15	Potsdam	49979	35610	2624	6122	5623
16	Schwerin	30724	21891	1613	3764	3456

Table 8.11 Number of visitors from other cities taking different transport modes

2. Visitors from foreign countries (284,200)

The number of foreign visitors accounted for 7% in the total, equal to 284,200. It is assumed that these visitors came from Europe (4%), America (1%), Asia (1%), and Oceania (1%). The number of visitors coming from these countries was thus 162,400, 40,600, 40,600, and 40,600 respectively.

8.2.2.2 Distance of visitor travel

1. Visitors from Germany

- Visitors from Hannover

Table 8.12 shows the distance for visitors from different districts in Hannover going to the Dutch Pavilion. The average point at which visitors can take different transport modes to reach the destination was chosen by using the mid-point of access.

1	2	3	4	5	6	7
Herrenhausen-Stöcken	Nord	Vahrenwald-List	Bothfeld-Vahrenheide	Ahlem-Badenstedt-Davenstedt	Linden-Limmer	Mitte
10.4km	9.0km	7.9km	8.8km	8.5km	7.4km	6.7km
8	9	10	11	12	13	14
Buchholz-Kleefeld	Misburg-Anderten	Ricklingen	Südstadt-Bult	Döhren-Wülfel	Kirchrode-Bemerode-Wülferode	Neustadt a. Rbge
6.3km	5.9km	6.2km	5.4km	3.7km	2.8km	23.9km
15	16	17	18	19	20	21
Wedemark	Burgwedel	Burgdorf	Uetze	Wunstorf	Garbsen	Langenhagen
18.9 km	16.7 km	14.7 km	18.1 km	19.9 km	15.9 km	13.4 km
22	23	24	25	26	27	28
Isernhagen	Seelze	Lehrte	Barsinghausen	Gehrden	Ronnenberg	Hemmingen
11.4 km	12.8 km	9.5 km	15.3 km	11.2 km	8.0 km	4.9 km
29	30	31	32	33		
Laatzen	Sehnde	Wennigsen	Pattensen	Springe		
0.5 km	5.3 km	11.7 km	4.8 km	11.5 km		

Table 8.12 A straight line distance for visitors from different districts going to the Dutch Pavilion

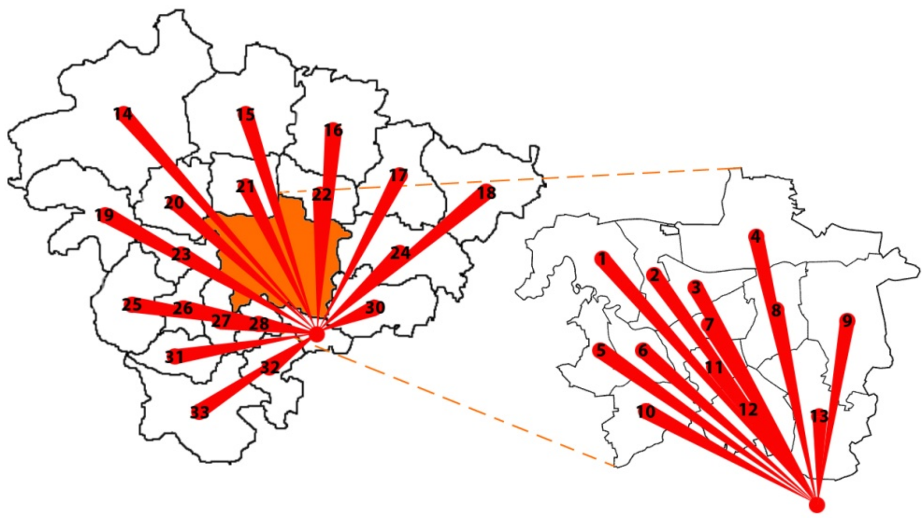


Figure 8.2 Distance from the Dutch Pavilion to districts in Hannover

- Visitors from other cities in Germany

Table 8.13 shows the travel distances for visitors from other cities in Germany going to the Dutch Pavilion. The same method of measuring the travel distance as for the host city is adopted here.

	Capital	Car (km)	Bus (km)	Train (km) (200km/h)	Air (km)
1	Berlin	286	286	300	256
2	Hamburg	257	257	266	128
3	Munich	632	632	916	481
4	Stuttgart	524	524	550	419
5	Dusseldorf	277	277	291	239
6	Bremen	125	125	131	143
8	Dresden	367	367	385	307
9	Wiesbaden	376	376	395	259
10	Kiel	247	247	259	223
11	Magdeburg	147	147	154	132
12	Erfurt	219	219	230	177
13	Mainz	373	373	391	264
14	Saarbrucken	526	526	552	397
15	Potsdam	257	257	270	157
16	Schwerin	225	225	236	(Lubeck to Hannover)

Table 8.13 Travel distances for visitors from other cities in Germany going to the Dutch Pavilion

2. Visitors from foreign courtiers

The travel distances of foreign visitors were measured by using a “place to place distance calculator” (Distancefromto, 2010). The average travel distances from different countries to the Dutch Pavilion are listed in Tables 8.14~8.16.

	Airplane	Distance
Europe	100%	See Table 8.15
America	100%	7,806 km
Asia	100%	See Table 8.16
Oceania	100%	14,648 km

Table 8.14 Travel distances for visitors from foreign countries going to the Dutch pavilion

Area	**Direct distance from different countries to Germany (km)**		**Average distance (km)** (Distancefromto, 2010)
Northern Europe	Denmark	571	1306
	Faroe Islands	1591	
	Estonia	1242	
	Finland	1514	
	Åland Islands	1163	
	Iceland	2280	
	Ireland	1293	
	Latvia	1120	
	Lithuania	998	
	Norway	1043	
	Svalbard and Jan Mayen	2989	
	Sweden	1121	
	United Kingdom	1034	
	Guernsey	945	
	Isle of Man	1066	
	Jersey	922	
Western Europe	Austria	503	535
	Belgium	429	
	France	817	
	Liechtenstein	450	
	Luxembourg	341	
	Monaco	857	
	Netherlands	372	
	Switzerland	510	
Central and Eastern Europe	Belarus	1218	1472
	Bulgaria	1474	
	Czech Republic	386	
	Hungary	795	
	Moldova	1363	
	Poland	607	
	Romania	1214	
	Russia	5427	
	Slovakia	718	
	Ukraine	1516	
Southern Europe	Albania	1341	1278
	Andorra	1171	
	Bosnia and Herzegovina	972	
	Croatia	761	
	Gibraltar	2092	
	Greece	1611	
	Italy	1047	
	Macedonia	1369	
	Malta	1724	
	Montenegro	1159	
	Portugal	1953	
	San Marino	818	
	Serbia	1121	
	Slovenia	650	
	Spain	1617	
	Vatican City	1042	

Table 8.15 Travel distances for visitors from European countries going to the Dutch pavilion

Area	Direct distance from different countries to Germany (km)		Average distance (km) (Distancefromto, 2010)
Eastern Asia	Japan	9059	8040
	Mongolia	6358	
	North Korea	8163	
	South Korea	8579	
Southern Asia	Afghanistan	4926	6702
	Bangladesh	7299	
	Bhutan	6994	
	India	6760	
	Maldives	7874	
	Nepal	6490	
	Pakistan	5307	
	Sri Lanka	7969	
Western Asia	Armenia	2928	3670
	Azerbaijan	3079	
	Bahrain	4399	
	Cyprus	2562	
	Iraq	3345	
	Iran	4069	
	Israel	3006	
	Jordan	3124	
	Kuwait	3911	
	Lebanon	2813	
	Oman	5120	
	Qatar	4483	
	Saudi Arabia	4238	
	Syria	2922	
	United Arab Emirates	4820	
	Turkey	2357	
	Yemen	5210	
Southeast Asia	Brunei	10609	9813
	Burma	7831	
	Cambodia	9245	
	East Timor	12537	
	Indonesia	11023	
	Laos	8450	
	Philippines	10329	
	Malaysia	9760	
	Singapore	10137	
	Thailand	8687	
	Vietnam	9339	
Central Asia	Kazakhstan	3989	4388
	Kyrgyzstan	4914	
	Tajikistan	4829	
	Turkmenistan	4007	
	Uzbekistan	4203	

Table 8.16 Travel distances for visitors from Asian countries going to the Dutch pavilion

8.2.2.3 Energy intensity of different transport modes

The energy intensity of different transport modes in Germany, including bus, car, light rail, train, and airplane, was sourced from European literature (Table 8.17), because of lack of some specific parameters in German sources. It should be noted that the energy intensity of different transport modes varies considerably across a range of published research.

Modes	Fuel	Energy intensity	Country	Reference
Bus	Fossil fuel	0.49–1.32 MJ/passenger-km	Western Europe	Michaelis et al, 1998, p.689.
	Fossil fuel	0.71 MJ/passenger-km (Express bus)	Norway	Walnum, 2011
Car	Fossil fuel	2.1 MJ/passenger-km	Germany	ODYSSEE database, 2001
	Diesel	0.829 MJ/passenger-km	Norway	Walnum, 2011
	Gasoline	0.94 MJ/passenger-km	Norway	Walnum, 2011
Light rail	Electricity	0.79 MJ/passenger-km	46 global cities	UNEP, 2011. p.9.
	Electricity	0.69 MJ/passenger-km	Western Europe	UNEP, 2011. p.11.
Train	Electricity /Diesel	0.75–2.8 MJ/passenger-km	Western Europe	Michaelis et al, 1998, p.689.
Airplane	Jet fuel	2.599 MJ/passenger-km (Boeing 737) (400km)	Norway	Walnum, 2011
		2.160 MJ/passenger-km (Boeing 737) (950km)	Norway	Walnum, 2011
	Jet fuel	1.5- 2.5 MJ/passenger-km	UK	ETSU, 1994

Table 8.17 Energy intensity of different transport modes in Europe

Table 8.18 shows the assumed energy intensity of different transport modes going to the Dutch Pavilion at Expo 2000.

Modes	Fuel	Energy intensity	Assumption
Bus	Fossil fuel	0.91 MJ/passenger-km	Average value of Western European figure (as Germany in Western Europe)
Car	Fossil fuel	2.1 MJ/passenger-km	German figure
Light rail	Electricity	0.69 MJ/passenger-km	Western European figure (as Germany in Western Europe)
Train	Electricity/ Diesel	1.78 MJ/passenger-km	Average value of Western European figure (as Germany in Western Europe)
Airplane	Jet fuel	2.599 MJ/passenger-km(400 km); 2.160 MJ/passenger-km(950 km)	Norway figure (Short haul) Norway figure (Long haul)

Table 8.18 Assumed energy intensity of different transport modes going to the Dutch Pavilion at Expo 2000, Hannover

8.2.2.4 CO_2 emissions coefficients

The associated CO_2 emission of visitor travel to go the Dutch Pavilion in Hannover is estimated. CO_2 emissions coefficients of different transport modes in Germany were sourced from Germany, Norway, UK, and European literature (Table 8.19). The emission coefficients for calculation in this research are selected from this range.

Modes	Fuel	CO_2 emissions coefficients	Country	Reference
Bus	Fossil fuel	40 g /passenger-km	Europe	EEA, 2011
	Diesel	576.98 g/km	Germany	Cox and Hickman, 1998
	Fossil fuel	52.2 g /passenger-km (Express bus)	Norway	Walnum, 2011
	Diesel	118.1 g /passenger-km	46 Global cities	UNEP, 2011. p.9.
Car*	Gasoline	118 g /passenger-km (165.01g/km)	Germany	Cox and Hickman, 1998
	Diesel	123 g /passenger-km (171.96 g/km)	Germany	Cox and Hickman, 1998
	Diesel	61.6 g /passenger-km	Norway	Walnum, 2011
	Gasoline	69.4 g /passenger-km	Norway	Walnum, 2011
Light rail	Electricity	4.7 – 327.1 g /passenger-km	46 global cities	UNEP, 2011. p.9.
	Electricity	78 g /passenger-km	UK	Defra, 2008, p.25
Train	Electricity/ Diesel	66 g /passenger-km	Germany	Umweltbundesamt, 2003, p.12
Airplane	Jet fuel	191 g /passenger-km (Boeing 737) (400km)	Norway	Walnum, 2011
		g /passenger-km (Boeing 737) (950km)	Norway	Walnum, 2011
*Car occupancy rate of Germany in 2005 was about 1.4 (Lac d'Annecy et al, 2008)				

Table 8.19 CO_2 emissions coefficients of different transport modes in Europe

Table 8.20 shows the assumed CO_2 emissions coefficients of different transport modes going to the Dutch Pavilion at Expo 2000.

Modes	Fuel	CO_2 emissions coefficients	Assumption
Bus	Fossil fuel	40 g /passenger-km	European figure
Car	Gasoline	69.4g /passenger-km	Norway figure
Light rail	Electricity	78 g /passenger-km	UK figure
Train	Electricity/Diesel	66 g /passenger-km	German figure
Airplane	Jet fuel	191 g /passenger-km (400km); 158 g /passenger-km (950km)	Norway figure (Short haul) Norway figure (Long haul)

Table 8.20 Assumed CO_2 emissions coefficients of different transport modes going to the Dutch Pavilion at Expo 2000, Hannover

8.2.3 Exhibition-related economic aspects

8.2.3.1 Exhibition-related economic income

For Expo 2000, economists at Poland Berger estimated that the value of the direct and indirect macro-economic effects for Germany generated by the Expo reached €5.47 billion (Walvis, 2003). Klenk and Bentele (1999) stated that because of Expo 2000 in Hannover, all the region’s key industries gained some benefit from the project (quoted in Kirchgeorg et al, 2005). The report from Canadian Heritage shows that “nearly all participants (94.1%) reported that participation in Expo 2000 was effective as a business strategy in enhancing their image, in promoting Canadian artists /culture (86.7%), and promoting tourism (80%)” (Canadian Heritage, 2002).

Because The Netherlands’ pavilion was one of the first ranked locations for visitors to the Expo, this made it possible to get a better view of the potential economic value of participating in Expo 2000 (Walvis, 2003). Walvis (2003) demonstrated that the design of the Dutch Pavilion helped to change the thinking about Holland, by being “worth seeing, surprising, and undreamed-of”. A survey showed the Dutch Pavilion was one of the favourite pavilions (EXPO 2000 Hannover GmbH, 2000) (Figure 8.3). In a survey, 85% of German visitors would like to have more contact with the Netherlands; 12% of them were thinking of starting up business relations (Walvis, 2003). More importantly, 92% of visitors to the expo planned to visit Holland as a tourist.

Walvis (2003) estimated €350 million of potential revenue from tourism was generated for the Dutch economy from the presence of the Dutch Pavilion at Expo 2000. The amount of potential revenue was around 10 times the original cost of the pavilion (€35 million). Since the total revenue of The Netherlands in 2002 was €173 billion (SWEM, 2003), the Expo revenue accounted for approximately 0.2% of total national revenue. This can be compared with similar values in section 9.2.3.

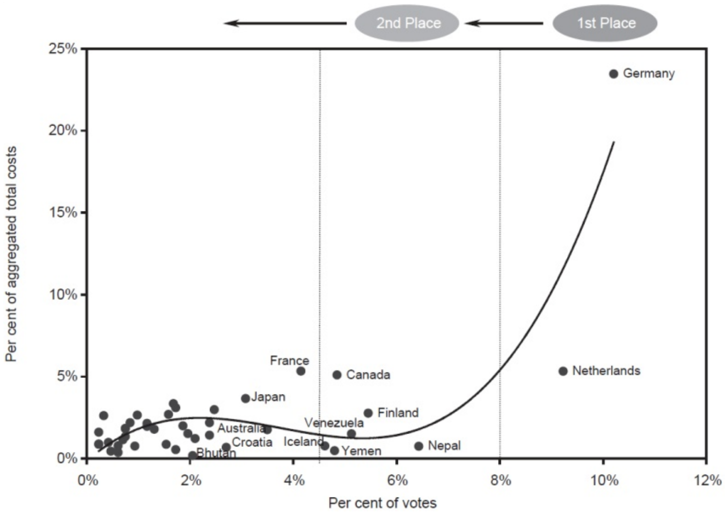


Figure 8.3 Top 10 results Expo 2000 (Walvis, 2003)

8.2.3.2 Economic-related ecological footprint

Research into the ecological footprint of tourism is a new field and as yet there are few comprehensive studies. Mahravan and Vale (2008) estimated the ecological footprint of a New Zealand tourist attraction, the Otago Central Rail Trail, in terms of the impact of the resource consumption for food, accommodation services, transportation, and water consumption. The results showed a monetary value of 480 NZD/gha for tourism impact which equals €260/gha. In the absence of any other data this value was used for this study.

8.3 Results and analysis

8.3.1 Building

8.3.1.1 Embodied energy

The quantitative results of energy usage for the case study building, the Dutch Pavilion, in its construction and maintenance phases (over the actual life and an assumed 50 year life) are shown in Tables 8.21 and 8.22. The total embodied energy of the Dutch Pavilion is 65,196 GJ for its actual five month life or 89,186 GJ over the assumed 50 years.

Floor	Initial embodied energy (GJ)	Recurring embodied energy (GJ)
Offices floor (Ground floor)	14,508	0
Dunes floor (First floor)	15,451	
Glass floor (Second floor)	1,908	
Pots floor (Third floor)	3,719	
Forest floor (Fourth floor)	1,996	
Rain floor (Fifth floor)	5,422	
Windmill floor (Sixth floor)	2,869	
Vertical circulation	1,523	
Building services	13,763	
Wind turbines and relevant equipment	4,038	
Total	65,196 GJ (10.6 GJ/m^2)	
Total embodied energy	65,196 GJ (10.6 GJ/m^2)	

Table 8.21 Quantification of initial and recurring embodied energy of the Dutch Pavilion (over the actual life, 5 months) (Appendix C)

Floor	Initial embodied energy (GJ)	Percent age (%)	Recurring embodied energy (GJ)	Percent age (%)
Offices floor (Ground floor)	14,508	22.3	5,746	24.0
Dunes floor (First floor)	15,451	23.7	0.023	0
Glass floor (Second floor)	1,908	2.9	1	0
Pots floor (Third floor)	3,719	5.7	11	0.5
Forest floor (Fourth floor)	1,996	3.1	318	1.3
Rain floor (Fifth floor)	5,422	8.3	10	0.4
Windmill floor (Sixth floor)	2,869	4.4	420	1.8
Vertical circulation	1,523	2.3	220	0.9
Building services	13,763	21.1	6,881	28.7
Wind turbines and relevant equipment	4,038	6.2	10,383	43.3
Total	65,196 GJ (10.6 GJ/m^2)	100	23,990GJ (3.9 GJ/m^2)	100
Total embodied energy	89,186 GJ (14.5 GJ/m^2)			

Table 8.22 Quantification of initial and recurring embodied energy of the Dutch Pavilion (over the assumed 50 year life) (Appendix C)

The initial embodied energy is estimated to be 65,196 GJ or 10.6 GJ/m^2. In detail, the office floor (22.3%), dunes floor (23.7%) and building services (21.1%) of the case study building account for the main proportion of the total embodied energy (more than 60%) because most of the energy is consumed in the production of the concrete (the main structural elements of the dunes floor are concrete).

Because the building was only used for five months in fact its total recurring embodied energy was zero. If the building were to be used over a life of 50 years, the total recurring embodied energy is estimated at 23,990 GJ or 3.9 GJ/m^2. The percentage of the energy used to maintain the wind turbines (43.4%), building services (28.7%) and office level (24%) makes 95% of the total. It seems that the main energy for maintenance is consumed by the turbines.

8.3.1.2 Operating energy

Over the actual life of five months the total operating energy of the Dutch Pavilion was 620 GJ, made up of an energy consumption of 695 GJ and 75 GJ generated by wind turbines.

If the operating energy is determined by the electricity usage of the building over the assumed 50 year life, the total operating energy of the Dutch Pavilion is 74,430 GJ, which is equal to 1.0 GJ/m^2/year. The result includes the energy consumption of the building operation (83,430 GJ) and energy generation (9,000 GJ) by the wind turbines over 50 years. Table 8.23 shows the energy consumed by the building in its operation phase for the assumed 50 year life.

Floor	Building services	Energy intensity (kWh/m^2/year)	Operating energy (50 year) (kWh)
Offices floor (Ground floor)	Heating, Cooling, Ventilation, Lighting	300	15,360,000
Dunes floor (First floor)	Lighting	30	1,536,000
Glass floor (Second floor)	Lighting	30	1,536,000
Pots floor (Third floor)	Lighting	30	1,536,000
Forest floor (Fourth floor)	Lighting	30	1,536,000
Rain floor (Fifth floor)	Lighting	30	1,536,000
Windmill floor (Sixth floor)	Heating, Cooling, Ventilation, Lighting	300	135,000
Total	23,175,000 kWh (=83,430 GJ)		

Table 8.23 Quantification of operating energy for each floor of the Dutch Pavilion (assumed 50 year life)

8.3.2 Visitor travel

Using the proportions in every district, the numbers of people choosing different transport modes in every district, city, and country were calculated. The total average energy consumption of all visitors who travelled by different transport modes to go to the Dutch Pavilion was 10,460,190 GJ (there and back). The total CO_2 emissions of visitor travel are 627,100 t (there and back). To avoid repetition of a similar process of calculation, the detailed quantitative work of visitor travel for this case study can be seen in Appendix C.

As the exhibition area of Expo 2000 in Hannover covered around 1,600,000 m^2, it was too large for a visitor to go to all pavilions in one day. Walvis (2003) reported that the average number of independent pavilions visited was only six to ten in a day (average eight). Total energy consumption and associated CO_2 emissions of visitor travel to go to the Dutch Pavilion independently were therefore 1,307,524 GJ (10,460,190 ÷ 8) (Table 8.24) and 78,388 t (627,100 ÷ 8) (Table 8.25), as visiting the Dutch Pavilion would be only one of several visits made while attending the Expo.

	Energy consumption
Visitors from Hannover	991 GJ
Visitors from other cities in Germany	570,567 GJ
Visitors from other countries	735,936 GJ
Total	1,307,524 GJ

Table 8.24 Total energy consumption of visitor travel going to the Dutch Pavilion at Expo 2000, Hannover, Germany

	CO_2 emissions
Visitors from Hannover	40 t
Visitors from other cities in Germany	21,900 t
Visitors from other countries	56,448 t
Total	78,388 t

Table 8.25 Total energy consumption of visitor travel going to the Dutch Pavilion at Expo 2000, Hannover, Germany

8.3.3 Exhibition-related economic aspects

Applying the value of €260/gha, the total ecological footprint of the exhibition-related economic benefit related to tourism from the Dutch Pavilion is 1,346,154gha.

8.4 Whole life-cycle impact

The total ecological footprint of the case study Dutch Pavilion was 1,359,887gha/year, or 0.335gha/visitor/year, as shown in Table 8.26.

	Total ecological footprint in a year (gha/year)	**Average ecological footprint (gha/visitor/year)**	**Average ecological footprint (gha/m^2/year)**
Dutch Pavilion	658	0.0002	0.107
Visitor travel going to the building	13,075	0.003	2.128
Exhibition-related economic aspects	1,346,154	0.332	219.101
Total	1,359,887	0.335	221.336

Table 8.26 Total ecological footprint of the case study over the assumed useful life of 50 years

The energy consumption of the Dutch Pavilion and the exhibition-related economic effect of tourism on The Netherlands are assessed. This reveals that the total energy consumed by the building is 36,440 MJ/m^2/year for 5 months or 1,300 MJ/m^2/year for 50 years. In addition, the total ecological footprint of the economic benefit for The Netherlands obtained from Expo 2000 is approximately 1,346,154gha, or 134,615,400 GJ, using the conversion of 100 GJ/ha (See Table 8.27).

	Actual life: 5 months		Assumed 50 years life
	Month (MJ/m^2/month)	Year (MJ/m^2/year)	Year (MJ/m^2/year)
Embodied energy	5,088	25,440	300
Operating energy	200	1,000	1,000
Energy impact of exhibition-related economic effect	4,382	21,910	21,910

Table 8.27 Energy use of Dutch Pavilion and its economic impact over 5 months and 50 years

For Expo 2000, 45 participating countries and companies built their own pavilion with an average budget of €13.3 million each, and these buildings were just run for five months (Walvis, 2003). As their useful life was so short, the sustainable technologies may not help to improve their energy efficiency over their whole life cycle. In addition, a previous study shows that the environmental impact of visitor travel broken down into different transport modes is much worse than that from the building operation

(Shen et al, 2009). However, if comparing this with the exhibition-related economic effects, the impacts from the buildings and visitor travel are extremely small. It is obvious that participants or sponsors are more focussed on the economic benefits generated from events, rather than their resource consumption.

8.5 Chapter conclusion

This chapter describes the energy, carbon and ecological footprint of the Dutch Pavilion, visitor travel for going to Expo 2000 in Hannover, and exhibition-related economic aspects. The results have been explained in section 8.4. It quantifies and estimates the real effect of the sustainable technologies used in this pavilion. It shows the significant direct and indirect environmental degradation aspects for the exhibition host city and the participating country.

Chapter 9 Modern sustainable exhibition case study 2: The Theme Pavilion and Expo 2010 in Shanghai

9.1 Introduction

This chapter explores the energy and resource consumption of Expo 2010 held in that year in Shanghai, China. The analysis includes the Theme Pavilion, visitor travel, and exhibition-related economic aspects. The main reasons for selection of this case study were explained in section 5.3.

The Theme Pavilion was designed as one of four permanent exhibition pavilions for World Expo 2010 in Shanghai, China. This building has two storeys above the ground and one floor underground (with one mezzanine). Its total construction area is around 143,000 m^2, and the total area for display is approximately 80,000 m^2. The building contains five different sizes of exhibition hall. The western hall (Hall 1) of the Theme Pavilion is built as a column-free space of 22,680 m^2, and has been described as the biggest column-free hall in the Asian area so far (BCSWE, 2010). The Theme Pavilion, a general international exhibition building, is mainly constructed of steel and erected above a box foundation, because of the requirement for the huge uninterrupted interior space. Different sizes and shapes of aluminium panels and frames have been used for the external and internal façade decoration in this building. In addition, photovoltaic panels and green walls have been used as part of the sustainable design approach, and these are also of unusually large size. The basic information for the Theme Pavilion is shown in Table 9.1.

	Floors	Area	Clear height
Construction area	Above ground	93,000 m^2	21 m
	Underground	50,000 m^2	9 m
	Total	143,000 m^2	
Sustainable technologies used	Photovoltaic panels (Roof)	30,000 m^2	
	Green eco-walls (Western and eastern walls)	4,860 m^2	
Number of visitors	16,250,000 (125,000/day)		

Table 9.1 Basic information for the Theme Pavilion at Expo 2010

9.2 Method

This section provides the detailed methods for quantifying the whole life cycle energy and resource consumption of the modern sustainable building and event case study, the Theme Pavilion (9.2.1), visitor travel (9.2.2), and exhibition-related economic aspects (9.2.3).

9.2.1 Building

The useful life of the Theme Pavilion for quantitative calculations in this paper is assumed to be 50 years, from 2010 to 2060. The 50 year life was taken because the pavilion was comparable in structure and construction to a normal permanent exhibition building. The whole life cycle study of energy analysis commonly consists of the energy consumption generated from the building construction, maintenance, operation, and demolition phases (Mithraratne et al, 2007), which are represented by initial and recurring embodied energy, operating energy, and energy for demolition. Embodied energy, operating energy, and building life are considered and discussed here. These factors have been accepted as the main influences on the whole life cycle assessment (Cole and Kernal, 1996; Fernandez, 2008; Energy Assessment, 2010). The energy usage for building demolition is not included in this study, as explained in previous chapters.

9.2.1.1 Embodied energy

The energy used for constructing and maintaining the condition of the Theme Pavilion is quantified as the initial embodied energy and recurring embodied energy over the assumed useful life of 50 years. This is so that the results derived from this building life assumption are comparable with energy data for the other case study buildings.

1. Initial embodied energy

The initial embodied energy of the case study building is quantified by measuring the volume, area, or weight of construction and finishing materials of different elements, according to the published drawings in terms of the plans, elevations, and sections of the Theme Pavilion (EXPO 2010, 2010; TJADRI, 2010). The calculated results are then multiplied by the relevant embodied energy coefficients. A list of the quantities of construction materials and drawings of building floor plans made using AutoCAD were prepared and used for quantitative calculations in this research.

The embodied energy coefficients of the construction materials used for the calculation though based on Australian data now partly come from Chinese data (Gong, 2004). This is because the Chinese database was more developed by the time this case study was started. Some European data also had to be used in the calculation for the case study building (Lawson, 1996; Hammond and Jones, 2008), owing to the lack of relevant research for other construction materials in China so far. Table 9.2 shows the list of embodied energy coefficients of different materials used in this research. The results will be reasonable, because the three main materials, reinforced concrete, steel, and glass, are calculated using the Chinese data. Furthermore, Table 9.3 compares the various embodied energy coefficients of different types of materials used for constructing and decorating the Theme Pavilion from Australian, New Zealand, and UK studies. Based on these findings, it seems that little difference can be found between the factors for a particular material produced in different countries.

Construction materials	Embodied energy coefficients	References
Reinforced concrete	3.2 GJ/t	Gong, 2004
Steel	31 GJ/t	
Glass (10mm)	24.5 GJ/t	
Cement	5.6 GJ/t	Lawson, 1996
Aluminium	170 GJ/t	
Sand	0.3 GJ/m^3	
Plasterboard	4.4 GJ/t	
Fiber Reinforced Plastic (skylight roof panels)	90 GJ/t	
Paint (double coat)	0.02 GJ/m^2	Hammond and Jones, 2008
100mm Glass wool	28 GJ/t	
Damp proof membrane (0.25mm)	0.07 GJ/m^2	Baird and Chan, 1983
Ceramic tiles	0.78 GJ/m^2	Stein et al, 1981
Carpet	0.41GJ/m^2	Treloar, 1994
Photovoltaic panels (PVs)	1652.4MJ/m^2	Vale and Vale, 2009

Table 9.2 Embodied energy coefficients of different construction materials used in the analysis

Construction materials	China (MJ/kg) (Gong, 2004)	Australia (MJ/kg) (Lawson, 1996)	New Zealand (MJ/kg) (Alcorn, 2003)	UK (MJ/kg) (Hammond and Jones, 2008)
Concrete	2.3-3.6	1.5-2.0	0.9-2.0	0.6-2.0
Steel	25-33	38	32	24.4
Glass	24.5 (10mm)	12.7	15.9	15
Cement	-	5.6	7.8	4.6
Aluminium	-	170	191	155
Plasterboard	-	4.4	6.1	6.78
Paint	-	61.5	90.4	68

Table 9.3 Embodied energy coefficients of the selected materials in different countries

As the building is designed to be a "sustainable exhibition pavilion", 30,000 m^2 of photovoltaic panels are installed on top of the roof of the Theme Pavilion. It is necessary to account for the energy embodied in the huge array of PV panels. Vale and Vale (2009, p.141) compared the studies for average energy consumption for the manufacture of photovoltaic panels between Hammond and Jones (2008) and Fthenakis and Alsema (2006). The research from Fthenakis and Alsema shows that the manufacturing processes of PV panels have become more efficient (Vale and Vale, 2009, p.141). It is therefore reasonable to use the modern figure of 459kWh/m^2 (Vale and Vale, 2009, p.141), which is equal to 1652 MJ/m^2, in the calculation of the embodied energy of PV panels for this study. The proportion of 20% of the total embodied energy is adopted for accounting for the energy embodied in the building services in this case study (the reason has been explained in section 7.2.1.1).

2. Recurring embodied energy

Recurring embodied energy is defined as the part of the energy required for building repairs, maintenance, and refurbishment over the useful life of the building (Mithraratne et al, 2007). The case study building, the Theme Pavilion, is assumed to have a useful life of 50 years from 2010 to 2060.

Energy consumption for maintenance and replacement of construction materials is estimated based on their expected durability (assuming correct installation and maintenance). Table 4 lists the durability assumptions used in this research. For example, durability of paint is usually about 8~10 years, which means some elements of the case study building need to be repainted 4 times during 50 years. The photovoltaic panels installed above the roof of the Theme Pavilion are seen as an integral building element in Table 9.4. They can be operated for at least 20 years with current manufacturing technologies, according to the research of Fthenakis and Alsema (Vale and Vale, 2009, p.140). The PV panels thus would probably be replaced once during the whole useful life of the sustainable building. The method of calculation for recurring embodied energy is the same as that for initial embodied energy.

Materials	Expected durability (assuming correct installation and maintenance) (years)
Reinforced concrete	100
Steel	50
Cement	50
Aluminium	50
Paint (double coat)	8-10
Glass (10mm)	50
Damp proof membrane	100
Sand	50
Ceramic tiles	50
Carpet	15-20
100mm Glass wool	100
Plasterboard	50
Fiber Reinforced Plastic (skylight roof panels)	50
Photovoltaic panels (PVs)	25

Table 9.4 Expected durability of different construction materials

9.2.1.2 Operating energy

The operating energy means the energy used for a building in its operation phase, such as that consumed by the lighting, heating and HVAC system. The figure for the total operating energy of the Theme Pavilion not only includes electricity consumption for building operation, but must also account for electricity generation from the roof mounted photovoltaic panels. The average electricity consumption of exhibition buildings in China is adopted for the calculation, owing to the lack of published data for the electricity usage of the pavilion. The amount of energy generated by the PV panels on the Theme Pavilion was announced by the official website of Expo 2010 (http://www.expo2010.cn/).

1. Energy consumption

Two relevant references are discussed for the calculation of the average electricity consumption of different types of buildings in China in the first decade of the 21st century, as listed in Table 9.5 and Table 9.6.

The report of the Ministry of Housing and Urban-Rural Development of the People's Republic of China (MHUDP, 2009) lists average electricity consumption of different types of building in China, as shown in Table 9.5. From this list, the average electricity consumption of an exhibition building is around 50-80W/m^2. This figure represents the average consumption for a general exhibition building in 2009.

Categories	Electricity consumption (W/m^2)
Car park	8-15
Primary school	12-20
Tertiary institutes	20-40
Apartment	30-50
Office building	30-70
Hotel	40-70
Stadium	40-70
Hospital	40-70
Commercial building	40-80 (general); 60-120 (large)
Theatre	50-80
Exhibition building	50-80

Table 9.5 Electricity consumption of different types of buildings in China (MHUDP, 2009)

Scale	Super large (>30,000m^2)	Large (15,000-30,000m^2)	Medium (8,000-15,000 m^2)	Small (<5,000 m^2)
Energy load (VA/m^2)	90-145	85-135	75-115	70-105
Energy load (W/m^2)	45-97	43-84	38-77	35-70

Table 9.6 Electricity consumption of Science and Technology Museums in China (CAST, 2007)

The other source published by the China Association for Science and Technology (CAST, 2007) reports that the average electricity consumption of Science and Technology Museums in the super large scale (>30,000m^2) in China is around 45-97W/m^2 (Table 9.6). The Theme Pavilion (143,000 m^2) falls into the category of super large scale public buildings.

According to the report from MHUDP (2009), it can be assumed that the average electricity consumption of the Theme Pavilion at Expo 2010 in Shanghai is 65 W/m^2

[(50+80)/2]. If this exhibition building is used for 5 days per week (fully operated during the day time and partly operated during the night time), the average electricity consumption will be 270kWh/m^2/year (Table 9.7). This figure is supported by data from the statistics of the government of Shanghai. Shanghai public buildings consumed 150~300 kWh/m^2/year in 2007 (Government of Shanghai, 2007). It is therefore reasonable to use 270kWh/m^2/year for accounting for the operating energy of the Theme Pavilion. For the purposes of this study, it is assumed that the building only uses electricity.

Time of usage		Energy load	Calculation
Day time	12 hours/day and 5 days/week	65 W/m^2	65×12×5×52= 203 kWh/m^2/year
Night time	12 hours/day and 5 days/week	22 W/m^2 (assuming that it consumes one third of day time energy usage)	22×12×5×52= 67 kWh/m^2/year
Total	270 kWh/m^2/year		

Table 9.7 Assumed Energy consumption of the Theme Pavilion in a year

2. Energy generation

According to the statement on the solar energy technology published on the official website of Expo 2010 (BCSWE, 2010), the PV panels (total area 30,000 m^2) can generate 2,560,000 kWh of electricity per year in Shanghai, which is equal to 85.3 kWh/m^2/year.

Table 9.8 lists electricity generation from PV panels, comparing China (Shanghai), Italy, UK, and New Zealand (Vale and Vale, 2009, p.140; BCSWE, 2010). It needs to be noted that the figure of 85.3kWh/m^2/year just represents the capability of power generation in Shanghai and the Yangtze River Delta. Although Shanghai is much nearer the equator than the UK, the fact there is a lot of pollution in the city means that the sun is often obscured, so the PVs do not generate as much electricity (Zhang, 2010).

	Shanghai	Italy	UK	NZ
Energy generation from PV panels (kWh/m^2/year)	85.3	176	88	120

Table 9.8 Comparison of electricity generation from PV panels between four different countries

9.2.1.3 Building demolition-related energy

The energy consumption from building demolition is assumed to be negligible in this study. The reason for this has been explained in Chapters 5, 7, 8.

9.2.2 Visitor travel

By the same methodology as for the case studies presented in Chapters 6~8, the energy consumption of visitor travel can be quantified and demonstrated using the number of visitors, the distances of travel, and the energy intensity of different transportation modes.

9.2.2.1 Number of visitors

The total number of visitors going to the World Expo in Shanghai from 1 May to 31 Oct 2010 is 73,080,000 (BCSWE, 2010b). The percentage of visitors from different cities and countries is listed in Table 9.9.

Visitors		Number of visitors	Percentage	Reference
From Shanghai		9,950,000	13.6%	-
From Mainland China (apart from Shanghai)		58,880,000	80.6%	Liu, 2010
Overseas	Hong Kong, Macao, Taiwan	1,500,000	2.1%	SMSB, 2010c
	Asian countries	1,333,333	1.7%	SMSB, 2010c
	European countries	708,333	1%	Assumed
	America	708,333	1%	Assumed

Table 9.9 Percentage of visitors going to Expo 2010 in Shanghai

Based on the report of BCSWE (2010), the total number of visitors going to the Theme Pavilion was 23,000,000 (125,000 visitors/day × 184 days). The percentage split according to journey origin of the number of tourists visiting Expo 2010 is applied to calculate the number of visitors going to the Theme Pavilion (Table 9.10).

	From Shanghai	**From Mainland China** (apart from Shanghai)	**Hong Kong, Macao, Taiwan**	**Asian countries**	**European countries**	**America**
Percentage	13.6%	80.6%	2.1%	1.7%	1%	1%
Number of visitors	3,128,000	18,538,000	483,000	391,000	230,000	230,000

Table 9.10 Number of visitors going to the Theme Pavilion during the World Expo in Shanghai

1. Number of visitors from Shanghai (total: 3,128,000)

The total number of visitors from Shanghai going to the Theme Pavilion at Expo 2010 was 3,128,000. Based on the percentage of passengers taking different transport modes in Shanghai (Table 9.11, repeated below and discussed in Chapter 7), the number of visitors from Shanghai taking various modes going to the Theme Pavilion was calculated and listed in Tables 9.12 and 9.13.

Mode	**Percentage**	**Mode (detail)**	**Percentage**
Public transport	27%	Underground	4.86%
		Taxi	6.21%
		Bus	15.93%
Private automotive vehicle	17.5%	Motorcycle	2.10%
		Car	Small (1.78%)
			Medium (11.06%)
			Large (2.56%)
Non-motorized vehicle	28.5%	Bike	22.14%
		Electric bike	5.53%
		Scooter	0.83%
Walk	27%	-	-
Small= Small petrol car (up to 1.4 litre engine) (Defra, 2007); Medium= Medium petrol car (1.4-2.0 litres) (Defra, 2007); Large= Large petrol car (above 2.0 litres) (Defra, 2007) The percentage of people using the underground accounted for 18% of public transport use in 2007. This figure is expected to increase to 40% in 2012 when 12 new underground lines will be completed (Zhang, 2007).			

Table 9.11 Percentage of passengers taking different transport modes in Shanghai

Area	The percentage of population	The number of visitors	The number of people taking various modes				
			Underground (4.86%)	Taxi (6.21%)	Bus (15.93%)	Motorcycle (2.1%)	Small petrol car (1.78%)
1	6.3%	197064	9577	12238	31392	4138	3508
2	5.1%	159528	7753	9907	25413	3350	2840
3	5.7%	178296	8665	11072	28403	3744	3174
4	7.8%	243984	11858	15151	38867	5124	4343
5	4.4%	137632	6689	8547	21925	2890	2450
6	2.3%	71944	3496	4468	11461	1511	1281
7	4.4%	137632	6689	8547	21925	2890	2450
8	13.9%	434792	21131	27001	69262	9131	7739
9	6.5%	203320	9881	12626	32389	4270	3619
10	2.3%	71944	3496	4468	11461	1511	1281
11	6%	187680	9121	11655	29897	3941	3341
12	6.4%	200192	9729	12432	31891	4204	3563
13	3.9%	121992	-	-	-	14639 (12.00%)	12407 (10.17%)
14	5.3%	165784	-	-	-	19894 (12.00%)	16860 (10.17%)
15	3.7%	115736	-	-	-	13888 (12.00%)	11770 (10.17%)
16	3.8%	118864	-	-	-	14264 (12.00%)	12088 (10.17%)
17	3.9%	121992	-	-	-	14639 (12.00%)	12407 (10.17%)
18	3.3%	103224	-	-	-	12387 (12.00%)	10498 (10.17%)
19	5.0%	156400	-	-	-	18768 (12.00%)	15906 (10.17%)
In all	100%	3,128,000	108,087	138,111	354,285	155,183	131,523

Table 9.12 Number of visitors (from Shanghai) taking various modes going to the Theme Pavilion at Expo 2010

Area	The percentage of population	The number of visitors	The number of people taking different transport modes					
			Medium petrol car (11.06%)	Large petrol car (2.56%)	Bike (22.14%)	Electric bike (5.53%)	Scooter (0.83%)	Walk (27%)
1	6.3%	197064	21795	5045	43630	10898	1636	53207
2	5.1%	159528	17644	4084	35320	8822	1324	43073
3	5.7%	178296	19720	4564	39475	9860	1480	48140
4	7.8%	243984	26985	6246	54018	13492	2025	65876
5	4.4%	137632	15222	3523	30472	7611	1142	37161
6	2.3%	71944	7957	1842	15928	3979	597	19425
7	4.4%	137632	15222	3523	30472	7611	1142	37161
8	13.9%	434792	48088	11131	96263	24044	3609	117394
9	6.5%	203320	22487	5205	45015	11244	1688	54896
10	2.3%	71944	7957	1842	15928	3979	597	19425
11	6.0%	187680	20757	4805	41552	10379	1558	50674
12	6.4%	200192	22141	5125	44323	11071	1662	54052
13	3.9%	121992	77099 (63.2%)	17847 (14.63%)	-	-	-	-
14	5.3%	165784	104776 (63.2%)	24254 (14.63%)	-	-	-	-
15	3.7%	115736	73145 (63.2%)	16932 (14.63%)	-	-	-	-
16	3.8%	118864	75122 (63.2%)	17390 (14.63%)	-	-	-	-
17	3.9%	121992	77099 (63.2%)	17847 (14.63%)	-	-	-	-
18	3.3%	103224	65238 (63.2%)	15102 (14.63%)	-	-	-	-
19	5.0%	156400	98845 (63.2%)	22881 (14.63%)	-	-	-	-
In all	100%	3,128,000	817,298	189,189	492,395	122,988	18,459	600,482

Table 9.13 Number of visitors (from Shanghai) taking various modes going to the Theme Pavilion at Expo 2010

2. Number of visitors (from Mainland China) (Total: 18,538,000)

The percentage split according to population numbers in different provinces (Table 9.14) is applied to calculate the number of visitors going to the Theme Pavilion from mainland China (Table 9.15).

Beijing	Tianjin	Chongqing	Guangdong Province	Henan Province	Shandong Province	Sichuan Province	Jiangsu Province
16.95	11.76	28.39	95.44	94.29	94.17	81.38	76.76
1.3%	0.9%	2.2%	7.4%	7.3%	7.2%	6.3%	5.9%
Anhui Province	Hubei Province	Zhejiang Province	Guangxi Province	Yunnan Province	Jiangxi Province	Liaoning Province	Heilongjiang Province
61.35	57.11	51.20	50.49	45.43	44.00	43.15	38.25
4.7%	4.4%	4.0%	3.9%	3.5%	3.4%	3.3%	3.0%
Fujian Province	Guangxi Province	Jilin Province	Gansu Province	Neimenggu Province	Xinjiang Province	Hainan Province	Ningxia Province
36.04	34.11	27.34	26.28	24.14	21.31	8.54	6.18
2.8%	2.6%	2.1%	2.0%	1.9%	1.6%	0.7%	0.5%
Hebei Province	Hunan Province	Guizhou Province	Shanxi Province	Qinghai Province	Xizang Province		
69.89	68.45	37.93	37.62	5.54	2.87		
5.4%	5.3%	2.9%	2.9%	0.4%	0.2%		

Table 9.14 Population density of different provinces and municipalities in China (millions) (NBSC, 2008)

Beijing	Tianjin	Chongqing	Guangdong Province	Henan Province	Shandong Province	Sichuan Province	Jiangsu Province
1.3%	0.9%	2.2%	7.4%	7.3%	7.2%	6.3%	5.9%
242848	168696	405982	1364397	1347713	1345859	1164186	1097450
Anhui Province	Hubei Province	Zhejiang Province	Guangxi Province	Yunnan Province	Jiangxi Province	Liaoning Province	Heilongjiang Province
4.7%	4.4%	4.0%	3.9%	3.5%	3.4%	3.3%	3.0%
871286	815672	741520	722982	648830	630292	611754	556140
Fujian Province	Guangxi Province	Jilin Province	Gansu Province	Neimenggu Province	Xinjiang Province	Hainan Province	Ningxia Province
2.8%	2.6%	2.1%	2.0%	1.9%	1.6%	0.7%	0.5%
519064	481988	389298	370760	352222	296608	129766	92690
Hebei Province	Hunan Province	Guizhou Province	Shanxi Province	Qinghai Province	Xizang Province		
5.4%	5.3%	2.9%	2.9%	0.4%	0.2%		
1001052	982514	537602	537602	74152	37076		

Table 9.15 Number of Chinese visitors from different provinces and municipalities outside of Shanghai visiting the Theme Pavilion

Table 9.16 shows the split between transport modes for all travel in China. Because bus and car have been combined in Table 9.16, based on the percentage of passengers taking buses and cars in Shanghai (15.93% and 15.4%), it is assumed that the percentage of passengers taking buses in Mainland China was same as that of cars, so the percentage taking bus and car was halved for allocation to each mode.

It is assumed that no passengers going to Shanghai from other cities in mainland China were taking ships, because it is more convenient to use other transportation modes, and the total percentage of passengers taking ships in China is fairly small (0.26% (CEIN, 2008, p.7)). For this research, transportation modes chosen by visitors from mainland China going to the Theme Pavilion are limited to four: train, plane, bus, and car. The percentage of visitors who travelled by ships is split equally into four and added to the other transport modes.

To check the assumptions, the original model which includes taking ships (Table 9.16) is calculated as well. It is used to make a comparison with the result of the calculation without ships (Table 9.17). This is a theoretical calculation since taking ships from inland provinces is not an option. However, the comparison shows a similar energy consumption for the two different models (Table 9.18 theoretical but with ships; Table 9.19 more likely, without ships), but the version without ships (Tables 9.17 and 9.19) is more realistic in terms of likely transport modes chosen.

Modes	Train	Plane	Ship	Bus and car
Percentage	33.64%	12.90%	0.26%	53.19% (26.6% by bus, 26.6% by car)

Table 9.16 Percentage of number of passengers taking different transport modes in China in 2007 (CEIN, 2008, p.7)

Modes	Train	Plane	Bus	Car
Percentage	33.71%	12.95%	26.67%	26.67%

Table 9.17 Percentage of number of visitors taking different transport modes going to the Theme Pavilion in 2010

Location	Number of visitors	Train (33.64%)	Car (26.6%)	Bus (26.6%)	Plane (12.9%)	Ship (0.26%)
Beijing	242848	81694	64598	64598	31327	631
Tianjin	168696	56749	44873	44873	21762	439
Chongqing	405982	136572	107991	107991	52372	1056
Guangdong Province	1364397	458983	362930	362930	176007	3547
Henan Province	1347713	453371	358492	358492	173855	3504
Shandong Province	1345859	452747	357998	357998	173616	3499
Sichuan Province	1164186	391632	309673	309673	150180	3027
Jiangsu Province	1097450	369182	291922	291922	141571	2853
Hebei Province	1001052	336754	266280	266280	129136	2603
Hunan Province	982514	330518	261349	261349	126744	2555
Anhui Province	871286	293101	231762	231762	112396	2265
Hubei Province	815672	274392	216969	216969	105222	2121
Zhejiang Province	741520	249447	197244	197244	95656	1928
Guangxi Province	722982	243211	192313	192313	93265	1880
Yunnan Province	648830	218266	172589	172589	83699	1687
Jiangxi Province	630292	212030	167658	167658	81308	1639
Liaoning Province	611754	205794	162727	162727	78916	1591
Heilongjiang Province	556140	187085	147933	147933	71742	1446
Guizhou Province	537602	180849	143002	143002	69351	1398
Shanxi Province	537602	180849	143002	143002	69351	1398
Fujian Province	519064	174613	138071	138071	66959	1350
Guangxi Province	481988	162141	128209	128209	62176	1253
Jilin Province	389298	130960	103553	103553	50219	1012
Gansu Province	370760	124724	98622	98622	47828	964
Neimenggu Province	352222	118487	93691	93691	45437	916
Xinjiang Province	296608	99779	78898	78898	38262	771
Hainan Province	129766	43653	34518	34518	16740	337
Ningxia Province	92690	31181	24656	24656	11957	241
Qinghai Province	74152	24945	19724	19724	9566	193
Xizang Province	37076	12472	9862	9862	4783	96
Total	18538000	6236183	4931108	4931108	2391402	48199

Table 9.18 Number of Chinese tourists visiting the Theme Pavilion by different transport modes (theoretical ship travel included)

Location	Number of visitors	Train (33.71%)	Car (26.67%)	Bus (26.67%)	Plane (12.95%)
Beijing	242848	81864	64768	64768	31449
Tianjin	168696	56867	44991	44991	21846
Chongqing	405982	136857	108275	108275	52575
Guangdong Province	1364397	459938	363885	363885	176689
Henan Province	1347713	454314	359435	359435	174529
Shandong Province	1345859	453689	358941	358941	174289
Sichuan Province	1164186	392447	310488	310488	150762
Jiangsu Province	1097450	369950	292690	292690	142120
Hebei Province	1001052	337455	266981	266981	129636
Hunan Province	982514	331205	262036	262036	127236
Anhui Province	871286	293711	232372	232372	112832
Hubei Province	815672	274963	217540	217540	105630
Zhejiang Province	741520	249966	197763	197763	96027
Guangxi Province	722982	243717	192819	192819	93626
Yunnan Province	648830	218721	173043	173043	84023
Jiangxi Province	630292	212471	168099	168099	81623
Liaoning Province	611754	206222	163155	163155	79222
Heilongjiang Province	556140	187475	148323	148323	72020
Guizhou Province	537602	181226	143378	143378	69619
Shanxi Province	537602	181226	143378	143378	69619
Fujian Province	519064	174976	138434	138434	67219
Guangxi Province	481988	162478	128546	128546	62417
Jilin Province	389298	131232	103826	103826	50414
Gansu Province	370760	124983	98882	98882	48013
Neimenggu Province	352222	118734	93938	93938	45613
Xinjiang Province	296608	99987	79105	79105	38411
Hainan Province	129766	43744	34609	34609	16805
Ningxia Province	92690	31246	24720	24720	12003
Qinghai Province	74152	24997	19776	19776	9603
Xizang Province	37076	12498	9888	9888	4801
Total	18538000	6249160	4944085	4944085	2400671

Table 9.19 Number of Chinese tourists visiting the Theme Pavilion by different transport modes (likely mode selections)

3. Number of visitors from Hong Kong, Macao, Taiwan (483,000)

The total number of visitors from Hong Kong, Macao, and Taiwan was 483,000. CEIN (2008, p.3) reported the percentage of number of visitors coming from these three cities in 2007. Based on these proportions (87.4%, 3.3%, and 9.3%), the number of tourists visiting the Theme Pavilion from Hong Kong, Macao, and Taiwan can be calculated, as shown in Table 9.20.

Furthermore, CEIN (2008, p.3) demonstrated the percentage of visitors from Hong Kong, Macao, and Taiwan taking different transport modes to go to mainland China, including airplane, train, bus, and car. Based on these figures, the number of visitors going to the Theme Pavilion from these three cities by different transport modes can be calculated (Table 9.21).

	Hong Kong	**Macao**	**Taiwan**
Percentage (CEIN, 2008, p.3)	87.4%	3.3%	9.3%
Number of visitors	422142	15939	44919
Transport modes	Fly, Rail, Road	Fly, Rail, Road	Fly

Table 9.20 Number of tourists visiting the Theme Pavilion from Hong Kong, Macao, Taiwan

Location	**Plane**		**Train**		**Bus**		**Car**	
	percentage	Number of visitors	percentage	Number of visitors	Percentage	Number of visitors	Percentage	Number of visitors
Hong Kong	6.45%	422142	3.95%	16675	44.80%	189120	44.80%	189120
Macao	5.03%	802	1.63%	260	46.67%	7439	46.67%	7439
Taiwan	100%	44919	-	-	-	-	-	-
Total	-	72949	-	16934	-	196558	-	196558

Table 9.21 Number of visitor going to the Theme Pavilion from Hong Kong, Macao, Taiwan by different transport modes

4. Number of visitors from other countries (851,000)

The total number of foreign visitors was 851,000, of which 153,000 came from other Asian countries. The percentage of visitors from Asian countries taking ship, airplane, train, and car to go to Mainland China was 12.8%, 67.6%, 3.7%, and 15.9% (CEIN, 2008, p.3). The number of Asian visitors using different transport modes to go to the Theme Pavilion is then calculated (Table 9.22). In addition, in this study, it is assumed that all the visitors from European countries and America used air travel to go to Shanghai.

Asian countries	Ship	Plane	Train	Car
Percentage (CEIN, 2008, p.3)	12.8%	67.6%	3.7%	15.9%
Number of visitors	50048	264316	14467	62169

Table 9.22 Number of visitors from Asian countries taking different transport modes coming to the Theme Pavilion

9.2.2.2 Distance of visitor travel

1. Visitors from Shanghai

The method of determining the travel distance from different districts to the Theme Pavilion was the same as the method for visitor travel to the Shanghai Exhibition Centre (explained in Chapter 7). The distances of travel from the 19 districts are listed in Table 9.23.

Area	Name of District	Distance of travel (km)	Area	Name of District	Distance of travel (km)
1	Pu Tuo	11.84	11	Bao Shan	16.34
2	Zha Bei	10.61	12	Min Hang	10.23
3	Hong Kou	10.48	13	Jia Ding	26.30
4	Yang Pu	11.50	14	Nan Hui	25.22
5	Chang Ning	11.17	15	Feng Xian	24.83
6	Jing An	7.23	16	Jin Shan	35.65
7	Huang Pu	4.26	17	Song Jiang	27.79
8	Pu Dong	6.75	18	Qing Pu	32.23
9	Xu Hui	5.72	19	Chong Ming	33.96
10	Lu Wan	3.26			

Table 9.23 Travel distance from different districts to the Theme Pavilion in Shanghai

2. Visitors from mainland China and Hong Kong, Macao, and Taiwan

The travel distance from each Chinese provincial capital city to Shanghai was calculated by the straight line distance, as listed in Tables 9.24 and 9.25.

No	Name of Province	Distance of travel (km)	No	Name of Province	Distance of travel (km)
1	Beijing	1088	16	Jiangxi Province	611
2	Tianjin	963	17	Liaoning Province	1191
3	Chongqing	1445	18	Heilongjiang Province	1675
4	Guangdong Province	1213	19	Guizhou Province	1527
5	Henan Province	827	20	Shanxi Province	1099
6	Shandong Province	729	21	Fujian Province	611
7	Sichuan Province	1659	22	Shanxi Province	1223
8	Jiangsu Province	266	23	Jilin Province	1444
9	Hebei Province	991	24	Gansu Province	1718
10	Hunan Province	886	25	Neimenggu Province	1374
11	Anhui Province	402	26	Xinjiang Province	3269
12	Hubei Province	684	27	Hainan Province	1630
13	Zhejiang Province	169	28	Ningxia Province	1595
14	Guangxi Province	1603	29	Qinghai Province	1913
15	Yunnan Province	1950	30	Xizang Province	2902

Table 9.24 A straight line distance of visitors from the main cities of mainland China to Shanghai

Hong Kong to Shanghai	1208 km
Macao to Shanghai	1276 km
Taipei to Shanghai	km

Table 9.25 Travel distance from Hong Kong, Macao, and Taiwan to Shanghai

3. Visitors from Asian, European, and American countries

The travel distances from foreign countries (Asia, Europe, and America) to China have been measured using the “place to place distance calculator” (Distancefromto, 2010). The average travel distance from the different countries has been adopted for the calculation. The detailed figures can be seen in Tables 9.26~9.28.

Area	Direct distance from different countries to China (km)		Average distance (km)
Eastern Asia	Japan	3050	2123
	Mongolia	1225	
	North Korea	2096	
	South Korea	2121	
Southern Asia	Afghanistan	3319	2988
	Bangladesh	1900	
	Bhutan	1598	
	India	2987	
	Maldives	4832	
	Nepal	2062	
	Pakistan	3288	
	Sri Lanka	3921	
Western Asia	Armenia	5117	5383
	Azerbaijan	4905	
	Bahrain	5170	
	Cyprus	6263	
	Iraq	5467	
	Iran	4618	
	Israel	6327	
	Jordan	6228	
	Kuwait	5296	
	Lebanon	6113	
	Oman	4923	
	Qatar	2610	
	Saudi Arabia	5773	
	Syria	5806	
	United Arab Emirates	5007	
	Turkey	5957	
	Yemen	5936	
North Asia	Russia	2858	2858
Southeast Asia	Brunei	3651	3149
	Burma	1746	
	Cambodia	2595	
	East Timor	5468	
	Indonesia	4203	
	Laos	1790	
	Philippines	3106	
	Malaysia	3531	
	Singapore	3842	
	Thailand	2248	
	Vietnam	2461	
Central Asia	Kazakhstan	3329	3251
	Kyrgyzstan	2617	
	Tajikistan	2916	
	Turkmenistan	3923	
	Uzbekistan	3469	

Table 9.26 Travel distance from Asian countries to China (Distancefromto, 2010)

Area	Direct distance from different countries to China (km)		Average distance (km)
Northern Europe	Denmark	7039	7026
	Faroe Islands	7538	
	Estonia	6078	
	Finland	5968	
	Åland Islands	6317	
	Iceland	7786	
	Ireland	8169	
	Latvia	6145	
	Lithuania	6237	
	Norway	6899	
	Svalbard and Jan Mayen	5908	
	Sweden	6386	
	United Kingdom	7788	
	Guernsey	8121	
	Isle of Man	7920	
	Jersey	8111	
Western Europe	Austria	7145	7561
	Belgium	7636	
	France	8031	
	Germany	7232	
	Liechtenstein	7498	
	Luxembourg	7573	
	Monaco	7833	
	Netherlands	7495	
	Switzerland	7605	
Central and Eastern Europe	Belarus	6023	6327
	Bulgaria	6575	
	Czech Republic	6976	
	Hungary	6822	
	Moldova	6184	
	Poland	6648	
	Romania	6484	
	Russia	4858	
	Slovakia	6744	
	Ukraine	5954	
Southern Europe	Albania	7049	7640
	Andorra	8302	
	Bosnia and Herzegovina	7100	
	Croatia	7219	
	Gibraltar	9209	
	Greece	7022	
	Italy	7575	
	Macedonia	6908	
	Malta	7766	
	Montenegro	7034	
	Portugal	9168	
	San Marino	7472	
	Serbia	6853	
	Slovenia	7181	
	Spain	8798	
	Vatican City	7581	

Table 9.27 Travel distance from European countries to China (Distancefromto, 2010)

Countries	Distance of travel by airplane
European countries	See Table 9.27
America (New York to Shanghai)	11,907km (Travelmath, 2011)

Table 9.28 Travel distance from European countries and USA to China

9.2.2.3 Energy intensity of different transport modes

The energy intensity of different transport modes, including underground, taxi, car, bus, motorcycle, electric bike, scooter, train, airplane, and ship, in China are sourced from the literature and are listed in Table 9.29.

Modes		Fuel	Energy intensity (MJ/passenger-km)	Reference
Underground		Electricity	0.071	See Table 7.6
Taxi		Fossil fuel	2.494	See Table 7.6
Car	Small	Fossil fuel	1.467	See Table 7.6
	Medium	Fossil fuel	2.304	
	Large	Fossil fuel	3.133	
Bus		Fossil fuel	0.648	See Table 7.6
Motorcycle		Fossil fuel	1.000	See Table 7.6
Electric bike		Electricity	0.036	See Table 7.6
Scooter		Fossil fuel	0.086	See Table 7.6
Train		Electricity/Fossil fuel	0.174	Xie et al, 2010
Airplane		Jet fuel	2.012	Xie et al, 2010
Ship		Fossil fuel	0.756 (SeaBus, Vancouver, Canada)	David and MacKay, 2009

Table 9.29 Energy intensity of different transport modes in China

9.2.2.4 CO_2 emissions coefficients

The associated CO_2 emissions of visitor travel to go the Theme Pavilion in Shanghai are estimated. CO_2 emissions coefficients of different transport modes in China were mainly from Chinese literature, as shown in Table 9.30.

Modes		**Fuel**	**CO_2 emissions coefficients (g/passenger-km)**	**Reference**
Underground		Electricity	16.6	See Table 7.7
Taxi		Fossil fuel	167.5	See Table 7.7
Car	Small	Fossil fuel	98.6	See Table 7.7
	Medium	Fossil fuel	155.0	
	Large	Fossil fuel	210.0	
Bus		Fossil fuel	43.5	See Table 7.7
Motorcycle		Fossil fuel	67.2	See Table 7.7
Electric bike		Electricity	8.4	See Table 7.7
Scooter		Fossil fuel	5.8	See Table 7.7
Train		Electricity/Fossil fuel	25	IFEU, 2008
Airplane		Jet fuel	145	IFEU, 2008
Ship		Fossil fuel	201 (Size of GT: 2,000-9,999, Cruise ship, Norway)	Walnum, 2011

Table 9.30 CO_2 emissions coefficients of different transport modes in China

9.2.3 Exhibition-related economic aspects

The ecological footprint of the exhibition-related economic aspects of Expo 2010 in Shanghai was found by converting the monetary value of the economic income. In this way the economic benefits and ecological footprint generated by Expo 2010 can be investigated.

9.2.3.1 Exhibition-related economic income

Three parts of the economic benefits generated by Expo 2010 are investigated in this research: tickets sold, direct economic benefits generated during the Expo 2010, and potential benefits after Expo 2010.

1. Tickets sold at Expo 2010

The Bureau of Coordination of Shanghai World Expo (BCSWE, 2010b) announced that the total number of visitors going to Expo 2010 was 73,080,000 and the average price of a ticket for the expo was 160 RMB. Thus, the total economic income of tickets sold for Expo 2010 was 11,692,800,000 RMB (1,794,584,664 USD) (160 RMB × 73,080,000).

2. Direct economic benefits generated during Expo 2010

Direct economic benefits mainly come from commercial sales in and out of the Expo Park and exhibition-related tourism.

Luo (2011) demonstrated the income from the commercial sales in the Expo Park was about 4,507,000,000 RMB (691,724,230 USD), including food sold (2,400,000,000 RMB) and retail trade. Secondly, 30,958,000,000 RMB (4,751,364,261 USD) came from expo licensed products (Luo, 2011).

In addition, based on the estimation of the China Tourism Academy, economic income from tourism resulting from the Expo was estimated to be around 55,040,000,000 RMB (8,447,415,496 USD), apart from the income of transportation (24,960,000,000 RMB) (Zheng, 2010). The detailed figures of income coming from these different categories are shown in Table 9.31.

Visitors from Mainland China		
Main industries	Percentage of income (Liu, 2010)	Income (RMB)
Accommodation	36.0%	28,800,000,000
Retail	5.8%	4,640,000,000
Restaurant	6.5%	5,200,000,000
Visitors from Hong Kong, Macao, Taiwan, and other countries		
Main industries	Percentage of income (Liu, 2010)	Income (RMB)
Accommodation	11.2%	8,960,000,000
Retail	4.8%	3,840,000,000
Restaurant	4.5%	3,600,000,000
Total	55,040,000,000 RMB	

Table 9.31 Income generated from different income categories of Expo 2010

The total direct economic benefits generated during Expo 2010 were 90,505,000,000 (13,890,504,770 USD).

3. Economic benefits generated after the Expo 2010 (Total: 12,980,779,024 USD)

Research has found 5% of local GDP was generated from Expo 2010 (Cai et al, 2009; Zheng, 2010). The GDP in Shanghai in 2010 was about 1,687,242,000,000 RMB (25,961,558,048 USD) (Wang, 2011). Thus 5% of GDP is 84,362,100,000 RMB (12,980,779,024 USD). For example, exhibition-related economic benefits after the Expo 2010 will be generated from land sales and related real estate (Li and Wu, 2010).

4. Total economic benefit

The international event, Expo 2010, brought a total income of 186,559,900,000 RMB (28,665,867,675 USD), as shown in Table 9.32.

Exhibition-related economic benefit	RMB	USD
Tickets sold	11,692,800,000	1,794,584,664
Commercial sale in the Expo Park	4,507,000,000	691,724,230
Expo licensed products (Souvenir)	30,958,000,000	4,751,364,261
Economic income from tourism	55,040,000,000	8,447,415,496
Economic benefits generated after the Expo 2010	84,362,100,000	12,980,779,024
Total economic income	186,559,900,000	28,665,867,675

Table 9.32 Total economic benefit of Expo 2010

9.2.3.2 Economic-related ecological footprint

The national Ecological Footprint intensity of China was about 5,139 RMB/gha in 2001 (Chen et al, 2006), which has been explained in Chapter 7. On this basis the ecological footprint of direct and indirect economic benefits is calculated.

9.3 Results and analysis

9.3.1 Building

9.3.1.1 Embodied energy

The calculated result of the total embodied energy of the Theme Pavilion is 1,284,266 GJ (9.0 GJ/m^2) for the assumed 50 year life. It includes 1,199,806 GJ (8.4 GJ/m^2) of initial embodied energy and 84,460 GJ (0.6 GJ/m^2) of recurring embodied energy.

Materials	Initial embodied energy (GJ)	Percentage (%)
Reinforced concrete	421,219	35.1
Damp proof membrane	3,199	0.3
Steel	120,385	10.0
Paint	6,340	0.5
Aluminium	242,800	20.2
Cement	15,843	1.3
Sand	500	0.04
Tiles	79,377	6.6
Carpet	3,670	0.3
Plasterboard	356	0.03
Glass	9,918	0.8
Glass wool	6,454	0.5
PV panels	49,560	4.1
FRP skylight roof panels	224	0.02
Building services	239,961	20.0
Total	1,199,806 GJ (8.4 GJ/m^2)	

Table 9.33 Quantitative breakdown of the initial embodied energy of different materials (Appendix D)

The initial embodied energy, shown in Table 9.33, is 1,199,806 GJ or 8.4 GJ/m^2. It can be seen that the building elements constructed of reinforced concrete, aluminium and steel in the Theme Pavilion have the highest initial embodied energy. The initial embodied energy of reinforced concrete and aluminium account for 35.1% and 20.2% respectively in the total. Aluminium panels and frames have been widely used for the inside and outside façades of the case study building, which means consuming more energy and resources than if other cladding materials had been chosen, because of their energy intensive and complex manufacturing process.

Materials	Recurring embodied energy (GJ)	Percentage (%)
Reinforced concrete	0	0
Damp proof membrane	0	0
Steel	0	0
Paint	27,560	32.6
Aluminium	0	0
Cement	0	0
Sand	0	0
Tiles	0	0
Carpet	7,340	8.7
Plasterboard	0	0
Glass	0	0
Glass wool	0	0
PV panels	49,560	58.7
FRP skylight roof panels	0	0
Building services	0	0
Total	84,460 GJ (0.6 GJ/m^2)	

Table 9.34 Quantitative breakdown of the recurring embodied energy of different materials (Appendix D)

The recurring embodied energy is calculated as 84,460 GJ or 0.6 GJ/m^2 (Table 9.34). Three construction materials, including paint, carpet, and photovoltaic panels, have to be reapplied or replaced in the useful life of 50 years. It seems that photovoltaic panels have a large recurring energy (49,560 GJ), which accounts for 59% of the total recurring energy, although they have the ability to generate renewable energy.

9.3.1.2 Operating energy

Total energy consumption of the Theme Pavilion in its operating phase in a year is based on 270 kWh/m^2/year and 143,000 m^2 (total construction area). The total electricity consumption of the Theme Pavilion is 1,930,500,000 kWh in 50 years or 38,610,000kWh/year. At the same time, the electricity produced by the PV panels will be about 128,000,000 kWh or 2,560,000kWh/year. Thus, the total operating energy of the building is equal to the consumption minus the electricity generation, and is approximately 36,050,000kWh/year or 252kWh/m^2/year.

9.3.2 Visitor travel

Using the proportions in every district, the numbers of people choosing different transport modes in every district, city, and country were calculated. The total energy consumption of visitors travelling by different transport modes to go to the Theme Pavilion is 67,609,950 GJ, or 2.94 GJ/visitor for the return trip. The total CO_2 emissions of visitor travel to go to the Theme Pavilion are 8,183,248 t (there and back). To avoid repetition of a similar process of calculation, the detailed quantitative work for the visitor travel of this case study can be seen in Appendix D.

As the total exhibition area of Expo 2010 was too large to visit in one day, the number of independent pavilions visited was four to six pavilions in a day (average five) (CEAIR, 2010). Total energy consumption and associated CO_2 emissions of visitor travel to go to the Theme Pavilion as part of an Expo 2010 visit were 13,521,990 GJ (67,609,950 ÷ 5) (Table 9.35) and 1,636,650 t (8,183,248 ÷ 5) (Table 9.36).

	Total energy consumption
From Shanghai	28,632 GJ
From mainland China	8,718,614 GJ
From HK, Macao, Taiwan	311,643 GJ
From Asian countries	941,208 GJ
From other countries	3,521,894 GJ
Total	13,521,990 GJ

Table 9.35 Total energy consumption of visitor travel assuming five pavilions were visited

	CO_2 emissions
From Shanghai	1,927 t
From mainland China	644,161 t
From HK, Macao, Taiwan	51,538 t
From Asian countries	471,321 t
From other countries	467,703 t
Total	1,636,650 t

Table 9.36 Total CO_2 emissions of visitor travel assuming five pavilions were visited

9.3.3 Exhibition-related economic aspects

The total ecological footprint of the direct and indirect economic benefits of Expo 2010 was 36,302,764 gha, or 0.50 gha/visitor, which was generated from the exhibition-related economic benefits of 186,559,900,000 RMB. Tables 9.37 and 9.38 show the ecological footprint of each category of economic benefit.

Exhibition-related economic benefit	RMB	EF (gha)
Tickets sold	11,692,800,000	2,275,307
Commercial sales in the Expo Park	4,507,000,000	877,019
Expo licensed products (Souvenir)	30,958,000,000	6,024,129
Economic income from tourism	55,040,000,000	10,710,255
Economic benefits generated after the Expo 2010	84,362,100,000	16,416,054
Total economic income	186,559,900,000	36,302,764

Table 9.37 Ecological footprint of exhibition-related economic benefit

Exhibition-related economic benefit	Average EF (gha/visitor)
Tickets sold	0.03
Commercial sales in the Expo Park	0.01
Expo licensed products (Souvenirs)	0.08
Economic income from tourism	0.16
Economic benefits generated after the Expo 2010	0.22
Total economic income	0.50

Table 9.38 Average ecological footprint of exhibition-related economic benefit

9.4 Whole life-cycle impact

The total ecological footprint of the case study building and event was 36,439,538 gha/year, or 0.503 gha/visitor/year, as shown in Table 9.39.

	Total ecological footprint in a year (gha/year)	Average ecological footprint (gha/visitor/year)	Average ecological footprint (gha/m^2/year)
Theme Pavilion	1,554	0.00006	0.011
Visitor travel going to the building	135,220	0.00588	0.946
Exhibition-related economic aspects	36,302,764	0.497	253.866
Total	36,439,538	0.503	254.823

Table 9.39 Ecological footprint of the case study over the assumed useful life of 50 years

9.5 Chapter conclusion

This chapter calculated the energy, carbon and ecological footprint of the Theme Pavilion at Expo 2010 in Shanghai, visitor travel going to the Expo, and exhibition-related economic aspects. It demonstrated the current effect of the sustainable technologies (30,000 m^2 of solar panels) used in this pavilion. In addition, energy and associated carbon emissions of visitor travel was examined at the international level, which is different from the Chapter 7 case study which only considered local travel. It also shows the significant direct and indirect environmental degradation to Shanghai, especially the exhibition-related economic aspects.

Chapter 10 Comparative analysis

10.1 Introduction

In some more recent world expositions sustainable technologies have been utilised in both exhibition buildings and in exhibition-related visitor travel (discussed in Sections 2.2.3 and 3.2.2). Some researchers have proposed that improving energy efficiency in commercial buildings (and exhibition buildings fall into this category) is one of the easiest and lowest cost ways to mitigate environmental degradation (Figueres and Philips, 2007; Kneifel, 2010). However, there are still some problems with the application of sustainable technologies in terms of reducing the energy consumption of exhibition pavilions and expo transportation (discussed in Chapter 3). The other fact is that any reduction in the energy use of large-scale events has to be measured over their whole life, and this thesis claims, to be truly sustainable, this should include the life-time aspects of exhibition buildings, exhibition-related visitor travel and the economic effect of holding expos (the research scope has been explained in Section 4.2).

This chapter, therefore, will explore the relative impacts of the components of the research hypothesis: "the exhibition industry does have large environmental impacts and these require concern in terms of infrastructure construction, transport modes, and exhibition-related economic benefits. The exhibition-related economic factor dominates, with the greatest impact on the environment, compared to the other factors." This exploration will be carried out by comparative analysis of the results from the four case studies in Chapters 6~9 (the Great Exhibition of 1851, Shanghai National Exhibitions, Expo 2000, and Expo 2010). It explores the real problems existing in the exhibition industry in terms of their environmental aspects and ends by attempting to define what a real sustainable exposition and sustainable exhibition building might be.

The four case studies, all exhibition buildings with comparable functions (discussed in Chapter 5), are detailed and quantified and then compared in terms of their energy intensity from buildings usage, visitor travel, and exhibition-related economic aspects.

The methods of quantification and detailed processes of calculation of the energy and resource consumption of the four case studies have been explained in Chapters 5~9. As clarification, the discussions and conclusions in this chapter are made in the context of the environmental aspect of sustainability, this being the most significant aspect for energy flows in the triple bottom line of sustainability (environment, economy, and society). In addition, the conclusions of the comparative analysis are formed in terms of the most significant aspects derived from the calculated results. It is noted that the Shanghai National Exhibition, as a national event, cannot be directly compared in some aspects (this will be discussed in the following sections).

Comparisons are made between the energy consumption of the four exhibition buildings (Section 10.2), related visitor travel (Section 10.3), and resource consumption in terms of the exhibition-related economic aspects (Section 10.4). Comparison is also made of the environmental impact of the four expositions over their whole life cycle (Section 10.5) (Figure 10.1).

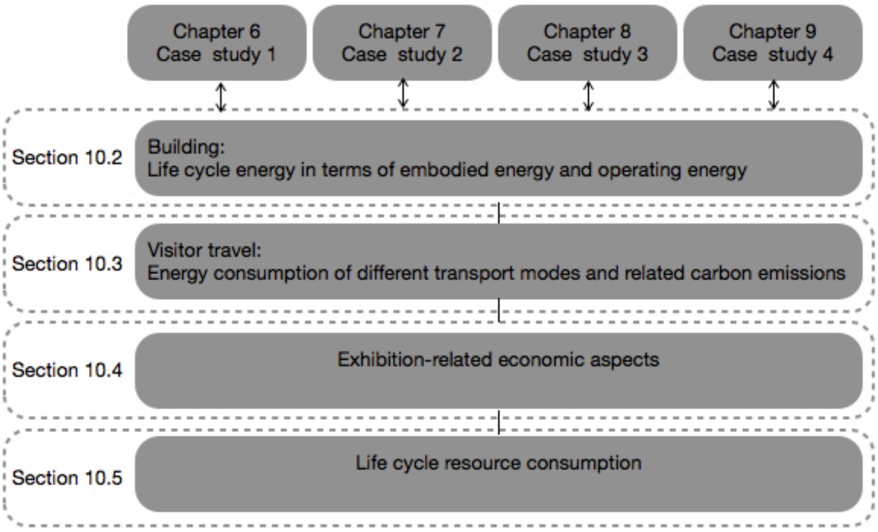


Figure 10.1 Diagram of comparisons made in the different sections in this chapter

10.2 Comparison of energy consumption of exhibition buildings

In this section, the energy consumptions of the four different case study buildings, the Crystal Palace, the Shanghai Exhibition Centre, the Dutch Pavilion, and the Theme Pavilion, are compared and discussed based on the average usage (for example

MJ/m^2/month or MJ/m^2/year). The energy consumption that is estimated and compared is covered by the categories depicted in Figure 10.2. The building demolition related energy is not discussed in this study (the reason for this has been explained in Chapter 5).

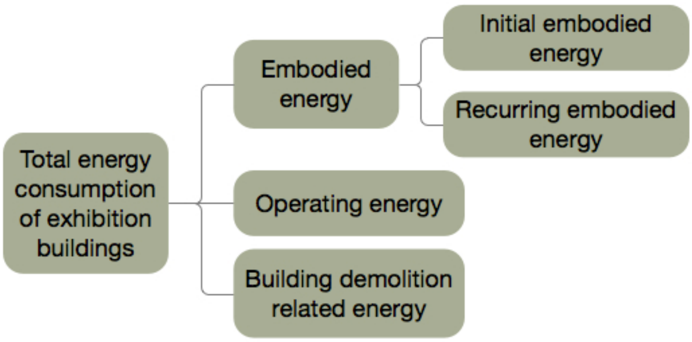


Figure 10.2 Energy consumption estimated and compared in this research

The energy consumptions of the four case study buildings in terms of both actual useful life and assumed useful life are estimated separately in sections 10.2.1 and 10.2.2. The reason for this is that the former result (energy consumption based on actual useful life of buildings) explores the truth of the supposed sustainable design of exhibition buildings, and the latter result (energy consumption based on assumed useful life of buildings) is to provide a more normalised comparison. The useful life of the Dutch Pavilion and the Theme Pavilion is assumed to be 50 years, based on the useful life of general exhibition and commercial buildings (shown in Table 10.1). As the exhibition halls for world expos (e.g. Crystal Palace and Theme Pavilion) were used for operating national exhibitions after the original international expositions, the life cycle energy consumption of the Shanghai Exhibition Centre as a general exhibition building can be compared with the others.

Exhibition buildings	Period	Actual useful life	Assumed useful life
Crystal Palace	1851-1936	82.5 years	50 years
Shanghai Exhibition Centre	1955-ongoing	56 years and more	50 years
Dutch Pavilion	June to October 2000	5 months	50 years
Theme Pavilion	May to October 2010 and March 2011-ongoing	13 months or more	50 years

Table 10.1 Two different useful periods of four case study buildings

10.2.1 Comparison of energy consumption of exhibition buildings over their actual useful life

The first comparison is made between the energy consumption of the four case study buildings over their actual useful life. Energy consumption of exhibition buildings includes the initial and recurring embodied energy, and operating energy. In this study, the building demolition related energy is not discussed, as indicated above. The actual useful life of the four buildings for calculation is given in Table 10.2.

Exhibition buildings	Period	Actual useful life
Crystal Palace	1851-1936	82.5 years
Shanghai Exhibition Centre	1955-2011	56 years
Dutch Pavilion	June to October 2000	5 months
Theme Pavilion	May to October 2010 and March to September 2011	13 months

Table 10.2 Actual useful life of four case study buildings for calculation

10.2.1.1 Embodied energy over actual useful life

Table 10.3 shows the comparison between the average embodied energy of the different case study buildings. The Dutch Pavilion had the highest embodied energy consumption. In its actual life, this was more than 700 times the embodied energy of the Crystal Palace, which was used in two different locations. The average embodied energy of the Theme Pavilion (built in 2010) is 100 times that of the Shanghai Exhibition Centre (built in 1955), although they were designed and constructed in the same city. However, these discrepancies are due largely to the very short actual lives of the Dutch pavilion and the Theme Pavilion to date.

	Initial embodied energy (MJ/m^2/month)	Recurring embodied energy (MJ/m^2/ month)	Total embodied energy (MJ/m^2/ month)
Crystal Palace (82.5 years)	1.3	1 .2	2.5
Shanghai Exhibition Centre (56 years)	8	6	14
Dutch Pavilion (5 months)	2,120	0	2,120
Theme Pavilion (13 months)	1,400	0	1,400

Table 10.3 Comparison of average embodied energy of four case study buildings based on actual life (note, figures are rounded)

Table 10.4 compares the percentage of initial and recurring embodied energy in the total embodied energy consumption of the four exhibition buildings over their actual useful life. There is no recurring embodied energy for the Dutch Pavilion and the Theme Pavilion, due to their short life, as shown in Table 10.4 and Figure 10.3.

	Initial embodied energy (GJ/m^2)	Percentage	Recurring embodied energy (GJ/m^2)	Percentage	Total lifetime embodied energy (GJ/m^2)
Crystal Palace (82.5 years)	1.34	53%	1.19	47%	2.53
Shanghai Exhibition Centre (56 years)	5.49	58%	4.00 (extension and maintenance)	42%	9.49
Dutch Pavilion (5 months)	10.61	100%	0.00	0%	10.61
Theme Pavilion (13 months)	8.39	100%	0.00	0%	8.39

Table 10.4 Comparison of percentage of initial and recurring embodied energy of four case study buildings over actual life

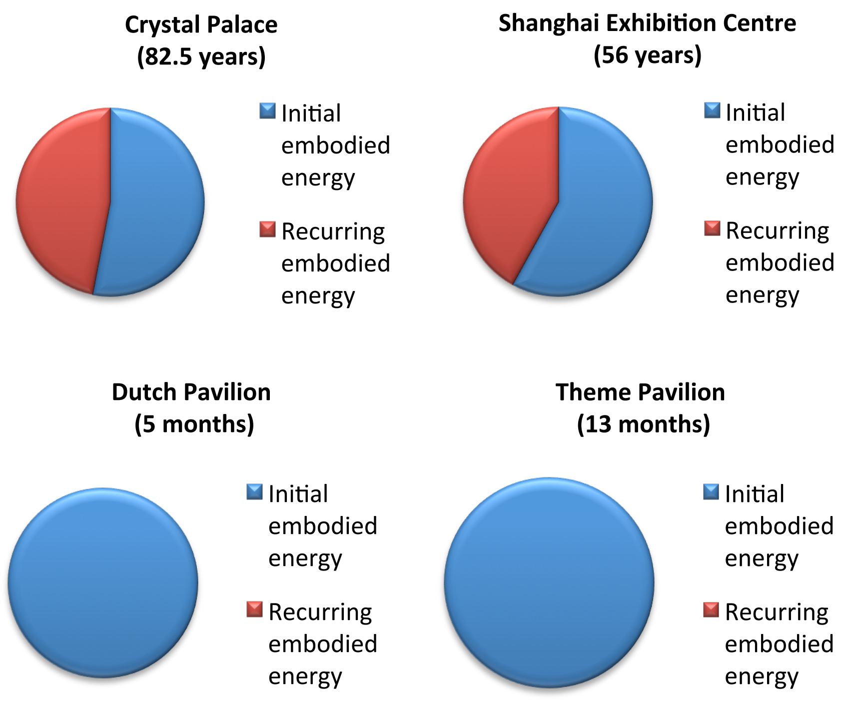


Figure 10.3 Percentage of initial and recurring embodied energy of the four case study buildings based on actual life

10.2.1.2 Operating energy over actual useful life

Table 10.5 shows that the average operating energy consumed for building services, such as lighting and heating or HVAC systems of the four different exhibition buildings with construction dates ranging from the 19th century to the 21st century, were close. It is noted that the average operating energy of the Shanghai Exhibition Centre seems much lower than the other buildings, as no air-conditioning was installed for heating and cooling from 1955 to 2001 (46 years) (discussed in section 7.2.1.2). This building would consume 63 MJ/m^2/month in its operation phase if it had the air-conditioning system since 1955.

	Average operating energy (MJ/m^2/month)
Crystal Palace (82.5 years)	93
Shanghai Exhibition Centre (56 years)	37
Dutch Pavilion (5 months)	83
Theme Pavilion (13 months)	76

Table 10.5 Comparison of average operating energy of four case study buildings over actual life

The heating system in the Crystal Palace depended on burning coal and the other three case study buildings used electricity as the main energy source. Although the electricity of different countries is generated from different natural resources, the average operating energy values of the Dutch Pavilion, and the Theme Pavilion were similar.

It needs to be noted that roughly 50 to 70 % of the thermal energy in the fuel can be supplied to a building from coal boilers by directly burning coal (Brown, 2006, p.24), the heating system of the Sydenham Crystal Palace. However, in the case of electricity, only 30% of thermal energy can be converted to electricity from burning coal in the process of electricity generation (Figure 10.4) (EurActiv, 2006). Modern buildings, such as the Shanghai Exhibition Centre, the Dutch Pavilion, and the Theme Pavilion are operated by electricity. Because of improvement in the technologies of energy efficiency, the average operating energy of modern exhibition buildings tends to be lower than that of the historic building. However, because the modern buildings use electricity their overall energy efficiency in terms of the primary energy used for their operation may be worse than that of the Crystal Palace, because the latter used coal directly.

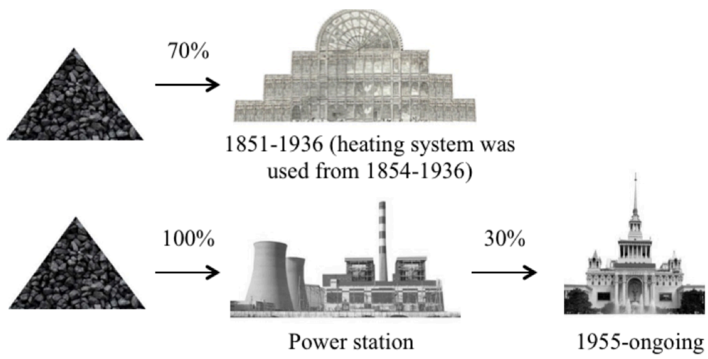


Figure 10.4 Operating energy conversions of historic and modern exhibition buildings

If the Dutch Pavilion and Theme Pavilion did not have PV panels and wind turbines installed, their operating energy consumptions would be even higher (Table 10.6). It is found that without its renewable energy contribution the average operating energy of the Dutch Pavilion is equal to that of the Crystal Palace using a coal-fired heating system in the 19th and early 20th Centuries. In fact the Shanghai Exhibition Centre designed in 1955 has a lower operating energy use than the Theme Pavilion at Expo 2010 Shanghai with its PVs. Whether using PV panels and other sustainable technologies could help to mitigate the energy usage of exhibition buildings in their operating phase is arguable. Using renewable energy is a good approach to decrease CO_2 emissions, but first it is essential to reduce energy demand significantly. The extra energy embodied in the manufacture of PV panels and wind turbines would also need to be calculated.

	Average operating energy (with PV panels) (MJ/m^2/month)	**Average operating energy (without PV panels) (MJ/m^2/month)**
Crystal Palace (82.5 years)	93	93
Shanghai Exhibition Centre (56 years)	37	37
Dutch Pavilion (5 months)	83	93
Theme Pavilion (13 months)	76	81

Table 10.6 Comparison of average operating energy of four case study buildings with and without PV panels/wind turbines over actual life

10.2.1.3 Total energy consumption over actual useful life

The total energy consumption (embodied and operating energy) of the four case study buildings is compared in this section. Table 10.7 and Figure 10.5 together show the result of the comparison of the total energy consumption over actual useful life.

The Dutch Pavilion had the highest average consumption compared to the other buildings, although it was partly supported by renewable energy (from six wind turbines installed on the roof top). Apparently, the Crystal Palace built in 1851 and reconstructed in 1854 consumed much less energy than the so-called sustainable buildings, the Dutch Pavilion and the Theme Pavilion, over their whole life cycles. The matter of short building useful life means that the sustainably designed buildings performed worse than normal exhibition buildings. Their short life has directly influenced the life cycle environmental impact of these exhibition buildings allegedly designed with sustainable principles. The real building performance over the actual useful life turns out to be completely opposite of what it was supposed to achieve.

	Average embodied energy ($MJ/m^2/month$)	Average operating energy ($MJ/m^2/month$)	Average total energy consumption ($MJ/m^2/month$)
Crystal Palace (82.5 years)	2.5	93	96
Shanghai Exhibition Centre (56 years)	16	37	53
Dutch Pavilion (5 months)	2,120	83	2,203
Theme Pavilion (13 months)	1,400	76	1,476

Table 10.7 Comparison of total energy consumption of four case study buildings over actual life

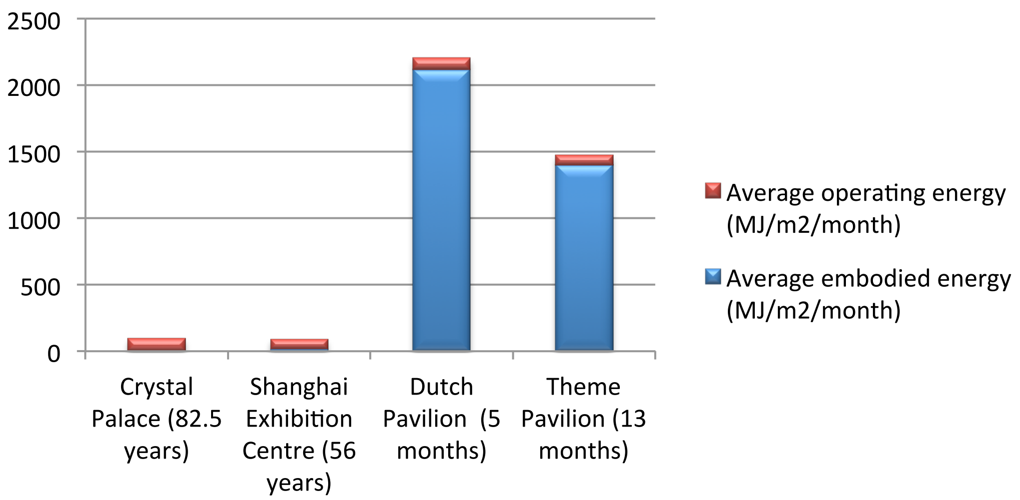


Figure 10.5 Comparison of total energy consumption of four case study buildings

In terms of the environmental analysis of a building, attention needs to be paid to the actual useful life of buildings both for and after World Expos (Table 10.8). This shows that a similar life period is found for the use of exhibition buildings during the events. The useful life after events, thus, has become one of the significant factors, dominating total energy consumption over the whole building life cycle.

After the Great Exhibition the Crystal Palace was moved to Sydenham in 1854 and reused until it was destroyed by fire in 1936. The Theme Pavilion has been reused after Expo 2010 for the period March to September 2011. In this thesis, for comparison the useful life of the Theme Pavilion following Expo 2010 is limited to this March to September period.

Exhibition buildings	Useful life for events	Useful life after events
Crystal Palace	6 months	82 years
Dutch Pavilion	5 months	0 year
Theme Pavilion	6 months	7 months or more (March to September 2011)

Table 10.8 Actual useful life of three buildings for and after events

Another estimation has been made of the energy consumption of the three buildings just used for expos, including the Hyde Park Crystal Palace for the Great Exhibition of 1851, the Dutch Pavilion for Expo 2000, and the Theme Pavilion for Expo 2010 (Table 10.9 and Figure 10.6). The results demonstrate that the energy consumption of the Dutch Pavilion was 1.5 times that of the Theme Pavilion and 6.6 times that of the Crystal Palace, even though it was designed as a sustainable building. The Hyde Park Crystal Palace and the Theme Pavilion were mainly constructed of metal and glass. However, the Crystal Palace also consumed much less operating energy than the modern exhibition buildings. This suggests that the design strategy of modern exhibition buildings might be the main determinant of the total life time energy consumption, if the building has a longer life than just the time it is used for the initial exposition.

	Average embodied energy ($MJ/m^2/month$)	Average operating energy ($MJ/m^2/month$)	Average total energy consumption ($MJ/m^2/month$)
Hyde Park Crystal Palace (6 months)	335	0	335
Dutch Pavilion (5 months)	2,122	83	2,205
Theme Pavilion (6 months)	1,398	76	1,474

Table 10.9 Comparison of energy consumption of case study buildings used for Expos in 1851, 2000, and 2010 over actual expo life

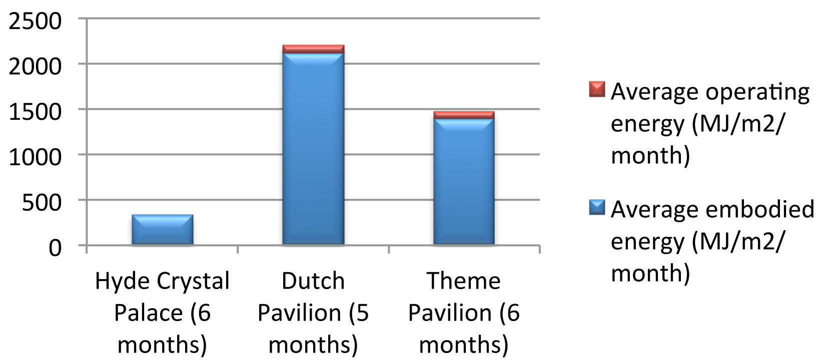


Figure 10.6 Comparison of energy consumption of case study buildings used for Expos in 1851, 2000, and 2010

10.2.2 Comparison of energy consumption of exhibition buildings over their assumed useful expo life

The assumed useful life of four case study buildings is listed in Table 10.10. This comparison of calculated results over each building's assumed life aims to provide a reasonable comparative model to generalise the findings of this research.

Exhibition buildings	Assumed useful life
Crystal Palace	50 years
Shanghai Exhibition Centre	50 years
Dutch Pavilion	50 years
Theme Pavilion	50 years

Table 10.10 Assumed useful life of four case study buildings for calculation

10.2.2.1 Embodied energy over assumed useful life

In the comparison between the average embodied energy of the different case study buildings over the assumed useful life, rather than the actual life, the Dutch Pavilion was still found to have the highest embodied energy consumption, including the initial and recurring embodied energy, as shown in Table 10.11 and Figure 10.7. It had 6 times and about 1.6 times the embodied energy of the historic building, the Crystal Palace, and the modern exhibition building, the Theme Pavilion, respectively. Although moving all the elements of the Crystal Palace from Hyde Park to Sydenham consumed energy for transportation, it was both necessary and worth doing, because it meant that the building continued to be used for a long time until its accidental destruction by fire, which resulted in a much lower total life time embodied energy. It is also noted that the Crystal Palace and the Theme Pavilion were buildings with metal structures, and the Shanghai Exhibition Centre and Dutch Pavilion were mainly built of concrete. The weight of buildings is discussed in Chapter 11 (Section 11.1.1).

	Initial embodied energy ($MJ/m^2/year$)	**Recurring embodied energy ($MJ/m^2/year$)**	**Total embodied energy ($MJ/m^2/year$)**
Crystal Palace (50 years)	26	23	49
Shanghai Exhibition Centre (50 years)	110	80	190
Dutch Pavilion (assumed to be used for 50 years)	212	88	300
Theme Pavilion (assumed to be used for 50 years)	168	12	180

Table 10.11 Comparison of average embodied energy of four case study buildings over the assumed life

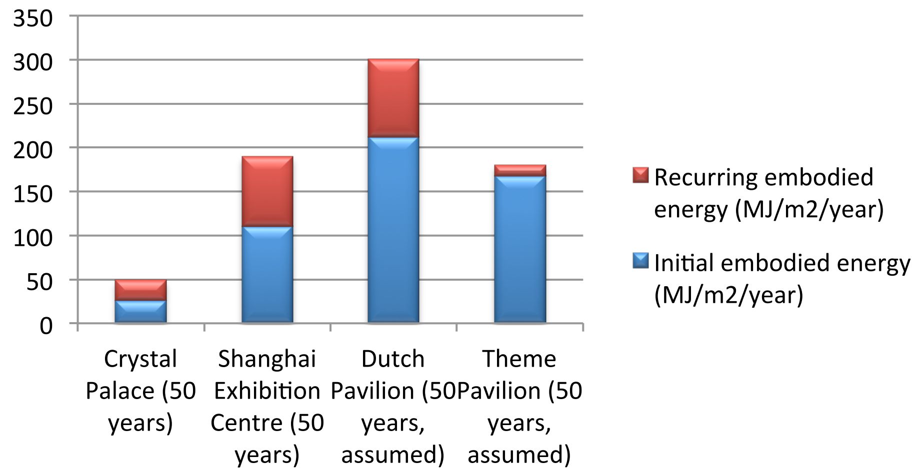


Figure 10.7 Average embodied energy of the four case study buildings

Comparing the percentage of initial and recurring embodied energy in the total embodied energy consumption, the percentage of recurring embodied energy has gradually decreased from 1851 to 2060 (from 47% to 7%) (Table 10.12 and Figure 10.8). This is partly because the materials chosen for construction in modern buildings (such as the Dutch Pavilion and Theme Pavilion) have higher durability than before. The energy consumed for the replacement of elements and general maintenance has been reduced, because most of the materials used in these two buildings can last for about 50 years. However, it is worth noting that Table 10.12 makes clear that the percentage of recurring embodied energy in the Crystal Palace is only high in relation to the very low initial embodied energy, not in per square metre terms, and the Crystal Palace has by far the lowest total value out of the four buildings.

	Initial embodied energy (GJ/m^2)	**Percentage**	**Recurring embodied energy (GJ/m^2)**	**Percentage**	**Total embodied energy (GJ/m^2)**
Crystal Palace (50 years)	1.34	53%	1.19	47%	2.53
Shanghai Exhibition Centre (50 years)	5.49	58%	4.00 (extension and maintenance)	42%	9.49
Dutch Pavilion (2000-2050, assumed to be used for 50 years)	10.61	73%	3.90	27%	14.52
Theme Pavilion (2010-2060, assumed to be used for 50 years)	8.39	93%	0.59	7%	8.98

Table 10.12 Comparison of percentage of initial and recurring embodied energy of the four case study buildings over the assumed life

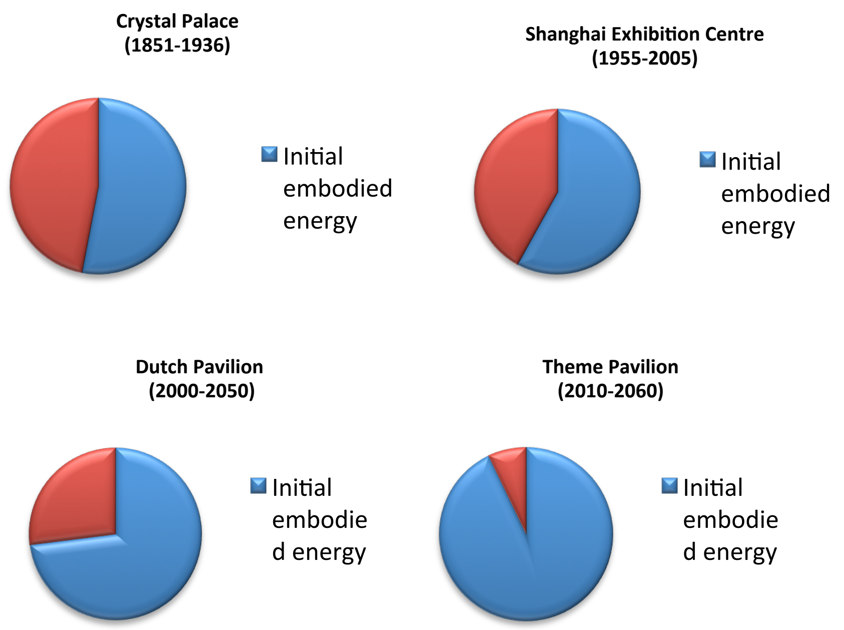


Figure 10.8 Percentage of initial and recurring embodied energy of the four case study buildings

However, it seems that the years of useful life for exhibition halls in current expos have become much shorter than for the older case study exhibition buildings. For example, the Dutch Pavilion was not reused after Expo 2000. Most of the national pavilions were demolished after Expo 2010 (Expo 2010), which shows the average useful life of most of the exhibition halls in an international exposition would be just five to six months. However, sustainable such expo buildings are claimed to be, their short life means they can never be held up as examples of sustainable buildings.

10.2.2.2 Operating energy over assumed useful life

The average operating energy consumed for building services in the assumed useful life has been taken to be the same as that in actual building life. Installing wind turbines and PV panels helped the Dutch Pavilion and the Theme Pavilion to save just 8%~12% of operating energy in total.

	Average operating energy (MJ/m^2/year)	**Average operating energy (MJ/m^2/year)**
Crystal Palace (50 years)	1,110	1,110
Shanghai Exhibition Centre (50 years)	446	446
Dutch Pavilion (assumed to be used for 50 years)	1,000 (with PVs)	1,121 (without PVs)
Theme Pavilion (assumed to be used for 50 years)	907 (with PVs)	972 (without PVs)

Table 10.13 Comparison of average operating energy of the four case study buildings over assumed useful life

10.2.2.3 Total energy consumption over assumed useful life

Table 10.14 shows the comparison of the total energy consumption of the case study buildings over the assumed useful life, including average embodied energy and operating energy.

The Dutch Pavilion still has the highest consumption (1,300 MJ/m^2/year) compared to the other buildings, although it was assumed here to be used over a life of 50 years. It is also noticeable that the energy consumption of the exhibition buildings built in the same city (the Shanghai Exhibition Centre, built in 1955, and the Theme Pavilion, built in 2010) has increased during the intervening 55 years. Based on the energy figures, it seems that the modern exhibition buildings (Dutch Pavilion and Theme Pavilion) are not getting better and are even consuming more energy than earlier buildings, even though they are designed as sustainable buildings. As the results discussed above demonstrate, a truly sustainable exhibition building might need to be local, flexible, and able to be used for the long term.

	Average embodied energy (MJ/m^2/year)	**Average operating energy (MJ/m^2/year)**	**Average total energy consumption (MJ/m^2/year)**
Crystal Palace (50 years)	49	1,110	1,159
Shanghai Exhibition Centre (50 years)	190	446	636
Dutch Pavilion (2000-2050, assumed to be used for 50 years)	300	1,000	1,300
Theme Pavilion (2010-2060, assumed to be used for 50 years)	180	907	1,087

Table 10.14 Comparison of total energy consumption of the four case study buildings over assumed useful life

10.2.3 Comparison of life cycle energy consumption of exhibition buildings over actual and assumed useful life

Table 10.15 shows the comparison of life cycle energy usage between the four buildings over the actual and assumed useful life of each. The life cycle energy includes initial and recurring embodied energy and operating energy. The average unit of MJ/m^2/month is used for this comparison. The Theme Pavilion would have a similar performance to the Crystal Palace, if its use is continued for 50 years. The Dutch Pavilion might need a somewhat longer useful life than this to reach a level of energy consumption similar to the other three buildings.

	Over actual useful life (MJ/m^2/month)	**Over assumed useful life (MJ/m^2/month)**
Crystal Palace	96	97
Shanghai Exhibition Centre	53	53
Dutch Pavilion	2,203	108
Theme Pavilion	1,476	91

Table 10.15 Comparison of life cycle energy consumption of four case study buildings over actual and assumed useful life

10.3 Comparison of energy consumption and CO_2 emissions of visitor travel (transportation)

With the increase of scale of exhibition events, the total number of pavilions in a expo and the number of pavilions visited in one day were various (Table 10.16). For the Crystal Palace and the Shanghai Exhibition Centre, they were the only exhibition hall for the events. However, people who travelled to the Dutch Pavilion at Expo 2000 and the Theme Pavilion at Expo 2010 also visited other pavilions on the same day. For this reason, the value of energy and CO_2 emissions of these case studies has been divided by the average number of pavilions visited in one day (this figure has been explained in Chapters 8 and 9).

Event	The pavilions estimated in this study	Number of pavilions in the events	Number of pavilions visited in a day
Great Exhibition of 1851	Crystal Palace	1	1
Shanghai National Exhibition	Shanghai Exhibition Centre	1	1
Expo 2000	Dutch Pavilion	32	8
Expo 2010	Theme Pavilion	263	5

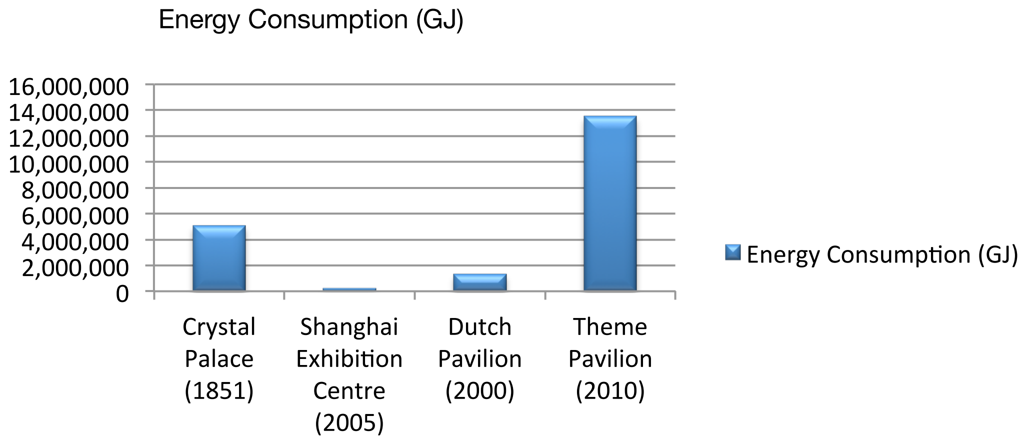
Table 10.16 Number of pavilions visited in a day for the four case studies

The comparison of the energy consumption and CO_2 emissions of visitor travel of the four case studies is shown in Table 10.17. The total energy usage and CO_2 emissions of visitor travel to go to the pavilion increases between the 1851 and 2010 expositions. It is noted that the energy consumption for visitor travel going to the Shanghai Exhibition Centre is not comparable, as it is estimated to be almost all local travel from the Shanghai region. The Dutch Pavilion figures are also low, partly because of the higher number of pavilions visits for each visitor to Expo 2000.

Visitor travel to go to	Energy consumption	CO_2 emissions
Crystal Palace (1851)	5,063,520 GJ	444,998 t
Shanghai Exhibition Centre (2005)	204,431 GJ	27,473 t
Dutch Pavilion (2000)	1,307,524 GJ	78,388 t
Theme Pavilion (2010)	13,521,990 GJ	1,636,645 t

Table 10.17 Comparison of visitor travel to go to the four case study buildings

Comparing the energy consumption and CO_2 emissions of visitor travel to go to the four case study buildings, travel to the Theme Pavilion showed the highest consumption and CO_2 emissions (13,521,990 GJ and 1,636,645 t) (Figure 10.9). One reason is because of the large number of visitors who consumed more energy for transportation, compared to other events.



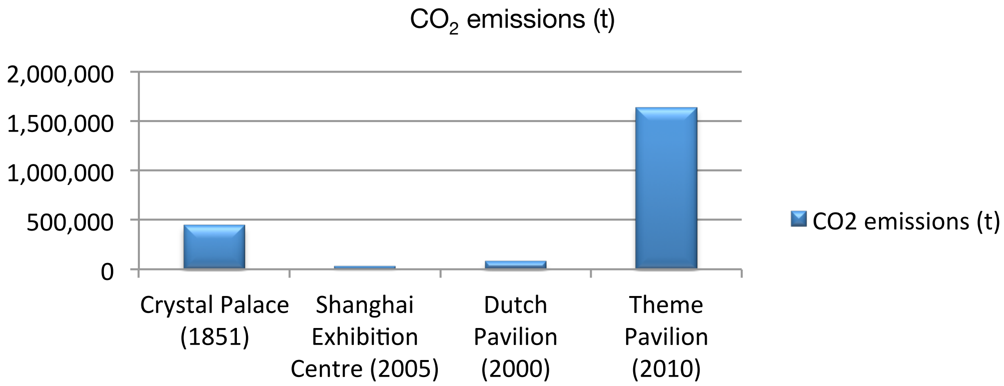


Figure 10.9 Comparison of energy consumption and CO_2 emissions of visitor travel to go to the four case study buildings

The average energy usage and CO_2 emissions of world expos per visitor seems to have decreased (Table 10.18). The average energy consumption of visitor travel to go the Dutch Pavilion was 322 MJ/visitor, which was 2.6 times lower than the travel in 1851. Visitors went to the Dutch Pavilion and seven other pavilions at Expo 2000 in one day. However, because the Great Exhibition put all the categories of exhibits in one building, it could be argued that this is an unfair comparison, since one visit to the Crystal Palace enabled the visitor to see as many exhibits as they could walk round in one day.

Visitor travel to go to	Average energy consumption	Average CO_2 emissions
Crystal Palace (1851)	838 MJ/visitor	74 kg/visitor
Dutch Pavilion (2000)	322 MJ/visitor	19 kg/visitor
Theme Pavilion (2010)	588 MJ/visitor	71 kg/visitor

Table 10.18 Energy consumption and CO_2 emissions of visitor travel to go to the four case study buildings

Because of this another comparison is made for total daily travel energy consumption of visitors to go to an international event (Table 10.19).

Visitor travel to go to	Total energy consumption	Average energy consumption
Great Exhibition (1851)	28,130 GJ/day	838 MJ/visitor/day
Expo 2000 (2000)	433,007 GJ/day	2,576 MJ/visitor/day
Expo 2010 (2010)	1,193,463 GJ/day	2,940 MJ/visitor/day

Table 10.19 Energy consumption of visitor travel to go to the events averaged over a day

It is obvious that the average energy consumption of visitor travel to an international event is increasing. Visitor travel to go to the Great Exhibition was 838 MJ/visitor/day, while going to Expo 2010 in Shanghai was 2,940 MJ/visitor/day. This is because more foreign visitors attended this large-scale event and their travel used more energy by taking airplanes (more discussion of location and environmental effect generated from different transport modes will be given in section 11.1.2).

It can be further pointed out that the analysis boundaries of an environmental assessment of transportation need to be considered carefully. It is essential to explore the environmental impact generated from the whole event-related visitor travel, rather than just focusing on the building-related travel consumption.

10.4 Comparison of resource consumption of exhibition-related economic aspects

The ecological footprint of exhibition-related economic aspects of the four case studies is converted using a monetary value per global hectare factor, using the methods explained in Chapters 6~9.

The comparison is made in terms of four factors - economic benefit per square metre and per visitor and ecological footprint per square metre and per visitor (Table 10.20).

The results show that the total economic income of Expo 2010 (international expo) was much greater than for the Shanghai National Exhibition Centre (national exhibitions). At the same time, the environmental impact of the international exhibition generated from the exhibition-related economic aspects was more than for a national exhibition.

The second comparison in Table 10.21 is used to explore the relationship between the size of buildings, the number of visitors, economic benefits, and the related environmental impact of expositions at the international level. The result shows that the exhibition-related economic benefit increases relative to the number of visitors. A large visitor flow at expo activities can bring or create more potential economic income for the host cities (more detailed discussion will be given in Chapter 11).

In addition, the ecological footprint of the exhibition-related economic aspect is different in different countries (Table 10.21). For example, the EF of exhibitions held in China was about 0.50gha/visitor for the world expo. The calculation of ecological footprint is related to various exhibition-related industries in different countries (more detailed discussion will be given in Chapter 11).

Events	Floor area of exhibition hall (m^2)	Number of visitors	Economic income (USD)	EF (gha)
Great Exhibition (6 months)	92,000	6,039,195	10,112,501	6,347,590
Shanghai National Exhibition (12 months)	80,000	7,500,000	7,180,581	9,068,000
Expo 2000 (5 months)	6,144	4,060,000	499,274,955	1,346,154
Expo 2010 (6 months)	143,000	73,080,000	28,665,867,675	36,302,764

Table 10.20 Exhibition-related information of the four case studies

Events	USD/visitor	gha/m^2	gha/visitor/year
Great Exhibition (1851)	2	46	0.11
Expo 2000 (2000)	123	219	0.33
Expo 2010 (2010)	446	254	0.50

Table 10.21 Comparison of annual economic benefit per square metre of four case study buildings

A further comparison is made between the average ecological footprint generated by three of the case study events (international events). The average units of gha/visitor/year and gha/visitor/day are used for comparison in Table 10.22. Expo

2010 held in Shanghai had the highest ecological footprint (0.50gha/visitor/year or 0.00271gha/visitor/day) of the three exhibitions compared. The first world expo, the Great Exhibition of 1851, consumed fewer resources than modern international events. The ecological footprint of international exhibition activities is increasing together with the increase in number of visitors.

Events	Average Ecological Footprint	Average Ecological Footprint
Great Exhibition (1851)	0.11 gha/visitor/year	0.00030 gha/visitor/day
Expo 2000 (2000)	0.33 gha/visitor/year	0.00217 gha/visitor/day
Expo 2010 (2010)	0.50 gha/visitor/year	0.00271 gha/visitor/day

Table 10.22 Comparison of exhibition-related economic effect

10.5 Comparison of energy and resource consumption of case study events over their whole life cycle

Based on the calculated results, expos are generally having a greater impact, which is causing more environmental damage. Table 10.23 compares the total ecological footprint of the four case study events, including buildings, visitor travel, and exhibition-related economic aspects. Expo 2010 in Shanghai consumed the most natural resources overall. The total ecological footprint of the Shanghai National Exhibition is not comparable with the others, as it holds different national exhibitions every month. The figures show that the total ecological footprint of the historic exhibition was less than that of modern exhibitions.

Event	Year	Total ecological footprint (gha/year)
Great Exhibition of 1851 (visited the Crystal Palace)	1851	686,973
Shanghai National Exhibition (visited the Shanghai Exhibition Centre)	2005	9,070,537
Expo 2000 (visited the Dutch Pavilion)	2000	1,359,887
Expo 2010 (visited the Theme Pavilion)	2010	36,439,538

Table 10.23 Total ecological footprint of four case study events

A further comparison is made between the resource consumption related to three aspects (building, visitor travel, and economic aspects), as listed in Tables 10.24-10.26. The results show that the exhibition-related economic aspects consumed most energy and resources, being significantly more than building related resource consumption and visitor-related transportation. The impact of the buildings was the least significant parameter. The environmental impact from potential economic income is always ignored by planners and event organisers, even when they are making a so-called sustainable exposition. The whole life cycle energy and resource consumption of large-scale expositions needs to be evaluated, if they are to be claimed as sustainable events. Whether the balance between exhibition-related economic income and resource consumption has been kept or not, needs to be evaluated in detail and clearly explored.

Building	Average ecological footprint
Crystal Palace (82.5 year)	0.011 gha/m^2/year
Shanghai Exhibition Centre (56 years)	0.011 gha/m^2/year
Dutch Pavilion (assumed to be used for 50 years)	0.107 gha/m^2/year
Theme Pavilion (assumed to be used for 50 years)	0.011 gha/m^2/year

Table 10.24 Ecological footprint of four case study buildings

Visitor travel to	Average ecological footprint
Crystal Palace	0.0084 gha/visitor/year
Shanghai Exhibition Centre	0.0003 gha/visitor/year
Dutch Pavilion	0.0032 gha/visitor/year
Theme Pavilion	0.0059 gha/visitor/year

Table 10.25 Ecological footprint of visitor travel going to the pavilion

Event	Average ecological footprint
Great Exhibition of 1851	0.105 gha/visitor/year
Shanghai National Exhibition	1.209 gha/visitor/year
Expo 2000	0.332 gha/visitor/year
Expo 2010	0.563 gha/visitor/year

Table 10.26 Ecological footprint of exhibition-related economic aspects

10.6 Chapter conclusion

This chapter brings the calculated results from the four case studies together to provide a comparative analysis of large-scale exhibitions and the three related factors; building, visitor travel, and exhibition-related economic aspects. The main findings are summarised below.

The comparisons show that the total energy and resource consumption of large-scale exhibitions is increasing (Table 10.27). The exhibition-related economic aspects consumed most energy and resources, which were much more than those for building consumption and visitor-related transportation.

	Building			Travel	Exhibition-related economic aspects	Total
	Initial embodied	Recurring embodied	Operating			
Energy and resource consumption	↑	↓	↑	↑	↑	↑

Table 10.27 Tendency of energy and resource consumption of large-scale exhibitions

- For exhibition buildings, energy and resources were consumed most in the building operating phase. The matter of short building useful life resulted in the sustainable design buildings performing worse than normal exhibition buildings. In addition, the useful life after events is one of the significant factors for the total energy and resource consumption of the building.

- The total energy usage and CO_2 emissions of visitor travel to go to the pavilions or the events increases from 1851 to 2010. The analysis boundaries of environmental assessment of transportation need to be considered comprehensively.

- Exhibition-related economic benefit rises in relation to the number of visitors. The ecological footprint of international exhibition activities is increasing together with the increasing of number of visitors.

Chapter 11 Discussion

Chapter 10 discussed the most significant factors in the process of exposition activities over the whole life cycle of a particular exposition building. It explored the real problems existing in the exhibition industry (infrastructure, transportation, and economic aspects) by means of comparative studies. This chapter will attempt to provide some further and deeper consideration of recent sustainable approaches for expositions (section 11.1) and assessment tools (section 11.2) in terms of environmental impact.

11.1 Making expositions sustainable

Three relevant aspects of large expositions are discussed here in terms of sustainable development; buildings (11.1.1), visitor travel (11.1.2), and exhibition-related economic aspects (11.1.3).

11.1.1 Exhibition buildings

Although many studies have investigated the life cycle energy use of public buildings (for example, studies of sustainable office buildings by Cole and Kernan, 1996; Schwarz, 2006; Wentz, 2007), there are few specific studies of sustainable exhibition buildings (see also Chapter 3). For this reason, studies of similar building types as references will be introduced in the following sections. It should be noted that the energy use of exhibition buildings as discussed in this section is broken down into the two components of operating and embodied energy. Demolition is not looked at here, as it is considered to be insignificant (Jurasovich, 2003, p.570; see also Chapter 5).

Based on the comparative analysis in Chapter 10, the discussion in this section is firstly focused on the operating energy-related approach in terms of sustainable technologies. The question of whether “high technology” makes exhibition buildings sustainable is investigated. The discussion in the following section is related to embodied energy, which results from the question of whether construction materials or building useful life can have any significant influence on the energy embodied in the construction elements. In this investigation, the figures used for each aspect have been justified in each of the relevant sections.

11.1.1.1 Eco technology for building environmental control

Since the mid-19th century industrialised technologies have become one of the elements of architectural design. The "high-tech" architecture movement emerged towards the end of modernism and was demonstrated by seminal buildings, for example Paris's Pompidou Centre in 1977 and London's Lloyd's Building in 1986 (Slessor, 1997). Gauzin-Müller and Favet (2002, p.16) state that "high-tech architecture is symbolised by the towering office buildings and dramatic steel and glass structures of today's international 'superstar' architectures".

In recent years, "high" or advanced technologies have been used for making buildings that are claimed to be environmentally friendly. In these high-tech sustainable buildings, technologies for making use of renewable energies, such as photovoltaic panels and wind turbines, have been incorporated into building design by architects. The Commerzbank tower in Frankfurt and the dome of the remodelled Reichstag in Berlin, both designed by Norman Foster, are seen as eco-tech landmark buildings (Gauzin-Müller and Favet, 2002, p.16). In current world expos, many large-scale exhibition buildings have been designed as high-tech sustainable buildings (discussed in Chapter 2). This approach is not only to match expo themes, but also to advertise the new type of design, as one of the main functions of expos is to promote the notion of the new, including new technologies (the Theme Pavilion of Expo 2010 was such an example). However, whether high technology, for example combining active and passive environmental control systems, makes exhibition buildings sustainable in reality is uncertain.

This section discusses whether the use of ecological technologies to reduce operating energy makes exhibition pavilions truly sustainable. The result of the comparative analysis of the four case studies in Chapters 6~9 shows that operating energy dominates the total energy consumption of both conventional and sustainable exhibition buildings, accounting for around 77~83% of the total over 50 years of useful life. In related studies of other building types, results have confirmed the dominance of operational energy use in terms of building life time energy consumption (Cole and Kernan, 1996; Suzuki and Oka, 1998; Camilleri and Jaques, 2001), although the results vary, because of different climates and the different resources used for electricity generation.

Installing PV panels as an active environmental control approach has been seen as one of the symbols for a sustainable exhibition building. However, the environmental sustainability of buildings cannot be achieved just by installing renewable energy technology to provide the energy needed for indoor temperature control in summer and winter (Gauzin-Müller and Favet, 2002, p.16). The approach of generating renewable energy by using high technologies to reduce the operating energy may not make buildings sustainable in the long term, usually because the building cannot provide sufficient surface area to support enough renewable energy generation.

One case study building, the Theme Pavilion at Expo 2010, can serve as a representative example of this observation. The large scale cutting-edge renewable energy and energy saving applications installed in the Theme Pavilion (more than 30,000 m^2 of PV panels) initially seem to help the event and the city become more sustainable than before. Table 11.1 compares the life-cycle energy consumption of the Theme Pavilion with and without the photovoltaic panels.

	Theme Pavilion (2010-2060, with PV panels)	**Theme Pavilion (2010-2060, without PV panels)**	**Reduction**
Operating energy	907 MJ/m^2/year	972 MJ/m^2/year	6.7%

Table 11.1 Total energy consumption of the Theme Pavilion from 2010 to 2060

However, the problem is that using the high-tech approach does little to mitigate the energy usage of the large expo pavilion. Ping (2010, p. 116) states that the data for the share of renewable energy in the total energy consumption of the Theme Pavilion have not so far been provided in a scientific and transparent way. Based on the calculated result of this case study, the PV panels produce enough energy to cover just 6.7% of the total energy consumption of the Theme Pavilion every year. It seems difficult to reduce significantly the environmental impact of large-scale exhibition buildings just by producing renewable energy from systems placed on the building, even when these amount to a very large PV array. To enable the total building operating energy load to be met by the PV panels, the demand would have to be reduced from 972 to 65 MJ/m^2/year. In further research it might be interesting to explore how much the total energy demand of the building could have been reduced if the money for the PV panels had been spent on energy savings rather than on the PVs.

The environmental design of modern buildings has probably raised the level of indoor comfort, but it has also contributed to increasing the operating energy consumption. However, exhibition buildings as a specific type of building for display may actually need to be treated by using different solutions from other commercial buildings in terms of sustainability. At Expo 2010 (May ~ October), visitors had to wait for 2 hours outdoors in order to enter some popular pavilions. It was not comfortable for visitors to suddenly enter a relatively cold environment, after being at 35^o Celsius outside in the summer. The "sustainable" buildings at Expo 2010 consumed a large amount of electricity but were not necessarily as comfortable for the visitors as the designers thought, because they paid no attention to issues of acclimatisation.

Compared to a conventional exhibition building, the Shanghai Exhibition Centre built in 1955, the average operating energy of the "sustainable" Theme Pavilion was higher (Table 11.2). The fact is that the modern exhibition building consumed more than the conventional building in total, although it had PV panels to produce renewable energy. In addition, in 1851, although the Crystal Palace, which was designed without environmental control systems, other than stack ventilation through the operation of the louvre systems, might be hot inside in summer, it still attracted more than 6 million local and foreign visitors to go to the Great Exhibition. Perhaps this demonstrates the feeling of comfort is never an absolute thing and may be influenced by development of technologies.

	Average operating energy (MJ/m^2/year)	**Comments**
Shanghai Exhibition Centre (56 years)	446	Without sustainable consideration
Theme Pavilion (2010-2060, assumed to be used for 50 years)	907	Using sustainable technologies

Table 11.2 Comparison of operating energy of conventional and sustainable exhibition buildings in the same city, Shanghai

Secondly, compared to general office buildings, the operating energy of sustainable exhibition buildings does not reveal a high level of energy efficiency (Table 11.3).

	Average operating energy (MJ/m^2/year)	**Percentage of renewable energy in operating (%)**	**Comments**
Crystal Palace (82.5 years)	1,114	0	Calculated by author
Shanghai Exhibition Centre (56 years)	446	0	Calculated by author
Dutch Pavilion (2000-2050, assumed to be used for 50 years)	1,000	10.8	Calculated by author
Theme Pavilion (2010-2060, assumed to be used for 50 years)	907	7.3	Calculated by author
Office building in Vancouver (50 years)	959	0	Cole and Kernan, 1996
Office building in Toronto (50 years)	1,634	0	Cole and Kernan, 1996
Office building in UK (60 years)	839	0	Howard and Sutcliffe, 1994, p.48
Office building in Japan (40 years)	1,210	0	Suzuki and Oka, 1998

Table 11.3 Comparison of operating energy of exhibition buildings and office buildings

This discussion suggests that the sustainable design of large-scale exhibition buildings needs to focus more on reducing total energy consumption in the operating phase, rather than relying on generation of renewable energy, which, from the case studies, appears to offer no more than a relatively token contribution.

11.1.1.2 Construction materials and building actual useful life

This section discusses the issue of construction materials, which is directly related to the initial and recurring embodied energy of exhibition buildings. In previous research, much study has been focused on choice of construction materials in terms of the influence this may have on sustainability (Howard and Sutcliffe, 1994, p.48; Cole and Kernan, 1996; Suzuki and Oka, 1998). The comparative analysis in the previous chapter suggests that there is a question to be resolved in terms of which factor has more influence on embodied energy consumption, choice of construction materials or building actual useful life.

Weight of buildings has been an issue for some architects. Norman Foster believes that "the model for architecture is a lightweight glider rather than a marble monument" (Sudjic, 2010). The same notion has been used for the design of sustainable public buildings. In Foster's design for City Hall in London, the 'green' building has been constructed using lightweight materials (steel and glass). However, City Hall, which seemed in theory to be an exemplary sustainable building, not only consumed 50% more energy (1,354 MJ/m^2) than it was designed to do (850 MJ/m^2) in 2003/2004 (Bennett, 2005), but even its target energy consumption was not significantly better than some of the conventional buildings in Table 11.3.

Considering the weight of buildings, Thomas and Fordham (1996, p.51) introduced two different models of buildings, which they described with the metaphor of the butterfly and the elephant. Butterflies are lightweight and quickly respond to the environment. This means that butterfly-type buildings with highly responsive skins (glass) have a quick reaction to changes in solar radiation, light, and temperature. On the other hand, elephants react slowly when their environment changes. Elephant-type buildings have fewer openings and more thermal mass.

Currently, designs of modern sustainable exhibition buildings are much closer to butterfly-type buildings, with glass cladding and high-tech sustainable equipment. For example, the Theme Pavilion is a butterfly-type building. Its weight is about 1,005 kg/m^2, half that of the Shanghai Exhibition Centre, as shown in Table 11.4. Conventional exhibition buildings, largely constructed of concrete, are more like elephant buildings. They have more thermal mass, for example, the Shanghai Exhibition Centre weighs 2,100 kg/m^2. The Crystal Palace can be seen as a passive butterfly-type building. It was a very lightweight exhibition building (194 kg/m^2) designed without sustainable considerations. On the other hand, the Dutch Pavilion was more like an active elephant building with its wind turbines. As the results show, weight of buildings cannot serve as the sole criterion for the design principles of sustainable exhibition buildings, as both elephant and butterfly buildings can perform well or badly in overall energy terms.

Case study buildings	Year of constructio n	Weight (t)	Average weight (kg/m^2)	Main materials
Crystal Palace	1851	17,847	194	Iron, Timber
Shanghai Exhibition Centre	1955	113,602	2,100	Reinforced concrete
Dutch Pavilion	2000	15,724	2,559	Reinforced concrete, Timber
Theme Pavilion	2010	143,769	1,005	Steel, Reinforced concrete

Table 11.4 Weight of four case study buildings

Secondly, many quantitative studies have made detailed analysis of the energy embodied in the construction and maintenance phases (Cole and Kernan, 1996; Schwarz, 2006). Some studies have encouraged designers to use specific construction materials, which have low embodied energy coefficients or have a good durability. Table 11.5 demonstrates the trend that the proportional initial embodied energy of exposition buildings is increasing (53% ~ 93%), while average recurring embodied energy has reduced (47% ~ 7%). This supports the idea that buildings are being constructed from more durable materials.

	Percentage of initial embodied energy	Percentage of recurring embodied energy
Crystal Palace (50 years)	53%	47%
Shanghai Exhibition Centre (50 years)	58%	42%
Dutch Pavilion (2000-2050, assumed to be used for 50 years)	73%	27%
Theme Pavilion (2010-2060, assumed to be used for 50 years)	93%	7%

Table 11.5 Percentage of initial and recurring embodied energy of four case study buildings over their assumed useful life

In the case of many design projects, it has been claimed that a large amount of the building elements they contain can be recycled after building demolition (Schwarz, 2006; Wentz, 2007), which not only helps to reduce the initial embodied energy, but also conserves natural resources.

However, the fact is there is no guarantee that these elements will be reused in other buildings in the future. Cellophane House is a five-story prefabricated dwelling, which was commissioned by the Museum of Modern Art's exhibition, Home Delivery: Fabricating the Modern Dwelling (Kieran, Timberlake and Timberlake, 2011). It was displayed from July to October, 2008 in New York. James Timberlake, the designer of Cellophane House, recognized that the building elements of Cellophane House were not reused after the exhibition, even though most components were prefabricated before installation and in theory could have been reused (personal comm., 2011).

	Total embodied energy (MJ/m^2/ month)	Actual useful life
Crystal Palace	3	82.5 years
Shanghai Exhibition Centre	16	56 years
Dutch Pavilion	2,120	5 months
Theme Pavilion	1,400	13 months

Table 11.6 Comparison of average embodied energy of four case study buildings based on actual life

A similar issue occurs with modern exposition pavilions. For example, at Expo 2010, most of the pavilions were demolished after the event (BCSWE, 2010). The result of the analysis of embodied energy of the four exhibition buildings in Chapters 6-9 shows that the Dutch Pavilion and the Theme Pavilion had the highest embodied energy over their actual life (5 months and 6 months), at 2,120 and 1,400 MJ/m^2/month respectively (Table 11.6). Compared to general office buildings, the average embodied energy of exhibition buildings used for 5 or 6 months was, not surprisingly, much higher than buildings used for a long time (Table 11.7). This demonstrates very clearly that the energy flow as influenced by actual useful life is very much larger than the aspects of design usually considered to be "sustainable", such as choices of types of construction materials, process of manufacture, and use of different resources for electricity generation.

	Average embodied energy (MJ/m^2/year)	Comments
Crystal Palace (82.5 years)	36	Calculated by author
Shanghai Exhibition Centre (56 years)	192	Calculated by author
Dutch Pavilion (5 months)	10,600	Calculated by author
Theme Pavilion (6 months)	8,400	Calculated by author
Office building in Vancouver (50 years)	212	Cole and Kernan, 1996
Office building in Toronto (50 years)	212	Cole and Kernan, 1996
Office building in UK (60 years)	180	Howard and Sutcliffe, 1994, p.48
Office building in Japan (40 years)	262	Suzuki and Oka, 1998

Table 11.7 Comparison of average embodied energy of exhibition buildings and office buildings

Thus, this research clearly suggests that it is not an effective approach to focus on the energy embodied in or related to every material, component or system in an exhibition building. Similar recommendations for other types of commercial buildings are presented in Cole and Kernan, 1996 and Jurasovich, 2003, p.570.

11.1.2 Visitor travel

In this section, two main factors related to visitor travel form the focus. The factors include location of exhibition pavilions (section 11.1.2.1) and choice of transport modes (section 11.1.2.2). According to the comparative analysis in the previous chapter (section 10.3), the discussion starts from levels of influence generated by these two factors, and explores which factor is more significant for mitigating environmental degradation.

11.1.2.1 Location of pavilions

Site selection is usually discussed when design of sustainable buildings is an issue. In the United States, the National Institute of Building Science WBDG Sustainable Committee (2010) stated that "the location of a building affects a wide range of environmental factors, and energy consumption as well as the energy consumed by transportation needs of occupants for commuting". They suggest buildings should be located in areas of existing development, in which infrastructure has already been constructed. Guthrie (2008) demonstrated that locating a building far away from public transport nodes leads to increased use of private transport and related energy consumption.

As types of exhibition buildings are serviced at different levels, buildings used for national and international exhibitions are discussed separately in this section. This addresses the question of whether the location of national or international exhibition buildings significantly affects the energy consumption of visitor travel.

- National exhibition buildings

For national exhibition buildings, visitor travel to the Shanghai Exhibition Centre is compared to that of the Theme Pavilion. Although the Theme Pavilion was built for Expo 2010, it has been reused for national exhibitions after the Expo closed.

Table 11.8 shows the average energy consumption of visitors from Shanghai to go to the two exhibition buildings constructed in different locations in the same city. The average energy consumption of visitor travel to the Shanghai Exhibition Centre located in the central city area was 27 MJ/visitor in 2005. It is located in the centre of the city of Shanghai (Figure 11.1).

The average travel energy consumption going to the Theme Pavilion was 9 MJ/visitor in 2010. The location of the Theme Pavilion is in the Pu Dong District, which is a suburb in the downtown area. If it is assumed that people only visited the Theme Pavilion in a day's visit, rather than a number of pavilions, the average energy use would be 23 MJ/visitor at Expo 2010. It would be similar to the Shanghai National Exhibition.

Visitors from Shanghai to	Number of visitors	Average energy use
Shanghai Exhibition Centre (2005)	7,500,000	27MJ/visitor
Theme Pavilion (2010)	3,128,000	9MJ/visitor

Table 11.8 Average energy consumption of visitors from Shanghai to go to two exhibition buildings in different locations in Shanghai

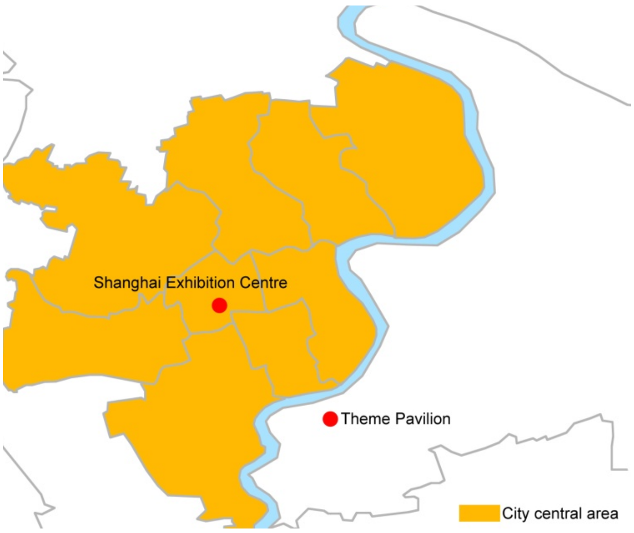


Figure 11.1 Location of Shanghai Exhibition Centre and Theme Pavilion in Shanghai

It is found that the average travel energy consumption of the Theme Pavilion was lower than that of the Shanghai Exhibition Centre (Table 11.8) because the location of the Theme Pavilion is more conveniently reached by public transport. This is because it is much closer to the underground railway stations than the Shanghai Exhibition Centre, even though not located in the centre of the city.

Therefore, the location of the exhibition buildings in terms of energy consumption for travel needs to be examined case by case, as city density may not directly influence the total energy consumption of visitor travel for attending national exhibition activities, if events are held in high population density cities, especially in Asian countries.

- International exhibition buildings

For those buildings used to hold international expositions, the transport-related environmental impact of exhibition buildings relative to specific sites cannot be evaluated. The important point here is where most participants come from.

Table 11.9 shows that a large number of visitors attending expos at a particular time have come from the host countries outside the host cities. These visitors accounted for 49.7% of all visitors to the Great Exhibition of 1851, 82.7% of those to Expo 2000, and also 82.7% of those to Expo 2010. As a result, these visitors caused a large transport energy consumption (92.6%, 43.6%, and 66.8% of the travel related energy consumption of all visitors respectively), as shown in Table 11.10.

Visitors	**Great Exhibition of 1851**		**Expo 2000 (Dutch Pavilion)**		**Expo 2010 (Theme Pavilion)**	
	Number of visitors	Percentage	Number of visitors	Percentage	Number of visitors	Percentage
From host cities	2,039,195	33.8%	416,773	10.3%	3,128,000	13.6%
From host countries (apart from host cities)	3,000,000	49.7%	3,359,027	82.7%	19,021,000	82.7%
From foreign countries	1,000,000	16.5%	284,200	7.0%	851,000	3.7%

Table 11.9 Percentage of number of visitors from different cities and countries going to the pavilions

Visitors	Great Exhibition of 1851		Expo 2000 (Dutch Pavilion)		Expo 2010 (Theme Pavilion)	
	Energy consumption (GJ)	Percent age	Energy consumption (GJ)	Percent age	Energy consumption (GJ)	Percent age
From host cities	157,196	3.1%	991	0.1%	28,632	0.2%
From host countries (apart from host cities)	4,687,346	92.6%	570,567	43.6%	9,030,257	66.8%
From foreign countries	218,978	4.3%	735,936	56.3%	4,463,102	33.0%

Table 11.10 Percentage of energy consumption of visitor travel to the pavilions

However, it is also apparent that the energy consumption of foreign visitor travel was more than that of local visitor travel per visitor, although there were fewer foreign visitors, forming 16.5% of the Great Exhibition, 7.0% of Expo 2000, and 3.7% of Expo 2010 in total visitor numbers.

For international exhibition buildings, the location of the buildings was not the significant influencing factor of their environmental impacts. On the contrary, they are more affected by the different transport modes. Based on the detailed study of travel energy consumption in previous chapters, choice of transport modes will be discussed in detail in the next section.

11.1.2.2 Transport modes of visitor travel

Reducing environmental impact by creating sustainable modes of transport has been suggested by many researchers (for example Thakuriah, 2009; City of London, 2009). Cycling, walking and taking public transport are always recommended for local travel and public transport for regional travel. However, “sustainable transport modes” are seldom discussed for the international level, such as for reaching international events. This section discusses how the different transport modes of visitors from exhibition host cities, host countries, and foreign countries travelling to the case study pavilions influenced energy or resource consumption. It should be noted the energy intensity of different transport modes is not discussed in this thesis, as a huge variety of values exist in other studies (Vale and Vale, 2009, p.110).

- Visitors from host cities

For visitors who come from host cities, Table 11.11 shows the energy consumption of visitors going to just one pavilion at the events.

Visitor travel to go to	Number of visitors from host cities	Energy consumption (GJ)	CO_2 emission (t)
Crystal Palace (1851) (London)	2,039,195	157,196	3,754
Shanghai Exhibition Centre (2005) (Shanghai)	7,500,000	204,431	27,473
Dutch Pavilion (2000) (Hannover)	416,773	991	40
Theme Pavilion (2010) (Shanghai)	3,128,000	28,632	1,927

Table 11.11 Comparison of visitor travel to go to the four case study buildings (just from host cities)

Visitor travel to go to the Shanghai Exhibition Centre had the highest fuel consumption (204,431 GJ) and CO_2 emissions (27,473 t) compared to other events. Although visitor travel to the Crystal Palace accounted for 53MJ/visitor (157,196 ÷ 2,039,195), its average associated CO_2 emissions (1.8 kg/visitor) were just half those for travelling to the Shanghai Exhibition Centre in 2005 (3.7 kg/visitor), as horse-related transport was the main mode used in the city area in 1851, and this generated zero greenhouse gases. Based on the local scale, Table 11.12 compares the average energy consumption and CO_2 emissions per km^2 of the four case studies.

Visitor travel to go to	Area of city (km^2)	Average energy consumption (KJ/visitor/km^2)	Average CO_2 emission (g/visitor/km^2)
Crystal Palace (1851) (London)	303 (Brown, 2004)	211.0	5.9
Shanghai Exhibition Centre (2005) (Shanghai)	7,037	3.8	0.5
Dutch Pavilion (2000) (Hannover)	2,290	0.9	0.04
Theme Pavilion (2010) (Shanghai)	7,037	1.3	0.08

Table 11.12 Comparison of visitor travel to go to the four case study buildings (just from host cities)

Shanghai is the biggest host city compared to Hannover and London. Based on the average square kilometres, the modern world expos in Hannover and Shanghai had roughly similar average carbon emission of visitor travel (0.04 and 0.08 g/visitor/km^2). Although the Shanghai Exhibition Centre and the Theme Pavilion were located in the same city, the energy usage and associated CO_2 emissions varied, probably due to the different locations in the city and the scale of the expositions.

However, the compared outcome would be different when looking at the average consumption and emissions of visitor travel to the whole events. Table 11.13 demonstrates the average energy consumption for visitors going to the events, as visitors went to one or several pavilions at one exposition (see Table 10.15).

Visitor from host cities to	Host city	Area of city (km^2)	Average (MJ/visitor)
Great Exhibition (1851)	London, UK	303	7
Shanghai National Exhibition (2005)	Shanghai, China	7,037	27
Expo 2000 (2000)	Hannover, Germany	2,290	10
Expo 2010 (2010)	Shanghai, China	7,037	23

Table 11.13 Energy consumption of visitors from host cities travelling to the four events

The average energy for travelling to the Crystal Palace in London in 1851 was the lowest, as only around 25% of visitors used steam trains and visitors had relatively short travel distances compared to the other case studies. However, a modern equivalent for this figure could be even lower, if for example electric trains were used, because the energy efficiency of steam trains was quite low in the mid-nineteenth century.

The result brings a need for further consideration in terms of the choice of transport modes (Table 11.14 and Figure 11.2). Comparing the modern exhibitions, in Shanghai more passengers used public transport or non-motor vehicles (e.g. bicycle). For example, 39% of visitors used cars in Hannover, but only 15.4% in Shanghai whereas more people rode bicycles, and took buses in Shanghai than in Hannover. It is interesting to find that walking, as a convenient transport mode, had similar preference levels for people going to expos in different cities and at different times (25% in London in 1851, 23% in Hannover in 2000, and 27% in Shanghai in 2010), although the figure for London is an estimate.

Modes	London (1851)	Hannover (2000)	Shanghai (2005, 2010)
Walking	25%	23%	27.00%
Horse	25%	-	-
Carriage	25%	-	-
Bicycle	-	16%	22.14%
Electric bike	-	-	5.53%
Scooter	-	-	0.83%
Motorcycle	-	-	2.10%
Underground and light rail	-	11%	4.86%
Bus	-	11%	15.93%
Car	-	39%	15.40%
Taxi	-	-	6.21%
Steam train	25%	-	-

Table 11.14 Percentage of passengers using different transport modes in the host cities

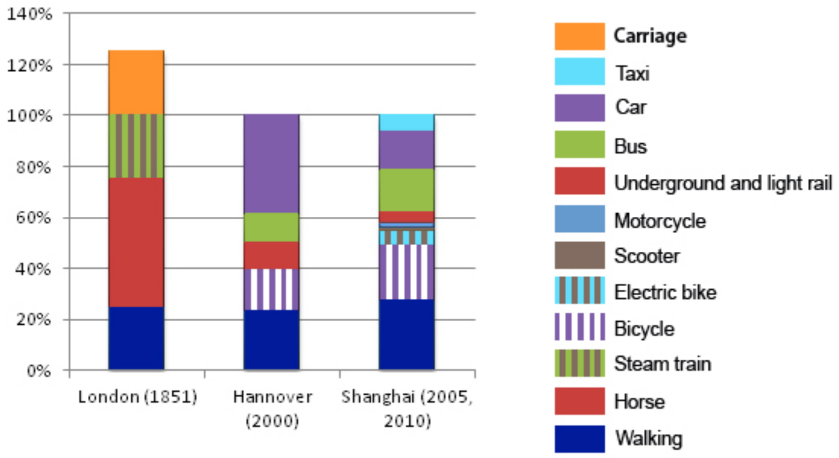


Figure 11.2 Percentage of passengers using different transport modes in the host cities

- Visitors from host countries and foreign countries

Table 11.15 compares the energy usage for travel of visitors from different countries who travelled to the Crystal Palace, Dutch Pavilion, and Theme Pavilion. For comparison, figure 11.3 shows the average energy consumption of visitor travel from host countries and foreign countries.

Visitors	Crystal Palace		Dutch Pavilion		Theme Pavilion	
	GJ	MJ/visitor	GJ	MJ/visitor	GJ	MJ/visitor
From host countries	4,687,346	1,567	570,567	170	9,030,257	475
From foreign countries	218,978	3,748	735,936	2,590	4,463,102	5,245
Total	4,906,342	5,315	1,306,503	2,760	13,493,359	5,720

Table 11.15 Energy consumption of visitors from different countries going to the Pavilions

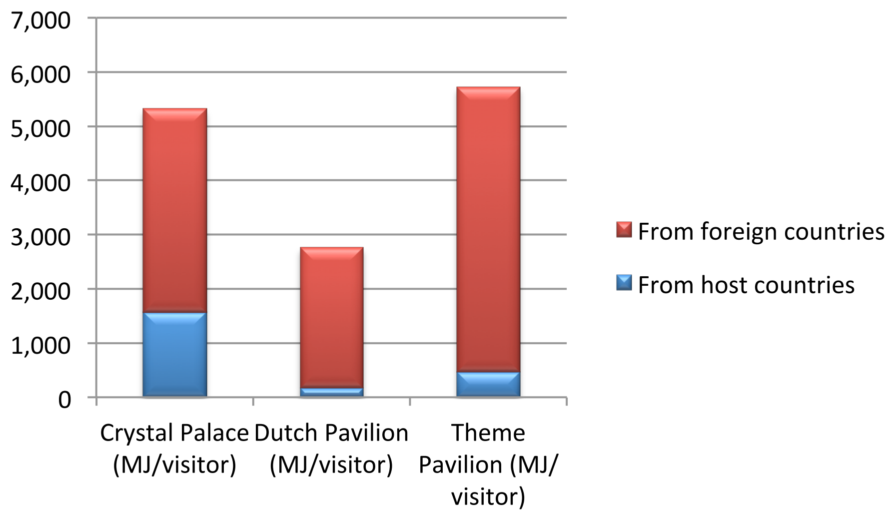


Figure 11.3 Average energy consumption of visitor travel from host countries and foreign countries

Travel from overseas to visit just the Theme Pavilion in Shanghai consumed more energy than the others. Comparing just the Dutch and Theme Pavilions, the average energy consumption for visitors travelling from both host countries and foreign countries has increased. This may be due, at least in part, to the fact that Expo 2010 was held in China, which has a huge land area compared with Germany and England, the sites of the other two expos, so the average travel distances for host country visitors would be far larger for Expo 2010. Because of the increasing trend of globalisation, Shanghai Expositions probably also attract more foreign visitors as well.

For visitors coming from the host countries and foreign counties, travelling to Expo 2010 in China had greater energy consumption per visitor than for the Exppo 2000 and Great Exhibition investigations (Table 11.16). Host visitor travel energy use to an event was similar for the Great Exhibition and Hannover 2000. However, this changes for foreign visitors (Table 11.17), which shows energy for foreign visitor travel is increasing. However, comparing the internal transport modes between different countries (Germany and China), more visitors used trains and buses for long distance travel in China (Table 11.18), comprising 26.67% and 33.71% in China, compared to 5% and 12% in Germany.

Visitor from host countries to	Host country	Area of country (km^2)	Average (MJ/visitor)
Great Exhibition (1851)	UK (United Kingdom of Great Britain and Ireland)	326,073	1,567
Expo 2000 (2000)	Germany	357,050	1,360
Expo 2010 (2010)	China	9,596,960	2,375

Table 11.16 Energy consumption of visitors from host countries travelling to three events (apart from host cities)

Visitors	Great Exhibition of 1851	Expo 2000	Expo 2010
From host countries (apart from host cities)	1,567 MJ/visitor	1,360 MJ/visitor	2,375 MJ/visitor
From foreign countries	3,748 MJ/visitor	20,720 MJ/visitor	26,225 MJ/visitor

Table 11.17 Average energy consumption of visitor travel from different countries going to the Expos

Modes	UK (1851)	Germany (2000)	China (2010)
Carriages	16.7%	-	-
Bus	-	5%	26.67%
Car	-	71%	26.67%
Train	-	12%	33.71%
Steam trains	72.2%	-	-
Ship	-	1%	-
Steamships	11.1%	-	-
Air	-	11%	12.95%

Table 11.18 Percentage of transport modes in different countries

The long distance visitor travel in China would be much more sustainable if all visitors only took trains and buses to go to Shanghai, rather than flying. The result for the energy consumption of visitors to go to the Theme Pavilion, based on all visitors from China using land transport rather than air transport is shown in Table 11.19. It is assumed that 46.5% of visitors took buses and 53.5% took trains.

Visitors	Expo 2010 (Actual)		Expo 2010 (Theoretical)	
	Energy consumption (GJ)	Percentage	Energy consumption (GJ)	Percentage
From host city	28,632	0.2%	28,632	0.4%
From host country (Apart from host cities)	9,030,257	66.8%	3,445,879	43.4%
From foreign countries	4,463,102	33.0%	4,463,102	56.2%

Table 11.19 Comparison of energy consumption between different actual transport modes and assumed modes

For foreign visitors from overseas going to the expos, the average travel related visitor energy consumption was much more than for local travelling. It is most convenient for foreign visitors to fly to the host countries when attending the exhibition activities. However, the fact this travelling results in significant energy consumption has not been seriously considered by expo planners. Tables 11.20 and 11.21 demonstrate the fact that because more visitors now travel by aeroplane this probably accounts for the increase in travel energy consumption and emissions between the 19th century and modern times.

Modes	Crystal Palace (1851)	Dutch Pavilion (2000)	Theme Pavilion (2010)
Horse	0	-	-
Steam train	415,324 t	-	-
Steam ship	6,138 t	-	-
Car	-	13,951 t	344,346 t
Bus	-	593 t	96,639 t
Train	-	2,609 t	67,398 t
Airplane	-	4,747 t	187,316 t

Table 11.20 CO_2 emissions of passengers from host countries using different transport modes

Modes	Crystal Palace (1851)	Dutch Pavilion (2000)	Theme Pavilion (2010)
Steam train	6,002 t	-	-
Steam ship	13,782 t	-	-
Car	-	-	76,134 t
Ship	-	-	79,084 t
Train	-	-	2,858 t
Airplane	-	56,448 t	780,949 t

Table 11.21 CO_2 emissions of passengers from foreign countries using different transport modes

To sum up, it is vital that local people are encouraged to take public transport to go to exhibitions. However, whether the environmental impact of long distance travel to go to exhibitions can be mitigated is still a question, and obviously air travel is not currently a sustainable transport mode.

11.1.3 Exhibition-related economic aspects

The discussion in this section focuses on the third aspect of sustainable expositions being considered in this thesis. Based on the calculated results in Chapters 6-9, the exhibition-related economic aspects account for the greatest level of energy and resource consumption over the whole life cycle of an exposition (discussed in Section 10.5).

In this section, several exhibition specific parameters and exhibition-related data (e.g. expenditure and tax income) are used to deepen the discussion of exposition activities in terms of direct and indirect economic benefits and impacts. Exhibition specific parameters comprise the size of exhibition buildings, number of visitors, and number of exhibitors. In Switzerland, the MCH Group Global Live Marketing developed an assessment tool to help exhibitors estimate the value of exhibition participation by means of specific parameters. These were expenditures of the exhibiting company, and the values of the exhibition participation in relation to various benefit segments (MCH Group, 2011). This research just looks at the two parameters of size of exhibition buildings and number of visitors, as they are the dominant factors.

A comparison is made here between several parameters of the case study exhibitions and a number of other exhibitions (Table 11.22). It needs to be noted that these five exhibitions are comparable because they were large-scale exhibitions and all held over several months. Figure 11.2 shows the exhibition-related benefit of different exhibitions. The average income per visitor of Expo 2010 was the highest at 2,553 RMB/visitor (392.3 USD/visitor, converted using the currency rate of 2010).

Table 11.22 shows the total economic income of different exhibitions, along with an increase in the number of visitors who came from outside the host cities. The reason for this increase could be because the number of visitors coming from outside the host city rose, and more food, transportation, and accommodation had to be consumed during the visit time. Thus, more expenditure and more tax resulted from those attending the exhibitions. This demonstrates that the number of visitors, especially visitors from outside the host city, is one of the significant influential factors for the exhibition-related economic aspect.

Table 11.22 also shows that the sizes of exhibition buildings are broadly similar but with some increase over time. Based on figures of official statistics, the size of exhibition buildings has gradually increased (UFI, 2009) as exhibition organisers and exhibitors expect this (VCC, 2000; Yao and Xing, 2010). For example, a study in 2000 reported that the demand for total square feet for shows held in the Vancouver Convention and Exhibition Centre would increase by 22% (VCC, 2000). Currently, the average square metre for occupancy of exhibition facilities per visitor is $0.42m^2$/visitor (UFI, 2009). It seems natural that the size of exhibition spaces will increase as the numbers of visitors increases.

However, the Dutch Pavilion is a counter example to this trend. It had a very small size compared with other buildings (in the context of the floor area of the building), but it attracted more visitors than many other pavilions at Expo 2000. This example shows that visitors were much more interested in the context of the exhibition, and exhibition pavilions may not need to occupy a lot of land resources. The suggestion from this is that there might be no direct relationship between the sizes of exhibition halls and increase in economic income.

Another comparison is made between the average monetary incomes of different national exhibitions (Table 11.23). These were about 1~3 USD/visitor, which was lower than for the international exhibitions. These venues hold regular exhibitions every month and have more local visitors attending.

Exhibition	Place	Size of building (m^2)	Number of visitors	Visitors who live outside host city	Total economic benefit for region	USD/ visitor	Reference
Great Exhibition of 1851	Crystal Palace, London, UK	92,000	6,039,195	66%	£256,437	-	Case study in this thesis (Chapter 6)
Expo 2000	Dutch Pavilion, Hannover, Germany	6,144	4,060,000	90%	€350,000,000 (=499,274,955 USD)	123.0	Case study in this thesis (Chapter 8)
The Salvador Dali exhibition (2005)	Philadelphia Museum of Art, Philadelphia, US	107,000	370,000	63%	54,900,000 USD	148.4	Urban Partners, 2005
Metropolitan Museum Exhibitions (2009)	Metropolitan Museum of Art, New York, US	130,000	-	74%	593,000,000 USD	-	Epoch Times Staff, 2009
Expo 2010	Theme Pavilion, Shanghai, China	143,000	23,000,000 (total: 73,080,000)	86%	186,559,900,000 RMB (=28,665,867,675 USD)	392.3	Case study in this thesis (Chapter 9)

Table 11.22 Comparison of economic benefit of different exhibitions

Event	Place (Population density of city)	Size of building (m^2)	Number of visitors	Total economic benefit for regional (USD)	USD/ visitor	Additional information
National exhibitions (2000)	Vancouver Convention and Exhibition Centre, Vancouver, Canada (578,041)	31, 600	125,000,000	329,767,052 (exhibitors expenditure and tax income)	2.6	VCC, 2000
National exhibitions (2005)	Shanghai Exhibition Centre, Shanghai, China (23,019,148)	80,000	7,500,000	7,180,581	1.0	Case study in this thesis (Chapter 7)
National exhibitions (2009)	The International Convention and Exhibition Centre, Auckland, NZ (1,354,900)	27,000	222,000	70,694,087 (tourism-related expenditure)	-	ACC, 2009

Table 11.23 Comparison of average economic benefit of different national exhibitions

The exhibition industry brings direct and indirect economic benefits and social benefits to a regional area, as it "…attracts large business affairs and tourists, and promotes the exploitation of production market, the intercommunion of technology and communication, foreign trade and travels" (Yao and Xing, 2010). For example, China has become the one of the biggest countries in the world in terms of holding exhibitions. In China, the conference and exhibition industry has developed at a rate of 20% per year since the reform (Yao and Xing, 2010).

As a possessor of the “Three highs” (high growth potential, high added-values, and highly beneficial innovations), the expansion of the exhibition industry seems to be continuous (MEA, 2009). However, these exhibition activities are leading to the consumption of more natural resources (as demonstrated in Section 10.4).

To make expositions more sustainable, the method of display might have to be gradually changed from physical attendance to an online platform. This could help to reduce the resource and energy consumption of exhibition buildings, transportation, and the impact emanating from visitor accommodation and other activities. However, this would still not deal with the largest aspect of environmental degradation, the increased economic activity resulting from holding an exhibition.

11.2 Measuring sustainable expositions (large-scale events)

A range of Sustainable Development Indicators have been proposed in the fields of environment, society, and economy (see in Section 2.3.2). However, there is little relevant study for specifically assessing the environmental impact of large-scale events (expositions fall into this category) (explained in Section 2.3.3).

In this research, Chapters 6~9 have demonstrated how two assessment methods (Life Cycle Analysis and Ecological Footprint Analysis) were combined and used to quantify and provide results for the environmental impacts related to event visitation under certain research boundaries as set out for the case studies.

This section will discuss the further issues of measuring sustainable expositions, including assessment boundaries (11.2.1) and measurement tools (11.2.2) for environmental impacts. Compared to some related assessment methods of the environmental impacts of large-scale events (e.g. sport events), this study identifies the necessity of setting up appropriate and broader research boundaries, and selecting the right assessment tools for measuring large-scale expositions at both national and international levels.

11.2.1 Assessment boundary

The assessment boundary is considered to be one of the significant factors in terms of quantitative measurement (discussed in section 5.1.1, Mithraratne et al, 2007, p.24; Maru and Woodford, 2007). It can have a large effect on the results of the environmental assessment of large-scale events, so that assessment results may influence related decision-making, for example, national policies for promoting sustainable exhibitions.

Commonly, the analysis boundary for assessing the environmental degradation considered in previous studies has consisted solely of the energy and resource consumption of infrastructure, visitor travel to an event, and food consumption. These impacts were generated during the operational period of the event. The assessment of the economic and environmental impact of the 2003/2004 FA Cup Final from the research of Collins et al (2007) is such an example. The authors estimated the environmental consequences of this event using Ecological Footprint Analysis and Environmental Input-Output Analysis. The geographical boundary of the study was the host city of Cardiff and the period for which the visitor footprint was calculated was the one day the event was held. The primary aspects of assessment for environmental impact included the infrastructure (the Stadium), visitor travel to go to the event, food and drink sold, and waste. Detailed information on the analysis boundary is given in Table 11.24.

Although both the economic and environmental impacts were explored in this study, the economic impact of this sporting event was evaluated by using monetary value. This means that the environmental impact of the event-related economic aspects, which potentially generated the largest effect (as has been discussed in Section 10.4), was not evaluated and not included in the whole environmental assessment. For the Cardiff research, the analysis boundary was just focused on the resource consumption of visitors in terms of their direct consumption patterns.

Other problems also existed in the analysis boundaries regarding the transport modes of visitor travel. For example, energy consumption for domestic air travel was not included in the research. Based on a related study, more than 5% of visitors take flights for long distance travel in the UK (Kuhnimhof et al, 2009). According to this figure, it could be that more than 3,600 visitors used air travel to go to the FA Cup Final in the UK. Whether the analysis boundary for the transportation in the study of Collins et al (2007) was appropriate in its exclusion of air travel or not is arguable.

As the problems above demonstrate, this thesis study suggests that the analysis boundaries for assessment of event-related environmental impact need to be considered in terms of their "whole life cycle". Although global environmental issues have attracted much research and some valuable results have ensued, there is at present no research considering the widely based "whole life-cycle" environmental impacts of expositions. This research shows that the broader boundaries of assessment for event-related environmental impact need to be considered. The "Whole life cycle" assessment in this thesis comprises whole life cycle consumption of buildings, visitor travel, and exhibition-related economic aspects. The economic aspects should not be isolated from the assessment of environmental impact. The whole life-cycle environmental impact in this study is different from conventional concerns as it is defined as the direct and indirect environmental effects of expositions during the whole process (before, during, and after the exhibition activities). Consideration of the whole life cycle of an exposition provides the most complete analysis of the associated material and energy flows, carbon dioxide emissions, and land usage. The analysis boundaries of these case studies have been delimited in detail in Section 5.1.1.

A comparison of the analysis boundaries for the environmental assessment of large-scale events is made below between the 2003/2004 FA Cup Final and one of the case studies in this thesis, Expo 2010 (Table 11.24).

	2003/2004 FA Cup Final		Expo 2010	
	Detail	Additional	Detail	Additional
Geographical boundary	The host city	Cardiff, UK	The host city	Shanghai, China
Study population	All event visitors	-	All event visitors	-
Period	One day	The day of the event	6 months	
Analysis boundary	Infrastructure of the event venue	Stadium (calculated according to capital investment)	Exhibition building LCA	Theme Pavilion
	Visitor travel to the event	Return journeys; only UK travel was counted; domestic air travel not included	Visitor travel to the event	Return journeys, domestic and international travel included; main transport modes included
	Food and waste	-	Exhibition-related economic aspects	Commercial sales in and out of the Expo Park (food, tickets, retail, accommodation); Economic benefits generated after the Expo 2010

Table 11.24 Comparison of the analysis boundary between the 2003/2004 FA Cup Final and the Expo 2010

Table 11.24 demonstrates that the analysis boundaries of "whole life cycle" assessment need to be broadened to obtain a true picture of the environmental impacts of these types of events.

11.2.2 Measurement tools

Life Cycle Analysis and Ecological Footprint Analysis are the measurement tools selected for this research. These tools and the reason for selection have been introduced and explained in Section 5.2. Life Cycle Analysis is used to measure the total energy consumption of exhibition buildings. The energy and resource consumption of visitor travel and exhibition-related economic aspects are evaluated using Ecological Footprint Analysis. This section further discusses the strengths and weaknesses of the application of these two tools specifically for measuring large-scale events, based on the case studies.

11.2.2.1 Life Cycle Analysis

Life Cycle Analysis has been used to quantify the energy consumption of exhibition buildings in this thesis. This method helps to assess the environmental impact of each construction component, and evaluate the energy consumption of buildings in every phase (construction, maintenance, operation, and demolition). The method also facilitates provision of a detailed description of the calculated results. For example, it can help to explore the environmental impact of the use of different construction materials by estimating their embodied energy consumption.

Life Cycle Analysis is one of the most used tools when it comes to the environmental impact of buildings. However, there is little standardisation of how it is used (Chambers et al, 2001, p.26). It has to rely on assumptions when assessing indirect resource consumption and subsequent effects, such as the details of the complex process of the manufacture of a material, or how electricity is generated nationally. Providing these assumptions are consistent, then LCA is useful for comparative studies, even if it cannot be relied on for an accurate prediction.

11.2.2.2 Ecological Footprint Analysis

In this thesis Ecological Footprint Analysis is mainly adopted to assess the environmental effect of exhibition-related economic aspects. The footprint of economic aspects is converted from the direct and indirect economic benefits generated by the large-scale exposition activities. Furthermore, the energy consumption of buildings and visitor travel can also be converted into Ecological Footprint values. The results are then used for making comparisons between factors.

Ecological Footprint Analysis as a measurement tool can be especially helpful in the context of an event (Collins et al, 2007). It not only provides an understanding of the environmental impacts of expositions at the national and international level (similar to the GDP indicator), but can also demonstrate the environmental effect of the direct and indirect consumption patterns of visitors when they attend exhibitions. Collins et al (2007) argued that “The Ecological Footprint Analysis is a sophisticated tool able to identify key environmental pressure-points”. In addition, it has the potential to be adopted in many conditions and can reflect the relative impact of different consumption activities within a certain population.

At the same time, Ecological Footprint Analysis has several weaknesses for the calculation of the impact of the case study events. The assessment results may not comprise all detailed visitor impacts from consumption at the expos. For example, it does not take account of the volume of water consumed during the activities, although other research into the ecological footprint of tourism has shown bottled water to be a very small component of the tourist EF (based on travel, accommodation, food and water) (Mahravan and Vale, 2010). The fact the ecological footprint method may not definitely accurately reflect the impacts because some things have to be left out to make the task manageable (Ferng, 2002; McGregor et al, 2004) has been widely criticised in the academic field (Dickson and Arcodia, 2010).

Methods	Strength	Weakness
Life Cycle Analysis	• Assess impacts of each product or process over whole life cycle; • Provide detailed description of assessment results of environmental impact	• Little standardisation of method; • Must rely on assumptions for assessing some indirect effects
Ecological Footprint Analysis	• Provides an understanding of the global environmental impacts; • Demonstrates the environmental effect of visitors' direct and indirect consumption patterns; • Reflects the impact of consumption activities with a certain population	• May not comprise all detailed visitor consumption categories at the expos; • May not accurately reflect the impacts

Table 11.25 Strengths and weaknesses of the two methods adopted in the calculation for case study events in this thesis

Table 11.25 summarises the strength and weakness of the two methods adopted in the calculation of the impact of the case study events in this thesis.

11.2.2.3 Mixed methods approach

A mixed methods approach, which is an integrated and customised assessment tool, is necessary for measuring large-scale events, based on the description in Table 11.24. The mixed methods approach can be used to assess different visitor scenarios. It should, therefore, be able to assist organisers and promoters to demonstrate whether expos are organised as sustainable events.

It is noted that many assumptions of data collection and calculation have been used in this study. This is because unavailabilty of data (e.g. for the historic case study in 1851) and some indirect resource consumption and effects cannot be captured. Sensitivity analysis can be used to explore the variations generated from a range of assumptions of the inputs.

However, it is impossible to examine each assumption in this research. Therefore, a sensitivity analysis in the calculation of embodied energy consumption of case study buildings, Crystal Palace, Shanghai Exhibition Centre, and Dutch Pavilion, as a typical example, has been done. The embodied energy coefficients for different countries vary slightly because the energy mixes for manufacturing materials are different in each country. Between 1994 and 2008 embodied energy coefficients from different countries have not changed very much. As explained above, in the absence of relevant data, coefficients from the UK were used for the Crystal Palace, those from Australia for the Shanghai building and from Germany for the Dutch Pavilion. The data were checked by applying all three sets of coefficients to all three buildings. The detailed results of this sensitivity analysis are given in Appendix F. The result of the sensitivity analysis demonstrated that the overall differences were very small. The maximum coefficient of variation was 6% (from 2.1% to 5.7%), as shown in Table 11.26. This justified the claim the calculated results are acceptable in terms of the confidence interval (detailed results, see Appendix F).

Total embodied energy	UK embodied energy coefficients	Australian embodied energy coefficients	German embodied energy coefficients	Coefficient of variation
Crystal Palace	348,189 GJ	346,379 GJ	379,027 GJ	4.2%
Shanghai Exhibition Centre	859,082 GJ	758,772 GJ	858,924 GJ	5.7%
Dutch Pavilion	93,054 GJ	93,590 GJ	89,186 GJ	2.1%

Table 11.26 Sensitivity analysis: embodied energy of buildings calculated using different embodied energy coefficients (Appendix F)

11.3 Chapter conclusion

This chapter provides further thoughts on how to make sustainable expositions and how to appropriately measure the impact of large-scale expositions. The main considerations are summarised below.

To make sustainable expositions:

- For buildings, using the high-tech approach currently does little to mitigate the energy and resource usage of large expo pavilions. Exhibition buildings as a specific type of building for display may actually need to be treated by using different solutions from other commercial buildings in terms of sustainability. Sustainable design of large-scale exhibition buildings needs to focus more on reducing total energy consumption in the operating phase. At the same time, the energy flow influenced by actual useful life is very much larger than the aspects of design usually considered to be "sustainable".
- For visitor travel, using public transport modes can effectively help to reduce energy and resource usage in host cities. For foreign visitors from overseas going to the expos by airplane leads to more energy usage than the average energy consumption for local travelling. Overseas 'visitors' to expos need to use the technology of virtual visiting if the event is to be sustainable.
- For exhibition-related economic aspects, the number of visitors, especially visitors from outside the host city, is one of the significant influential factors for environmental protection. Again, virtual visiting could help to reduce these impacts.

To measure large-scale expositions:

- The analysis boundary for assessment of event-related environmental impacts needs to be the "whole life cycle" and it needs to be broadened for the environmental assessment of these types of events to include not just exhibition buildings, but visitor travel (local and international travel), and event-related economic aspects.
- The mixed methods approach, which is an integrated and customised assessment tool, is necessary for measuring the environmental impact of large-scale events.

Chapter 12 Conclusions and Recommendations

This chapter provides the answers to the research questions and draws conclusions for this study on the basis of the comparative analysis and related further considerations in Chapters 10 and 11. Limitations of the research and opportunities for further research are then discussed.

12.1 Answers to research questions

This research aims to create an appropriate and specific methodology for assessing the chief environmental impacts generated by holding large-scale exhibitions and to define what a real sustainable exposition and sustainable exhibition building might be. This section answers the research questions set out in section 4.1.

The first main research question was: How can the environmental impact generated by the contemporary exhibition industry be measured at both the national and international level?

This thesis has shown it is possible to measure the impacts of the modern exhibition industry using a modified form of Life Cycle Assessment. To limit the scope of the research this has meant identifying what might be the biggest impacts of the exhibition industry. Because this research is undertaken within the discipline of architecture exhibition buildings were examined, although research showed that their overall contribution to modern exhibitions is small when it comes to total environmental impact.

There were two related subsidiary questions:

(a) How can the system boundaries of measurement be set up and appropriate methods for assessment applied?

The system boundary was set up in Chapter 5 by focusing on what were perceived to be the three most significant factors of large-scale expositions with the potential for generating significant environment impacts. A mixed methods approach (including Life Cycle Analysis and Ecological Footprint Analysis) was adopted to establish the calculation models for quantifying and estimating the impacts of four typical case studies. The reason for doing this was to check that results obtained under different methods were comparable. This provided a justification for the research method and the results.

(b) Do the analysis boundaries of Life Cycle Assessment need to be broadened for the environmental assessment of exposition?

This thesis suggests it is vital that analysis boundaries be broadened to investigate the true sustainability of current actions, such as holding exhibitions. This is because the conventional assessment indicators for estimating the environmental impacts of large-scale events have separated out the effects from provision and use of infrastructure (such as that for visitor travel) and the economic benefits that accrue from exhibitions. Both of the latter have been shown in this research to be much greater than the impacts of exhibition buildings. This suggests it is not the buildings that should be the focus of environmental research but the activities that occur within them. The broader analysis boundary of the environmental assessment (energy consumption, carbon emissions, and ecological footprint) of expositions used here comprises the impacts generated from exhibition buildings, visitor travel, and exhibition-related economic aspects.

The second main research question was: What is the environmental impact generated by a large-scale international exhibition or exposition over its whole life cycle?

Because of the way data is currently collected many assumptions have had to be made in this research to calculate the environmental impacts of exhibition buildings. This is why four case studies were undertaken so that their results could be compared to minimise the effect of making assumptions. For all case studies it was the economic impact that was the largest environmental impact over the assumed life-cycle of a large scale exposition, followed by that of visitor travel, and then that of the buildings examined.

There were five related subsidiary questions:

(a) What is the average initial and recurring embodied energy and operating energy of an exhibition building?

The first problem in answering this question was defining the life of an exhibition building. In fact this study quantified the initial, recurring embodied energy, and operating energy of four case studies over their actual life and an assumed useful life. As a summary of the results, tables 12.1 and 12.2 show the average energy consumption of the case study buildings over their actual life and an assumed life of 50 years, the latter to give a direct comparison.

	Initial embodied energy (MJ/m^2/month)	**Recurring embodied energy (MJ/m^2/ month)**	**Average operating energy (MJ/m^2/month)**
Crystal Palace (82.5 years)	1	1	93
Shanghai Exhibition Centre (56 years)	8	6	37
Dutch Pavilion (5 months) (with sustainable consideration)	2,120	0	83
Theme Pavilion (13 months) (with sustainable consideration)	1,400	0	76

Table 12.1 Average initial, recurring embodied energy, and operating energy of the four case study buildings based on actual life

	Initial embodied energy (MJ/m^2/year)	**Recurring embodied energy (MJ/m^2/year)**	**Average operating energy (MJ/m^2/year)**
Crystal Palace (50 years)	26	23	1,110
Shanghai Exhibition Centre (50 years)	110	80	446
Dutch Pavilion (assumed to be used for 50 years) (with sustainable consideration)	212	88	1,000
Theme Pavilion (assumed to be used for 50 years) (with sustainable consideration)	168	12	907

Table 12.2 Average initial, recurring embodied energy, and operating energy of the four case study buildings based on an assumed useful life of 50 years

(b) Are buildings getting better? Given current improvements in energy efficiency is there a significant difference between modern and historic large single space exhibition buildings in terms of the embodied energy in the construction and energy use in the operating phases?

The quantified results show that modern exhibition buildings consumed more energy for building construction and maintenance than the older buildings, even though both these have been upgraded in their lifetimes. For the building operating phase, using PV panels and other sustainable technologies has not helped to mitigate the energy usage of exhibition buildings to any significant point, noting that the more conventional Shanghai Exhibition Centre has the lowest operational energy use. Because the Sydenham Crystal Palace used coal for heating its operational energy is relatively high compared to that of a more modern building. However, as originally designed without heating, its energy use was zero (see chapter 6).

(c) What is the total energy consumption and associated CO_2 emissions of visitor travel for attending expositions or exhibitions?

This study quantified the energy consumption and CO_2 emissions of visitor travel going to the four exhibition buildings. Table 12.3 lists the energy consumption and CO_2 emissions of visitor travel to go to the four case study buildings. Table 12.4 shows the per capita energy consumption for each exposition.

Visitor travel to go to	Average energy consumption	Average CO_2 emissions
Crystal Palace (1851)	838 MJ/visitor	74 kg/visitor
Dutch Pavilion (2000)	322 MJ/visitor	19 kg/visitor
Theme Pavilion (2010)	588 MJ/visitor	71 kg/visitor

Table 12.3 Energy consumption and CO_2 emissions of visitor travel to go to the four case study buildings

Visitor travel to go to	Total energy consumption	Average energy consumption
Great Exhibition (1851)	28,130 GJ/day	838 MJ/visitor/day
Expo 2000 (2000)	433,007 GJ/day	2,576 MJ/visitor/day
Expo 2010 (2010)	1,193,463 GJ/day	2,940 MJ/visitor/day

Table 12.4 Energy consumption of visitor travel to go to the events averaged over a day

(d) Has the environmental impact of visitor travel to exhibitions increased or decreased over time? Does the location of buildings influence the energy consumption and carbon emissions of visitor travel?

The total energy usage and CO_2 emissions of visitor travel are increasing over the years based on visitor travel to an event rather than a pavilion. The location of exhibition buildings in relation to travel consumption still needs to be evaluated on a case by case basis, as it can be affected by different population densities in different cities. The choice of visitor transport modes also affects the environmental impact of visitor travel. This should be of concern for those organising large scale expositions.

(e) What is the most significant factor in the process of exposition activities, in terms of the whole life cycle environmental assessment?

Comparing the total energy and resource consumption of three factors, the exhibition-related economic aspects consumed most energy and resources, which were much more than those for building consumption and visitor-related transportation taken together.

12.2 Conclusions and recommendations

12.2.1 Conclusions

A whole life cycle assessment of the energy and resource usage of large-scale expositions (comprising exhibition buildings, visitor travel, and exhibition-related economic aspects) has been undertaken using the mixed methods approach developed in this thesis. The investigation examines the environmental consequences of the four expositions in London, Hannover, and Shanghai from 1851 to 2011 as listed below;

- Great Exhibition of 1851 (Crystal Palace, 1851~1936);
- Shanghai National Exhibitions (Shanghai Exhibition Centre, 1955~2011)

- Expo 2000 (Dutch Pavilion, 2000)
- Expo 2010 (Theme Pavilion, 2010~2011).

This research concludes that the environmental impacts of large-scale expositions can be measured by the mixed methods approach in terms of the three selected and related factors over their whole life cycle, and within an appropriate analysis boundary. The modified Life Cycle Assessment method has the potential to be developed as a generalised framework for gauging the environmental impact of large-scale events at the national and international level.

The results of the assessment show that the total energy and resource consumption of large-scale exhibitions is increasing. Across the three factors, the exhibition-related economic aspects consume most energy and resources, this being considerably greater than both building energy consumption and visitor-related transportation energy consumption.

For exhibition buildings, this study shows that modern exhibition buildings do have an impact on the environment and are not becoming more sustainable, whatever their promoters may claim. For a short period of useful life, it is impossible for exhibition building design to achieve the goal of sustainability. In detail, energy and resources are consumed most in the building operating phase. Using sustainable technologies, such as wind turbines or PV panels, for exhibition buildings does not seem the best approach for reducing their operating energy consumption. Exhibition buildings as a specific type of building for display may actually need to be treated by using different solutions from other commercial buildings in terms of sustainability. The Crystal Palace showed how operating an exhibition building in the summer and only during the hours of daylight made a huge reduction in its operating energy. This changed dramatically when the same building was heated all year round. This suggests exhibitions should be held for short period at the most climatically favourable times of year and day. However, these same buildings need to be reusable as the matter of short building useful life resulted in the sustainably designed buildings performing worse than normal buildings.

The choice of visitor transport modes can affect the environment. The location of the buildings in relation to choice of travel mode needs to be considered carefully. Choice of different transport modes has a large influence on the overall transport energy consumption and environmental impacts. Foreign visitors flying to expos involve more energy consumption than local travelling.

The exhibition-related economic stimulus has by far the highest ecological footprint for a large-scale exhibition, when compared to the other relevant factors. Currently this important part is largely ignored by sponsors and politicians. For exhibition-related economic aspects, the increase of the number of visitors, especially visitors from outside the host city, is one of the significant influential factors on the environmental impact. The influence of exhibitions raises a question about moving societies to a sustainable situation. It seems that the vicious circle between exhibition-related economic growth and environmental deterioration cannot be collapsed at present. The more benefits the organizers achieved, the more significant environmental impact resulted. The contradiction between economic growth and environmental protection cannot be easily removed, based on the present public understanding of sustainable development and the design principles for established sustainable expositions.

12.2.2 Recommendations

For sustainability assessment, the whole life cycle energy and resource consumption of large-scale expositions needs to be evaluated, if these are to be claimed as sustainable events. Such evaluation requires the boundaries of what needs to be dealt with to be set much wider than now. Furthermore, the boundaries of environmental analysis for a large-scale exhibition building need to be standardised and clarified. It might be better if the scope of the analysis went beyond pure energy accounting of buildings to look at the whole exhibition industry so as to fully understand its overall impact on the environment.

Exhibition buildings will only reach the goal of sustainability if they are used continuously for a long time. Buildings for events like Expos need to be guaranteed a long and useful life. At the same time, making a building that is easy to disassemble and move may be more important than having a building which incorporates sustainable technologies and gadgets. In addition, how to reduce the operating energy, such as for lighting or air conditioning systems, should be the primary focus. Furthermore, looking at how buildings were made in the past, when energy resources were harder to come by, may also provide useful lessons for how to design buildings with lower environmental impact now. For example the Crystal Palace made extensive use of wood in its construction, which has helped to lower its overall impact in spite of its structure being of iron.

For visitor travel, using public transport modes can effectively help to reduce energy and resource usage in host cities, as the travel mode choices of visitors can have a dramatic effect on the total energy usage. At the same time, plans will also be needed to ensure that visitors can access exhibition buildings by the lowest energy consuming forms of public transport.

Policy makers and event-organisers really need to consider how to develop a more sustainable exposition industry. The method of display might have to be gradually changed from physical attendance to an online expo platform. This could help to reduce the resource and energy consumption of exhibition buildings, transportation, and the impact emanating from visitor accommodation and other activities. Currently, some international expos have established their own virtual expo, for example, the Shanghai Expo 2010. However, it is not well designed and is particularly built for commercial purposes, rather than the consideration of the exhibition-generated environmental impacts.

Moreover, not only architects, planners and officials, but also the general public need to cultivate much greater awareness of sustainability and their personal responsibility as determined by their behavioural choices, for effective environmental conservation.

Finally, although the procurement and use of exhibition buildings has to be changed, buildings are the least of the problems of exposition-related environmental issues. Visitor travel has to be avoided where possible, as described above. However, holding an exhibition event with the intention of generating economic growth is the biggest environmental impact and, therefore, forms the biggest question for the future of the industry and of moving towards sustainability. Whether these types of events should be reduced needs to be considered by policy markers.

For example, the Hannover Principles (McDonough et al, 1992) determined the concept of sustainability as the guidelines for building World Expo 2000 in Germany. Nine principles were listed in this report, of which all are relevant to the sustainable construction of exhibition buildings. Meanwhile, it established the principles for transportation requirements with local, bio-regional, and global imperatives (McDonough et al, 1992). Vehicles which used renewable energy, for example hydrogen power or solar energy were most encouraged. However, these high-tech equipements do not successfully help to mitigate the energy use and the resulting enviromental impacts of exhibition-realted buildings and transportation at present. For visitor travel, these principles attempted to provide detailed improvement approaches and practical restrictions to the local transport, rather than the whole transport system (including the international travel). The Hannover Principles did not contribute to reducing air travel to participate in the exposition. These principles did not truly deal with the environmental problem of large-scale events, as the current various interpretations of sustainability and their economic-orientation continue to demonstrate.

12.3 Limitations and further research

The assessment of the environmental impacts of large-scale expositions addressed in this investigation only covers a selection of effects connected with holding exhibitions, these being the energy and resource consumption of exhibition buildings, visitor travel, and exhibition-related economic aspects. Many other effects on the environment and other exhibition-related aspects need to be investigated in further research, as shown below.

In detail, exploration of other human behaviour-related effects of expositions, such as waste creation and water consumption, is vital. For building environmental assessment, other environmental effects generated from HVAC leakage and building demolition need to be evaluated. For visitor travel, research into the national energy usage of transport modes needs to be completed to define the extent of the environmental impacts of different modes visitors can choose for each proposed exposition site.

Furthermore, a framework for measuring large-scale events over their whole life cycle needs to be established for study of their long term impacts. Having systematic methods with an updated database for quantification coefficients, such as reliable embodied energy coefficients for different countries, will significantly improve the accuracy of estimation of the overall impact of large-scale expositions.

Further areas of investigation are to explore the potential for designing demountable components for exhibition infrastructure and to investigate how to establish an online platform for international exhibitions in the future. Only in this way will the energy and resource consumption of large-scale expositions be reduced in the long term.

The purpose of holding expositions needs to be considered. Linking these to untrammelled economic growth will mean they can never contribute to sustainability. However, holding expositions that demonstrate how to live sustainably within a no-growth economy could be of huge benefit to all.

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Appendix A: Quantitative work on the Great Exhibition of 1851

Table 1 Embodied energy of the Crystal Palace in Hyde Park and Sydenham (1851-1936)

			Original (1851)		Rebuild and maintenance (1854-1936)	
Materials	Building elements	Embodied energy coefficient (GJ/t) *	Weight/ Volume	Embodied energy(GJ)	Total weight	Embodied energy(GJ)
Glass	Main building	15	408t	6,120	527t	7,905
	Colonnade		-	-	18t	270
Iron	columns	25	2,669t	66,718	3,325t	83,125
	Girders		1,668t	41,700		
	Pipes		906t	22,653		
	Connection collars		469t	11,732		
	Metal louvres		40t	1,000		
	Roof trusses		565t	14,125		
	Boilers		-	-		
	Colonnade		-	-	60t	1,500
	Total		6,317t	157,925	3,385t	84,625
Wood	-	1.6	8,495t	13,592	0 t	0
Concrete	Foundations (footing)	2	855t	1,710	719t	1,438
Brickwork	Foundations	2.5	-	-	15,297 t	38,243
Paint (Durability: 5 years)	Columns	30.6 MJ/ m^2 (Triple coat for initial) 10.2 MJ/m^2 (Single coat for recurring)	18,661 m^2	571	18,661 m^2	3,046
	Girders		12,921 m^2	395	12,921 m^2	2,109
	Pipes		25,918 m^2	793	25,918 m^2	4,230
	Connection collars		3,110 m^2	95	3,110 m^2	508
	Metal louvers		8,208 m^2	251	8,208 m^2	1,340
	Roof trusses		6,263 m^2	192	6,263 m^2	1,022
	New iron elements built for Sydenham Crystal Palace		-	-	1800 m^2 (total: 300m^3) (1m^3/elements)	55(first time) 275(rest)
	Boilers		-	-	Boilers: 138m^2 Pipes: 12,637 m^2	391 (first time) 1955(rest)
	Colonnade		-	-	48 m^2	2 (first time) 7 (rest)
	Wood	30.6 MJ/ m^2 (Triple coat for initial) 10.2 MJ/m^2(Single coat for recurring)	101,940m^2	3,119	101,940m^2	16,637
Total	-	-	-	184,763	-	164,058
In all	**348,821 GJ** (31 MJ/m^2/year)					
Hammond, G., & Jones, C. (2008). *Inventory of Carbon and Energy (ICE), Version 1.6a, Sustainable Energy Research Team (SERT).* Department of Mechanical Engineering, University of Bath, UK.						

Appendix B: Quantitative work on National Exhibitions at Shanghai Exhibition Centre between 1955~2011

- Initial embodied energy of Shanghai Exhibition Centre

Table 1 Initial Embodied Energy of the Front Hall of the Shanghai Exhibition Centre

Halls	Elements	Materials	Volume	Material energy intensities*	Material quantities (MJ)
Front Hall (excluding the four small decorating towers and external decoration)	Box foundation	Reinforced concrete	2628 m^3	7.0 GJ/m^3	18396000
			2578 m^3		18046000
		Damp proof membrane	2190 m^2	0.07GJ/m^2 **	153000
	Columns	Reinforced concrete	506 m^3	7.0 GJ/m^3	3542000
		Cement mortar 1:3	19.74 m^3	Cement: 11.4 GJ/t (=9.5 GJ/ m^3) (1m^3=1.2t), Sand: 0.3 GJ/m^3	194700
		Granite	18.71 m^3 (=50.5t)	5.86 GJ/t , 0.1-13.9 GJ/t ***	296000
		Paint	583 m^2	0.02 GJ/m^2**	12000
	Beams	Reinforced concrete	274 m^3	7.0 GJ/m^3	1918000
		Cement mortar 1:3	11.92 m^3	Cement: 11.4 GJ/t (=9.5 GJ/ m^3)(1m^3=1.2t), Sand: 0.3 GJ/m^3	115200
	Floors	Reinforced concrete	605 m^3	7.0 GJ/m^3	4235000
		Cement mortar 1:3	30.4 m^3	Cement: 11.4 GJ/t (=9.5 GJ/ m^3) (1m^3=1.2t), Sand: 0.3 GJ/m^3	298000
		Terrazzo	121 m^3	1.4 GJ/t *** (=0.6GJ/ m^3) (2.3 t/m^3)	73000
	External walls	Reinforced concrete	2508 m^3	7.0 GJ/m^3	17556000
		Rockwool	2492 m^2	0.14 GJ/ m^3 **	7000
		Cement mortar 1:3	21 m^3	Cement: 11.4 GJ/t (=9.5 GJ/ m^3) (1m^3=1.2t), Sand: 0.3 GJ/m^3	206000
		Paint	4178 m^2	0.02 GJ/m^2**	84000
	Internal walls	Reinforced concrete	1314 m^3	7.0 GJ/m^3	9198000
		Cement mortar 1:3	4.4 m^3	Cement: 11.4 GJ/t (=9.5 GJ/ m^3) (1m^3=1.2t), Sand: 0.3 GJ/m^3	43000
		Paint	943 m^2	0.02 GJ/m^2**	19000
	Windows	Float glass	300 m^2	3.1 GJ/m^2	930000
		Steel	0.78 m^3	36.8 GJ/t (=30.7 GJ/ m^3) (1.2-3.8t=1 m^3)	24000
	Doors	Timber (hardwood)	15.2 m^3	10.9 GJ/ m^3	166000
		Copper	0.38 m^3	45.9 GJ/t (=14 GJ/ m^3) (3.25 t/ m^3)	532000
	Ceiling	Plywood	4501 m^2	0.98 GJ/ m^2	4411000
		Plaster	4501 m^2	6.5 GJ/m^3 **	45000
		Paint	4501 m^2	0.02 GJ/m^2**	90000
	Staircases	Reinforced concrete	16.8 m^3	7.0 GJ/m^3	118000
		Terrazzo	0.6 m^3	1.4 GJ/t *** (=0.6GJ/ m^3) (2.3 t/m^3)	400
		Reinforced concrete	36.8 m^3	7.0 GJ/m^3	258000
		Terrazzo	4 m^3	1.4 GJ/t *** (=0.6GJ/ m^3) (2.3 t/m^3)	2000
	Roof	Reinforced concrete	349 m^3	7.0 GJ/m^3	2443000
		Rockwool	3483 m^2	0.14GJ/ m^3 **	10000
		Asphalt	3483 m^2	2.6 GJ/t *** (2.5 GJ/ m^3) (1.02t/ m^3)	87000
		Cement mortar 1:3	18.3 m^3	Cement: 11.4 GJ/t (=9.5 GJ/ m^3) (1m^3=1.2t), Sand: 0.3 GJ/m^3	174000 5500
		Paint	3483 m^2	0.02 GJ/m^2**	70000
	Services	20%	-	-	20,940000
Total	104,698000 MJ				

* Treloar, G. J. (1994). *Energy analysis of the construction of office buildings.* Masters thesis. Faculty of Science and Technology, Deakin University, pp 58-59
** Baird, G., & Chan, S. A. (1983). *Energy Cost of House and Light Construction Buildings and Remodelling of Existing Houses (Report No.76).* New Zealand Energy Research and Development Committee, University of Auckland.
*** Hammond, G., & Jones, C. (2008). *Inventory of Carbon and Energy (ICE), Version 1.6a, Sustainable Energy Research Team (SERT).* Department of Mechanical Engineering, University of Bath, UK.

Table 2 Initial Embodied Energy of the Central Hall of the Shanghai Exhibition Centre

Halls	Elements	Materials	Volume	Material energy intensities*	Material quantities (MJ)
Central Hall (excluding external decoration)	Box foundation	Reinforced concrete	2223 m^3	7.0 GJ/m^3	15561000
			3489 m^3		24423000
		Damp proof membrane	2190 m^2	0.07 GJ/m^2**	153000
	Columns	Reinforced concrete	117 m^3	7.0 GJ/m^3	819000
		Cement mortar 1:3	0.6 m^3	Cement: 11.4 GJ/t (=9.5 GJ/ m^3) (1m^3=1.2t), Sand: 0.3 GJ/m^3	4680
		Paint	1.27 m^2	0.02 GJ/m^2**	30
	Arch structure (internal)	Reinforced concrete	690 m^3	7.0 GJ/m^3	4830000
		Cement mortar 1:3	13.8 m^3	Cement: 11.4 GJ/t (=9.5 GJ/ m^3) (1m^3=1.2t), Sand: 0.3 GJ/m^3	131000 4000
		Paint	2760 m^2	0.02 GJ/m^2**	55000
	Beams	Reinforced concrete	299 m^3	7.0 GJ/m^3	2093000
		Cement mortar 1:3	7.44 m^3	Cement: 11.4 GJ/t (=9.5 GJ/ m^3) (1m^3=1.2t), Sand: 0.3 GJ/m^3	38200
	Floors	Reinforced concrete	150 m^3	7.0 GJ/m^3	1050000
		Cement mortar 1:3	7.6 m^3	Cement: 11.4 GJ/t (=9.5 GJ/ m^3) (1m^3=1.2t), Sand: 0.3 GJ/m^3	74000
		Terrazzo	30 m^3	1.4 GJ/t (UK) *** (=0.6GJ/ m^3) (2.3 t/m^3)	18000
	External walls	Reinforced concrete	824 m^3	7.0 GJ/m^3	5768000
		Rockwool	687 m^2	0.14 GJ/ m^3 **	2000
		Cement mortar 1:3	3.4 m^3	Cement: 11.4 GJ/t (=9.5 GJ/ m^3) (1m^3=1.2t), Sand: 0.3 GJ/m^3	33000
		Paint	687 m^2	0.02 GJ/m^2**	14000
	Internal walls	Reinforced concrete	833 m^3	7.0 GJ/m^3	5831000
		Cement, sand	21.1 m^3	Cement: 11.4 GJ/t (=9.5 GJ/ m^3) (1m^3=1.2t), Sand: 0.3 GJ/m^3	204000
		Paint	4161 m^2	0.02 GJ/m^2**	83000
	Windows	Float glass	224 m^2	3.1 GJ/m^2	694000
		Steel	1.12 m^2	36.8 GJ/t (=30.7 GJ/ m^3) (1.2-3.8t=1 m^3)	34000
	Doors	Timber (hardwood)	12.8 m^3	10.9 GJ/ m^3	140000
		Glass	55 m^2	3.1 GJ/m^2	171000
		Copper	0.14 m^3	45.9 GJ/t (=14 GJ/ m^3) (3.25 t/ m^3)	2000
	Ceiling	Plywood, paint	2708 m^2 1012 m^2	0.98 GJ/ m^2 0.02 GJ/m^2**	3647000 74000
	Staircases	Reinforced concrete	28 m^3	7.0 GJ/m^3	196000
		Terrazzo	3 m^3	1.4 GJ/t *** (=0.6GJ/ m^3) (2.3 t/m^3)	1800
	Roof	Reinforced concrete	371 m^3	7.0 GJ/m^3	3597000
		Rockwool	3705 m^2	0.14 GJ/ m^3 **	12000
		Asphalt	3705 m^2	2.6 GJ/t *** (=2.5 GJ/ m^3) (1.02t/ m^3)	93000
		Cement mortar 1:3	18.5 m^3	Cement: 11.4 GJ/t (=9.5 GJ/ m^3) (1m^3=1.2t), Sand: 0.3 GJ/m^3	182000
		Paint	3705 m^2	0.02 GJ/m^2**	74000
	Services	20%	-	-	17,527000
Total	87,634000 MJ				

Table 3 Initial Embodied Energy of the Eastern Hall of the Shanghai Exhibition Centre

Halls	Elements	Materials	Volume	Material energy intensities [1]	Material quantities (MJ)
Eastern Hall (excluding external decoration)	Strip foundation	Reinforced concrete	673 m^3	7.0 GJ/m^3	4711000
		Damp proof membrane	4834 m^2	0.07 [2] GJ/m^2	338000
	Columns	Reinforced concrete	424 m^3	7.0 GJ/m^3	3024000
		Cement mortar 1:3	18.84 m^3	Cement: 11.4 GJ/t (=9.5 GJ/ m^3) (1m^3=1.2t), Sand: 0.3 GJ/m^3	186000
		Granite	3.1 m^3 (=8.4t)	5.86 GJ/t, 0.1-13.9 GJ/t ***	50000
		Paint	3623 m^2	0.02 GJ/m^2**	73000
	Beams	Reinforced concrete	560 m^3	7.0 GJ/m^3	3920000
		Cement mortar 1:3	30 m^3	Cement: 11.4 GJ/t (=9.5 GJ/ m^3) (1m^3=1.2t), Sand: 0.3 GJ/m^3	294000

	Floors	Reinforced concrete	806 m^3	7.0 GJ/m^3	6342000
		Cement mortar 1:3	45 m^3	Cement: 11.4 GJ/t (=9.5 GJ/ m^3) ($1m^3$=1.2t), Sand: 0.3 GJ/m^3	55000
		Terrazzo	182 m^3	1.4 GJ/t *** (0.6GJ/ m^3) (2.3 t/m^3)	109000
	External walls	Reinforced concrete	2856m^3	7.0 GJ/m^3	19992000
		Rockwool	4760 m^2	0.14 GJ/ m^3 **	13000
		Cement mortar 1:3	23.8 m^3	Cement: 11.4 GJ/t (=9.5 GJ/ m^3) ($1m^3$=1.2t), Sand: 0.3 GJ/m^3	233000
		Paint	4760 m^2	0.02 GJ/m^2**	95000
	Internal walls	Reinforced concrete	1410 m^3	7.0 GJ/m^3	9870000
		Cement mortar 1:3	17.7 m^3	Cement: 11.4 GJ/t (=9.5 GJ/ m^3) ($1m^3$=1.2t), Sand: 0.3 GJ/m^3	173000
		Paint	3525 m^2	0.02 GJ/m^2**	71000
	Windows	Float glass	1138 m^2	3.1 GJ/m^2	3528000
		Steel	5.7 m^3	36.8 GJ/t (=30.7 GJ/ m^3) (1.2-3.8t=1 m^3)	175000
	Doors	Timber (hardwood)	2.78 m^3	10.9 GJ/ m^3	30000
		Glass	184 m^2	3.1 GJ/m^2	570000
		Copper	0.43 m^3	45.9 GJ/t (=14 GJ/ m^3) (3.25 t/ m^3)	6000
	Ceiling	Plaster	9742 m^2	6.5 GJ/m^3 **	633000
		Paint	9742 m^2	0.02 GJ/m^2**	195000
	Staircases	Reinforced concrete	55.7 m^3	7.0 GJ/m^3	383000
		Terrazzo	4.9 m^3	1.4 GJ/t*** (0.6GJ/ m^3) (2.3 t/m^3)	3000
		Reinforced concrete	76 m^3	7.0 GJ/m^3	532000
		Terrazzo	9.8 m^3	1.4 GJ/t *** (0.6GJ/ m^3) (2.3 t/m^3)	5500
		Stone	8.4 m^3	Local: 1.9 GJ/ m^3**	16000
	Roof	Reinforced concrete	487.5 m^3	7.0 GJ/m^3	3413
		Rockwool	4834 m^2	0.14 GJ/ m^3 **	14000
		Asphalt	4834 m^2	2.6 GJ/t*** (2.5 GJ/ m^3) (1.02t/ m^3)	121000
		Cement mortar 1:3	244.3 m^3	Cement: 11.4 GJ/t (=9.5 GJ/ m^3) ($1m^3$=1.2t), Sand: 0.3 GJ/m^3	2394000
		Paint	4879 m^2	0.02 GJ/m^2**	98000
	Galleries	Reinforced concrete	704 m^3	7.0 GJ/m^3	4928000
		Cement mortar 1:3	388.1 m^3	Cement: 11.4 GJ/t (=9.5 GJ/ m^3) ($1m^3$=1.2t), Sand: 0.3 GJ/m^3	3803000
		Paint	1402m^2	0.02 GJ/m^2**	28000
	Services	20%	-	-	17,606000
Total: 88,030000 MJ					

Table 4 Initial Embodied Energy of the Western Hall of the Shanghai Exhibition Centre

Halls	Elements	Materials	Volume	Material energy intensities*	Material quantities (MJ)
Western Hall (excluding external decoration)	Strip foundation	Reinforced concrete	673 m^3	7.0 GJ/m^3	4711000
		Damp proof membrane	4834 m^2	0.07 GJ/m^2**	338000
	Columns	Reinforced concrete	448 m^3	7.0 GJ/m^3	3136000
		Cement mortar 1:3	19.2 m^3	Cement: 11.4 GJ/t (=9.5 GJ/ m^3) ($1m^3$=1.2t), Sand: 0.3 GJ/m^3	188000
		Granite	3.1 m^3 (=8.4t)	5.86 GJ/t, 0.1-13.9 GJ/t ***	50000
		Paint	3693 m^2	0.02 GJ/m^2**	74000
	Beams	Reinforced concrete	560 m^3	7.0 GJ/m^3	3920000
		Cement mortar 1:3	30 m^3	Cement: 11.4 GJ/t (=9.5 GJ/ m^3) ($1m^3$=1.2t), Sand: 0.3 GJ/m^3	294000
	Floors	Reinforced concrete	1009 m^3	7.0 GJ/m^3	7063000
		Cement mortar 1:3	50 m^3	Cement: 11.4 GJ/t (=9.5 GJ/ m^3) ($1m^3$=1.2t), Sand: 0.3 GJ/m^3	490000
		Terrazzo	202 m^3	1.4 GJ/t***(0.6GJ/ m^3) (2.3 t/m^3)	122000
	External walls	Reinforced concrete	3097m^3	7.0 GJ/m^3	21679000
		Rockwool	5162 m^2	0.14 GJ/ m^3**	15000
		Cement mortar 1:3	25.8 m^3	Cement: 11.4 GJ/t (=9.5 GJ/ m^3) ($1m^3$=1.2t), Sand: 0.3 GJ/m^3	253000
		Paint	5162 m^2	0.02 GJ/m^2**	103000
	Internal walls	Reinforced concrete	2078 m^3	7.0 GJ/m^3	14546000
		Cement mortar 1:3	26 m^2	Cement: 11.4 GJ/t (=9.5 GJ/ m^3) ($1m^3$=1.2t), Sand: 0.3 GJ/m^3	274000

		Paint	5196 m^2	0.02 GJ/m^2**	104000
	Windows	Float glass	1192 m^2	3.1 GJ/m^2	3695000
		Steel	6 m^3	36.8 GJ/t (=30.7 GJ/ m^3) (1.2-3.8t=1 m^3)	184000
	Doors	Timber (hardwood)	4.26 m^3	10.9 GJ/ m^3	46000
		Glass	171 m^2	3.1 GJ/m^2	530000
		Copper	0.3 m^3	45.9 GJ/t(=14 GJ/ m^3) (3.25 t/ m^3)	4000
	Ceiling	Plaster	10156 m^2	6.5 GJ/m^3**	660000
		Paint	10156 m^2	0.02 GJ/m^2**	203000
	Staircases	Reinforced concrete	24.8 m^3	7.0 GJ/m^3	174000
		Terrazzo	1.3 m^3	1.4 GJ/t *** (=0.6GJ/ m^3)(2.3 t/m^3)	800
		Reinforced concrete	76 m^3	7.0 GJ/m^3	532000
		Terrazzo	9.8 m^3	1.4 GJ/t ***(=0.6GJ/ m^3) (2.3 t/m^3)	5500
		Stone	8.4 m^3	Local: 1.9 GJ/ m^3 **	16000
	Roof	Reinforced concrete	516.5 m^3	7.0 GJ/m^3	3616000
		Rockwool	5115 m^2	0.14 GJ/ m^3**	14000
		Asphalt	5115 m^2	2.6 GJ/t ***(2.5 GJ/ m^3) (1.02t/ m^3)	128000
		Cement mortar 1:3	257.3 m^3	Cement: 11.4 GJ/t (=9.5 GJ/ m^3) (1m^3=1.2t), Sand: 0.3 GJ/m^3	2521000
		Paint	5160 m^2	0.02 GJ/m^2**	103000
	Galleries	Reinforced concrete	704 m^3	7.0 GJ/m^3	4928000
		Cement mortar 1:3	388.1 m^3	Cement: 11.4 GJ/t (=9.5 GJ/ m^3) (1m^3=1.2t), Sand: 0.3 GJ/m^3	3803000
		Paint	1405 m^2	0.02 GJ/m^2**	4956000
	Services	20%	-	-	20,870000
Total: 104,349000 MJ					

Table 5 Initial Embodied Energy of the Convention Hall of the Shanghai Exhibition Centre

Halls	Elements	Materials	Volume	Material energy intensities [1]	Material quantities (MJ)
Convention Hall (excluding external decoration)	Box foundation	Reinforced concrete	3388 m^3	7.0 GJ/m^3	23716000
		Damp proof membrane	1257 m^2	0.07 GJ/m^2**	88000
	Columns	Reinforced concrete	276 m^3	7.0 GJ/m^3	1932000
		Cement mortar 1:3	8.12 m^3	Cement: 11.4 GJ/t (=9.5 GJ/ m^3) (1m^3=1.2t), Sand: 0.3 GJ/m^3	79000
		Granite	8.5 m^3 (=23t)	5.86 GJ/t	135000
		Paint	188 m^2	0.02 GJ/m^2**	4000
	Beams	Reinforced concrete	218.6 m^3	7.0 GJ/m^3	1530000
		Cement mortar 1:3	12 m^3	Cement: 11.4 GJ/t (=9.5 GJ/ m^3) (1m^3=1.2t), Sand: 0.3 GJ/m^3	118000
	Floors	Reinforced concrete	338 m^3	7.0 GJ/m^3	2366000
		Cement mortar 1:3	24.9 m^3	Cement: 11.4 GJ/t (=9.5 GJ/ m^3) (1m^3=1.2t), Sand: 0.3 GJ/m^3	251000
		Terrazzo	68 m^3	1.4 GJ/t ***(=0.6GJ/ m^3) (2.3 t/m^3)	41000
	External walls	Reinforced concrete	1028 m^3	7.0 GJ/m^3	7196000
		Rockwool	2569 m^2	0.14 GJ/ m^3 **	7000
		Cement mortar 1:3	13 m^3	Cement: 11.4 GJ/t (=9.5 GJ/ m^3) (1m^3=1.2t), Sand: 0.3 GJ/m^3	128000
		Paint	2569 m^2	0.02 GJ/m^2**	51000
	Internal walls	Reinforced concrete	302 m^3	7.0 GJ/m^3	2114000
		Cement mortar 1:3	5.8 m^3	Cement: 11.4 GJ/t (=9.5 GJ/ m^3) (1m^3=1.2t), Sand: 0.3 GJ/m^3	57000
		Paint	1166 m^2	0.02 GJ/m^2**	23000
	Windows	Float glass	185 m^2	3.1 GJ/m^2	574000
		Timber	1.02 m^3	10.9 GJ/ m^3	11000
	Doors	Glass	114 m^2	3.1 GJ/m^2	353000
		Timber	13.08 m^3	10.9 GJ/ m^3	143000
	Ceiling	Plasterboard	4989 m^2	0.14 GJ/ m^2	699000
		Plaster	4989 m^2	6.5 GJ/m^3 **	324000
		Paint	4989 m^2	0.02 GJ/m^2**	100000
	Staircases	Reinforced concrete	30.5 m^3	7.0 GJ/m^3	214000
		Terrazzo	3.2 m^3	1.4 GJ/t *** (0.6GJ/ m^3) (2.3 t/m^3)	17000
		Reinforced concrete	65.7 m^3	7.0 GJ/m^3	460000

		Terrazzo	3.4 m^3	1.4 GJ/t ***(0.6GJ/ m^3) (2.3 t/m^3)	2000
	Roof	Reinforced concrete	178 m^3	7.0 GJ/m^3	1246000
		Rockwool	1781 m^2	0.14 GJ/ m^3 **	5000
		Asphalt	1781 m^2	2.6 GJ/t ***(2.5 GJ/ m^3) (1.02t/ m^3)	45000
		Cement mortar 1:3	8.9 m^3	Cement: 11.4 GJ/t (=9.5 GJ/ m^3) (1m^3=1.2t), Sand: 0.3 GJ/m^3	88000
		Paint	1781 m^2	0.02 GJ/m^2**	36000
	Services	20%	-	-	11035000
Total: 55,173000 MJ					

- Recurring embodied energy of Shanghai Exhibition Centre

Table 6 Recurring Embodied Energy of the Front Hall of the Shanghai Exhibition Centre (1955~2011)

Halls	Elements	Materials	Material quantities (MJ)	Useful life (years)	Recurring embodied energy (MJ) (56 years)
Front Hall (excluding the four small decorating towers and external decoration)	Box foundation	Reinforced concrete	36442000	100	0
		Damp proof membrane	153000	100	0
	Columns	Reinforced concrete	3542000	100	0
		Cement mortar 1:3	194700	50	0
		Granite	296000	50	0
		Paint	12000	10	60000
	Beams	Reinforced concrete	1918000	100	0
		Cement mortar 1:3	115200	50	0
	Floors	Reinforced concrete	4235000	100	0
		Cement mortar 1:3	298000	50	0
		Terrazzo	73000	50	0
	External walls	Reinforced concrete	17556000	100	0
		Rockwool	7000	100	0
		Cement mortar 1:3	206000	50	0
		Paint	84000	10	420000
	Internal walls	Reinforced concrete	9198000	100	0
		Cement mortar 1:3	43000	50	0
		Paint	19000	10	95000
	Windows	Float glass	930000	50	0
		Steel	24000	50	0
	Doors	Timber (hardwood)	166000	30	166000
		Copper	532000	50	0
	Ceiling	Plywood	4411000	50	0
		Plaster	45000	50	0
		Paint	90000	10	450000
	Staircases	Reinforced concrete	118000	100	0
		Terrazzo	400	50	0
		Reinforced concrete	258000	100	0
		Terrazzo	2000	50	0
	Roof	Reinforced concrete,	2443000	100	0
		Rockwool	10000	100	0
		Asphalt	87000	25	174000
		Cement mortar 1:3	239000	50	0
		Paint	70000	10	350000
	Services	20%	20,940000	-	10470000
Total	12185000				

Table 7 Recurring Embodied Energy of the Central Hall of the Shanghai Exhibition Centre (1955~2011)

Halls	Elements	Materials	Material quantities (GJ)	Useful life (years)	Recurring embodied energy (MJ) (56 years)
Central Hall (excluding external decoration)	Box foundation	Reinforced concrete	39984000	100	0
		Damp proof membrane	153000	100	0
	Columns	Reinforced concrete	819000	100	0
		Cement mortar 1:3	4680	50	0
		Paint	30	10	150
	Arch structure (internal)	Reinforced concrete	4830000	100	0
		Cement mortar 1:3	135000	50	0
		Paint	55000	10	275000
	Beams	Reinforced concrete	2093000	100	0
		Cement mortar 1:3	38200	50	0
	Floors	Reinforced concrete	1050000	100	0

		Cement mortar 1:3	74000	50	0
		Terrazzo	18000	50	0
	External walls	Reinforced concrete	5768000	100	0
		Rockwool	2000	100	0
		Cement mortar 1:3	33000	50	0
		Paint	14000	10	60000
	Internal walls	Reinforced concrete	5831000	100	0
		Cement, sand	204000	50	0
		Paint	83000	10	415000
	Windows	Float glass	694000	50	0
		Steel	34000	50	0
	Doors	Timber(hardwood)	140000	30	140000
		Glass	171000	50	0
		Copper	2000	50	0
	Ceiling	Plywood, paint	3721000	50	0
	Staircases	Reinforced concrete	196000	100	0
		Terrazzo	1800	50	0
	Roof	Reinforced concrete	3597000	100	0
		Rockwool	12000	100	0
		Asphalt	93000	25	186000
		Cement mortar 1:3	182000	50	0
		Paint	74000	10	370000
	Services	20%	17,527000	-	8763500
Total	10209650				

Table 8 Recurring Embodied Energy of the Eastern Hall of the Shanghai Exhibition Centre (1955~2011)

Halls	Elements	Materials	Material quantities (GJ)	Useful life (years)	Recurring embodied energy (MJ) (56 years)
Eastern Hall (excluding external decoration)	Strip foundation	Reinforced concrete	4711000	100	0
		Damp proof membrane	338000	100	0
	Columns	Reinforced concrete	3024000	100	0
		Cement mortar 1:3	185000	50	0
		Granite	50000	50	0
		Paint	73000	10	365000
	Beams	Reinforced concrete	3920000	100	0
		Cement mortar 1:3	294000	50	0
	Floors	Reinforced concrete	6342000	100	0
		Cement mortar 1:3	55000	50	0
		Terrazzo	109000	50	0
	External walls	Reinforced concrete	19992000	100	0
		Rockwool	13000	100	0
		Cement mortar 1:3	233000	50	0
		Paint	95000	10	475000
	Internal walls	Reinforced concrete	9870000	100	0
		Cement mortar 1:3	173000	50	0
		Paint	71000	10	355000
	Windows	Float glass	3528000	50	0
		Steel	175000	50	0
	Doors	Timber (hardwood)	30000	30	30000
		Glass	570000	50	0
		Copper	6000	50	0
	Ceiling	Plaster	633000	50	0
		Paint	195000	10	975000
	Staircases	Reinforced concrete	383000	100	0
		Terrazzo	3000	50	0
		Reinforced concrete	532000	100	0
		Terrazzo	5500	50	0
		Stone	16000	50	0
	Roof	Reinforced concrete	3413	100	0
		Rockwool	14000	100	0
		Asphalt	121000	25	242000
		Cement mortar 1:3	2394000	50	0
		Paint	98000	10	490000
	Galleries	Reinforced concrete	4928000	100	0
		Cement mortar 1:3	3803000	50	0

		Paint	28000	10	140000
	Services	20%	17,606000		8803000
Total: 11875000					

Table 9 Recurring Embodied Energy of the Western Hall of the Shanghai Exhibition Centre (1955~2011)

Halls	Elements	Materials	Material quantities (GJ)	Useful life (years)	Recurring embodied energy (MJ) (56 years)
Western Hall (excluding external decoration)	Strip foundation	Reinforced concrete	4711000	100	0
		Damp proof membrane	338000	100	0
	Columns	Reinforced concrete	3136000	100	0
		Cement mortar 1:3	188000	50	0
		Granite	50000	50	0
		Paint	74000	10	370000
	Beams	Reinforced concrete	3920000	100	0
		Cement mortar 1:3	294000	50	0
	Floors	Reinforced concrete	7063000	100	0
		Cement mortar 1:3	490000	50	0
		Terrazzo	122000	50	0
	External walls	Reinforced concrete	21679000	100	0
		Rockwool	15000	100	0
		Cement mortar 1:3	253000	50	0
		Paint	103000	10	515000
	Internal walls	Reinforced concrete	14546000	100	0
		Cement mortar 1:3	274000	50	0
		Paint	104000	10	520000
	Windows	Float glass	3695000	50	0
		Steel	184000	50	0
	Doors	Timber (hardwood)	46000	30	46000
		Glass	530000	50	0
		Copper	4000	50	0
	Ceiling	Plaster	660000	50	0
		Paint	203000	10	1015000
	Staircases	Reinforced concrete	174000	100	0
		Terrazzo	800	50	0
		Reinforced concrete	532000	100	0
		Terrazzo	5500	50	0
		Stone	16000	50	0
	Roof	Reinforced concrete	3616000	100	0
		Rockwool	14000	100	0
		Asphalt	128000	25	256000
		Cement mortar 1:3	2521000	50	0
		Paint	103000	10	515000
	Galleries	Reinforced concrete	4928000	100	0
		Cement mortar 1:3	3803000	50	0
		Paint	4956000	10	24780000
	Services	20%	20,870000		10435000
Total: 38452000					

Table 10 Recurring Embodied Energy of the Convention Hall of the Shanghai Exhibition Centre (1955~2011)

Halls	Elements	Materials	Material quantities (GJ)	Useful life (years)	Recurring embodied energy (MJ) (56 years)
Convention Hall (excluding external decoration)	Box foundation	Reinforced concrete	23716000	100	0
		Damp proof membrane	88000	100	0
	Columns	Reinforced concrete	1932000	100	0
		Cement mortar 1:3	79000	50	0
		Granite	135000	50	0
		Paint	4000	10	20000
	Beams	Reinforced concrete	1530000	100	0
		Cement mortar 1:3	118000	50	0
	Floors	Reinforced concrete	2366000	100	0
		Cement mortar 1:3	251000	50	0
		Terrazzo	41000	50	0
	External walls	Reinforced concrete	7196000	100	0
		Rockwool	7000	100	0
		Cement mortar 1:3	128000	50	0

		Paint	51000	10	255000
	Internal walls	Reinforced concrete	2114000	100	0
		Cement mortar 1:3	57000	50	0
		Paint	23000	10	115000
	Windows	Float glass	574000	50	0
		Timber	11000	30	11000
	Doors	Glass	353000	50	0
		Timber	143000	30	143000
	Ceiling	Plasterboard	699000	50	0
		Plaster	324000	50	0
		Paint	100000	10	500000
	Staircases	Reinforced concrete	214000	100	0
		Terrazzo	17000	50	0
		Reinforced concrete	460000	100	0
		Terrazzo	2000	50	0
	Roof	Reinforced concrete	1246000	100	0
		Rockwool	5000	100	0
		Asphalt	45000	25	90000
		Cement mortar 1:3	88000	50	0
		Paint	36000	10	180000
	Services	20%	11035000		5517500
Total: 6831500					

Appendix C: Quantitative work on Dutch participation at Expo 2000

- Embodied energy of the Dutch Pavilion

Table 1 Initial embodied energy of the offices floor (Ground floor)

	Materials	Volume	Weight (kg)	Factors (MJ/kg) * ** ***	Embodied energy (MJ)
Pile foundations	Reinforced concrete	77m³	192,500	2.54	488950
		307m³	767,500		1949450
	Damp proof membrane	10m³	14,000	134****	1876000
Columns	Reinforced concrete	33 m³	82,500	2.54	209550
	Cement	1.4 m³	2,520	4.4	11088
	Sand	1.4 m³	1,722	0.017	29
	Paint	0.476 m³	0.1	68 ****	6.8
Beams	Reinforced concrete	136 m³	340,000	2.54	863600
	Cement	6 m³	10,800	4.4	47520
	Sand	6 m³	7,380	0.017	126
Slabs	Reinforced concrete	102 m³	255,000	2.54	647700
	Cement	10 m³	18,000	4.4	79200
	Sand	10 m³	12,300	0.017	209
	Timber	1,920 m³	980,352	5.56	5450757
	Carpet	10 m³	1,100	74.4 ****	81840
External walls	Reinforced concrete	205 m³	512,500	2.54	1301750
	Mineral wool (Insulation)	12.3 m³	246	5	1230
	Cement	4 m³	7,200	4.4	31680
	Sand	4 m³	4,920	0.017	84
	Brick (decoration)	5 m³	3,350	2.22	7437
	Paint	0.204 m³	0.04	68 ****	2.8
Internal walls	Reinforced concrete	186 m³	465,000	2.54	1181100
	Cement	9.3 m³	16,740	4.4	73656
	Sand	9.3 m³	11,439	0.017	195
	Paint	3.712 m³	0.8	68 ****	55
Doors	Timber	17.4 m³	8,884	5.56	49398
	Glass	0.84 m³	2,100	15	31500
	Paint	0.07 m³	0.014	68 ****	1
Ceiling	Steel	0.6 m³	4,680	15	70200
	Plaster	10 m³	9000	3.39	30510
Internal stair	Reinforced concrete	2.5 m³	6,250	2.54	15875
	Brick (pavement)	0.9 m³	603	2.22	1339
	Steel (handrail)	0.0003 m³	2.3	15	35
Internal lift	Reinforced concrete	0.68 m³	1700	2.54	4318
	Steel	0.008 m³	62	15	930
	Plastic (Decoration)	0.002 m³	5	80.5 ****	403
Total			**14,507,725 MJ**		

* Anon. (1994). *BEW Forschungsprojekt: Energie – und Stoffbilanzen von Gebauden.* Schlussbericht: Universitat Karlsruhe.
** Eyerer, P., Reinhardt, H., Kreissig, J., Kummel, J., Betz, M., Baitz, M., Hutter, V., Saur, K., & Schoech, H. (2000). *Okologische Bilanzierung von Baustoffen und Gebauden, Wege zu einer ganzheitlichen Bilanzierung.* Birkhauser Verlag Basel.
*** Pohlmann, C. M. (2002). *Okologische Betrachtung fur den Hausbau – Ganzheitliche Energie – und Kohlendioxidbilanzen fur zwei verschiedene Holzhauskonstruktionen.* PhD thesis. zur Erlangung des Doktorgrades, an der Universitat Hamburg, Fachbereich Biologie.
**** Hammond, G., & Jones, C. (2008). *Inventory of Carbon and Energy (ICE), Version 1.6a, Sustainable Energy Research Team (SERT).* Department of Mechanical Engineering, University of Bath, UK.

Table 2 Initial embodied energy of the dunes floor (First floor)

	Materials	Volume	Weight (kg)	Factors(MJ/kg) * ** ***	Embodied energy (MJ)
Wall	Reinforced concrete	2,048 m³	5,120,000	2.54	13004800
	Cement	10 m³	18,000	4.4	79200

	Sand	21 m^3	25,830	0.017	439
Slabs	Reinforced concrete	102 m^3	255,000	2.54	647700
	Cement	10 m^3	18,000	4.4	79200
	Sand	10 m^3	12,300	0.017	209
	Brick	31 m^3	20,770	2.22	46109
Ceiling	Tile	5 m^3	9,000	2.29	20610
Connected bridge	Steel	0.53 m^3	4134	15	62010
	Timber	0.7 m^3	4.2	5.56	23.4
Internal staircases	Reinforced concrete	235 m^3	587,500	2.54	1492250
	Cement	1.2 m^3	2,160	4.4	9504
	Sand	1.2 m^3	1,476	0.017	25
Maintenance structure	Steel (handrail)	0.01 m^3	78	15	1170
	Glass	0.2 m^3	500	15	7500
Total	**15,450,750 MJ**				

Table 3 Initial embodied energy of the glass floor (Second floor)

	Materials	Volume	Weight (kg)	Factors(MJ/kg) * ** ***	Embodied energy (MJ)
Columns	Reinforced concrete	123 m^3	2623	2.54	6662
	Cement	2.5 m^3	4500	4.4	19800
	Sand	2.5 m^3	3075	0.017	53
	Paint	1 m^3	0.2	68 ****	14
Beams	Reinforced concrete	136 m^3	340,000	2.54	863600
	Cement	6 m^3	10800	4.4	47520
	Sand	6 m^3	7380	0.017	126
Slabs	Reinforced concrete	102 m^3	255000	2.54	647700
	Cement	10 m^3	18000	4.4	79200
	Sand	10 m^3	12300	0.017	209
	Paint	2 m^3	0.4	68 ****	27
External maintenance structure	Steel	0.42 m^3	3276	15	52416
	Glass	2.05 m^3	5125	15	76875
Doors	Timber	0.3 m^3	153	5.56	852
	Glass	0.015 m^3	38	15	570
	Paint	0.0012 m^3	0.0003	68 ****	0.02
Ceiling	Plaster	10 m^3	9000	3.39	30510
	Paint	2 m^3	0.4	68 ****	27
Shelves for flowers	Steel	0.7 m^3	5460	15	81900
Total	**1,908,061 MJ**				

Table 4 Initial embodied energy of the pots floor (Third floor)

	Materials	Volume	Weight (kg)	Factors(MJ/kg) * ** ***	Embodied energy (MJ)
Beams	Reinforced concrete	136 m^3	340000	2.54	863600
	Cement	6 m^3	10800	4.4	47520
	Sand	6 m^3	7380	0.017	126
Slabs	Reinforced concrete	102 m^3	255000	2.54	647700
	Cement	10 m^3	18000	4.4	79200
	Sand	10 m^3	12300	0.017	209
	Paint	2 m^3	0.4	68 ****	27
External walls	Plastic sheeting	0.819 m^3	197	80.5 ****	15859
Internal walls	Reinforced concrete	299 m^3	747500	2.54	1898650
	Cement	15 m^3	27000	4.4	118800
	Sand	15 m^3	18450	0.017	314
	Paint	4.3 m^3	0.9	68 ****	61
Doors	Timber	3.6 m^3	1838	5.56	10219
	Glass	0.17 m^3	425	15	6375
	Paint	0.001 m^3	0.0002	68 ****	0.01
Ceiling	Plaster	10 m^3	9000	3.39	30510
	Paint	2 m^3	0.4	68 ****	27
Total	**3,719,197 MJ**				

Table 5 Initial embodied energy of the forest floor (Fourth floor)

	Materials	Volume	Weight (kg)	Factors(MJ/kg) * ** ***	Embodied energy (MJ)
Columns	Timber	112 m^3	57187	5.56	317960
Beams	Reinforced concrete	136 m^3	340000	2.54	863600
	Cement	6 m^3	10800	4.4	47520

	Sand	6 m³	7380	0.017	126
Slabs	Reinforced concrete	102 m³	255000	2.54	647700
	Cement	10 m³	18000	4.4	79200
	Sand	10 m³	12300	0.017	209
	Paint	2 m³	0.4	68 ****	27
Ceiling	Plaster	10 m³	9000	3.39	30510
	Paint	2 m³	0.4	68 ****	27
Maintenance structure	Steel (handrail)	0.01 m³	78	15	1170
	Glass	0.2 m³	500	15	7500
Total	**1,995,549 MJ**				

Table 6 Initial embodied energy of the rain floor (Fifth floor)

	Materials	Volume	Weight (kg)	Factors(MJ/kg) * ** ***	Embodied energy (MJ)
Columns	Reinforced concrete	23 m³	57,500	2.54	146050
Beams	Reinforced concrete	136 m³	340,000	2.54	863600
	Cement	6 m³	10,800	4.4	47520
	Sand	6 m³	7,380	0.017	126
Slabs	Reinforced concrete	102 m³	255,000	2.54	647700
	Cement	10 m³	18,000	4.4	79200
	Sand	10 m³	12,300	0.017	209
	Paint	2 m³	0.4	68 ****	27
Internal walls	Reinforced concrete	153 m³	382,500	2.54	971550
	Cement	8 m³	14,400	4.4	63360
	Sand	8 m³	0.04	0.017	0.0007
	Steel (decoration)	2 m³	15,600	15	234000
Door	Timber	3.6 m³	1838	5.56	10219
	Glass	0.17 m³	425	15	6375
	Paint	0.001 m³	0.0002	68 ****	0.01
Ceiling (internal)	Plaster	4 m³	3600	3.39	12204
	Paint	0.8 m³	0.16	68 ****	11
Maintenance structure	Steel	20 m³	156000	15	2340000
Total	**5,422,151 MJ**				

Table 7 Initial embodied energy of the windmills (Sixth floor)

	Materials	Volume	Weight (kg)	Factors(MJ/kg) * ** ***	Embodied energy (MJ)
Green roof	Waterproofing PVC	2.5 m³	138	77.2 ****	10654
	Asphalt (Waterproofing layer)	2.5 m³	25000	2.6 ****	65000
	Mineral wool (Insulation)	2.5 m³	50	5	250
	PVC (Drainage layer)	2.5 m³	138	77.2 ****	10653
	PVC (Substrate)	2.5 m³	138	77.2 ****	10653
	Vegetation	2.5 m³	-	-	-
Water roof	Reinforced concrete (Structure)	205 m³	512500	2.54	1301750
	Mineral wool (Thermal insulation layer)	31 m³	620	5	3100
	Asphalt (Waterproof layer)	3 m³	30000	2.6 ****	78000
Slabs	Reinforced concrete	102 m³	255000	2.54	647700
	Cement	10 m³	18000	4.4	79200
	Sand	10 m³	12300	0.017	209
	Paint	2 m³	0.4	68 ****	27
Walls (VIP room)	Reinforced concrete (Structure)	75 m³	187500	2.54	476250
	Reinforced concrete (Internal wall)	11 m³	27500	2.54	69850
	Cement	0.01 m³	18	4.4	79
	Sand	0.01 m³	12.3	0.017	0.2
	Paint	0.006 m³	0.001	68 ****	0.07
Ceiling (VIP room)	Plaster	0.1 m³	90	3.39	305
	Paint	0.02 m³	0.004	68 ****	0.3
Bridge	Timber	13.3 m³	6791	5.56	37758
	Steel (handrail)	0.66 m³	5148	15	77220
Total	**2,868,659 MJ**				

Table 8 Initial embodied energy of vertical circulation

	Materials	Volume	Weight (kg)	Factors(MJ/kg) * ** ***	Embodied energy (MJ)
External stair	Steel (structure)	3.3 m³	25740	15	386100

	Steel (handrail)	0.7 m^3	5460	15	81900
	Timber	77 m^3	39316	5.56	218597
External lift	Reinforced concrete (Structure)	40 m^3	100000	2.54	254000
	Steel	4.8 m^3	37440	15	561600
	Timber	0.3 m^3	153	5.56	851
	Glass	0.54 m^3	1350	15	20250
Total	**1,523,298 MJ**				

Table 9 Initial embodied energy of building services

Building Services	Heating, cooling, ventilation, lighting (6 levels)	6,144 m^2 (total construction area)	2,240 MJ/m^2 (Energy intensity)	**13,762,560 MJ**

Table 10 Initial embodied energy of wind turbines

	Materials	Weight (kg) ******	Factors (MJ/kg) * ** *** *****	Embodied energy (MJ)	
Wind turbine	Steel	6643	15	99645	1285421
	Cast iron	600	25	15000	193500
	Glass reinforced plastic (76% of glass fibres, 24% of epoxy resin)	495	100	49500	638550
	Copper	92	50	4600	59340
	Paint	39	68	2652	34211
	Aluminium	9	155	1395	17996
	PVC	7	77.2	540.4	6971
	Bronze	0.5	77	39	503
Total embodied energy	173,371 MJ				
Cable trench	Soil	110595	0.45	49768	642007
	Stone	110595	1	110595	1426675
	PVC	1083	77.2	83608	1078543
	Sand	280228	0.017	4764	61456
	Concrete	768	2	1536	19814
Cable	Poly butadiene	514	83	42662	550340
	Aluminium	829	155	128495	1657586
	Copper	289	50	14450	186405
	PVC	761	77.2	58749	757862
Main transformer room	Steel	14	15	210	2709
	Concrete	2400	2	4800	61920
Total embodied energy	499,637 MJ				
	In all (6 wind turbines)	**4,038,048 MJ**			

* Anon. (1994). *BEW Forschungsprojekt: Energie – und Stoffbilanzen von Gebauden.* Schlussbericht: Universitat Karlsruhe.
** Eyerer, P., Reinhardt, H., Kreissig, J., Kummel, J., Betz, M., Baitz, M., Hutter, V., Saur, K., & Schoech, H. (2000). *Okologische Bilanzierung von Baustoffen und Gebauden, Wege zu einer ganzheitlichen Bilanzierung.* Birkhauser Verlag Basel.
*** Pohlmann, C. M. (2002). *Okologische Betrachtung fur den Hausbau – Ganzheitliche Energie – und Kohlendioxidbilanzen fur zwei verschiedene Holzhauskonstruktionen.* PhD thesis. zur Erlangung des Doktorgrades, an der Universitat Hamburg, Fachbereich Biologie.
**** Hammond, G., & Jones, C. (2008). *Inventory of Carbon and Energy (ICE), Version 1.6a, Sustainable Energy Research Team (SERT).* Department of Mechanical Engineering, University of Bath, UK.
***** Ardente, F., Beccali, M., Cellura, M., & Brano, V. L. (2008). Energy Performances and Life Cycle Assessment of An Italian Wind Farm. *Renewable and Sustainable Energy Reviews*, *12*: 200-217.

Table 11 Recurring embodied energy of the offices floor (Ground floor)

	Materials	Embodied energy (MJ)	Useful life (years)	Recurring embodied energy (MJ) (50 years)
Pile foundations	Reinforced concrete	488950	100	0
		1949450	100	0
	Damp proof membrane	1876000	100	0
Columns	Reinforced concrete	209550	50	0
	Cement	11088	50	0
	Sand	29	8-10	145
	Paint	6.8	100	0
Beams	Reinforced concrete	863600	50	0
	Cement	47520	50	0
	Sand	126	100	0
Slabs	Reinforced concrete	647700	100	0

	Cement	79200	50	0
	Sand	209	50	0
	Timber	5450757	30	5450757
	Carpet (carpet)	81840	15-20	245520
External walls	Reinforced concrete	1301750	100	0
	Mineral wool (Insulation)	1230	50	0
	Cement	31680	50	0
	Sand	84	50	0
	Brick	7437	50	0
	Paint	2.8	8-10	14
Internal walls	Reinforced concrete	1181100	100	0
	Cement	73656	50	0
	Sand	195	50	0
	Paint	55	8-10	275
Doors	Timber	49398	30	49398
	Glass	31500	50	0
	Paint	1	8-10	5
Ceiling	Steel	70200	50	0
	Plaster	30510	50	0
Internal stair	Reinforced concrete	15875	100	0
	Brick (pavement)	1339	50	0
	Steel (handrail)	35	50	0
Internal lift	Reinforced concrete	4318	100	0
	Steel	930	50	0
	Plastic (Decoration)	403	50	0
Total	**5,746,114 MJ**			

Table 12 Recurring embodied energy of the dunes floor (First floor)

	Materials	Embodied energy (MJ)	Useful life (years)	Recurring embodied energy (MJ) (50 years)
Wall	Reinforced concrete	13004800	100	0
	Cement	79200	50	0
	Sand	439	50	0
Slabs	Reinforced concrete	647700	100	0
	Cement	79200	50	0
	Sand	209	50	0
	Brick	46109	50	0
Ceiling	Tile	20610	60	0
Connected bridge	Steel	62010	50	0
	Timber	23.4	30	23.4
Internal staircases	Reinforced concrete	1492250	100	0
	Cement	9504	50	0
	Sand	25	50	0
Maintenance structure	Steel (handrail)	1170	50	0
	Glass	7500	50	0
Total	**23 MJ**			

Table 13 Recurring embodied energy of the glass floor (Second floor)

	Materials	Embodied energy (MJ)	Useful life (years)	Recurring embodied energy (MJ) (50 years)
Columns	Reinforced concrete	6662	100	0
	Cement	19800	50	0
	Sand	53	50	0
	Paint	14	8-10	70
Beams	Reinforced concrete	863600	100	0
	Cement	47520	50	0
	Sand	126	50	0
Slabs	Reinforced concrete	647700	100	0
	Cement	79200	50	0
	Sand	209	50	0
	Paint	27	8-10	135
External maintenance structure	Steel	52416	50	0
	Glass	76875	50	0
Doors	Timber	852	30	852
	Glass	570	50	0
	Paint	0.02	8-10	0.1
Ceiling	Plaster	30510	50	0

	Paint	27	8-10	135
Shelves for flowers	Steel	81900	50	0
Total	**1,192 MJ**			

Table 14 Recurring embodied energy of the pots floor (Third floor)

	Materials	Embodied energy (MJ)	Useful life (years)	Recurring embodied energy (MJ) (50 years)
Beams	Reinforced concrete	863600	100	0
	Cement	47520	50	0
	Sand	126	50	0
Slabs	Reinforced concrete	647700	100	0
	Cement	79200	50	0
	Sand	209	50	0
	Paint	27	8-10	135
External walls	Plastic sheeting	15859	50	0
Internal walls	Reinforced concrete	1898650	100	0
	Cement	118800	50	0
	Sand	314	50	0
	Paint	61	8-10	305
Doors	Timber	10219	30	10219
	Glass	6375	50	0
	Paint	0.01	8-10	0.05
Ceiling	Plaster	30510	50	0
	Paint	27	8-10	135
Total	**10,794 MJ**			

Table 15 Recurring embodied energy of the forest floor (Fourth floor)

	Materials	Embodied energy (MJ)	Useful life (years)	Recurring embodied energy (MJ) (50 years)
Columns	Timber	317960	30	317960
Beams	Reinforced concrete	863600	100	0
	Cement	47520	50	0
	Sand	126	50	0
Slabs	Reinforced concrete	647700	100	0
	Cement	79200	50	0
	Sand	209	50	0
	Paint	27	8-10	135
Ceiling	Plaster	30510	50	0
	Paint	27	8-10	135
Maintenance structure	Steel (handrail)	1170	50	0
	Glass	7500	50	0
Total	**318,230 MJ**			

Table 16 Recurring embodied energy of the rain floor (Fifth floor)

	Materials	Embodied energy (MJ)	Useful life (years)	Recurring embodied energy (MJ) (50 years)
Columns	Reinforced concrete	146050	100	0
Beams	Reinforced concrete	863600	100	0
	Cement	47520	50	0
	Sand	126	50	0
Slabs	Reinforced concrete	647700	100	0
	Cement	79200	50	0
	Sand	209	50	0
	Paint	27	8-10	135
Internal walls	Reinforced concrete	971550	100	0
	Cement	63360	50	0
	Sand	0.0007	50	0
	Steel (decoration)	234000	50	0
Door	Timber	10219	30	10219
	Glass	6375	50	0
	Paint	0.01	8-10	0.05
Ceiling (internal)	Plaster	12204	50	0
	Paint	11	8-10	55
Maintenance structure	Steel	2340000	50	0
Total	**10,409 MJ**			

Table 17 Recurring embodied energy of the windmills (Sixth floor)

	Materials	Embodied energy (MJ)	Useful life (years)	Recurring embodied energy (MJ) (50 years)
Green roof	Waterproofing PVC	10654	15-20	31962
	Asphalt (Waterproofing layer)	65000	20-25	130000
	Mineral wool (Insulation)	250	50	0
	PVC (Drainage layer)	10653	15-20	31959
	PVC (Substrate)	10653	15-20	31959
	Vegetation	-	-	-
Water roof	Reinforced concrete (Structure)	1301750	100	0
	Mineral wool (Thermal insulation layer)	3100	50	0
	Asphalt (Waterproof layer)	78000	20-25	156000
Slabs	Reinforced concrete	647700	100	0
	Cement	79200	50	0
	Sand	209	50	0
	Paint	27	8-10	135
Walls (VIP room)	Reinforced concrete (Structure)	476250	100	0
	Reinforced concrete (Internal wall)	69850	100	0
	Cement	79	50	0
	Sand	0.2	50	0
	Paint	0.07	8-10	0.35
Ceiling (VIP room)	Plaster	305	50	0
	Paint	0.3	8-10	1.5
Bridge	Timber	37758	30	37758
	Steel (handrail)	77220	50	0
Total	**419,774 MJ**			

Table 18 Recurring embodied energy of vertical circulation

	Materials	Embodied energy (MJ)	Useful life (years)	Recurring embodied energy (MJ) (50 years)
External stair	Steel (structure)	386100	50	0
	Steel (handrail)	81900	50	0
	Timber	218597	30	218597
External lift	Reinforced concrete (Structure)	254000	100	0
	Steel	561600	50	0
	Timber	851	30	851
	Glass	20250	50	0
Total	**219,448 MJ**			

Table 19 Recurring embodied energy of building services

	Materials	Embodied energy (MJ)	Useful life (years)	Recurring embodied energy (MJ) (50 years)
Building Services	Pump, pipe …. (50%)	6,881,280	25	6,881,280
	Steel… (50%)	6,881,280	50	0
Total	**6,881,280 MJ**			

Table 18 Recurring embodied energy of wind turbines

	Embodied energy (MJ)	Useful life (years)	Recurring embodied energy (MJ)
Wind turbines	4,038,048	20	8,076,096
Transportation of personnel inspection(7000kg of diesel)	317100 (45.3 MJ/kg)	20	792,750
Maintenance of space parts	605,707 (15% of embodied energy of wind turbines)	20	1,514,268
Total	**10,383,114 MJ**		
Note: The useful life of the wind farm is generally in 20 years long and the electrical company has scheduled maintenance and control cycles. It was supposed a daily inspection during the first operation period and, successively, one inspection every 2-3 weeks. The personnel is transported by diesel car. It was supposed an overall consumption of about 7000 kg of diesel during the 20 years of useful life. Ordinary maintenance cycles occur 2-3 times per year. They mainly imply lubrication, painting and substitution of space parts. During the average useful life of a wind generator, it is supposed to substitute one blade and the 15% of generator's components. (Source from Ardente, F., Beccali, M., Cellura, M., & Brano, V. L. (2008). Energy Performances and Life Cycle Assessment of An Italian Wind Farm. *Renewable and Sustainable Energy Reviews*, *12*: 200-217.)			

- Visitor travel to go to the Dutch Pavilion

1. Energy consumption of different transport modes

Table 19 Visitors from Hannover

	District	Distance(km)	Car (2.1)	Light rail (0.69)	Bus (0.91)
1	Herrenhausen-Stöcken	10.4	88386	8195	10808
2	Nord	9.0	36250	3360	4431
3	Vahrenwald-List	7.9	130779	12118	15981
4	Bothfeld-Vahrenheide	8.8	102435	9491	12517
5	Ahlem-Badenstedt-Davenstedt	8.5	65867	6105	8052
6	Linden-Limmer	7.4	78306	7256	9569
7	Mitte	6.7	546127	50613	66750
8	Buchholz-Kleefeld	6.3	66878	6199	8175
9	Misburg-Anderten	5.9	45917	4254	5611
10	Ricklingen	6.2	66024	6118	8068
11	Südstadt-Bult	5.4	54931	5090	6713
12	Döhren-Wülfel	3.7	30435	2821	3721
13	Kirchrode-Bemerode-Wülferode	2.8	20357	1886	2487
14	Neustadt a. Rbge	23.9	265154	24572	32406
15	Wedemark	18.9	134827	12493	16477
16	Burgwedel	16.7	83782	7767	10243
17	Burgdorf	14.7	107891	10001	13190
18	Uetze	18.1	89590	8305	10953
19	Wunstorf	19.9	200383	18564	24483
20	Garbsen	15.9	240441	22282	29387
21	Langenhagen	13.4	170613	15811	20852
22	Isernhagen	11.4	63824	5915	7801
23	Seelze	12.8	102225	9477	12498
24	Lehrte	9.5	100847	9347	12328
25	Barsinghausen	15.3	126399	11708	15441
26	Gehrden	11.2	40149	3717	4902
27	Ronnenberg	8.0	45326	4201	5540
28	Hemmingen	4.9	22247	2062	2720
29	Laatzen	0.5	4932	457	603
30	Sehnde	5.3	29673	2750	3627
31	Wennigsen	11.7	3587	331	437
32	Pattensen	4.8	16380	1517	2001
33	Springe	11.5	82424	7641	10078
	Total	-	3263385	302422	398846
	In all		3,964,653 MJ		

Table 20 Visitors from other cities in Germany

		Car (2.1)		Bus (0.91)		Train (1.78)		Air (2.599)	
		Distance (km)	Energy (MJ)	Distance (km)	Energy (MJ)	Distance (km)	Energy (MJ)	Distance (km)	Energy (MJ)
1	Berlin	286	477380904	286	15242647	300	72974838	256	83501337
2	Hamburg	257	221763809	257	7080882	266	33449468	128	21583427
3	Munich	632	406705841	632	12986210	916	85903469	481	60487008
4	Stuttgart	524	152489030	524	4869013	550	23324675	419	23826904
5	Dusseldorf	277	78542879	277	2507844	291	12024388	239	13242531
6	Bremen	125	33104663	125	1057079	131	5056042	143	7400806
8	Dresden	367	91784204	367	2930587	385	14032203	307	15003580
9	Wiesbaden	376	50467284	376	1611574	395	7726366	259	6793339
10	Kiel	247	28440321	247	908071	259	4346036	223	5017398
11	Magdeburg	147	16386105	147	523174	154	2501619	132	2875253
12	Erfurt	219	21591385	219	689344	230	3304677	177	3410150
13	Mainz	373	35682448	373	1139467	391	5450915	264	4935376
14	Saarbrucken	526	44729672	526	1428321	552	6840583	397	6597348
15	Potsdam	257	19218717	257	613675	270	2942233	157	2294426

1 6	Schwerin	225	10343498	225	330262	236	1581181	157	1410197
	Total	-	1688630761	-	53918150	-	281458693	-	258379081
	In all	2,282,386,684 MJ							

Table 21 Visitors from European and Asian countries

Area	Average distance (km)	Air (2.160)
Northern Europe	1306	114531
Western Europe	535	46917
Central and Eastern Europe	1472	129089
Southern Europe	1278	112076
Total	402612 GJ	
Eastern Asia	8040	141015
Southern Asia	6702	117548
Western Asia	3670	64369
Southeast Asia	9813	172112
Central Asia	4388	76962
Total	572006 GJ	

Table 22 Visitors from other foreign countries

	Energy consumption
Europe	402612 GJ
America	684555 GJ
Asia	572006 GJ
Oceania	1284571 GJ
Total	2943744 GJ

2. CO_2 emissions of different transport modes

Table 23 Visitors from Hannover

	District	Distance (km)	Car (0.0000694 t/passenger-km)	Light rail (0.000078 t/passenger-km)	Bus (0.00004 t/passenger-km)
1	Herrenhausen-Stöcken	10.4	2.92	0.93	0.48
2	Nord	9.0	1.20	0.38	0.19
3	Vahrenwald-List	7.9	4.32	1.37	0.70
4	Bothfeld-Vahrenheide	8.8	3.39	1.07	0.55
5	Ahlem-Badenstedt-Davenstedt	8.5	2.18	0.69	0.35
6	Linden-Limmer	7.4	2.59	0.82	0.42
7	Mitte	6.7	18.05	5.72	2.93
8	Buchholz-Kleefeld	6.3	2.21	0.70	0.36
9	Misburg-Anderten	5.9	1.52	0.48	0.25
10	Ricklingen	6.2	2.18	0.69	0.35
11	Südstadt-Bult	5.4	1.82	0.58	0.30
12	Döhren-Wülfel	3.7	1.01	0.32	0.16
13	Kirchrode-Bemerode-Wülferode	2.8	0.67	0.21	0.11
14	Neustadt a. Rbge	23.9	8.76	2.78	1.42
15	Wedemark	18.9	4.46	1.41	0.72
16	Burgwedel	16.7	2.77	0.88	0.45
17	Burgdorf	14.7	3.57	1.13	0.58
18	Uetze	18.1	2.96	0.94	0.48
19	Wunstorf	19.9	6.62	2.10	1.08
20	Garbsen	15.9	7.95	2.52	1.29
21	Langenhagen	13.4	5.64	1.79	0.92
22	Isernhagen	11.4	2.11	0.67	0.34
23	Seelze	12.8	3.38	1.07	0.55
24	Lehrte	9.5	3.33	1.06	0.54
25	Barsinghausen	15.3	4.18	1.32	0.68
26	Gehrden	11.2	1.33	0.42	0.22
27	Ronnenberg	8.0	1.50	0.47	0.24
28	Hemmingen	4.9	0.74	0.23	0.12
29	Laatzen	0.5	0.16	0.05	0.03
30	Sehnde	5.3	0.98	0.31	0.16
31	Wennigsen	11.7	0.12	0.04	0.02
32	Pattensen	4.8	0.54	0.17	0.09

33	Springe	11.5	2.72	0.86	0.44
	Total	-	107.85	34.19	17.53
	In all	**159.57 t**			

Table 24 Visitors from other cities in Germany

		Car (0.0000694 t/passenger-km)		Bus (0.00004 t/passenger-km)		Train (0.000066 t/passenger-km)		Air (0.000191 t/passenger-km)	
		Distance (km)	CO_2 emissions	Distance (km)	CO_2 emissions	Distance (km)	CO_2 emissions	Distance (km)	CO_2 emissions
1	Berlin	286	15776.30	286	670.01	300	2705.81	256	6136.50
2	Hamburg	257	7328.77	257	311.25	266	1240.26	128	1586.16
3	Munich	632	13440.66	632	570.82	916	3185.18	481	4445.18
4	Stuttgart	524	5039.40	524	214.02	550	864.85	419	1751.03
5	Dusseldorf	277	2595.66	277	110.23	291	445.85	239	973.19
6	Bremen	125	1094.03	125	46.47	131	187.47	143	543.88
8	Dresden	367	3033.25	367	128.82	385	520.30	307	1102.61
9	Wiesbaden	376	1667.82	376	70.84	395	286.48	259	499.24
10	Kiel	247	939.88	247	39.92	259	161.15	223	368.73
11	Magdeburg	147	541.52	147	23.00	154	92.76	132	211.30
12	Erfurt	219	713.54	219	30.30	230	122.53	177	250.61
13	Mainz	373	1179.22	373	50.09	391	202.11	264	362.70
14	Saarbrucken	526	1478.21	526	62.78	552	253.64	397	484.84
15	Potsdam	257	635.13	257	26.97	270	109.09	157	168.62
16	Schwerin	225	341.83	225	14.52	236	58.63	157	103.64
	Total	-	55805.23	-	2370.03	-	10436.11	-	18988.23
	In all	87,599.6 t							

Table 25 Visitors from European and Asian countries

Area	Average distance (km)	Air (0.000158 t/passenger-km)
Northern Europe	1306	33510.92
Western Europe	535	13727.67
Central and Eastern Europe	1472	37770.34
Southern Europe	1278	32792.46
Total	117801.4t	
Eastern Asia	8040	51574.99
Southern Asia	6702	42991.99
Western Asia	3670	23542.32
Southeast Asia	9813	62948.43
Central Asia	4388	28148.14
Total	209205.9t	

Table 26 Visitors from other foreign countries

	CO_2 emissions
Europe	29450.4t
America	50073.9t
Asia	52301.5t
Oceania	93964.0t
Total	225789.8t

Appendix D: Quantitative work on Theme Pavilion at Expo 2010 in Shanghai

- Embodied energy of Theme Pavilion

Table 1 Quantitative breakdown of the volume of different elements and materials

Elements	Materials		Size (m) (L,W,H)		Items	Volume
Box foundations	Reinforced concrete		Walls: H: 4.2m, L: 181.5m, W: 0.3m; H: 4.2m, L: 105.5m, W: 0.3m; Columns: H: 4.2m, L: 1.5m, W: 1.5m; Floor: T: 0.3m, L: 181.5m, W: 251.5m		4 36 154 1	915m^3 4,786m^3 1,455 m^3 13,694 m^3
	Damp proof membrane		L: 181.5m, W: 251.5m		1	45700 m^2
Columns	Cylinder	Steel	H: 12m, Diameter: 1m, T: 0.01m H: 7.8m, D: 0.8m, T: 0.005m H: 4.5m, D: 0.6m, T: 0.005m		58 202 259	22 m^3 20 m^3 11 m^3
		Paint	H: 12m, Diameter: 1m, H: 7.8m, D: 0.8m, H: 4.5m, D: 0.6m		58 202 259	2,187 m^2 3,960 m^2 2,197 m^2
	Square column	Steel	H: 19.8, L: 1m, W: 1m, T: 0.01m; H: 9m, L: 0.8m, W: 0.8m, T: 0.005m; H: 4.5m, L: 0.8m, W: 0.8m, T: 0.005m		24 41 110	19 m^3 6 m^3 8 m^3
		Aluminium panels	H: 19.8, L: 1m, T: 0.002m; H: 9m, L: 0.8m, T: 0.002m; H: 4.5m, L: 0.8m, T: 0.002m		96 164 440	4 m^3 2 m^3 3 m^3
		Aluminium frames	H: 2m, L: 1m, T: 0.002m; H: 2.3m, L: 0.8m, T: 0.002m; H: 1.5m, L: 0.8m, T: 0.002m		960 656 1320	0.11 m^3 0.08 m^3 0.12 m^3
	External columns	Steel	H: 25.8m, D: 0.5m, T: 0.005m		36	7 m^3
		Paint	H: 25.8m, D: 0.5m		36	1,459 m^2
Beams	Main beams	Steel (Length is measured by AutoCAD)	Hall 1	H: 0.8m, T: 0.01m, Length: 1,470m	-	12 m^3
			Hall 2 & 3	H: 0.8m, T: 0.01m, Length: 2,158 m	-	17 m^3
			Hall 4	H: 0.8m, T: 0.01m, Length: 2,700 m	-	22 m^3
			Hall 5	H: 0.8m, T: 0.01m, Length: 2,092 m	-	17 m^3
			Car park	H: 0.8m, T: 0.01m, Length: 4,710.6 m	-	38 m^3
			Atrium	H: 0.8m, T: 0.01m, Length: 4,064.3 m	-	33 m^3
		Paint	Hall 1	H: 0.8m, L: 1,470m	-	2352 m^2
			Hall 2 & 3	H: 0.8m, L: 2,158 m	-	3453 m^2
			Hall 4	H: 0.8m, L: 2,700 m	-	4320 m^2
			Hall 5	H: 0.8m, L: 2,092 m	-	3347 m^2
			Car park	H: 0.8m, L: 4,710.6 m	-	7537 m^2
			Atrium	H: 0.8m, L: 4,064.3 m	-	6503 m^2
	Secondary beams	Steel	Hall 1	H: 0.5m, T: 0.01m, L: 11.8m	66	4 m^3
			Hall 2 & 3	H: 0.5m, T: 0.01m, L: 18m	300	27 m^3
			Hall 4	H: 0.5m, T: 0.01m, L: 18m	462	42 m^3
			Hall 5	H: 0.5m, T: 0.01m, L: 14.7m	378	28 m^3
			Car park	H: 0.5m, T: 0.01m, L: 16.5m H: 0.5m, T: 0.01m, L: 14.7m	480 378	40 m^3 28 m^3
			Atrium	H: 0.5m, T: 0.01m, L: 11.8m H: 0.5m, T: 0.01m, L: 12.6m	378 72	22 m^3 5 m^3
		Paint	Hall 1	H: 0.5m, L: 11.8m	66	779 m^2
			Hall 2 & 3	H: 0.5m, L: 18m	300	5400 m^2
			Hall 4	H: 0.5m, L: 18m	462	8316 m^2
			Hall 5	H: 0.5m, L: 14.7m	378	5557 m^2
			Car park	H: 0.5m, L: 16.5m H: 0.5m, L: 14.7m	480 378	7920 m^2 5557 m^2
			Atrium	H: 0.5m, L: 11.8m H: 0.5m, L: 12.6m	378 72	4460 m^2 907 m^2
Slabs	Reinforced concrete		Hall 1	Total area: 28,314m^2, T: 0.1m	-	2,831m^3
			Hall 2 & 3	Total area: 36,702m^2, T: 0.1m	-	3,670 m^3
			Hall 4	Total area: 20,508m^2, T: 0.1m	-	2,051 m^3
			Hall 5	Total area: 11,670m^2, T: 0.1m	-	1,167 m^3
			Car park	Total area: 27,562m^2, T: 0.1m	-	2,756 m^3

			Atrium	Total area: 13,348m^2, T: 0.1m	-	1,335 m^3
	Cement (T: 0.005m)		Hall 1	Total area: 28,314m^2	-	141 m^3
			Hall 2 & 3	Total area: 36,702m^2	-	184 m^3
			Hall 4	Total area: 20,508m^2	-	103 m^3
			Hall 5	Total area: 11,670m^2	-	58 m^3
			Car park	Total area: 27,562m^2	-	138 m^3
			Atrium	Total area: 13,348m^2	-	67 m^3
	Sand (T: 0.005m)		Hall 1	Total area: 28,314m^2	-	141 m^3
			Hall 2 & 3	Total area: 36,702m^2	-	184 m^3
			Hall 4	Total area: 20,508m^2	-	103 m^3
			Hall 5	Total area: 11,670m^2	-	58 m^3
			Car park	Total area: 27,562m^2	-	138 m^3
			Atrium	Total area: 13,348m^2	-	67 m^3
	Tiles		Hall 1	Total area: 24,066 m^2	-	24,066 m^2
			Hall 2 & 3	Total area: 35,172 m^2	-	35,172 m^2
			Hall 4	Total area: 17,334 m^2	-	17,334 m^2
			Hall 5	Total area: 11,670 m^2	-	11,670 m^2
			Car park	-	-	-
			Atrium	Total area: 13,348 m^2	-	13,348 m^2
	Carpet		Hall 1	Total area: 4,248 m^2	-	4,248 m^2
			Hall 2 & 3	Total area: 1,530 m^2	-	1,530 m^2
			Hall 4	Total area: 3,172 m^2	-	3,172 m^2
			Hall 5	-	-	-
			Car park	-	-	-
			Atrium	-	-	-
	Paint		Total area: 165,566 m^2			165,566 m^2
Ceiling	Plasterboard (T: 0.01m)		Hall 1	Total area: 4,248 m^2	-	42 m^3
			Hall 2 & 3	Total area: 1,530 m^2	-	15 m^3
			Hall 4	Total area: 3,172 m^2	-	32 m^3
	Aluminium panels (T: 0.002m)		Hall 1	Total area: 4,248 m^2	-	9 m^3
			Hall 2 & 3	Total area: 1,530 m^2	-	3 m^3
			Hall 4	Total area: 3,172 m^2	-	6 m^3
	Aluminium frames (H: 0.01m)		Hall 1	L: 2m, W: 1m, T: 0.01m	2124	1.3 m^3
			Hall 2 & 3	L: 2m, W: 1m, T: 0.01m	765	0.5 m^3
			Hall 4	L: 2m, W: 1m, T: 0.01m	1086	0.6 m^3
Walls	External northern and southern wall	Glass	H: 25.2m, W: 284m, T: 0.01m		2	143 m^3
		Aluminium panels	Total area: 121 m^2, T: 0.002m		32	7.7 m^3
		Aluminium frames	L: 2m, W: 1m, T: 0.01m, H: 0.01m (0.000596 m^3)		128* 32	2.4 m^3
	External western and eastern wall (eco-wall)	Reinforced concrete	H: 27m, W: 180m, T: 0.3m		2	1,458 m^3
		Cement	H: 27m, W: 180m, T: 0.005m		2	48.6 m^3
		Sand	H: 27m, W: 180m, T: 0.005m		2	48.6 m^3
		Glass wool	H: 27m, W: 180m, T: 0.1m		2	972 m^3
		Aluminium panels	Area: 1.74 m^2/panel, T: 0.002m		7820	27 m^3
		Aluminium frames	L: 1m, W: 0.01m, T: 0.01m (0.0004m^3/frame)		7820	3 m^3
		Paint	H: 27m, W: 180m		2	9720 m^2
		Soil and plant	-		-	-
	Internal wall	Reinforced concrete	Hall 1	H: 5.8m, T: 0.2m, Length: 1654 m	-	1919 m^3
			Hall 2 & 3	H: 5.8m, T: 0.2m, Length: 1822 m	-	2114 m^3
			Hall 4	H: 4.5m, T: 0.2m, Length: 3228m	-	2905 m^3
			Hall 5	H: 4.5m, T: 0.2m, Length: 2054 m	-	1849 m^3
			Car park	H: 4.5m, T: 0.2m, Length: 3178 m	-	2860 m^3
			Atrium	H: 5.8m, T: 0.2m, Length: 5966m	-	6921 m^3
		Cement (T:0.005m)	Hall 1	H: 5.8m, length: 1654 m	-	95 m^3
			Hall 2 & 3	H: 5.8m, length: 1822 m	-	106 m^3
			Hall 4	H: 4.5m, length: 3228m	-	145 m^3
			Hall 5	H: 4.5m, length: 2054 m	-	92 m^3
			Car park	H: 4.5m, length: 3178 m	-	143 m^3
			Atrium	H: 5.8m, length: 5966m	-	346 m^3
		Sand (T: 0.005m)	Hall 1	H: 5.8m, length: 1654 m	-	95 m^3
			Hall 2 & 3	H: 5.8m, length: 1822 m	-	106 m^3
			Hall 4	H: 4.5m, length: 3228m	-	145 m^3
			Hall 5	H: 4.5m, length: 2054 m	-	92 m^3
			Car park	H: 4.5m, length: 3178 m	-	143 m^3
			Atrium	H: 5.8m, length: 5966m	-	346 m^3

		Paint	Hall 1	H: 5.8m, length: 1654 m	-	9593 m^2
			Hall 2 & 3	H: 5.8m, length: 1822 m	-	10568 m^2
			Hall 4	H: 4.5m, length: 3228m	-	14526 m^2
			Hall 5	H: 4.5m, length: 2054 m	-	9243 m^2
			Car park	H: 4.5m, length: 3178 m	-	14301 m^2
			Atrium	H: 5.8m, length: 5966m	-	34603 m^2
		Aluminium panels (T:0.002m)	Hall 1	H: 5.8m, length: 1654 m	-	19 m^3
			Hall 2 & 3	H: 5.8m, length: 1822 m	-	21 m^3
			Hall 4	H: 4.5m, length: 3228m	-	29 m^3
			Hall 5	H: 4.5m, length: 2054 m	-	18 m^3
			Car park	-	-	-
			Atrium	H: 5.8m, length: 5966m	-	69 m^3
		Aluminium panels	Hall 1	L: 2m, W: 1m, T: 0.01m, H: 0.01m (0.000596 m^3)	4796	3 m^3
			Hall 2 & 3	L: 2m, W: 1m, T: 0.01m, H: 0.01m (0.000596 m^3)	3284	3 m^3
			Hall 4	L: 2m, W: 1m, T: 0.01m, H: 0.01m (0.000596 m^3)	7263	4 m^3
			Hall 5	L: 2m, W: 1m, T: 0.01m, H: 0.01m (0.000596 m^3)	4622	3 m^3
			Car park	-	-	-
			Atrium	L: 2m, W: 1m, T: 0.01m, H: 0.01m (0.000596 m^3)	1730 0	10 m^3
Doors	Aluminium (frames and connection)			L: 2m, W: 1m, T: 0.01m, H: 0.01m (0.000596 m^3)	599	0.4 m^3
	Glass			L: 2m, W: 1m, T: 0.01m	599	12 m^3
Roof	Structure	Steel		Main trusses: Length: 287m, volume: 0.013 m^3/m Reinforced trusses for huge free column space: D: 0.1m, T: 0.01m, L: 556m Purlin: L: 18m, W: 0.1, T: 0.01m	11 9 1350	41 m^3 14.2 m^3 2.4 m^3
		Aluminium panels		L: 287, W: 18m, T: 0.002m	12	124 m^3
	Thermal insulation layer	Glass wool		L: 287, W: 18m, T: 0.1m	12	6199 m^3
	Facade	Aluminium frames		L: 3m, W: 1m, T: 0.01m, H: 0.01m (0.000796 m^3)	1728	1.4 m^3
		Aluminium panels		Main roof panels: L: 287, W: 18m, T: 0.002m Other roof panels: area: 295m^2/group, T: 0.002m	12 16	124 m^3 9.4 m^3
		PV panels		-	-	30,000m^2
		Polyethylene panels		105m^2/panel, T: 0.002m	36	7.6 m^3
Vertical circulation	Staircases	Steel		Main stairs: Rise: 0.15m, Going: 0.3m, W: 3.9m, T: 0.005m (0.008775m^3) Secondary stairs: Rise: 0.15m, Going: 0.3m, W: 1.5m, T: 0.005m (0.003375 m^3)	300 1612	2.6 m^3 5.4 m^3
		Glass		H: 1m, T: 0.01m, L: 0.3m	1912	5.7 m^3
	Internal lift	Steel		Rise: 0.15m, Going: 0.3m, W: 1.5m	304	1 m^3
		Aluminium panels		W: 1.5m, T: 0.002m, L: 26.8m	4	0.3 m^3
	Internal bridge	Reinforced concrete		L: 22m, W: 4m, T: 0.1m	2	17.6 m^3
		Cement		L: 22m, W: 4m, T: 0.005	2	0.9 m^3
		Sand		L: 22m, W: 4m, T: 0.005	2	0.9 m^3
		Paint		L: 22m, W: 4m	2	176 m^2
		Tile		L: 22m, W: 4m	2	176 m^2
		Aluminum		L: 22m, D: 0.05m, T: 0.005m	4	0.02 m^3
		Glass		L: 22m, H: 1.2m, T: 0.01m	4	1.1 m^3
Building Services	Heating, cooling, ventilation, lighting (20%)			—	-	-

Table 2 Embodied energy coefficients and durability of different construction materials

Materials	Factors	References	Expected durability (assuming correct installation and maintenance) (years)
Reinforced concrete	3.2 (GJ/t) (= 7.7 GJ/m^3)	Gong (2004)	100
Steel	31 (GJ/t) (= 243.4 GJ/ m^3)	Gong (2004)	50
Cement	5.6 GJ/t (= 9.5 GJ/ m^3)	Lawson (1996)	50
Aluminium	170 GJ/t (= 476 GJ/ m^3)	Lawson (1996)	50

Paint (double coat)	0.02 GJ/m^2	Hammond and Jones (2004)	8-10
Glass (10mm)	24.5 GJ/t (= 61.3GJ/m^3)	Gong (2004)	50
Damp proof membrane	0.07 GJ/m^2	Baird and Chan (1983)	100
Sand	0.3 GJ/m^3	Lawson (1996)	50
Ceramic tiles	0.78 GJ/m^2	Stein et al (1981)	50
Carpet	0.41 GJ/m^2	Treloar (1994)	15-20
100mm Glass wool	28 GJ/t (= 0.9 GJ/m^3)	Hammond and Jones (2008)	100
Plasterboard	4.4 GJ/t (=4.0 GJ/m^3)	Lawson (1996)	50
Fiber Reinforced Plastic (skylight roof panels)	90 GJ/t (= 29.5 GJ/m^3)	Lawson (1996)	50
Photovoltaic panels (PVs)	1652.4MJ/m^2 (459KWh/m^2)	Vale and Vale (2009, p.141)	15

Table 3 Quantitative breakdown of the initial embodied energy of different materials

Elements	Materials		Volume	Factors	Initial embodied energy (GJ)
Box foundations	Reinforced concrete		20850 m^3	7.7 GJ/m^3	160545
	Damp proof membrane		45700 m^2	0.07 GJ/m^2	3199
Columns	Cylinder	Steel	53 m^3	243.4 GJ/ m^3	12900
		Paint	8344 m^2	0.02 GJ/m^2	167
	Square column	Steel	33 m^3	243.4 GJ/ m^3	8032
		Aluminium panels	9 m^3	476 GJ/ m^3	4284
		Aluminium frames	0.31 m^3	476 GJ/ m^3	148
	External columns	Steel	7 m^3	243.4 GJ/ m^3	1704
		Paint	1,459 m^2	0.02 GJ/m^2	29
Beams	Main beams	Steel	139 m^3	243.4 GJ/ m^3	33833
		Paint	27512 m^2	0.02 GJ/m^2	550
	Secondary beams	Steel	196 m^3	243.4 GJ/ m^3	47706
		Paint	38896 m^2	0.02 GJ/m^2	778
Slabs	Reinforced concrete		13810m^3	7.7 GJ/m^3	106337
	Cement		691 m^3	9.5 GJ/ m^3	6565
	Sand		691 m^3	0.3 GJ/m^3	207
	Tiles		101590 m^2	0.78 GJ/m^2	79240
	Carpet		8950 m^2	0.41 GJ/m^2	3670
	Paint		165,566 m^2	0.02 GJ/m^2	3311
Ceiling	Plasterboard		89 m^3	4.0 GJ/m^3	356
	Aluminium panels		18 m^3	476 GJ/ m^3	8568
	Aluminium frames		2.4 m^3	476 GJ/ m^3	1142
Walls	External northern and southern wall	Glass	143 m^3	61.3GJ/m^3	8766
		Aluminium panels	7.7 m^3	476 GJ/ m^3	3665
		Aluminium frames	2.4 m^3	476 GJ/ m^3	1142
	External western and eastern wall (eco-wall)	Reinforced concrete	1,458 m^3	7.7 GJ/m^3	11227
		Cement	48.6 m^3	9.5 GJ/ m^3	462
		Sand	48.6 m^3	0.3 GJ/m^3	15
		Glass wool	972 m^3	0.9 GJ/m^3	875
		Aluminium panels	27 m^3	476 GJ/ m^3	12852
		Aluminium frames	3 m^3	476 GJ/ m^3	1428
		Paint	9720 m^2	0.02 GJ/m^2	194
		Soil and plants	-	-	-
	Internal wall	Reinforced concrete	18568 m^3	7.7 GJ/m^3	142974
		Cement (T:0.005m)	927 m^3	9.5 GJ/ m^3	8807
		Sand	927 m^3	0.3 GJ/m^3	278
		Paint	92834 m^2	0.02 GJ/m^2	1857
		Aluminium panels	156 m^3	476 GJ/ m^3	74256
		Aluminium panels	23 m^3	476 GJ/ m^3	10948
Doors	Aluminium (frames and connection)		0.4 m^3	476 GJ/ m^3	190
	Glass		12 m^3	61.3GJ/m^3	736
Roof	Structure	Steel	57.6 m^3	243.4 GJ/ m^3	14020
		Aluminium panels	124 m^3	476 GJ/ m^3	59024
	Thermal insulation layer	Glass wool	6199 m^3	0.9 GJ/m^3	5579
	Facade	Aluminium frames	1.4 m^3	476 GJ/ m^3	666
		Aluminium panels	134 m^3	476 GJ/ m^3	63784
		PV panels	30,000m^2	1.652 GJ/m^2	49560
		FRP skylight roof panels	7.6 m^3	29.5 GJ/m^3	224
Vertical circulation	Staircases	Steel	8 m^3	243.4 GJ/ m^3	1947
		Glass	5.7 m^3	61.3GJ/m^3	349
	Internal lift	Steel	1 m^3	243.4 GJ/ m^3	243
		Aluminium panels	0.3 m^3	476 GJ/ m^3	143
	Internal	Reinforced concrete	17.6 m^3	7.7 GJ/m^3	136

	bridge	Cement	0.9 m^3	9.5 GJ/ m^3	9
		Sand	0.9 m^3	0.3 GJ/m^3	0.27
		Paint	176 m^2	0.02 GJ/m^2	4
		Tile	176 m^2	0.78 GJ/m^2	137
		Aluminum	0.02 m^3	476 GJ/ m^3	10
		Glass	1.1 m^3	61.3GJ/m^3	67
Building Services	Heating, cooling, ventilation, lighting (20%)		-	-	239,961
Total	1,199,806 GJ (8.4 GJ/m^2)				

Table 4 Quantitative breakdown of the recurring embodied energy of different materials (50 years)

Elements	Materials		Initial embodied energy (GJ)	Expected durability (years)	Recurring embodied energy (GJ)
Box foundations	Reinforced concrete		160545	100	0
	Damp proof membrane		3199	100	0
Columns	Cylinder	Steel	12900	50	0
		Paint	167	8-10	668
	Square column	Steel	8032	50	0
		Aluminium panels	4284	50	0
		Aluminium frames	148	50	0
	External columns	Steel	1704	50	0
		Paint	29	8-10	116
Beams	Main beams	Steel	33833	50	0
		Paint	550	8-10	2200
	Secondary beams	Steel	47706	50	0
		Paint	778	8-10	3112
Slabs	Reinforced concrete		106337	100	0
	Cement		6565	50	0
	Sand		207	50	0
	Tiles		79240	50	0
	Carpet		3670	15-20	7340
	Paint		3311	8-10	13244
Ceiling	Plasterboard		356	50	0
	Aluminium panels		8568	50	0
	Aluminium frames		1142	50	0
Walls	External northern and southern wall	Glass	8766	50	0
		Aluminium panels	3665	50	0
		Aluminium frames	1142	50	0
	External western and eastern wall (eco-wall)	Reinforced concrete	11227	100	0
		Cement	462	50	0
		Sand	15	50	0
		Glass wool	875	100	0
		Aluminium panels	12852	50	0
		Aluminium frames	1428	50	0
		Paint	194	8-10	776
		Soil and plants	-	-	-
	Internal wall	Reinforced concrete	142974	100	0
		Cement	8807	50	0
		Sand	278	50	0
		Paint	1857	8-10	7428
		Aluminium panels	74256	50	0
		Aluminium panels	10948	50	0
Doors	Aluminium (frames and connection)		190	50	0
	Glass		736	50	0
Roof	Structure	Steel	14020	50	0
		Aluminium panels	59024	50	0
	Thermal insulation layer	Glass wool	5579	100	0
	Facade	Aluminium frames	666	50	0
		Aluminium panels	63784	50	0
		PV panels	49560	20	49560
		FRP skylight roof panels	224	50	0
Vertical circulation	Staircases	Steel	1947	50	0
		Glass	349	50	0
	Internal lift	Steel	243	50	0
		Aluminium panels	143	50	0
	Internal bridge	Reinforced concrete	136	100	0
		Cement	9	50	0
		Sand	0.27	50	0

		Paint	4	8-10	16
		Tile	137	50	0
		Aluminum	10	50	0
		Glass	67	50	0
Building Services	Heating, cooling, ventilation, lighting (20%)		239,961	50	0
Total	84,460 GJ (0.6 GJ/m^2)				

- Visitor travel to go to the Theme Pavilion

1. Energy consumption of visitor travel

Table 5 Energy consumption of visitor travel going to the Theme Pavilion (from Shanghai)

Area	Distance (km)	Visitors taking various modes (GJ)								
		Underground (0.071)	Taxi (2.494)	Bus (0.648)	Motor cycle (1)	Small petrol car (1.467)	Medium petrol car (2.304)	Large petrol car (3.133)	Electric bike (0.036)	Scooter (0.086)
1	11.84	8	361	241	49	61	595	187	19	11
2	10.61	6	262	175	36	44	431	136	13	8
3	10.48	6	289	193	39	49	476	150	15	9
4	11.50	10	435	290	59	73	715	225	22	13
5	11.17	5	238	159	32	40	392	123	12	7
6	7.23	2	81	54	11	14	133	42	4	2
7	4.26	2	91	61	12	15	149	47	5	3
8	6.75	10	455	303	62	77	748	235	23	14
9	5.72	4	180	120	24	30	296	93	9	6
10	3.26	1	36	24	5	6	60	19	2	1
11	16.34	11	475	317	64	80	781	246	24	15
12	10.23	7	317	211	43	53	522	164	16	10
13	26.30	-	-	-	385	479	4672	1471	-	-
14	25.22	-	-	-	502	624	6088	1916	-	-
15	24.83	-	-	-	345	429	4185	1317	-	-
16	35.65	-	-	-	509	632	6170	1942	-	-
17	27.79	-	-	-	407	506	4937	1554	-	-
18	32.23	-	-	-	399	496	4844	1525	-	-
19	33.96	-	-	-	637	792	7734	2434	-	-
In all	-	72	3220	2146	3620	4501	43928	13827	166	99
Total		71,579 GJ								

Table 6 Model1: Energy consumption of visitor travel going to the Theme Pavilion (from Mainland China)

Area	Distance (km)	Visitors taking various modes (GJ)			
		Train (0.17)	Car (2.30)	Bus (0.65)	Plane (2.01)
1	1088	15142	162075	45804	68775
2	963	9049	96857	27373	41100
3	1445	33619	359852	101697	152701
4	1213	94844	1015203	286905	430791
5	827	63872	683681	193214	290114
6	729	56226	601836	170084	255384
7	1659	110682	1184729	334815	502729
8	266	16729	179068	50606	75986
9	991	56851	608530	171976	258223
10	886	49886	533977	150907	226590
11	402	20072	214851	60719	91171
12	684	31973	342234	96718	145224
13	169	7182	76870	21724	32619
14	1603	66415	710904	200908	301666
15	1950	72506	776098	219332	329328
16	611	22069	236230	66761	100242
17	1191	41754	446930	126306	189650
18	1675	53384	571414	161487	242473
19	1527	2332	47044	503558	142310
20	1099	33858	362417	102422	153788
21	611	18175	194541	54979	82552
22	1223	33781	361587	102188	153435
23	1444	32215	344827	97451	146324
24	1718	36503	390722	110422	165798
25	1374	27734	296863	83896	125971
26	3269	55566	594767	168086	252387
27	1630	12121	129749	36668	55058

28	1595	8472	90685	25628	38481
29	1913	8129	87012	24590	36925
30	2902	6166	65998	18652	28004
In all	-	1097305	11767554	3815876	5115801
Total		21,796,535 GJ			

Table 7 Model 2: Energy consumption of visitor travel going to the Theme Pavilion (from Mainland China)

Area	Distance (km)	Visitors taking various modes (GJ)				
		Train (0.17)	Car (2.30)	Bus (0.65)	Plane (2.01)	Ship (0.76)
1	1088	15110	161650	45684	68508	522
2	963	9290	99389	28088	42123	321
3	1445	33549	358908	101431	152112	1160
4	1213	94647	1012538	286152	429128	3270
5	827	63739	681888	192707	288994	2202
6	729	56109	600255	169637	254398	1939
7	1659	110452	1181619	333936	500789	3817
8	266	16694	178598	50473	75692	577
9	991	56733	606932	171524	257227	1960
10	886	49783	532577	150511	225713	1720
11	402	20031	214287	60559	90818	692
12	684	31906	341336	96464	144663	1103
13	169	7167	76669	21667	32493	248
14	1603	66277	709039	200381	300503	2290
15	1950	72355	774062	218757	328058	2500
16	611	22024	235610	66585	99855	761
17	1191	41667	445758	125975	188918	1440
18	1675	53272	569912	161062	241537	1841
19	1527	46947	502237	141937	212857	1622
20	1099	33788	361466	102153	153196	1168
21	611	18137	194031	54835	82233	627
22	1223	33711	360639	101920	152843	1165
23	1444	32148	343920	97195	145758	1111
24	1718	36427	389695	110131	165159	1259
25	1374	27676	296082	83675	125485	957
26	3269	55450	593210	167646	251408	1916
27	1630	12096	129408	36572	54845	417
28	1595	8455	90451	25562	38334	292
29	1913	8112	86784	24526	36783	281
30	2902	6153	65825	18603	27899	212
In all	-	1139906	12194775	3446350	5168329	39387
Total		21,988,747 GJ				

Table 8 Energy consumption of visitor travel going to the Theme Pavilion (from Hong Kong, Macao, Taiwan)

Location	Distance (km)	Plane (2.01)	Train (0.17)	Bus (0.65)	Car (2.30)
Hong Kong	1208	66112	3424	148497	525451
Macao	1276	2057	56	6170	21832
Taiwan	661	5508	-	-	-
Total	-	73676	3481	154667	547283
In all	779,107 GJ				

Table 9 Energy consumption of visitor travel going to the Theme Pavilion (from Asian countries)

Asian countries	Distance (km)	Ship (0.76)	Plane (2.01)	Train (0.17)	Car (2.30)
Eastern Asia	2123	13458	187984	870	50597
Southern Asia	2988	18941	264577	1225	71212
Western Asia	5383	34124	476646	2206	128291
North Asia	2858	18117	253066	1171	68114
Southeast Asia	3149	19962	278833	1291	75049
Central Asia	3251	20609	287865	1333	77480
	-	125211	1748971	8096	470742
Total	2,353,019 GJ				

Table 10 Energy consumption of visitor travel going to the Theme Pavilion (from other countries)

Countries	Number of visitors	Distance (km)	Plane (2.01)
European countries	230,000	See Table below	3,300,129
America	230,000	12	5,504,606
Total	8,804,735 GJ		

Table 11 Energy consumption of visitor travel going to the Theme Pavilion (from other countries)

European countries	Distance (km)	Plane (2.01)

Northern Europe	7026	812030
Western Europe	7561	873863
Central and Eastern Europe	6327	731243
Southern Europe	7640	882993
Total	3,300,129 GJ	

Table 12 Total energy consumption of visitor travel

From Shanghai	71,579 GJ	0.023 GJ/visitor (71,579/3128000)
From mainland China	21,796,535 GJ	1.176 GJ/visitor
From HK, Macao, Taiwan	779,107 GJ	1.613 GJ/visitor
From Asian countries	2,353,019 GJ	6.018 GJ/visitor
From other countries	8,804,735 GJ	19.141 GJ/visitor
Total	33,804,975 GJ (one way) 67,609,950 GJ (return)	2.940 GJ/visitor

2. CO_2 emissions

Table 13 CO_2 emissions of visitor travel going to the Theme Pavilion (from Shanghai)

Area	Distance (km)	Visitors taking various modes (t)								
		Under ground (0.0000166)	Taxi (0.0001 675)	Bus (0.0000 435)	Motor cycle (0.0000672)	Small petrol car (0.0000986)	Medium petrol car (0.000155)	Large petrol car (0.00021)	Electric bike (0.0000084)	Scooter (0.0000 058)
1	11.84	1.88	24.27	16.17	3.29	4.10	40.00	12.54	1.08	0.11
2	10.61	1.37	17.61	11.73	2.39	2.97	29.02	9.10	0.77	0.08
3	10.48	1.51	19.44	12.95	2.64	3.28	32.03	10.04	0.87	0.09
4	11.50	2.26	29.18	19.44	3.96	4.92	48.10	15.08	1.30	0.14
5	11.17	1.24	15.99	10.65	2.17	2.70	26.35	8.26	0.71	0.07
6	7.23	0.42	5.41	3.60	0.73	0.91	8.92	2.80	0.24	0.03
7	4.26	0.47	6.10	4.06	0.83	1.03	10.05	3.15	0.27	0.03
8	6.75	2.37	30.53	20.34	4.14	5.15	50.31	15.78	1.36	0.14
9	5.72	0.94	12.10	8.06	1.64	2.04	19.94	6.25	0.54	0.06
10	3.26	0.19	2.44	1.63	0.33	0.41	4.02	1.26	0.11	0.01
11	16.34	2.47	31.90	21.25	4.33	5.38	52.57	16.49	1.42	0.15
12	10.23	1.65	21.30	14.19	2.89	3.59	35.11	11.01	0.95	0.10
13	26.30	-	-	-	25.87	32.17	314.29	98.57	-	-
14	25.22	-	-	-	33.72	41.93	409.58	128.45	-	-
15	24.83	-	-	-	23.17	28.82	281.51	88.29	-	-
16	35.65	-	-	-	34.17	42.49	415.11	130.19	-	-
17	27.79	-	-	-	27.34	34.00	332.10	104.15	-	-
18	32.23	-	-	-	26.83	33.36	325.91	102.21	-	-
19	33.96	-	-	-	42.83	53.26	520.30	163.18	-	-
In all	-	17	216	144	243.27	302.52	2955.22	926.82	9.7	1.00
Total		4816 t								

Table 14 CO_2 emissions of visitor travel going to the Theme Pavilion (from Mainland China)

Area	Distance (km)	Visitors taking various modes (t)			
		Train (0.000025)	Car (0.000155)	Bus (0.0000435)	Plane (0.00015)
1	1088	2226.70	10922.48	3065.34	5132.48
2	963	1369.07	6715.58	1884.70	3155.65
3	1445	4943.96	24250.89	6805.90	11395.63
4	1213	13947.62	68415.84	19200.57	32148.56
5	827	9392.94	46074.18	12930.49	21650.32
6	729	8268.48	40558.54	11382.56	19058.50
7	1659	16276.74	79840.44	22406.83	37517.12
8	266	2460.17	12067.61	3386.72	5670.59
9	991	8360.45	41009.62	11509.15	19270.39
10	886	7336.19	35985.40	10099.13	16909.66
11	402	2951.80	14479.10	4063.49	6803.77
12	684	4701.87	23063.59	6472.69	10837.64
13	169	1056.11	5180.40	1453.85	2434.28
14	1603	9766.96	47908.77	13445.37	22512.37
15	1950	10662.65	52302.25	14678.37	24576.73
16	611	3245.49	15919.82	4467.82	7480.75
17	1191	6140.26	30119.23	8452.82	14153.01
18	1675	7850.52	38508.36	10807.18	18095.03
19	1527	6918.30	33935.42	9523.81	15946.23
20	1099	4979.18	24423.73	6854.40	11476.69
21	611	2672.76	13110.39	3679.37	6160.62
22	1223	4967.76	24367.82	6838.71	11450.40
23	1444	4737.48	23238.34	6521.73	10919.67

24	1718	5368.02	26331.29	7389.75	12372.95
25	1374	4078.51	20005.98	5614.58	9400.84
26	3269	8171.44	40082.11	11248.85	18834.83
27	1630	1782.57	8743.96	2453.95	4108.82
28	1595	1245.93	6111.40	1715.14	2871.72
29	1913	1195.48	5863.88	1645.67	2755.58
30	2902	906.73	4447.72	1248.23	2089.88
In all	-	167982.14	823,984.12	231,247.16	387190.73
Total		1,610,404 t			

Table 15 CO_2 emissions of visitor travel going to the Theme Pavilion (from Hong Kong, Macao, Taiwan)

Location	Distance (km)	Plane (0.00015)	Train (0.000025)	Bus (0.0000435)	Car (0.000155)
Hong Kong	1208	76492.13	503.59	9938	35411
Macao	1276	153.50	8.29	413	1471
Taiwan	661	4453.72	-	-	-
Total	-	81099.35	511.88	10351	36882
In all	128844 t				

Table 16 CO_2 emissions of visitor travel going to the Theme Pavilion (from Asian countries)

Asian countries	Distance (km)	Ship (0.0002)	Plane (0.00015)	Train (0.000025)	Car (0.000155)
Eastern Asia	2123	21250.38	84171.43	767.84	20457.64
Southern Asia	2988	29908.68	118466.43	1080.68	28792.95
Western Asia	5383	53881.68	213421.95	1946.90	51871.64
North Asia	2858	28607.44	113312.27	1033.67	27540.25
Southeast Asia	3149	31520.23	124849.66	1138.91	30344.38
Central Asia	3251	32541.21	128893.70	1175.81	31327.27
	-	197709.62	783115.44	7143.80	190334.12
Total	1178303 t				

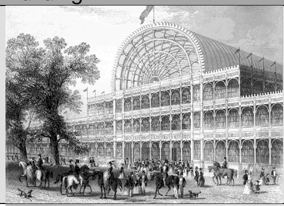
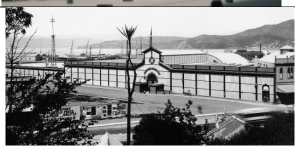
Table 17 CO_2 emissions of visitor travel going to the Theme Pavilion (from other countries)

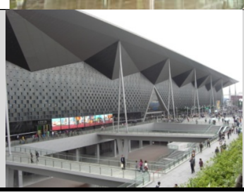
Countries	Number of visitors	Distance (km)	Plane (0.00015)
European countries	230,000	See Table below	758465.27t
America	230,000	11,907 km	410792 t
Total	1169257 t		

Table 18 CO_2 emissions of visitor travel going to the Theme Pavilion (from other countries)

European countries	Distance (km)	Plane (0.00015)
Northern Europe	7026	186628.04
Western Europe	7561	200838.97
Central and Eastern Europe	6327	168060.86
Southern Europe	7640	202937.4
Total	758465.27t	

Appendix E: Selected exhibition buildings erected in different countries from 1851 to 2010

Year	Name	Building	Source
1851	Crystal Palace, London		Wikipedia, the free encyclopedia, The Crystal Palace, retrieved 24th Feb 2009, from http://en.wikipedia.org/wiki/The_Crystal_Palace
1870	Exhibition building, Prince Alfred Park, Sydney		Intercolonial Exhibition Building, retrieved 20th Juan 2011, from http://www.dictionaryofsydney.org/building/intercolonial_exhibition_building
1880	Royal Exhibition Building, Melbourne		Wikipedia, the free encyclopedia.htm, Retrieved 12th Oct
1885	New Zealand Industrial Exhibition building, Wellington		New Zealand Industrial Exhibition building, retrieved 11th Oct 2008, from http://tpo.tepapa.govt.nz/ViewImageFileDetail.asp?ImageFileID=TPO_WOO020&Language=English&dumbyparam=search
1935	All-Russian Exhibition Centre, Moscow		All-Russian Exhibition Centre , retrieved on 20 Juan 2011, from http://www.v-like-vintage.net/en/tags/Exhibition%20Building/
1940	Centennial exhibition Centre, Wellington		Centennial exhibition Centre , retrieved on 20th Juan 2011, from http://www.nzhistory.net.nz/culture/centennial/centennial-exhibition, Retrieved 11th Oct 2008
1955	Shanghai Exhibition Centre, Shanghai		Shen, S.2009
1992	Shanghai International Exhibition Centre, Shanghai		Shanghai International Exhibition Centre, retrieved on 28 Sept 2010, from http://www.expo-china.com/web/hall/hall_detail.aspx?id=37

1996	The Melbourne Exhibition Centre, Melbourne		A part of Melbourne Convention Exhibition Centre, retrieved 11th Oct 2010, from http://www.mcec.com.au/explore/flash.html#/explore/melbourne.html
1997	Hong Kong Convention and Exhibition Centre, Hong Kong		Hong Kong Convention and Exhibition Centre, retrieved 13th Sept 2010, from http://scenery.cultural-china.com/en/148Scenery6071.html
1999	Shanghai International Convention and Exhibition Centre, Shanghai		Shen, S. 2009
2000	ExCeL Exhibition Centre, London		ExCeL Exhibition Centre, retrieved on 13th Sept 2010, from http://www.excel-london.co.uk/module.php?obj=gallery&act=gallery&gid=3
2000	Dutch Pavilion, Hannover		Dutch Pavilion, retrieved on 13th Sept 2010, from http://www.archreh.com/ecotarium-research.html
Beginning of 21st Century	Frankfurt Messe, Frankfurt		Frankfurt Messe, retrieved 25th Sept 2010, from http://www.waytostay.com/area-info-Frankfurt-en-252.htm
2000	Hannover Messe Hall 26, Hannover		Hannover Messe Hall 26, retrieved 10th Mar 2010, from http://www.lock.de/gb_neu/anwendungen/glasbau/original.php?navid=19
2003	Shanghai New International Exhibition Centre, Shanghai		Shanghai New International Exhibition Centre, retrieved on 23th Sept 2009, from http://www.expo-china.com/web/hall/hall_detail.aspx?id=2
2005	the ASB Showgrounds, Auckland		ASB Showgrounds, retrieved on 23th Sept 2010, from http://www.asbshowgrounds.co.nz/, Retrieved 2ed Oct 2008
2010	Theme Pavilion, Shanghai		Shen, S. 2010

Appendix F: A sensitivity analysis: embodied energy of buildings calculated using different embodied energy coefficients

- **Embodied energy of the Crystal Palace**

1. UK embodied energy coefficients

Embodied energy of the Crystal Palace in Hyde Park and Sydenham (1851-1936)

			Original (1851)		Rebuild and maintenance (1854-1936)	
Materials	Building elements	Embodied energy coefficient (GJ/t) *	Weight/ Volume	Embodied energy (GJ)	Total weight	Embodied energy(GJ)
Glass	Main building	15	408t	6,120	527t	7,905
	Colonnade		-	-	18t	270
Iron	Columns, Girders, Pipes, Connection collars, Metal louvres, Roof trusses, Boilers, Colonnade	25	6,317t	157,925	3,385t	84,625
Wood	-	1.6	8,495t	13,592	0 t	0
Concrete	Foundations (footing)	2	539 t	1,710	719t	1,438
Brickwork	Foundations	2.5	-	-	15,297 t	38,243
Paint (Durability: 5 years)	Columns	30.6 MJ/ m^2 (Triple coat for initial) 10.2 MJ/m^2 (Single coat for recurring)	18,661 m^2	571	18,661 m^2	3,046
	Girders		12,921 m^2	395	12,921 m^2	2,109
	Pipes		25,918 m^2	793	25,918 m^2	4,230
	Connection collars		3,110 m^2	95	3,110 m^2	508
	Metal louvers		8,208 m^2	251	8,208 m^2	1,340
	Roof trusses		6,263 m^2	192	6,263 m^2	1,022
	New iron elements built for Sydenham Crystal Palace		-	-	1800 m^2 (total: 300m^3) (1m^3/elements)	55(first time) 275(rest)
	Boilers		-	-	Boilers: 138m^2 Pipes: 12,637 m^2	391(first time) 1955(rest)
	Colonnade		-	-	48 m^2	2 (first time) 7 (rest)
	Wood	30.6 MJ/ m^2 (Triple coat for initial) 10.2 MJ/m^2 (Single coat for recurring)	101,940m^2	3,119	101,940m^2	16,637
Total	-	-	-	184,131	-	164,058
In all	**348,189 GJ** (31 MJ/m^2/year)					
* Hammond, G., & Jones, C. (2008). *Inventory of Carbon and Energy (ICE), Version 1.6a, Sustainable Energy Research Team (SERT)*. Department of Mechanical Engineering, University of Bath, UK.						

2. Australian embodied energy coefficients

Embodied energy of the Crystal Palace in Hyde Park and Sydenham (1851-1936)

			Original (1851)		Rebuild and maintenance (1854-1936)	
Materials	Building elements	Embodied energy coefficient (GJ/t)	Weight/ Volume	Embodied energy (GJ)	Total weight	Embodied energy(GJ)
Glass	Main building	12.7*	408t	5182	527t	6,693
	Colonnade		-	-	18t	229

Iron	Columns, Girders, Pipes, Connection collars, Metal louvres, Roof trusses, Boilers, Colonnade	25**	6,317t	157,925	3,385t	84,625
Wood	-	2.0*	8,495t	16,990	0 t	0
Concrete	Foundations (footing)	1.9*	539 t	1,625	719t	1,366
Brickwork	Foundations	2.5*	-	-	15,297 t	38,243
Paint (Durability: 5 years)	Columns	61.5MJ/kg * 27.6MJ/m^2 (Triple coat for initial) 9.2MJ/m^2 (Single coat for recurring)	18,661 m^2	515	18,661 m^2	2,747
	Girders		12,921 m^2	357	12,921 m^2	1,902
	Pipes		25,918 m^2	715	25,918 m^2	3,815
	Connection collars		3,110 m^2	86	3,110 m^2	458
	Metal louvers		8,208 m^2	227	8,208 m^2	1,208
	Roof trusses		6,263 m^2	173	6,263 m^2	922
	New iron elements built for Sydenham Crystal Palace		-	-	1800 m^2 (total: 300m) (1m/elements)	50 (first time) 265 (rest)
	Boilers		-	-	12,775 m^2	353 (first time) 1880 (rest)
	Colonnade		-	-	48 m^2	1(first time) 7(rest)
	Wood	27.6MJ/m^2 (Triple coat for initial) 9.2MJ/m^2 (Single coat for recurring)	101,940m^2	2,814	101,940m^2	15,006
Total	-	-	-	186,609	-	159,770
In all	**346,379 GJ** (31 MJ/m^2/year)					

* Lawson, B. (1996). *Buildings Materials, Energy and the Environment: Towards Ecological Sustainable Development.* Canberra: RAIA.
** Hammond, G., & Jones, C. (2008). *Inventory of Carbon and Energy (ICE), Version 1.6a, Sustainable Energy Research Team (SERT).* Department of Mechanical Engineering, University of Bath, UK.

3. German embodied energy coefficients

Embodied energy of the Crystal Palace in Hyde Park and Sydenham (1851-1936)

			Original (1851)		Rebuild and maintenance (1854-1936)	
Materials	Building elements	Embodied energy coefficient (GJ/t)	Weight/ Volume	Embodied energy (GJ)	Total weight	Embodied energy(GJ)
Glass	Main building	15*	408t	6,120	527t	7,905
	Colonnade		-	-	18t	270
Iron	Columns, Girders, Pipes, Connection collars, Metal louvres, Roof trusses, Boilers, Colonnade	25**	6,317t	157,925	3,385t	84,625
Wood	-	5.56*	8,495t	47,232	0 t	0
Concrete	Foundations (footing)	2.54*	539 t	2,172	719t	1,826
Brickwork	Foundations	2.22*	-	-	15,297 t	33,959
Paint (Durability: 5 years)	Columns	30.6 MJ/ m^2 ** (Triple coat for initial) 10.2 MJ/m^2** (Single coat for recurring)	18,661 m^2	571	18,661 m^2	3,046
	Girders		12,921 m^2	395	12,921 m^2	2,109
	Pipes		25,918 m^2	793	25,918 m^2	4,230
	Connection collars		3,110 m^2	95	3,110 m^2	508
	Metal louvers		8,208 m^2	251	8,208 m^2	1,340
	Roof trusses		6,263 m^2	192	6,263 m^2	1,022

	New iron elements built for Sydenham Crystal Palace		-	-	1800 m^2 (total: 300m^3) (1m^3/elements)	55(first time) 275(rest)
	Boilers		-	-	Boilers: 138m^2 Pipes: 12,637 m^2	391(first time) 1955(rest)
	Colonnade		-	-	48 m^2	2 (first time) 7 (rest)
	Wood	30.6 MJ/ m^2 ** (Triple coat for initial) 10.2 MJ/m^2 ** (Single coat for recurring)	101,940m^2	3,119	101,940m^2	16,637
Total	-	-	-	218,865	-	160,162
In all	**379,027 GJ** (33 MJ/m^2/year)					

* Pohlmann, C. M. (2002). *Okologische Betrachtung fur den Hausbau – Ganzheitliche Energie – und Kohlendioxidbilanzen fur zwei verschiedene Holzhauskonstruktionen.* PhD thesis. zur Erlangung des Doktorgrades, an der Universitat Hamburg, Fachbereich Biologie, p.82-86.
** Hammond, G., & Jones, C. (2008). *Inventory of Carbon and Energy (ICE), Version 1.6a, Sustainable Energy Research Team (SERT).* Department of Mechanical Engineering, University of Bath, UK.

- **Embodied energy of the Shanghai Exhibition Centre**

1. UK embodied energy coefficients

- Initial embodied energy

Initial Embodied Energy of the Front Hall of the Shanghai Exhibition Centre

Halls	Elements	Materials	Volume	Weight (kg)	Factors* (MJ/kg)	Material quantities (MJ)
Front Hall (excluding the four small decorating towers and external decoration)	Box foundation	Reinforced concrete	5206 m^3	13015000	2	26030000
		damp proof membrane	2190 m^2	3066	134	411000
	Columns	Reinforced concrete	506 m^3	1265000	2	2530000
		Cement mortar 1:3	19.74 m^3	35532	4.6	163000
		Granite	50.5t		7	354000
		Paint	583 m^2		10.2MJ/m^2	6000
	Beams	Reinforced concrete	274 m^3	685000	2	1370000
		Cement mortar 1:3	11.92 m^3	21456	4.6	99000
	Floors	Reinforced concrete	605 m^3	1512500	2	3025000
		Cement mortar 1:3	30.4 m^3	54720	4.6	251712
		Terrazzo	121m^3		0.6GJ/ m^3	72600
	External walls	Reinforced concrete	2508 m^3	6270000	2	12540000
		Rockwool	50 m^3		0.14 GJ/ m^3	7000
		Cement mortar 1:3	21 m^3	37800	4.6	173880
		Paint	4178 m^2		10.2MJ/m^2	42616
	Internal walls	Reinforced concrete	1314 m^3	3285000	2	6570000
		Cement mortar 1:3	4.4 m^3	7920	4.6	36432
		Paint	943 m^2		10.2MJ/m^2	9619
	Windows	Float glass	3 m^3	7500	15	112500
		Steel	0.78 m^3	6084	24.4	148450
	Doors	Timber (hardwood)	15.2 m^3	7761	8.5	65969
		Copper	0.38 m^3	3397	48	163056
	Ceiling	Plywood	4501m^2	2298211	15	34473159
		Plaster	45m^3	40500	6.75	273375
		Paint	4501m^2		10.2MJ/m^2	45910
	Staircases	Reinforced concrete	16.8 m^3	42000	2	84000
		Terrazzo	0.6 m^3		0.6GJ/ m^3	360
		Reinforced concrete	36.8 m^3	92000	2	184000
		Terrazzo	4 m^3		0.6GJ/ m^3	2400
	Roof	Reinforced concrete	349 m^3	872500	2	1745000
		Rockwool	70m^3		0.14 GJ/ m^3	9800
		Asphalt	3483m^2	348300	2.6	905580

		Cement mortar 1:3	18.3 m³	32940	4.6	151524
		Paint	3483m²		10.2MJ/m²	70
	Services	20%	-		-	23014253
Total	115071265 MJ					
* Hammond, G., & Jones, C. (2008). *Inventory of Carbon and Energy (ICE), Version 1.6a, Sustainable Energy Research Team (SERT)*. Department of Mechanical Engineering, University of Bath, UK.						

Initial Embodied Energy of the Central Hall of the Shanghai Exhibition Centre

Halls	Elements	Materials	Volume	Weight	Material energy intensities	Material quantities (GJ)
Central Hall (excluding external decoration)	Box foundation	Reinforced concrete	5712 m³	14280000	2	28560000
		damp proof membrane	2190 m²		0.07 GJ/m²	153300
	Columns	Reinforced concrete	117 m³	292500	2	585000
		Cement mortar 1:3	0.6 m³	1080	4.6	4968
		Paint	1.27 m²	1.27	10.2MJ/m²	13
	Arch structure (internal)	Reinforced concrete	690 m³	1725000	2	3450000
		Cement mortar 1:3	13.8 m³	24840	4.6	114264
		Paint	2760 m²	2760	10.2MJ/m²	28152
	Beams	Reinforced concrete	299 m³	747500	2	1495000
		Cement mortar 1:3	7.44 m³	13392	4.6	61603.2
	Floors	Reinforced concrete	150 m³	375000	2	750000
		Cement mortar 1:3	7.6 m³	13680	4.6	62928
		Terrazzo	30 m³	30	0.6GJ/ m³	18000
	External walls	Reinforced concrete	824 m³	2060000	2	4120000
		Rockwool	14 m³	14	0.14 GJ/ m³	1960
		Cement mortar 1:3	3.4 m³	6120	4.6	28152
		Paint	687 m²	687	10.2MJ/m²	7007
	Internal walls	Reinforced concrete	833 m³	2082500	2	4165000
		Cement, sand	20.8 m³	37440	4.6	172224
		Paint	4161 m²	4161	10.2MJ/m²	42442
	Windows	Float glass	224 m²	560000	15	8400000
		Steel	1.12 m³	8736	24.4	213158
	Doors	Timber (hardwood)	12.8 m³	6536	8.5	55556
		Glass	55 m²	6875	15	103125
		Copper	0.14 m³	1252	48	60096
	Ceiling	Plywood	3720 m²	1899432	15	28491480
		paint	3720 m²	3720	10.2MJ/m²	37944
	Staircases	Reinforced concrete	28 m³	70000	2	140000
		Terrazzo	3 m³	3	0.6GJ/ m³	1800
	Roof	Reinforced concrete	371 m³	927500	2	1855000
		Rockwool	74 m³	74	0.14 GJ/ m³	10360
		Asphalt	37.05 m³	370500	2.6	963300
		Cement mortar 1:3	18.5 m³	33300	4.6	153180
		Paint	3705 m²	3705	10.2MJ/m²	37791
	Services	20%	-		-	21085701
Total	105428504 MJ					

Initial Embodied Energy of the Eastern Hall of the Shanghai Exhibition Centre

Halls	Elements	Materials	Volume	Weight	Material energy intensities	Material quantities (GJ)
Eastern Hall (excluding external decoration)	Strip foundation	Reinforced concrete	673 m³	1682500	2	3365000
		damp proof membrane	4834 m²	4834	70 MJ/m²	338380
	Columns	Reinforced concrete	432 m³	1080000	2	2160000
		Cement mortar 1:3	19 m³	34200	4.6	157320
		Granite	8.4t	8400	7	58800
		Paint	3623 m²	3623	10.2MJ/m²	36955
	Beams	Reinforced concrete	560 m³	1400000	2	2800000
		Cement mortar 1:3	30 m³	54000	4.6	248400
	Floors	Reinforced concrete	906 m³	2265000	2	4530000
		Cement mortar 1:3	45 m³	81000	4.6	372600
		Terrazzo	182 m³	182	600MJ/ m³	109200
	External walls	Reinforced concrete	2856m³	7140000	2	14280000
		Rockwool	4760 m²	95	140 MJ/ m³	13300

		Cement mortar 1:3	23.8 m^3	42840	4.6	197064
		Paint	4760 m^2	4760	10.2MJ/m^2	48552
	Internal walls	Reinforced concrete	1410 m^3	3525000	2	7050000
		Cement mortar 1:3	17.7 m^3	31860	4.6	146556
		Paint	3525 m^2	3525	10.2MJ/m^2	35955
	Windows	Float glass	1138 m^2	2845000	15	42675000
		Steel	5.7 m^3	44460	24.4	1084824
	Doors	Timber (hardwood)	2.78 m^3	1420	8.5	12070
		Glass	184 m^2	460000	15	6900000
		Copper	0.43 m^3	3844	48	184512
	Ceiling	Plaster	9742 m^2	8767800	6.75	59182650
		Paint	9742 m^2	9742	10.2MJ/m^2	99368
	Staircases	Reinforced concrete	55 m^3	137500	2	275000
		Terrazzo	4.9 m^3	4.9	600MJ/ m^3	2940
		Reinforced concrete	76 m^3	190000	2	380000
		Terrazzo	9.8 m^3	9.8	600MJ/ m^3	5880
		Stone	8.4 m^3	8.4	1900 MJ/ m^3	15960
	Roof	Reinforced concrete	488 m^3	1220000	2	2440000
		Rockwool	4834 m^2	97	140 MJ/ m^3	13580
		Asphalt	4834 m^2	48	2.6	125
		Cement mortar 1:3	244.3 m^3	439740	4.6	2022804
		Paint	4879 m^2	4879	10.2MJ/m^2	49766
	Galleries	Reinforced concrete	704 m^3	1760000	2	3520000
		Cement mortar 1:3	388 m^3	698400	4.6	3212640
		Paint	1402m^2	1402	10.2MJ/m^2	14300
	Services	20%	-		-	39509875
Total: 197549376 MJ						

Initial Embodied Energy of the Western Hall of the Shanghai Exhibition Centre

Halls	Elements	Materials	Volume	Weight	Material energy intensities [1]	Material quantities (GJ)
Western Hall (excluding external decoration)	Strip foundation	Reinforced concrete	673 m^3	1682500	2	3365000
		damp proof membrane	4834 m^2	4834	70	338380
	Columns	Reinforced concrete	448 m^3	120000	2	240000
		Cement mortar 1:3	19.2 m^3	34560	4.6	158976
		Granite	8400	8400	7	58800
		Paint	3693 m^2	3693	10.2	37669
	Beams	Reinforced concrete	560 m^3	1400000	2	2800000
		Cement mortar 1:3	30 m^3	54000	4.6	248400
	Floors	Reinforced concrete	1009 m^3	2522500	2	5045000
		Cement mortar 1:3	50 m^3	90000	4.6	414000
		Terrazzo	202 m^3	202	600	121200
	External walls	Reinforced concrete	3097m^3	7742500	2	15485000
		Rockwool	5162 m^2	103	140	14420
		Cement mortar 1:3	25.8 m^3	46440	4.6	213624
		Paint	5162 m^2	5162	10.2	52652
	Internal walls	Reinforced concrete	2078 m^3	5195000	2	10390000
		Cement mortar 1:3	26 m3	46800	4.6	215280
		Paint	5196 m^2	5196	10.2	52999
	Windows	Float glass	1192 m^2	149000	15	2235000
		Steel	6 m^3	45800	24.4	1117520
	Doors	Timber (hardwood)	4.3 m^3	2196	8.5	18666
		Glass	171 m^2	21375	15	320625
		Copper	0.3 m^3	2682	48	128736
	Ceiling	Plaster	10156 m^2	91404	6.75	616977
		Paint	10156 m^2	10156	10.2	103591
	Staircases	Reinforced concrete	25 m^3	62500	2	125000
		Terrazzo	1.3 m^3	1.3	600	780
		Reinforced concrete	76 m^3	190000	2	380000
		Terrazzo	9.8 m^3	9.8	600	5880
		Stone	8.4 m^3	8.4	1900	15960
	Roof	Reinforced concrete	516.5 m^3	1291250	2	2582500
		Rockwool	5115 m^2	102	140	14280
		Asphalt	5115 m^2	511500	2.6	1329900

		Cement mortar 1:3	257.3 m^3	463140	4.6	2130444
		Paint	5160 m^2	5160	10.2	52632
	Galleries	Reinforced concrete	704 m^3	1760000	2	3520000
		Cement mortar 1:3	388 m^3	698400	4.6	3212640
		Paint	1402 m^2	1402	10.2	14300
	Services	20%	-		-	14294208
Total: 71471040 MJ						

Initial Embodied Energy of the Convention Hall of the Shanghai Exhibition Centre

Halls	Elements	Materials	Volume	Weight	Material energy intensities	Material quantities (GJ)
Convention Hall (excluding external decoration)	Box foundation	Reinforced concrete	3388 m^3	8470000	2	16940000
		damp proof membrane	1257 m^2	1257	70	87990
	Columns	Reinforced concrete	276 m^3	690000	2	1380000
		Cement mortar 1:3	8.12 m^3	14616	4.6	67234
		Granite	23000	23000	7	161000
		Paint	188 m^2	188	10.2	1918
	Beams	Reinforced concrete	219 m^3	547500	2	1095000
		Cement mortar 1:3	12 m^3	21600	4.6	99360
	Floors	Reinforced concrete	338 m^3	845000	2	1690000
		Cement mortar 1:3	25 m^3	45000	4.6	207000
		Terrazzo	68 m^3	68	600	40800
	External walls	Reinforced concrete	1028 m^3	2570000	2	5140000
		Rockwool	2569 m^2	51	140	7140
		Cement mortar 1:3	13 m^3	23400	4.6	107640
		Paint	2569 m^2	2569	10.2	26204
	Internal walls	Reinforced concrete	302 m^3	755000	2	1510000
		Cement mortar 1:3	5.8 m^3	10440	4.6	48024
		Paint	1166 m^2	1166	10.2	11893
	Windows	Float glass	185 m^2	462500	15	6937500
		Timber	1.02 m^3	521	8.5	4429
	Doors	Glass	114 m^2	14250	15	213750
		Timber	13.08 m^3	6679	8.5	56772
	Ceiling	Plasterboard	4989m^2	44901	6.75	303082
		Plaster	4989m^2	44901	6.75	303082
		Paint	4989m^2	4989	10.2	50888
	Staircases	Reinforced concrete	30.5 m^3	76250	2	152500
		Terrazzo	3.2 m^3	3.2	600	1920
		Reinforced concrete	65.7 m^3	164250	2	328500
		Terrazzo	3.4 m^3	3.4	600	2040
	Roof	Reinforced concrete	178 m^3	445000	2	890000
		Rockwool	1781 m^2	36	140	5040
		Asphalt	17.81 m^2	1781	2.6	4631
		Cement mortar 1:3	8.9 m^3	16020	4.6	73692
		Paint	1781 m^2	1781	10.2	18166
	Services	20%	-		-	9491798
Total	47458990 MJ					

- Recurring embodied energy

Recurring Embodied Energy of the Front Hall of the Shanghai Exhibition Centre

Halls	Elements	Materials	Material quantities (MJ)	Useful life (years)	Recurring embodied energy (MJ)
Front Hall (excluding the four small decorating	Box foundation	Reinforced concrete	26030000	100	0
		damp proof membrane	411000	100	0
	Columns	Reinforced concrete	2530000	100	0
		Cement mortar 1:3	163000	50	0
		Granite	354000	50	0
		Paint	6000	10	30000
	Beams	Reinforced concrete	1370000	100	0
		Cement mortar 1:3	99000	50	0
	Floors	Reinforced concrete	3025000	100	0

towers and external decoration)		Cement mortar 1:3	251712	50	0
		Terrazzo	72600	50	0
	External walls	Reinforced concrete	12540000	100	0
		Rockwool	7000	100	0
		Cement mortar 1:3	173880	50	0
		Paint	42616	10	213080
	Internal walls	Reinforced concrete	6570000	100	0
		Cement mortar 1:3	36432	50	0
		Paint	9619	10	48095
	Windows	Float glass	112500	50	0
		Steel	148450	50	0
	Doors	Timber (hardwood)	65969	30	65969
		Copper	163056	50	0
	Ceiling	Plywood	34473159	50	0
		Plaster	273375	50	0
		Paint	45910	10	229550
	Staircases	Reinforced concrete	84000	100	0
		Terrazzo	360	50	0
		Reinforced concrete	184000	100	0
		Terrazzo	2400	50	0
	Roof	Reinforced concrete	1745000	100	0
		Rockwool	9800	100	0
		Asphalt	905580	25	1811160
		Cement mortar 1:3	151524	50	0
		Paint	70	10	350
	Services	20%	23014253	-	11507127
Total	13905331 MJ				

Recurring Embodied Energy of the Central Hall of the Shanghai Exhibition Centre

Halls	Elements	Materials	Material quantities (GJ)	Useful life (years)	Recurring embodied energy (MJ)
Central Hall (excluding external decoration)	Box foundation	Reinforced concrete	28560000	100	0
		damp proof membrane	153300	100	0
	Columns	Reinforced concrete	585000	100	0
		Cement mortar 1:3	4968	50	0
		Paint	13	10	65
	Arch structure (internal)	Reinforced concrete	3450000	100	0
		Cement mortar 1:3	114264	50	0
		Paint	28152	10	140760
	Beams	Reinforced concrete	1495000	100	0
		Cement mortar 1:3	61603.2	50	0
	Floors	Reinforced concrete	750000	100	0
		Cement mortar 1:3	62928	50	0
		Terrazzo	18000	50	0
	External walls	Reinforced concrete	4120000	100	0
		Rockwool	1960	100	0
		Cement mortar 1:3	28152	50	0
		Paint	7007	10	35035
	Internal walls	Reinforced concrete	4165000	100	0
		Cement, sand	172224	50	0
		Paint	42442	10	212210
	Windows	Float glass	8400000	50	0
		Steel	213158	50	0
	Doors	Timber (hardwood)	55556	30	55556
		Glass	103125	50	0
		Copper	60096	50	0
	Ceiling	Plywood	28491480	50	0
		paint	37944	10	189720
	Staircases	Reinforced concrete	140000	100	0
		Terrazzo	1800	50	0
	Roof	Reinforced concrete	1855000	100	0
		Rockwool	10360	100	0
		Asphalt	963300	25	1926600
		Cement mortar 1:3	153180	50	0

		Paint	37791	10	188955
	Services	20%	21085701		10542851
Total	13291752 MJ				

Recurring Embodied Energy of the Eastern Hall of the Shanghai Exhibition Centre

Halls	Elements	Materials	Material quantities (GJ)	Useful life (years)	Recurring embodied energy (MJ)
Eastern Hall (excluding external decoration)	Strip foundation	Reinforced concrete	3365000	100	0
		damp proof membrane	338380	100	0
	Columns	Reinforced concrete	2160000	100	0
		Cement mortar 1:3	157320	50	0
		Granite	58800	50	0
		Paint	36955	10	184775
	Beams	Reinforced concrete	2800000	100	0
		Cement mortar 1:3	248400	50	0
	Floors	Reinforced concrete	4530000	100	0
		Cement mortar 1:3	372600	50	0
		Terrazzo	109200	50	0
	External walls	Reinforced concrete	14280000	100	0
		Rockwool	13300	100	0
		Cement mortar 1:3	197064	50	0
		Paint	48552	10	242760
	Internal walls	Reinforced concrete	7050000	100	0
		Cement mortar 1:3	146556	50	0
		Paint	35955	10	179775
	Windows	Float glass	42675000	50	0
		Steel	1084824	50	0
	Doors	Timber (hardwood)	12070	30	12070
		Glass	6900000	50	0
		Copper	184512	50	0
	Ceiling	Plaster	59182650	50	0
		Paint	99368	10	496840
	Staircases	Reinforced concrete	275000	100	0
		Terrazzo	2940	50	0
		Reinforced concrete	380000	100	0
		Terrazzo	5880	50	0
		Stone	15960	50	0
	Roof	Reinforced concrete	2440000	100	0
		Rockwool	13580	100	0
		Asphalt	125	25	250
		Cement mortar 1:3	2022804	50	0
		Paint	49766	10	248830
	Galleries	Reinforced concrete	3520000	100	0
		Cement mortar 1:3	3212640	50	0
		Paint	14300	10	71500
	Services	20%	39509875		19754938
Total: 21191738 MJ					

Recurring Embodied Energy of the Western Hall of the Shanghai Exhibition Centre

Halls	Elements	Materials	Material quantities (GJ)	Useful life (years)	Recurring embodied energy (MJ)
Western Hall (excluding external decoration)	Strip foundation	Reinforced concrete	3365000	100	0
		damp proof membrane	338380	100	0
	Columns	Reinforced concrete	240000	100	0
		Cement mortar 1:3	158976	50	0
		Granite	58800	50	0
		Paint	37669	10	188345
	Beams	Reinforced concrete	2800000	100	0
		Cement mortar 1:3	248400	50	0
	Floors	Reinforced concrete	5045000	100	0
		Cement mortar 1:3	414000	50	0
		Terrazzo	121200	50	0
	External	Reinforced concrete	15485000	100	0

	walls	Rockwool	14420	100	0
		Cement mortar 1:3	213624	50	0
		Paint	52652	10	263260
	Internal walls	Reinforced concrete	10390000	100	0
		Cement mortar 1:3	215280	50	0
		Paint	52999	10	264995
	Windows	Float glass	2235000	50	0
		Steel	1117520	50	0
	Doors	Timber (hardwood)	18666	30	18666
		Glass	320625	50	0
		Copper	128736	50	0
	Ceiling	Plaster	616977	50	0
		Paint	103591	10	517955
	Staircases	Reinforced concrete	125000	100	0
		Terrazzo	780	50	0
		Reinforced concrete	380000	100	0
		Terrazzo	5880	50	0
		Stone	15960	50	0
	Roof	Reinforced concrete	2582500	100	0
		Rockwool	14280	100	0
		Asphalt	1329900	25	2659800
		Cement mortar 1:3	2130444	50	0
		Paint	52632	10	263160
	Galleries	Reinforced concrete	3520000	100	0
		Cement mortar 1:3	3212640	50	0
		Paint	14300	10	71500
	Services	20%	14294208		7147104
Total: 11394785 MJ					

Recurring Embodied Energy of the Convention Hall of the Shanghai Exhibition Centre

Halls	Elements	Materials	Material quantities (GJ)	Useful life (years)	Recurring embodied energy (MJ)
Convention Hall (excluding external decoration)	Box foundation	Reinforced concrete	16940000	100	0
		damp proof membrane	87990	100	0
	Columns	Reinforced concrete	1380000	100	0
		Cement mortar 1:3	67234	50	0
		Granite	161000	50	0
		Paint	1918	10	9590
	Beams	Reinforced concrete	1095000	100	0
		Cement mortar 1:3	99360	50	0
	Floors	Reinforced concrete	1690000	100	0
		Cement mortar 1:3	207000	50	0
		Terrazzo	40800	50	0
	External walls	Reinforced concrete	5140000	100	0
		Rockwool	7140	100	0
		Cement mortar 1:3	107640	50	0
		Paint	26204	10	131020
	Internal walls	Reinforced concrete	1510000	100	0
		Cement mortar 1:3	48024	50	0
		Paint	11893	10	59465
	Windows	Float glass	6937500	50	0
		Timber	4429	30	4429
	Doors	Glass	213750	50	0
		Timber	56772	30	56772
	Ceiling	Plasterboard	303082	50	0
		Plaster	303082	50	0
		Paint	50888	10	254440
	Staircases	Reinforced concrete	152500	100	0
		Terrazzo	1920	50	0
		Reinforced concrete	328500	100	0
		Terrazzo	2040	50	0
	Roof	Reinforced concrete	890000	100	0
		Rockwool	5040	100	0

		Asphalt	4631	25	9262
		Cement mortar 1:3	73692	50	0
		Paint	18166	10	90830
	Services	20%	9491798		4745899
Total	5361707 MJ				

Total energy consumption of Shanghai Exhibition Centre (UK embodied energy coefficients)

	Initial embodied energy (MJ)	Recurring embodied energy (MJ)	Total embodied energy (MJ)
Front Hall	115071265	13905331	128976596
Central Hall	105428504	13291752	118720256
Eastern Hall	197549376	21191738	218741114
Western Hall	71471040	11394785	82865825
Convention Hall	47458990	5361707	52820697
Total	536979175	65145313+256957655	859,082,143

2. Australian embodied energy coefficients

- Initial embodied energy

Initial Embodied Energy of the Front Hall of the Shanghai Exhibition Centre

Halls	Elements	Materials	Volume	Material energy intensities *	Material quantities (MJ)
Front Hall (excluding the four small decorating towers and external decoration)	Box foundation	Reinforced concrete	5206 m^3	7.0 GJ/m^3	36442000
		Damp proof membrane	2190 m^2	0.07 GJ/m^2 **	153000
	Columns	Reinforced concrete	506 m^3	7.0 GJ/m^3	3542000
		Cement mortar 1:3	19.74 m^3	Cement: 11.4 GJ/t, Sand: 0.3 GJ/m^3	194700
		Granite	18.71 m^3	0.1-13.9 GJ/t ***	296000
		Paint	583 m^2	0.02 GJ/m^2**	12000
	Beams	Reinforced concrete	274 m^3	7.0 GJ/m^3	1918000
		Cement mortar 1:3	11.92 m^3	Cement: 11.4 GJ/t, Sand: 0.3 GJ/m^3	115200
	Floor	Reinforced concrete	605 m^3	7.0 GJ/m^3	4235000
		Cement mortar 1:3	30.4 m^3	Cement: 11.4 GJ/t, Sand: 0.3 GJ/m^3	298000
		Terrazzo	121 m^3	1.4 GJ/t ***	73000
	External walls	Reinforced concrete	2508 m^3	7.0 GJ/m^3	17556000
		Rockwool	2492 m^2	16.8 GJ/t ***	7000
		Cement mortar 1:3	21 m^3	Cement: 11.4 GJ/t, Sand: 0.3 GJ/m^3	206000
		Paint	4178 m^2	0.02 GJ/m^2**	84000
	Internal walls	Reinforced concrete	1314 m^3	7.0 GJ/m^3	9198000
		Cement mortar 1:3	4.4 m^3	Cement: 11.4 GJ/t, Sand: 0.3 GJ/m^3	43000
		Paint	943 m^2	0.02 GJ/m^2**	19000
	Windows	Float glass	300 m^2	3.1 GJ/m^2	930000
		Steel	0.78 m^3	36.8 GJ/t	24000
	Doors	Timber (hardwood)	15.1 m^3	10.9 GJ/ m^3	166000
		Copper	0.38 m^3	45.9 GJ/t	532000
	Ceiling	Plywood	4501 m^2	0.98 GJ/ m^2	4411000
		Plaster	4501 m^2	6.5 GJ/m^3 **	45000
		Paint	4501 m^2	0.02 GJ/m^2**	90000
	Staircases	Reinforced concrete	16.8 m^3	7.0 GJ/m^3	118000
		Terrazzo	0.6 m^3	1.4 GJ/t ***	400
		Reinforced concrete	36.8 m^3	7.0 GJ/m^3	258000
		Terrazzo	4 m^3	1.4 GJ/t ***	2000
	Roof	Reinforced concrete	349 m^3	7.0 GJ/m^3	2443000
		Rockwool	3483 m^2	16.8 GJ/t ***	10000
		Asphalt	3483 m^2	2.6 GJ/t ***	87000
		Cement mortar 1:3	18.3 m^3	Cement: 11.4 GJ/t, Sand: 0.3 GJ/m^3	179500
		Paint	3483 m^2	0.02 GJ/m^2**	70000
	Services	20%	-	-	20,940000
Total	104,698000 MJ				

* Treloar, G. J. (1994). *Energy analysis of the construction of office buildings.* Masters thesis. Faculty of Science and Technology, Deakin University, pp 58-59
** Baird, G., & Chan, S. A. (1983). *Energy Cost of House and Light Construction Buildings and Remodelling of Existing Houses (Report No.76).* New Zealand Energy Research and Development Committee, University of Auckland.

*** Hammond, G., & Jones, C. (2008). *Inventory of Carbon and Energy (ICE), Version 1.6a, Sustainable Energy Research Team (SERT).* Department of Mechanical Engineering, University of Bath, UK.

Initial Embodied Energy of the Central Hall of the Shanghai Exhibition Centre

Halls	Elements	Materials	Volume	Material energy intensities *	Material quantities (GJ)
Central Hall (excluding external decoration)	Box foundation	Reinforced concrete	5712 m^3	7.0 GJ/m^3	39984000
		Damp proof membrane	2190 m^2	0.07 GJ/m^2 **	153000
	Columns	Reinforced concrete	117 m^3	7.0 GJ/m^3	819000
		Cement mortar 1:3	0.6 m^3	Cement: 11.4 GJ/t, Sand: 0.3 GJ/m^3	4680
		Paint	1.27 m^2	0.02 GJ/m^2**	30
	Arch structure (internal)	Reinforced concrete	690 m^3	7.0 GJ/m^3	4830000
		Cement mortar 1:3	13.8 m^3	Cement: 11.4 GJ/t, Sand: 0.3 GJ/m^3	135000
		Paint	2760 m^2	0.02 GJ/m^2**	55000
	Beams	Reinforced concrete	299 m^3	7.0 GJ/m^3	2093000
		Cement mortar 1:3	7.44 m^3	Cement: 11.4 GJ/t, Sand: 0.3 GJ/m^3	38200
	Floors	Reinforced concrete	150 m^3	7.0 GJ/m^3	1050000
		Cement mortar 1:3	7.6 m^3	Cement: 11.4 GJ/t, Sand: 0.3 GJ/m^3	74000
		Terrazzo	30 m^3	1.4 GJ/t ***	18000
	External walls	Reinforced concrete	824 m^3	7.0 GJ/m^3	5768000
		Rockwool	687 m^2	16.8 GJ/t ***	2000
		Cement mortar 1:3	3.4 m^3	Cement: 11.4 GJ/t, Sand: 0.3 GJ/m^3	33000
		Paint	687 m^2	0.02 GJ/m^2**	14000
	Internal walls	Reinforced concrete	833 m^3	7.0 GJ/m^3	5831000
		Cement, sand	20.8 m^3	Cement: 11.4 GJ/t, Sand: 0.3 GJ/m^3	204000
		Paint	4161 m^2	0.02 GJ/m^2**	83000
	Windows	Float glass	224 m^2	3.1 GJ/m^2	694000
		Steel	1.13 m^2	36.8 GJ/t	34000
	Doors	Timber (hardwood)	12.8 m^3	10.9 GJ/ m^3	140000
		Glass	55 m^2	3.1 GJ/m^2	171000
		Copper	0.14 m^3	45.9 GJ/t	2000
	Ceiling	Plywood, paint	3720 m^2	0.98 GJ/ m^2	3721000
	Staircases	Reinforced concrete	28 m^3	7.0 GJ/m^3	196000
		Terrazzo	3 m^3	1.4 GJ/t ***	1800
	Roof	Reinforced concrete	371 m^3	7.0 GJ/m^3	3597000
		Rockwool	3705 m^2	16.8 GJ/t ***	12000
		Asphalt	3705 m^2	2.6 GJ/t ***	93000
		Cement mortar 1:3	18.5 m^3	Cement: 11.4 GJ/t, Sand: 0.3 GJ/m^3	182000
		Paint	3705 m^2	0.02 GJ/m^2**	74000
	Services	20%	-	-	17,527000
Total	87,634000 MJ				

Initial Embodied Energy of the Eastern Hall of the Shanghai Exhibition Centre

Halls	Elements	Materials	Volume	Material energy intensities *	Material quantities (GJ)
Eastern Hall (excluding external decoration)	Strip foundation	Reinforced concrete	673 m^3	7.0 GJ/m^3	4711000
		Damp proof membrane	4834 m^2	0.07 GJ/m^2 **	338000
	Columns	Reinforced concrete	432 m^3	7.0 GJ/m^3	3024000
		Cement mortar 1:3	18.84 m^3	Cement: 11.4 GJ/t, Sand: 0.3 GJ/m^3	185000
		Granite	3.1 m^3	5.86 GJ/t	50000
		Paint	3623 m^2	0.02 GJ/m^2**	73000
	Beams	Reinforced concrete	560 m^3	7.0 GJ/m^3	3920000
		Cement mortar 1:3	30 m^3	Cement: 11.4 GJ/t, Sand: 0.3 GJ/m^3	294000
	Floors	Reinforced concrete	906 m^3	7.0 GJ/m^3	6342000
		Cement mortar 1:3	45m^3	Cement: 11.4 GJ/t, Sand: 0.3 GJ/m^3	55000
		Terrazzo	182 m^3	1.4 GJ/t ***	109000
	External walls	Reinforced concrete	2856m^3	7.0 GJ/m^3	19992000
		Rockwool	4760 m^2	16.8 GJ/t ***	13000
		Cement mortar 1:3	23.8 m^3	Cement: 11.4 GJ/t, Sand: 0.3 GJ/m^3	233000
		Paint	4760 m^2	0.02 GJ/m^2**	95000
	Internal	Reinforced concrete	1410 m^3	7.0 GJ/m^3	9870000

	walls	Cement mortar 1:3	17.7 m^3	Cement: 11.4 GJ/t, Sand: 0.3 GJ/m^3	173000
		Paint	3525 m^2	0.02 GJ/m^2**	71000
	Windows	Float glass	1138 m^2	3.1 GJ/m^2	3528000
		Steel	5.7 m^3	36.8 GJ/t	175000
	Doors	Timber (hardwood)	2.78 m^3	10.9 GJ/ m^3	30000
		Glass	184 m^2	3.1 GJ/m^2	570000
		Copper	0.43 m^3	45.9 GJ/t	6000
	Ceiling	Plaster	9742 m^2	6.5 GJ/m^3 **	633000
		Paint	9742 m^2	0.02 GJ/m^2**	195000
	Staircases	Reinforced concrete	54.7 m^3	7.0 GJ/m^3	383000
		Terrazzo	4.9 m^3	1.4 GJ/t ***	3000
		Reinforced concrete	76 m^3	7.0 GJ/m^3	532000
		Terrazzo	9.8 m^3	1.4 GJ/t ***	5500
		Stone	8.4 m^3	Local: 1.9 GJ/ m^3 **	16000
	Roof	Reinforced concrete	487.5 m^3	7.0 GJ/m^3	3413
		Rockwool	4834 m^2	16.8 GJ/t ***	14000
		Asphalt	4834 m^2	2.6 GJ/t ***	121000
		Cement mortar 1:3	244.3 m^3	Cement: 11.4 GJ/t, Sand: 0.3 GJ/m^3	2394000
		Paint	4879 m^2	0.02 GJ/m^2**	98000
	Galleries	Reinforced concrete	393 m^3	7.0 GJ/m^3	4928000
		Cement mortar 1:3	388.1 m^3	Cement: 11.4 GJ/t, Sand: 0.3 GJ/m^3	3803000
		Paint	1404.6 m^2	0.02 GJ/m^2**	28000
	Services	20%	-	-	17,606000
Total: 88,030000 MJ					

Initial Embodied Energy of the Western Hall of the Shanghai Exhibition Centre

Halls	Elements	Materials	Volume	Material energy intensities *	Material quantities (GJ)
Western Hall (excluding external decoration)	Strip foundation	Reinforced concrete	673 m^3	7.0 GJ/m^3	4711000
		Damp proof membrane	4834 m^2	0.07 GJ/m^2**	338000
	Columns	Reinforced concrete	446 m^3	7.0 GJ/m^3	3136000
		Cement mortar 1:3	19.2 m^3	Cement: 11.4 GJ/t, Sand: 0.3 GJ/m^3	188000
		Granite	3.1 m^3	5.86 GJ/t	50000
		Paint	3692.8 m^2	0.02 GJ/m^2**	74000
	Beams	Reinforced concrete	560 m^3	7.0 GJ/m^3	3920000
		Cement mortar 1:3	30 m^3	Cement: 11.4 GJ/t, Sand: 0.3 GJ/m^3	294000
	Floors	Reinforced concrete	1009 m^3	7.0 GJ/m^3	7063000
		Cement mortar 1:3	50 m^3	Cement: 11.4 GJ/t, Sand: 0.3 GJ/m^3	490000
		Terrazzo	202 m^3	1.4 GJ/t ***	122000
	External walls	Reinforced concrete	3097m^3	7.0 GJ/m^3	21679000
		Rockwool	5162 m^2	16.8 GJ/t ***	15000
		Cement mortar 1:3	25.8 m^3	Cement: 11.4 GJ/t, Sand: 0.3 GJ/m^3	253000
		Paint	5162 m^2	0.02 GJ/m^2**	103000
	Internal walls	Reinforced concrete	2078m^3	7.0 GJ/m^3	14546000
		Cement mortar 1:3	26 m^2	Cement: 11.4 GJ/t, Sand: 0.3 GJ/m^3	274000
		Paint	5196 m^2	0.02 GJ/m^2**	104000
	Windows	Float glass	1192 m^2	3.1 GJ/m^2	3695000
		Steel	6 m^3	36.8 GJ/t	184000
	Doors	Timber (hardwood)	4.26 m^3	10.9 GJ/ m^3	46000
		Glass	171 m^2	3.1 GJ/m^2	530000
		Copper	0.3 m^3	45.9 GJ/t	4000
	Ceiling	Plaster	10156 m^2	6.5 GJ/m^3 **	660000
		Paint	10156 m^2	0.02 GJ/m^2**	203000
	Staircases	Reinforced concrete	24.8 m^3	7.0 GJ/m^3	174000
		Terrazzo	1.3 m^3	1.4 GJ/t ***	800
		Reinforced concrete	76 m^3	7.0 GJ/m^3	532000
		Terrazzo	9.8 m^3	1.4 GJ/t ***	5500
		Stone	8.4 m^3	Local: 1.9 GJ/ m^3 **	16000
	Roof	Reinforced concrete	516.5 m^3	7.0 GJ/m^3	3616000
		Rockwool	5115 m^2	16.8 GJ/t ***	14000
		Asphalt	5115 m^2	2.6 GJ/t ***	128000
		Cement mortar 1:3	257.3 m^3	Cement: 11.4 GJ/t, Sand: 0.3 GJ/m^3	2521000
		Paint	5170 m^2	0.02 GJ/m^2**	103000

	Galleries	Reinforced concrete	704 m^3	7.0 GJ/m^3	4928000
		Cement mortar 1:3	388.1 m^3	Cement: 11.4 GJ/t, Sand: 0.3 GJ/m^3	3803000
		Paint	1401.6 m^2	0.02 GJ/m^2**	4956000
	Services	20%	-	-	20,870000
Total: 104,349000 MJ					

Initial Embodied Energy of the Convention Hall of the Shanghai Exhibition Centre

Halls	Elements	Materials	Volume	Material energy intensities *	Material quantities (GJ)
Convention Hall (excluding external decoration)	Box foundation	Reinforced concrete	3388 m^3	7.0 GJ/m^3	23716000
		Damp proof membrane	1257 m^2	0.07 GJ/m^2**	88000
	Columns	Reinforced concrete	276 m^3	7.0 GJ/m^3	1932000
		Cement mortar 1:3	8.12 m^3	Cement: 11.4 GJ/t, Sand: 0.3 GJ/m^3	79000
		Granite	8.5 m^3	5.86 GJ/t	135000
		Paint	188 m^2	0.02 GJ/m^2**	4000
	Beams	Reinforced concrete	218.6 m^3	7.0 GJ/m^3	1530000
		Cement mortar 1:3	12 m^3	Cement: 11.4 GJ/t, Sand: 0.3 GJ/m^3	118000
	Floors	Reinforced concrete	338 m^3	7.0 GJ/m^3	2366000
		Cement mortar 1:3	24.9 m^3	Cement: 11.4 GJ/t, Sand: 0.3 GJ/m^3	251000
		Terrazzo	68 m^3	1.4 GJ/t ***	41000
	External walls	Reinforced concrete	1028 m^3	7.0 GJ/m^3	7196000
		Rockwool	2569 m^2	16.8 GJ/t ***	7000
		Cement mortar 1:3	13 m^3	Cement: 11.4 GJ/t, Sand: 0.3 GJ/m^3	128000
		Paint	2569 m^2	0.02 GJ/m^2**	51000
	Internal walls	Reinforced concrete	302 m^3	7.0 GJ/m^3	2114000
		Cement mortar 1:3	5.8 m^3	Cement: 11.4 GJ/t, Sand: 0.3 GJ/m^3	57000
		Paint	1166 m^2	0.02 GJ/m^2**	23000
	Windows	Float glass	185 m^2	3.1 GJ/m^2	574000
		Timber	1.02 m^3	10.9 GJ/ m^3	11000
	Doors	Glass	114 m^2	3.1 GJ/m^2	353000
		Timber	13.08 m^3	10.9 GJ/ m^3	143000
	Ceiling	Plasterboard	4989m^2	0.14 GJ/ m^2	699000
		Plaster	4989 m^2	6.5 GJ/m^3 **	324000
		Paint	4989 m^2	0.02 GJ/m^2**	100000
	Staircases	Reinforced concrete	31.5 m^3	7.0 GJ/m^3	214000
		Terrazzo	3.2 m^3	1.4 GJ/t ***	17000
		Reinforced concrete	65.7 m^3	7.0 GJ/m^3	460000
		Terrazzo	3.4 m^3	1.4 GJ/t ***	2000
	Roof	Reinforced concrete,	178 m^3	7.0 GJ/m^3	1246000
		Rockwool	1781 m^2	16.8 GJ/t ***	5000
		Asphalt	1781 m^2	2.6 GJ/t ***	45000
		Cement mortar 1:3	8.9 m^3	Cement: 11.4 GJ/t, Sand: 0.3 GJ/m^3	88000
		Paint	1781 m^2	0.02 GJ/m^2**	36000
	Services	20%	-	-	11035000
Total: 55,173000 MJ					

- Recurring embodied energy

Recurring Embodied Energy of the Front Hall of the Shanghai Exhibition Centre

Halls	Elements	Materials	Material quantities (MJ)	Useful life (years)	Recurring embodied energy (MJ)
Front Hall (excluding the four small decorating towers and	Box foundation	Reinforced concrete	36442000	100	0
		damp proof membrane	153000	100	0
	Columns	Reinforced concrete	3542000	100	0
		Cement mortar 1:3	194700	50	0
		Granite	296000	50	0
		Paint	12000	10	60000
	Beams	Reinforced concrete	1918000	100	0
		Cement mortar 1:3	115200	50	0
	Floors	Reinforced concrete	4235000	100	0
		Cement mortar 1:3	298000	50	0
		Terrazzo	73000	50	0

external decoration)	External walls	Reinforced concrete	17556000	100	0
		Rockwool	7000	100	0
		Cement mortar 1:3	206000	50	0
		Paint	84000	10	420000
	Internal walls	Reinforced concrete	9198000	100	0
		Cement mortar 1:3	43000	50	0
		Paint	19000	10	95000
	Windows	Float glass	930000	50	0
		Steel	24000	50	0
	Doors	Timber (hardwood)	166000	30	166000
		Copper	532000	50	0
	Ceiling	Plywood	4411000	50	0
		Plaster	45000	50	0
		Paint	90000	10	450000
	Staircases	Reinforced concrete	118000	100	0
		Terrazzo	400	50	0
		Reinforced concrete	258000	100	0
		Terrazzo	2000	50	0
	Roof	Reinforced concrete	2443000	100	0
		Rockwool	10000	100	0
		Asphalt	87000	25	174000
		Cement mortar 1:3	239000	50	0
		Paint	70000	10	350000
	Services	20%	20,940000	-	10470000
Total	26392370 MJ				

Recurring Embodied Energy of the Central Hall of the Shanghai Exhibition Centre

Halls	Elements	Materials	Material quantities (GJ)	Useful life (years)	Recurring embodied energy (MJ)
Central Hall (excluding external decoration)	Box foundation	Reinforced concrete	39984000	100	0
		damp proof membrane	153000	100	0
	Columns	Reinforced concrete	819000	100	0
		Cement mortar 1:3	4680	50	0
		Paint	30	10	150
	Arch structure (internal)	Reinforced concrete	4830000	100	0
		Cement mortar 1:3	135000	50	0
		Paint	55000	10	275000
	Beams	Reinforced concrete	2093000	100	0
		Cement mortar 1:3	38200	50	0
	Floors	Reinforced concrete	1050000	100	0
		Cement mortar 1:3	74000	50	0
		Terrazzo	18000	50	0
	External walls	Reinforced concrete	5768000	100	0
		Rockwool	2000	100	0
		Cement mortar 1:3	33000	50	0
		Paint	14000	10	60000
	Internal walls	Reinforced concrete	5831000	100	0
		Cement, sand	204000	50	0
		Paint	83000	10	415000
	Windows	Float glass	694000	50	0
		Steel	34000	50	0
	Doors	Timber(hardwood)	140000	30	140000
		Glass	171000	50	0
		Copper	2000	50	0
	Ceiling	Plywood, paint	3721000	50	0
	Staircases	Reinforced concrete	196000	100	0
		Terrazzo	1800	50	0
	Roof	Reinforced concrete	3597000	100	0
		Rockwool	12000	100	0
		Asphalt	93000	25	186000
		Cement mortar 1:3	182000	50	0
		Paint	74000	10	370000
	Services	20%	17,527000	-	8763500
Total	24417020 MJ				

Recurring Embodied Energy of the Eastern Hall of the Shanghai Exhibition Centre

Halls	Elements	Materials	Material quantities (GJ)	Useful life (years)	Recurring embodied energy (MJ)
Eastern Hall (excluding external decoration)	Strip foundation	Reinforced concrete	4711000	100	0
		damp proof membrane	338000	100	0
	Columns	Reinforced concrete	3024000	100	0
		Cement mortar 1:3	185000	50	0
		Granite	50000	50	0
		Paint	73000	10	365000
	Beams	Reinforced concrete	3920000	100	0
		Cement mortar 1:3	294000	50	0
	Floors	Reinforced concrete	6342000	100	0
		Cement mortar 1:3	55000	50	0
		Terrazzo	109000	50	0
	External walls	Reinforced concrete	19992000	100	0
		Rockwool	13000	100	0
		Cement mortar 1:3	233000	50	0
		Paint	95000	10	475000
	Internal walls	Reinforced concrete	9870000	100	0
		Cement mortar 1:3	173000	50	0
		Paint	71000	10	355000
	Windows	Float glass	3528000	50	0
		Steel	175000	50	0
	Doors	Timber (hardwood)	30000	30	30000
		Glass	570000	50	0
		Copper	6000	50	0
	Ceiling	Plaster	633000	50	0
		Paint	195000	10	975000
	Staircases	Reinforced concrete	383000	100	0
		Terrazzo	3000	50	0
		Reinforced concrete	532000	100	0
		Terrazzo	5500	50	0
		Stone	16000	50	0
	Roof	Reinforced concrete	3413	100	0
		Rockwool	14000	100	0
		Asphalt	121000	25	242000
		Cement mortar 1:3	2394000	50	0
		Paint	98000	10	490000
	Galleries	Reinforced concrete	4928000	100	0
		Cement mortar 1:3	3803000	50	0
		Paint	28000	10	140000
	Services	20%	17,606000		8803000
Total: 26082370 MJ					

Recurring Embodied Energy of the Western Hall of the Shanghai Exhibition Centre

Halls	Elements	Materials	Material quantities (GJ)	Useful life (years)	Recurring embodied energy (MJ)
Western Hall (excluding external decoration)	Strip foundation	Reinforced concrete	4711000	100	0
		damp proof membrane	338000	100	0
	Columns	Reinforced concrete	3136000	100	0
		Cement mortar 1:3	188000	50	0
		Granite	50000	50	0
		Paint	74000	10	370000
	Beams	Reinforced concrete	3920000	100	0
		Cement mortar 1:3	294000	50	0
	Floors	Reinforced concrete	7063000	100	0
		Cement mortar 1:3	490000	50	0
		Terrazzo	122000	50	0
	External walls	Reinforced concrete	21679000	100	0
		Rockwool	15000	100	0
		Cement mortar 1:3	253000	50	0
		Paint	103000	10	515000
	Internal walls	Reinforced concrete	14546000	100	0
		Cement mortar 1:3	274000	50	0
		Paint	104000	10	520000

	Windows	Float glass	3695000	50	0
		Steel	184000	50	0
	Doors	Timber (hardwood)	46000	30	46000
		Glass	530000	50	0
		Copper	4000	50	0
	Ceiling	Plaster	660000	50	0
		Paint	203000	10	1015000
	Staircases	Reinforced concrete	174000	100	0
		Terrazzo	800	50	0
		Reinforced concrete	532000	100	0
		Terrazzo	5500	50	0
		Stone	16000	50	0
	Roof	Reinforced concrete	3616000	100	0
		Rockwool	14000	100	0
		Asphalt	128000	25	256000
		Cement mortar 1:3	2521000	50	0
		Paint	103000	10	515000
	Galleries	Reinforced concrete	4928000	100	0
		Cement mortar 1:3	3803000	50	0
		Paint	4956000	10	24780000
	Services	20%	20,870000		10435000
Total: 52659370 MJ					

Recurring Embodied Energy of the Convention Hall of the Shanghai Exhibition Centre

Halls	Elements	Materials	Material quantities (GJ)	Useful life (years)	Recurring embodied energy (MJ)
Convention Hall (excluding external decoration)	Box foundation	Reinforced concrete	23716000	100	0
		damp proof membrane	88000	100	0
	Columns	Reinforced concrete	1932000	100	0
		Cement mortar 1:3	79000	50	0
		Granite	135000	50	0
		Paint	4000	10	20000
	Beams	Reinforced concrete	1530000	100	0
		Cement mortar 1:3	118000	50	0
	Floors	Reinforced concrete	2366000	100	0
		Cement mortar 1:3	251000	50	0
		Terrazzo	41000	50	0
	External walls	Reinforced concrete	7196000	100	0
		Rockwool	7000	100	0
		Cement mortar 1:3	128000	50	0
		Paint	51000	10	255000
	Internal walls	Reinforced concrete	2114000	100	0
		Cement mortar 1:3	57000	50	0
		Paint	23000	10	115000
	Windows	Float glass	574000	50	0
		Timber	11000	30	11000
	Doors	Glass	353000	50	0
		Timber	143000	30	143000
	Ceiling	Plasterboard	699000	50	0
		Plaster	324000	50	0
		Paint	100000	10	500000
	Staircases	Reinforced concrete	214000	100	0
		Terrazzo	17000	50	0
		Reinforced concrete	460000	100	0
		Terrazzo	2000	50	0
	Roof	Reinforced concrete,	1246000	100	0
		Rockwool	5000	100	0
		Asphalt	45000	25	90000
		Cement mortar 1:3	88000	50	0
		Paint	36000	10	180000
	Services	20%	11035000		5517500
Total: 21038870 MJ					

Total embodied energy of Shanghai Exhibition Centre (Australian embodied energy coefficients)

	Initial embodied energy (MJ)	Recurring embodied energy (MJ)	Total embodied energy (MJ)
Front Hall	104698000	26392370	131090370
Central Hall	87634000	24417020	112051020
Eastern Hall	88030000	26082370	114112370
Western Hall	104349000	52659370	157008370
Convention Hall	55,173,000	21038870	76211870
Total	439884000	150590 000+168298000	758772000

3. Germany embodied energy coefficients

- Initial embodied energy

Initial Embodied Energy of the Front Hall of the Shanghai Exhibition Centre

Halls	Elements	Materials	Volume	Weight (kg)	Factors (MJ/kg) * ** ***	Material quantities (MJ)
Front Hall (excluding the four small decorating towers and external decoration)	Box foundation	Reinforced concrete	5206 m^3	13015000	2.54	33058100
		Damp proof membrane	2190 m^2	3066	134	410844
	Columns	Reinforced concrete	506 m^3	1265000	2.54	3213100
		Cement mortar 1:3	19.74 m^3	35532	4.4	156340.8
		Granite	50500	50500	7****	353500
		Paint	583 m^2	117	68****	7956
	Beams	Reinforced concrete	274 m^3	685000	2.54	1739900
		Cement mortar 1:3	11.92 m^3	21456	4.4	94406.4
	Floors	Reinforced concrete	605 m^3	1512500	2.54	3841750
		Cement mortar 1:3	30.4 m^3	54720	4.4	240768
		Terrazzo	121m^3	121	600 MJ/ m^3 ****	72600
	External walls	Reinforced concrete	2508 m^3	6270000	2.54	15925800
		Rockwool	50 m^3	1000	3.37	3370
		Cement mortar 1:3	21 m^3	37800	4.4	166320
		Paint	4178 m^2	836	68****	56848
	Internal walls	Reinforced concrete	1314 m^3	3285000	2.54	8343900
		Cement mortar 1:3	4.4 m^3	7920	4.4	34848
		Paint	943 m^2	189	68****	12852
	Windows	Float glass	3 m^3	7500	15	112500
		Steel	0.78 m^3	6084	15	91260
	Doors	Timber (hardwood)	15.2 m^3	7761	5.56	43151.16
		Copper	0.38 m^3	3397	48****	163056
	Ceiling	Plywood	4501m^2	2298211	15****	34473165
		Plaster	45m^3	40500	3.39	137295
		Paint	4501m^2	900	68****	61200
	Staircases	Reinforced concrete	16.8 m^3	42000	2.54	106680
		Terrazzo	0.6 m^3	0.6	600 MJ/ m^3 ****	360
		Reinforced concrete	36.8 m^3	92000	2.54	233680
		Terrazzo	4 m^3	4	600 MJ/ m^3 ****	2400
	Roof	Reinforced concrete	349 m^3	872500	2.54	2216150
		Rockwool	70m^3	1400	3.37	4718
		Asphalt	3483m^2	348300	2.6	905580
		Cement mortar 1:3	18.3 m^3	32940	4.4	144936
		Paint	3483m^2	697	68****	47396
	Services	20%	-		-	26619183
Total	133095913 MJ					

* Anon. (1994). *BEW Forschungsprojekt: Energie – und Stoffbilanzen von Gebauden.* Schlussbericht: Universitat Karlsruhe.
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*** Pohlmann, C. M. (2002). *Okologische Betrachtung fur den Hausbau – Ganzheitliche Energie – und Kohlendioxidbilanzen fur zwei verschiedene Holzhauskonstruktionen.* PhD thesis. zur Erlangung des Doktorgrades, an der Universitat Hamburg, Fachbereich Biologie.

**** Hammond, G., & Jones, C. (2008). *Inventory of Carbon and Energy (ICE), Version 1.6a, Sustainable Energy Research Team (SERT).* Department of Mechanical Engineering, University of Bath, UK.

Initial Embodied Energy of the Central Hall of the Shanghai Exhibition Centre

Halls	Elements	Materials	Volume	Weight	Material energy intensities	Material quantities (GJ)
Central Hall (excluding external decoration)	Box foundation	Reinforced concrete	5712 m^3	14280000	2.54	36271200
		damp proof membrane	2190 m^2	30660	134	4108440
	Columns	Reinforced concrete	117 m^3	292500	2.54	742950
		Cement mortar 1:3	0.6 m^3	1080	4.4	4752
		Paint	1.27 m^2	0.254	68	18
	Arch structure (internal)	Reinforced concrete	690 m^3	1725000	2.54	4381500
		Cement mortar 1:3	13.8 m^3	24840	4.4	109296
		Paint	2760 m^2	552	68	37536
	Beams	Reinforced concrete	299 m^3	747500	2.54	1898650
		Cement mortar 1:3	7.44 m^3	13392	4.4	58925
	Floors	Reinforced concrete	150 m^3	375000	2.54	952500
		Cement mortar 1:3	7.6 m^3	13680	4.4	60192
		Terrazzo	30 m^3	30	600	18000
	External walls	Reinforced concrete	824 m^3	2060000	2.54	5232400
		Rockwool	14 m^3	280	3.37	944
		Cement mortar 1:3	3.4 m^3	6120	4.4	26928
		Paint	687 m^2	137	68	9316
	Internal walls	Reinforced concrete	833 m^3	2082500	2.54	5289550
		Cement, sand	20.8 m^3	37440	4.4	164736
		Paint	4161 m^2	832	68	56576
	Windows	Float glass	224 m^2	560000	15	8400000
		Steel	1.12 m^3	8736	15	131040
	Doors	Timber (hardwood)	12.8 m^3	6536	5.56	36340
		Glass	55 m^2	6875	15	103125
		Copper	0.14 m^3	1252	48	60096
	Ceiling	Plywood	3720 m^2	1899432	15	28491480
		Paint	3720 m^2	744	68	50592
	Staircases	Reinforced concrete	28 m^3	70000	2.54	177800
		Terrazzo	3 m^3	3	600	1800
	Roof	Reinforced concrete	371 m^3	927500	2.54	2355850
		Rockwool	74 m^3	30	3.37	101
		Asphalt	37.05 m^3	370500	2.6	963300
		Cement mortar 1:3	18.5 m^3	33300	4.4	146520
		Paint	3705 m^2	741	68	50388
	Services	20%	-		-	25098210
Total	125491051 MJ					

Initial Embodied Energy of the Eastern Hall of the Shanghai Exhibition Centre (1955~2001)

Halls	Elements	Materials	Volume	Weight	Material energy intensities	Material quantities (GJ)
Eastern Hall (excluding external decoration)	Strip foundation	Reinforced concrete	673 m^3	1682500	2.54	4273550
		damp proof membrane	4834 m^2	67676	134	9068584
	Columns	Reinforced concrete	432 m^3	1080000	2.54	2743200
		Cement mortar 1:3	19 m^3	34200	4.4	150480
		Granite	8.4t	8400	7	58800
		Paint	3623 m^2	725	68	49300
	Beams	Reinforced concrete	560 m^3	1400000	2.54	3556000
		Cement mortar 1:3	30 m^3	54000	4.4	237600
	Floors	Reinforced concrete	906 m^3	2265000	2.54	5753100
		Cement mortar 1:3	45 m^3	81000	4.4	356400
		Terrazzo	182 m^3	182	600	109200
	External walls	Reinforced concrete	2856m^3	7140000	2.54	18135600
		Rockwool	4760 m^2	1904	3.37	6416
		Cement mortar 1:3	23.8 m^3	42840	4.4	188496
		Paint	4760 m^2	952	68	64736
	Internal	Reinforced concrete	1410 m^3	3525000	2.54	8953500

	walls	Cement mortar 1:3	17.7 m^3	31860	4.4	140184
		Paint	3525 m^2	705	68	47940
	Windows	Float glass	1138 m^2	142250	15	2133750
		Steel	5.7 m^3	44460	15	666900
	Doors	Timber (hardwood)	2.78 m^3	1420	5.56	7895
		Glass	184 m^2	230000	15	3450000
		Copper	0.43 m^3	3844	48	184512
	Ceiling	Plaster	9742 m^2	8767800	3.39	29722842
		Paint	9742 m^2	1948	68	132464
	Staircases	Reinforced concrete	55 m^3	137500	2.54	349250
		Terrazzo	4.9 m^3	4.9	600	2940
		Reinforced concrete	76 m^3	190000	2.54	482600
		Terrazzo	9.8 m^3	9.8	600	5880
		Stone	8.4 m^3	8.4	1900 MJ/ m3	15960
	Roof	Reinforced concrete	488 m^3	1220000	2.54	3098800
		Rockwool	4834 m^2	1934	3.37	6517.58
		Asphalt	4834 m^2	48	2.6	125
		Cement mortar 1:3 (1800 kg/m^3)	244.3 m^3	439740	4.4	1934856
		Paint	4879 m^2	976	68	66368
	Galleries	Reinforced concrete	704 m^3	1760000	2.54	4470400
		Cement mortar 1:3	388 m^3	698400	4.4	3072960
		Paint	1402m^2	281	68	19108
	Services	20%	-		-	25929304
Total: 129646518 MJ						

Initial Embodied Energy of the Western Hall of the Shanghai Exhibition Centre

Halls	Elements	Materials	Volume	Weight	Material energy intensities	Material quantities (GJ)
Western Hall (excluding external decoration)	Strip foundation	Reinforced concrete	673 m^3	1682500	2.54	4273550
		damp proof membrane	4834 m^2	67676	134	9068584
	Columns	Reinforced concrete	448 m^3	120000	2.54	304800
		Cement mortar 1:3	19.2 m^3	34560	4.4	152064
		Granite	8400	8400	7	58800
		Paint	3693 m^2	739	68	50252
	Beams	Reinforced concrete	560 m^3	1400000	2.54	3556000
		Cement mortar 1:3	30 m^3	54000	4.4	237600
	Floors	Reinforced concrete	1009 m^3	2522500	2.54	6407150
		Cement mortar 1:3	50 m^3	90000	4.4	396000
		Terrazzo	202 m^3	202	600	121200
	External walls	Reinforced concrete	3097m^3	7742500	2.54	19665950
		Rockwool	5162 m^2	2065	3.37	6959
		Cement mortar 1:3	25.8 m^3	46440	4.4	204336
		Paint	5162 m^2	1032	68	70176
	Internal walls	Reinforced concrete	2078 m^3	5195000	2.54	13195300
		Cement mortar 1:3	26 m3	46800	4.4	205920
		Paint	5196 m^2	1039	68	70652
	Windows	Float glass	1192 m^2	149000	15	2235000
		Steel	6 m^3	45800	15	687000
	Doors	Timber (hardwood)	4.3 m^3	2196	5.56	12210
		Glass	171 m^2	21375	15	320625
		Copper	0.3 m^3	2682	48	128736
	Ceiling	Plaster	10156 m^2	91404	3.39	309860
		Paint	10156 m^2	2031	68	138108
	Staircases	Reinforced concrete	25 m^3	62500	2.54	158750
		Terrazzo	1.3 m^3	1.3	600	780
		Reinforced concrete	76 m^3	190000	2.54	482600
		Terrazzo	9.8 m^3	9.8	600	5880
		Stone	8.4 m^3	8.4	1900	15960
	Roof	Reinforced concrete	516.5 m^3	1291250	2.54	3279775
		Rockwool	5115 m^2	2046	3.37	6895
		Asphalt	5115 m^2	511500	2.6	1329900
		Cement mortar 1:3	257.3 m^3	463140	4.4	2037816
		Paint	5160 m^2	1032	68	70176

	Galleries	Reinforced concrete	704 m^3	1760000	2.54	4470400
		Cement mortar 1:3	388 m^3	698400	4.4	3072960
		Paint	1402 m^2	280	68	19040
	Services	20%	-		-	19206941
Total: 96034704 MJ						

Initial Embodied Energy of the Convention Hall of the Shanghai Exhibition Centre

Halls	Elements	Materials	Volume	Weight	Material energy intensities	Material quantities (GJ)
Convention Hall (excluding external decoration)	Box foundation	Reinforced concrete	3388 m^3	8470000	2.54	21513800
		damp proof membrane	1257 m^2	17592	134	2357328
	Columns	Reinforced concrete	276 m^3	690000	2.54	1752600
		Cement mortar 1:3	8.12 m^3	14616	4.4	64310
		Granite	23000	23000	7	161000
		Paint	188 m^2	38	68	2584
	Beams	Reinforced concrete	219 m^3	547500	2.54	1390650
		Cement mortar 1:3	12 m^3	21600	4.4	95040
	Floors	Reinforced concrete	338 m^3	845000	2.54	2146300
		Cement mortar 1:3	25 m^3	45000	4.4	198000
		Terrazzo	68 m^3	68	600	40800
	External walls	Reinforced concrete	1028 m^3	2570000	2.54	6527800
		Rockwool	2569 m^2	1028	3.37	3464
		Cement mortar 1:3	13 m^3	23400	4.4	102960
		Paint	2569 m^2	514	68	34952
	Internal walls	Reinforced concrete	302 m^3	755000	2.54	1917700
		Cement mortar 1:3	5.8 m^3	10440	4.4	45936
		Paint	1166 m^2	233	68	15844
	Windows	Float glass	185 m^2	23125	15	346875
		Timber	1.02 m^3	521	5.56	2897
	Doors	Glass	114 m^2	14250	15	213750
		Timber	13.08 m^3	6679	5.56	37135
	Ceiling	Plasterboard	4989m^2	44901	3.39	152214
		Plaster	4989m^2	44901	3.39	152214
		Paint	4989m^2	998	68	67864
	Staircases	Reinforced concrete	30.5 m^3	76250	2.54	193675
		Terrazzo	3.2 m^3	3.2	600	1920
		Reinforced concrete	65.7 m^3	164250	2.54	417195
		Terrazzo	3.4 m^3	3.4	600	2040
	Roof	Reinforced concrete	178 m^3	445000	2.54	1130300
		Rockwool	1781 m^2	712	3.37	2399
		Asphalt	17.81 m^2	1781	2.6	4631
		Cement mortar 1:3	8.9 m^3	16020	4.4	70488
		Paint	1781 m^2	356	68	24208
	Services	20%	-		-	10297719
Total	51488593 MJ					

- Recurring embodied energy

Recurring Embodied Energy of the Front Hall of the Shanghai Exhibition Centre

Halls	Elements	Materials	Material quantities (MJ)	Useful life (years)	Recurring embodied energy (MJ)
Front Hall (excluding the four small decorating towers and external	Box foundation	Reinforced concrete	33058100	100	0
		damp proof membrane	410844	100	0
	Columns	Reinforced concrete	3213100	100	0
		Cement mortar 1:3	156340.8	50	0
		Granite	353500	50	0
		Paint	7956	10	39780
	Beams	Reinforced concrete	1739900	100	0
		Cement mortar 1:3	94406.4	50	0
	Floors	Reinforced concrete	3841750	100	0
		Cement mortar 1:3	240768	50	0
		Terrazzo	72600	50	0
	External	Reinforced concrete	15925800	100	0

decoration)	walls	Rockwool	3370	100	0
		Cement mortar 1:3	166320	50	0
		Paint	56848	10	284240
	Internal walls	Reinforced concrete	8343900	100	0
		Cement mortar 1:3	34848	50	0
		Paint	12852	10	64260
	Windows	Float glass	112500	50	0
		Steel	91260	50	0
	Doors	Timber (hardwood)	43151.16	30	43151
		Copper	163056	50	0
	Ceiling	Plywood	34473165	50	0
		Plaster	137295	50	0
		Paint	61200	10	306000
	Staircases	Reinforced concrete	106680	100	0
		Terrazzo	360	50	0
		Reinforced concrete	233680	100	0
		Terrazzo	2400	50	0
	Roof	Reinforced concrete	2216150	100	0
		Rockwool	4718	100	0
		Asphalt	905580	25	1811160
		Cement mortar 1:3	144936	50	0
		Paint	47396	10	236980
	Services	20%	26619183		13309592
Total	16095163 MJ				

Recurring Embodied Energy of the Central Hall of the Shanghai Exhibition Centre

Halls	Elements	Materials	Material quantities (GJ)	Useful life (years)	Recurring embodied energy (MJ)
Central Hall (excluding external decoration)	Box foundation	Reinforced concrete	36271200	100	0
		damp proof membrane	4108440	100	0
	Columns	Reinforced concrete	742950	100	0
		Cement mortar 1:3	4752	50	0
		Paint	18	10	90
	Arch structure (internal)	Reinforced concrete	4381500	100	0
		Cement mortar 1:3	109296	50	0
		Paint	37536	10	187680
	Beams	Reinforced concrete	1898650	100	0
		Cement mortar 1:3	58925	50	0
	Floors	Reinforced concrete	952500	100	0
		Cement mortar 1:3	60192	50	0
		Terrazzo	18000	50	0
	External walls	Reinforced concrete	5232400	100	0
		Rockwool	944	100	0
		Cement mortar 1:3	26928	50	0
		Paint	9316	10	46580
	Internal walls	Reinforced concrete	5289550	100	0
		Cement, sand	164736	50	0
		Paint	56576	10	282880
	Windows	Float glass	8400000	50	0
		Steel	131040	50	0
	Doors	Timber (hardwood)	36340	30	36340
		Glass	103125	50	0
		Copper	60096	50	0
	Ceiling	Plywood	28491480	50	0
		Paint	50592	10	252960
	Staircases	Reinforced concrete	177800	100	0
		Terrazzo	1800	50	0
	Roof	Reinforced concrete	2355850	100	0
		Rockwool	101	100	0
		Asphalt	963300	25	1926600
		Cement mortar 1:3	146520	50	0
		Paint	50388	10	251940
	Services	20%	25098210		12549105
Total	15534175 MJ				

Recurring Embodied Energy of the Eastern Hall of the Shanghai Exhibition Centre

Halls	Elements	Materials	Material quantities (GJ)	Useful life (years)	Recurring embodied energy (MJ)
Eastern Hall (excluding external decoration)	Strip foundation	Reinforced concrete	4273550	100	0
		damp proof membrane	9068584	100	0
	Columns	Reinforced concrete	2743200	100	0
		Cement mortar 1:3	150480	50	0
		Granite	58800	50	0
		Paint	49300	10	246500
	Beams	Reinforced concrete	3556000	100	0
		Cement mortar 1:3	237600	50	0
	Floors	Reinforced concrete	5753100	100	0
		Cement mortar 1:3	356400	50	0
		Terrazzo	109200	50	0
	External walls	Reinforced concrete	18135600	100	0
		Rockwool	6416	100	0
		Cement mortar 1:3	188496	50	0
		Paint	64736	10	323680
	Internal walls	Reinforced concrete	8953500	100	0
		Cement mortar 1:3	140184	50	0
		Paint	47940	10	239700
	Windows	Float glass	2133750	50	0
		Steel	666900	50	0
	Doors	Timber (hardwood)	7895	30	7895
		Glass	3450000	50	0
		Copper	184512	50	0
	Ceiling	Plaster	29722842	50	0
		Paint	132464	10	662320
	Staircases	Reinforced concrete	349250	100	0
		Terrazzo	2940	50	0
		Reinforced concrete	482600	100	0
		Terrazzo	5880	50	0
		Stone	15960	50	0
	Roof	Reinforced concrete	3098800	100	0
		Rockwool	6517.58	100	0
		Asphalt	125	25	250
		Cement mortar 1:3	1934856	50	0
		Paint	66368	10	331840
	Galleries	Reinforced concrete	4470400	100	0
		Cement mortar 1:3	3072960	50	0
		Paint	19108	10	95540
	Services	20%	25929304		12964652
Total: 14872377 MJ					

Recurring Embodied Energy of the Western Hall of the Shanghai Exhibition Centre

Halls	Elements	Materials	Material quantities (GJ)	Useful life (years)	Recurring embodied energy (MJ)
Western Hall (excluding external decoration)	Strip foundation	Reinforced concrete	4273550	100	0
		damp proof membrane	9068584	100	0
	Columns	Reinforced concrete	304800	100	0
		Cement mortar 1:3	152064	50	0
		Granite	58800	50	0
		Paint	50252	10	251260
	Beams	Reinforced concrete	3556000	100	0
		Cement mortar 1:3	237600	50	0
	Floors	Reinforced concrete	6407150	100	0
		Cement mortar 1:3	396000	50	0
		Terrazzo	121200	50	0
	External walls	Reinforced concrete	19665950	100	0
		Rockwool	6959	100	0
		Cement mortar 1:3	204336	50	0
		Paint	70176	10	350880
	Internal walls	Reinforced concrete	13195300	100	0
		Cement mortar 1:3	205920	50	0

		Paint	70652	10	353260
	Windows	Float glass	2235000	50	0
		Steel	687000	50	0
	Doors	Timber (hardwood)	12210	30	12210
		Glass	320625	50	0
		Copper	128736	50	0
	Ceiling	Plaster	309860	50	0
		Paint	138108	10	690540
	Staircases	Reinforced concrete	158750	100	0
		Terrazzo	780	50	0
		Reinforced concrete	482600	100	0
		Terrazzo	5880	50	0
		Stone	15960	50	0
	Roof	Reinforced concrete	3279775	100	0
		Rockwool	6895	100	0
		Asphalt	1329900	25	2659800
		Cement mortar 1:3	2037816	50	0
		Paint	70176	10	350880
	Galleries	Reinforced concrete	4470400	100	0
		Cement mortar 1:3	3072960	50	0
		Paint	19040	10	95200
	Services	20%	19206941		9603471
Total: 14367501 MJ					

Recurring Embodied Energy of the Convention Hall of the Shanghai Exhibition Centre

Halls	Elements	Materials	Material quantities (GJ)	Useful life (years)	Recurring embodied energy (MJ)
Convention Hall (excluding external decoration)	Box foundation	Reinforced concrete	21513800	100	0
		damp proof membrane	2357328	100	0
	Columns	Reinforced concrete	1752600	100	0
		Cement mortar 1:3	64310	50	0
		Granite	161000	50	0
		Paint	2584	10	12920
	Beams	Reinforced concrete	1390650	100	0
		Cement mortar 1:3	95040	50	0
	Floors	Reinforced concrete	2146300	100	0
		Cement mortar 1:3	198000	50	0
		Terrazzo	40800	50	0
	External walls	Reinforced concrete	6527800	100	0
		Rockwool	3464	100	0
		Cement mortar 1:3	102960	50	0
		Paint	34952	10	174760
	Internal walls	Reinforced concrete	1917700	100	0
		Cement mortar 1:3	45936	50	0
		Paint	15844	10	79220
	Windows	Float glass	346875	50	0
		Timber	2897	30	2897
	Doors	Glass	213750	50	0
		Timber	37135	30	37135
	Ceiling	Plasterboard	152214	50	0
		Plaster	152214	50	0
		Paint	67864	10	339320
	Staircases	Reinforced concrete	193675	100	0
		Terrazzo	1920	50	0
		Reinforced concrete	417195	100	0
		Terrazzo	2040	50	0
	Roof	Reinforced concrete	1130300	100	0
		Rockwool	2399	100	0
		Asphalt	4631	25	9262
		Cement mortar 1:3	70488	50	0
		Paint	24208	10	121040
	Services	20%	10297719		5148860
Total		5925414			

Total embodied energy of Shanghai Exhibition Centre (Germany embodied energy coefficients)

	Initial embodied energy (MJ)	Recurring embodied energy (MJ)	Total embodied energy (MJ)
Front Hall	133095913	16095163	149191076
Central Hall	125491051	15534175	141025226
Eastern Hall	129646518	14872377	144518895
Western Hall	96034704	14367501	110402205
Convention Hall	51488593	5925414	57414007
Total	535756779	66794630 +256372709	858924118

- **Embodied energy of the Dutch Pavilion**

- UK embodied energy coefficients

- Initial embodied energy

Initial embodied energy of the offices floor (Ground floor)

	Materials	Volume	Weight (kg)	Factors* (MJ/kg)	Embodied energy (MJ)
Pile foundations	Reinforced concrete	384m^3	960000	2	1920000
	Damp proof membrane	10m^3	14,000	134	1876000
Columns	Reinforced concrete	33 m^3	82,500	2	165000
	Cement	1.4 m^3	2,520	4.6	11592
	Sand	1.4 m^3	1,722	0.1	172
	Paint	0.476 m^3	0.1	68	6.8
Beams	Reinforced concrete	136 m^3	340,000	2	680000
	Cement	6 m^3	10,800	4.6	49680
	Sand	6 m^3	7,380	0.1	738
Slabs	Reinforced concrete	102 m^3	255,000	2	510000
	Cement	10 m^3	18,000	4.6	82800
	Sand	10 m^3	12,300	0.1	1230
	Carpet (timber)	1,920 m^3	980,352	8.5	8332992
	Carpet (carpet)	10 m^3	1,100	74.4	81840
External walls	Reinforced concrete	205 m^3	512,500	2	1025000
	Mineral wool (Insulation)	12.3 m^3	246	16.6	4084
	Cement	4 m^3	7,200	4.6	33120
	Sand	4 m^3	4,920	0.1	492
	Brick (decoration)	5 m^3	3,350	3	10050
	Paint	0.204 m^3	0.04	68	2.8
Internal walls	Reinforced concrete	186 m^3	465,000	2	930000
	Cement	9.3 m^3	16,740	4.6	77004
	Sand	9.3 m^3	11,439	0.1	1144
	Paint	3.712 m^3	0.8	68	55
Doors	Timber	17.4 m^3	8,884	8.5	75514
	Glass	0.84 m^3	2,100	15	31500
	Paint	0.07 m^3	0.014	68	1
Ceiling	Steel	0.6 m^3	4,680	24.4	114192
	Plaster	10 m^3	9000	1.8	16200
Internal stair	Reinforced concrete	2.5 m^3	6,250	2	12500
	Brick (pavement)	0.9 m^3	603	3	1809
	Steel (handrail)	0.0003 m^3	2.3	24.4	56
Internal lift	Reinforced concrete	0.68 m^3	1700	2	3400
	Steel	0.008 m^3	62	24.4	1513
	Plastic (Decoration)	0.002 m^3	5	80.5	403
Total	**16,050,091 MJ**				
* Hammond, G., & Jones, C. (2008). *Inventory of Carbon and Energy (ICE), Version 1.6a, Sustainable Energy Research Team (SERT).* Department of Mechanical Engineering, University of Bath, UK.					

Initial embodied energy of the dunes floor (First floor)

	Materials	Volume	Weight (kg)	Factors (MJ/kg)	Embodied energy (MJ)
Wall	Reinforced concrete	2,048 m^3	5,120,000	2	10240000
	Cement	10 m^3	18,000	4.6	828000
	Sand	21 m^3	25,830	0.1	2583
Slabs	Reinforced concrete	102 m^3	255,000	2	510000
	Cement	10 m^3	18,000	4.6	82800

	Sand	10 m^3	12,300	0.1	1230
	Brick	31 m^3	20,770	3	62310
Ceiling	Tile	5 m^3	9,000	9	81000
Connected bridge	Steel	0.53 m^3	4134	24.4	100870
	Timber	0.7 m^3	4.2	8.5	36
Internal staircases	Reinforced concrete	235 m^3	587,500	2	1175000
	Cement	1.2 m^3	2,160	4.6	9936
	Sand	1.2 m^3	1,476	0.1	148
Maintenance structure	Steel (handrail)	0.01 m^3	78	24.4	1903
	Glass	0.2 m^3	500	15	7500
Total	**13,103,316 MJ**				

Initial embodied energy of the glass floor (Second floor)

	Materials	Volume	Weight (kg)	Factors (MJ/kg)	Embodied energy (MJ)
Columns	Reinforced concrete	123 m^3	2623	2	5246
	Cement	2.5 m^3	4500	4.6	20700
	Sand	2.5 m^3	3075	0.1	308
	Paint	1 m^3	0.2	68	14
Beams	Reinforced concrete	136 m^3	340,000	2	680000
	Cement	6 m^3	10800	4.6	49680
	Sand	6 m^3	7380	0.1	738
Slabs	Reinforced concrete	102 m^3	255000	2	510000
	Cement	10 m^3	18000	4.6	82800
	Sand	10 m^3	12300	0.1	1230
	Paint	2 m^3	0.4	68	27
External maintenance structure	Steel	0.42 m^3	3276	24.4	79934
	Glass	2.05 m^3	5125	15	76875
Doors	Timber	0.3 m^3	153	8.5	1301
	Glass	0.015 m^3	38	15	570
	Paint	0.0012 m^3	0.0003	68	0.02
Ceiling	Plaster	10 m^3	9000	1.8	16200
	Paint	2 m^3	0.4	68	27
Shelves for flowers	Steel	0.7 m^3	5460	24.4	133224
Total	**1,658,873 MJ**				

Initial embodied energy of the pots floor (Third floor)

	Materials	Volume	Weight (kg)	Factors (MJ/kg)	Embodied energy (MJ)
Beams	Reinforced concrete	136 m^3	340000	2	680000
	Cement	6 m^3	10800	4.6	49680
	Sand	6 m^3	7380	0.1	738
Slabs	Reinforced concrete	102 m^3	255000	2	510000
	Cement	10 m^3	18000	4.6	82800
	Sand	10 m^3	12300	0.1	1230
	Paint	2 m^3	0.4	68	27
External walls	Plastic sheeting	0.819 m^3	197	80.5	15859
Internal walls	Reinforced concrete	299 m^3	747500	2	1495000
	Cement	15 m^3	27000	4.6	124200
	Sand	15 m^3	18450	0.1	1845
	Paint	4.3 m^3	0.9	68	61
Doors	Timber	3.6 m^3	1838	8.5	15623
	Glass	0.17 m^3	425	15	6375
	Paint	0.001 m^3	0.0002	68	0.01
Ceiling	Plaster	10 m^3	9000	1.8	16200
	Paint	2 m^3	0.4	68	27
Total	**2,999,665 MJ**				

Initial embodied energy of the forest floor (Fourth floor)

	Materials	Volume	Weight (kg)	Factors (MJ/kg)	Embodied energy (MJ)
Columns	Timber	112 m^3	57187	8.5	486090
Beams	Reinforced concrete	136 m^3	340000	2	680000
	Cement	6 m^3	10800	4.6	49680
	Sand	6 m^3	7380	0.1	738
Slabs	Reinforced concrete	102 m^3	255000	2	510000
	Cement	10 m^3	18000	4.6	82800
	Sand	10 m^3	12300	0.1	1230

	Paint	2 m^3	0.4	68	27
Ceiling	Plaster	10 m^3	9000	1.8	16200
	Paint	2 m^3	0.4	68	27
Maintenance structure	Steel (handrail)	0.01 m^3	78	24.4	1903
	Glass	0.2 m^3	500	15	7500
Total	**1,836,195 MJ**				

Initial embodied energy of the rain floor (Fifth floor)

	Materials	Volume	Weight (kg)	Factors (MJ/kg)	Embodied energy (MJ)
Columns	Reinforced concrete	23 m^3	57,500	2	115000
Beams	Reinforced concrete	136 m^3	340,000	2	680000
	Cement	6 m^3	10,800	4.6	49680
	Sand	6 m^3	7,380	0.1	738
Slabs	Reinforced concrete	102 m^3	255,000	2	510000
	Cement	10 m^3	18,000	4.6	82800
	Sand	10 m^3	12,300	0.1	1230
	Paint	2 m^3	0.4	68	27
Internal walls	Reinforced concrete	153 m^3	382,500	2	765000
	Cement	8 m^3	14,400	4.6	66240
	Sand	8 m^3	0.04	0.1	0.004
	Steel (decoration)	2 m^3	15,600	24.4	380640
Door	Timber	3.6 m^3	1838	8.5	15623
	Glass	0.17 m^3	425	15	6375
	Paint	0.001 m^3	0.0002	68	0.01
Ceiling (internal)	Plaster	4 m^3	3600	1.8	6480
	Paint	0.8 m^3	0.16	68	11
Maintenance structure	Steel	20 m^3	156000	24.4	3806400
Total	**6,486,244 MJ**				

Initial embodied energy of the windmills (Sixth floor)

	Materials	Volume	Weight (kg)	Factors (MJ/kg)	Embodied energy (MJ)
Green roof	Waterproofing PVC	2.5 m^3	138	77.2	10654
	Asphalt (Waterproofing layer)	2.5 m^3	25000	2.6	65000
	Mineral wool (Insulation)	2.5 m^3	50	16.6	830
	PVC (Drainage layer)	2.5 m^3	138	77.2	10653
	PVC (Substrate)	2.5 m^3	138	77.2	10653
	Vegetation	2.5 m^3	-	-	-
Water roof	Reinforced concrete	205 m^3	512500	2	1025000
	Mineral wool (Thermal insulation layer)	31 m^3	620	16.6	10292
	Asphalt (Waterproof layer)	3 m^3	30000	2.6	78000
Slabs	Reinforced concrete	102 m^3	255000	2	510000
	Cement	10 m^3	18000	4.6	82800
	Sand	10 m^3	12300	0.1	1230
	Paint	2 m^3	0.4	68	27
Walls (VIP room)	Reinforced concrete (structure)	75 m^3	187500	2	375000
	Reinforced concrete (Internal wall)	11 m^3	27500	2	55000
	Cement	0.01 m^3	18	4.6	83
	Sand	0.01 m^3	12.3	0.1	1
	Paint	0.006 m^3	0.001	68	0.07
Ceiling (VIP room)	Plaster	0.1 m^3	90	1.8	162
	Paint	0.02 m^3	0.004	68	0.3
Bridge	Timber	13.3 m^3	6791	8.5	57724
	Steel (handrail)	0.66 m^3	5148	24.4	125611
Total	**2,418,721 MJ**				

Initial embodied energy of vertical circulation

	Materials	Volume	Weight (kg)	Factors (MJ/kg)	Embodied energy (MJ)
External stair	Steel (structure)	3.3 m^3	25740	24.4	628056
	Steel (handrail)	0.7 m^3	5460	24.4	133224
	Timber	77 m^3	39316	8.5	334186
External lift	Reinforced concrete (Structure)	40 m^3	100000	2	200000
	Steel	4.8 m^3	37440	24.4	913536

	Timber	0.3 m^3	153	8.5	1301
	Glass	0.54 m^3	1350	15	20250
Total	**2,230,553 MJ**				

Initial embodied energy of building services

Building Services	Heating, cooling, ventilation, lighting (6 levels)	6,144 m^2 (total construction area)	2,240 MJ/m^2 (Energy intensity)	**13,762,560 MJ**

Initial embodied energy of wind turbines

	Materials	Weight (kg) *	Factors (MJ/kg)	Embodied energy (MJ)
Wind turbine	Steel	6643	24.4	162089
	Cast iron	600	25	15000
	Glass reinforced plastic (76% of glass fibres, 24% of epoxy resin)	495	100	49500
	Copper	92	45	4140
	Paint	39	68	2652
	Aluminum	9	155	1395
	PVC	7	77.2	540.4
	Bronze	0.5	77	39
Total embodied energy		235,355 MJ		
Cable trench	Soil	110595	0.45	49768
	Stone	110595	1	110595
	PVC	1083	77.2	83608
	Sand	280228	0.1	28023
	Concrete	768	2	1536
Cable	Poly butadiene	514	83	42662
	Aluminum	829	155	128495
	Copper	289	45	13005
	PVC	761	77.2	58749
Main transformer room	Steel	14	24.4	342
	Concrete	2400	2	4800
Total embodied energy		521,583 MJ		
	In all (6 wind turbines)	**756,938*6= 4,541,630 MJ**		

* Ardente, F., Beccali, M., Cellura, M., & Brano, V. L. (2008). Energy Performances and Life Cycle Assessment of An Italian Wind Farm. *Renewable and Sustainable Energy Reviews*, *12*: 200-217.

- Recurring embodied energy for 50 years

Recurring embodied energy of the offices floor (Ground floor)

	Materials	Embodied energy (MJ)	Useful life (years)	Recurring embodied energy (MJ) (50 years)
Pile foundations	Reinforced concrete	1920000	100	0
	Damp proof membrane	1876000	100	0
Columns	Reinforced concrete	165000	50	0
	Cement (thickness: 0.005m)	11592	50	0
	Sand (thickness: 0.005m)	172	8-10	860
	Paint	6.8	100	0
Beams	Reinforced concrete	680000	50	0
	Cement (thickness: 0.005m)	49680	50	0
	Sand (thickness: 0.005m)	738	100	0
Slabs	Reinforced concrete	510000	100	0
	Cement (thickness: 0.005m)	82800	50	0
	Sand (thickness: 0.005m)	1230	50	0
	Carpet (timber)	8332992	30	8332992
	Carpet (carpet)	81840	15-20	163680
External walls	Reinforced concrete	1025000	100	0
	Mineral wool (Insulation)	4084	50	0
	Cement (thickness: 0.005m)	33120	50	0
	Sand (thickness: 0.005m)	492	50	0
	Brick (decoration)	10050	50	0
	Paint	2.8	8-10	14
Internal walls	Reinforced concrete	930000	100	0
	Cement (thickness: 0.005m)	77004	50	0
	Sand (thickness: 0.005m)	1144	50	0
	Paint	55	8-10	275

Doors	Timber	75514	30	75514
	Glass	31500	50	0
	Paint	1	8-10	5
Ceiling	Steel	114192	50	0
	Plaster	16200	50	0
Internal stair	Reinforced concrete	12500	100	0
	Brick (pavement)	1809	50	0
	Steel (handrail)	56	50	0
Internal lift	Reinforced concrete	3400	100	0
	Steel	1513	50	0
	Plastic (Decoration)	403	50	0
Total	**8,573,340 MJ**			

Recurring embodied energy of the dunes floor (First floor)

	Materials	Embodied energy (MJ)	Useful life (years)	Recurring embodied energy (MJ) (50 years)
Wall	Reinforced concrete	10240000	100	0
	Cement (thickness: 0.005m)	828000	50	0
	Sand (thickness: 0.005m)	2583	50	0
Slabs	Reinforced concrete	510000	100	0
	Cement (thickness: 0.005m)	82800	50	0
	Sand (thickness: 0.005m)	1230	50	0
	Brick	62310	50	0
Ceiling	Tile	81000	60	0
Connected bridge	Steel	100870	50	0
	Timber	36	30	36
Internal staircases	Reinforced concrete	1175000	100	0
	Cement (thickness: 0.005m)	9936	50	0
	Sand (thickness: 0.005m)	148	50	0
Maintenance structure	Steel (handrail)	1903	50	0
	Glass	7500	50	0
Total	**36 MJ**			

Recurring embodied energy of the glass floor (Second floor)

	Materials	Embodied energy (MJ)	Useful life (years)	Recurring embodied energy (MJ) (50 years)
Columns	Reinforced concrete	5246	100	0
	Cement (thickness: 0.005m)	20700	50	0
	Sand (thickness: 0.005m)	308	50	0
	Paint	14	8-10	70
Beams	Reinforced concrete	680000	100	0
	Cement (thickness: 0.005m)	49680	50	0
	Sand (thickness: 0.005m)	738	50	0
Slabs	Reinforced concrete	510000	100	0
	Cement (thickness: 0.005m)	82800	50	0
	Sand (thickness: 0.005m)	1230	50	0
	Paint	27	8-10	135
External maintenance structure	Steel	79934	50	0
	Glass	76875	50	0
Doors	Timber	1301	30	1301
	Glass	570	50	0
	Paint	0.02	8-10	1
Ceiling	Plaster	16200	50	0
	Paint	27	8-10	135
Shelves for flowers	Steel	133224	50	0
Total	**1,642 MJ**			

Recurring embodied energy of the pots floor (Third floor)

	Materials	Embodied energy (MJ)	Useful life (years)	Recurring embodied energy (MJ) (50 years)
Beams	Reinforced concrete	680000	100	0
	Cement (thickness: 0.005m)	49680	50	0
	Sand (thickness: 0.005m)	738	50	0
Slabs	Reinforced concrete	510000	100	0
	Cement (thickness: 0.005m)	82800	50	0
	Sand (thickness: 0.005m)	1230	50	0
	Paint	27	8-10	135

External walls	Plastic sheeting	15859	50	0
Internal walls	Reinforced concrete	1495000	100	0
	Cement (thickness: 0.005m)	124200	50	0
	Sand (thickness: 0.005m)	1845	50	0
	Paint	61	8-10	305
Doors	Timber	15623	30	15623
	Glass	6375	50	0
	Paint	0.01	8-10	0.05
Ceiling	Plaster	16200	50	0
	Paint	27	8-10	135
Total	**16,189 MJ**			

Recurring embodied energy of the forest floor (Fourth floor)

	Materials	Embodied energy (MJ)	Useful life (years)	Recurring embodied energy (MJ) (50 years)
Columns	Timber	486090	30	486090
Beams	Reinforced concrete	680000	100	0
	Cement (thickness: 0.005m)	49680	50	0
	Sand (thickness: 0.005m)	738	50	0
Slabs	Reinforced concrete	510000	100	0
	Cement (thickness: 0.005m)	82800	50	0
	Sand (thickness: 0.005m)	1230	50	0
	Paint	27	8-10	135
Ceiling	Plaster	16200	50	0
	Paint	27	8-10	135
Maintenance structure	Steel (handrail)	1903	50	0
	Glass	7500	50	0
Total	**486,360 MJ**			

Recurring embodied energy of the rain floor (Fifth floor)

	Materials	Embodied energy (MJ)	Useful life (years)	Recurring embodied energy (MJ) (50 years)
Columns	Reinforced concrete	115000	100	0
Beams	Reinforced concrete	680000	100	0
	Cement (thickness: 0.005m)	49680	50	0
	Sand (thickness: 0.005m)	738	50	0
Slabs	Reinforced concrete	510000	100	0
	Cement (thickness: 0.005m)	82800	50	0
	Sand (thickness: 0.005m)	1230	50	0
	Paint	27	8-10	135
Internal walls	Reinforced concrete	765000	100	0
	Cement (thickness: 0.005m)	66240	50	0
	Sand (thickness: 0.005m)	0.004	50	0
	Steel (decoration)	380640	50	0
Door	Timber	15623	30	15623
	Glass	6375	50	0
	Paint	0.01	8-10	0.05
Ceiling (internal)	Plaster	6480	50	0
	Paint	11	8-10	55
Maintenance structure	Steel	3806400	50	0
Total	**15,813 MJ**			

Recurring embodied energy of the windmills (Sixth floor)

	Materials	Embodied energy (MJ)	Useful life (years)	Recurring embodied energy (MJ) (50 years)
Green roof	Waterproofing PVC	10654	15-20	31208
	Asphalt (Waterproofing layer)	65000	20-25	130000
	Mineral wool (Insulation)	830	50	0
	PVC (Drainage layer)	10653	15-20	21306
	PVC (Substrate)	10653	15-20	21306
	Vegetation	-	-	-
Water roof	Reinforced concrete (Structure)	1025000	100	0
	Mineral wool (Thermal insulation layer)	10292	50	0
	Asphalt (Waterproof layer)	78000	20-25	156000
Slabs	Reinforced concrete	510000	100	0

	Cement (thickness: 0.005m)	82800	50	0
	Sand (thickness: 0.005m)	1230	50	0
	Paint	27	8-10	135
Walls (VIP room)	Reinforced concrete (Structure)	375000	100	0
	Reinforced concrete (Internal wall)	55000	100	0
	Cement (thickness: 0.005m)	83	50	0
	Sand (thickness: 0.005m)	1	50	0
	Paint	0.07	8-10	0.35
Ceiling (VIP room)	Plaster	162	50	0
	Paint	0.3	8-10	1.5
Bridge	Timber	57724	30	57724
	Steel (handrail)	125611	50	0
Total	**417,681 MJ**			

Recurring embodied energy of vertical circulation

	Materials	Embodied energy (MJ)	Useful life (years)	Recurring embodied energy (MJ) (50 years)
External stair	Steel (structure)	628056	50	0
	Steel (handrail)	133224	50	0
	Timber	334186	30	334186
External lift	Reinforced concrete (Structure)	200000	100	0
	Steel	913536	50	0
	Timber	1301	30	1301
	Glass	20250	50	0
Total	**335,487 MJ**			

Recurring embodied energy of building services

	Materials	Embodied energy (MJ)	Useful life (years)	Recurring embodied energy (MJ) (50 years)
Building Services	Pump, pipe …. (50%)	6,881,280	25	6,881,280
	Steel… (50%)	6,881,280	50	0
Total	**6,881,280 MJ**			

Recurring embodied energy of wind turbines

	Initial embodied energy (MJ)	Useful life (years)	Recurring embodied energy (MJ)
Wind turbines	4,541,630	20	9,083,260
Transportation of personnel inspection(7000kg of diesel)	317100 (45.3 MJ/kg)	20	792,750
Maintenance of space parts	681,245 (15% of embodied energy of wind turbines)	20	1,362,490
Total	**11,238,500 MJ**		

Total embodied energy of Dutch Pavilion (UK embodied energy coefficient)

Floor	Initial embodied energy (MJ)	Recurring embodied energy (MJ)
Offices floor (Ground floor)	16,050,091	8,573,340
Dunes floor (First floor)	13103316	36
Glass floor (Second floor)	1,658,873	1,642
Pots floor (Third floor)	2,999,665	16,189
Forest floor (Fourth floor)	1,836,195	486,360
Rain floor (Fifth floor)	6,486,244	15,813
Windmills (Sixth floor)	2,418,721	417,681
Vertical circulation	2,230,553	335,487
Building services	13,762,560	6,881,280
Wind turbines	4,541,630	11,238,500
Total	65,087,848	27,966,328
In all	93,054,176 MJ	

- Australian embodied energy coefficients
- Initial embodied energy

Initial embodied energy of the offices floor (Ground floor)

	Materials	Volume	Weight (kg)	Factors*	Embodied energy (MJ)
Pile foundations	Reinforced concrete	77m³	192,500	1.9MJ/kg**	365750
		307m³	767,500		1458250
	Damp proof membrane	10m³	14,000	0.07GJ/m²	700000
Columns	Reinforced concrete	33 m³	82,500	1.9MJ/kg**	156750
	Cement	1.4 m³	2,520	5.6MJ/kg**	14112
	Sand	1.4 m³	1,722	0.3GJ/m³	420
	Paint	0.476 m³	0.1	61.5MJ/kg**	6.15
Beams	Reinforced concrete	136 m³	340,000	1.9MJ/kg**	646000
	Cement	6 m³	10,800	5.6MJ/kg**	60480
	Sand	6 m³	7,380	0.3GJ/m³	1800
Slabs	Reinforced concrete	102 m³	255,000	1.9MJ/kg**	484500
	Cement	10 m³	18,000	5.6MJ/kg**	100800
	Sand	10 m³	12,300	0.3GJ/m³	3000
	Carpet (timber)	1,920 m³	980,352	2.0MJ/kg **	1960704
	Carpet (carpet)	10 m³	1,100	0.41GJ/m²	4100000
External walls	Reinforced concrete	205 m³	512,500	1.9MJ/kg**	973750
	Mineral wool (Insulation)	12.3 m³	246	16.8MJ/kg	4132.8
	Cement	4 m³	7,200	5.6MJ/kg**	40320
	Sand	4 m³	4,920	0.3GJ/m³	1200
	Brick (decoration)	5 m³	3,350	3MJ/kg***	10050
	Paint	0.204 m³	0.04	61.5MJ/kg**	2.46
Internal walls	Reinforced concrete	186 m³	465,000	1.9MJ/kg**	883500
	Cement	9.3 m³	16,740	5.6MJ/kg**	93744
	Sand	9.3 m³	11,439	0.3GJ/m³	2790
	Paint	3.712 m³	0.8	61.5MJ/kg**	49.2
Doors	Timber	17.4 m³	8,884	2.0MJ/kg **	17768
	Glass	0.84 m³	2,100	12.7MJ/kg**	26670
	Paint	0.07 m³	0.014	61.5MJ/kg**	0.861
Ceiling	Steel	0.6 m³	4,680	36.8MJ/kg	172224
	Plaster	10 m³	9000	4.4MJ/kg**	39600
Internal stair	Reinforced concrete	2.5 m³	6,250	1.9MJ/kg**	11875
	Brick (pavement)	0.9 m³	603	3MJ/kg***	1809
	Steel (handrail)	0.0003 m³	2.3	36.8MJ/kg	84.64
Internal lift	Reinforced concrete	0.68 m³	1700	1.9MJ/kg**	3230
	Steel	0.008 m³	62	36.8MJ/kg	2281.6
	Plastic (Decoration)	0.002 m³	5	90MJ/kg **	450
Total	**12,338,104 MJ**				

* Treloar, G. J. (1994). *Energy analysis of the construction of office buildings.* Masters thesis. Faculty of Science and Technology, Deakin University, pp 58-59
** Lawson, B. (1996). *Buildings Materials, Energy and the Environment: Towards Ecological Sustainable Development.* Canberra: RAIA.
*** Hammond, G., & Jones, C. (2008). *Inventory of Carbon and Energy (ICE), Version 1.6a, Sustainable Energy Research Team (SERT).* Department of Mechanical Engineering, University of Bath, UK.

Initial embodied energy of the dunes floor (First floor)

	Materials	Volume	Weight (kg)	Factors	Embodied energy (MJ)
Wall	Reinforced concrete	2,048 m³	5,120,000	1.9MJ/kg**	9728000
	Cement	10 m³	18,000	5.6MJ/kg**	100800
	Sand	21 m³	25,830	0.3GJ/m³	6300
Slabs	Reinforced concrete	102 m³	255,000	1.9MJ/kg**	484500
	Cement	10 m³	18,000	5.6MJ/kg**	100800
	Sand	10 m³	12,300	0.3GJ/m³	3000
	Brick	31 m³	20,770	3MJ/kg***	62310
Ceiling	Tile	5 m³	9,000	0.78GJ/m²	78000
Connected bridge	Steel	0.53 m³	4134	36.8MJ/kg	152131.2
	Timber (510.6 kg/m³)	0.7 m³	4.2	2.0MJ/kg **	8.4
Internal staircases	Reinforced concrete	235 m³	587,500	1.9MJ/kg**	1116250
	Cement	1.2 m³	2,160	5.6MJ/kg**	12096
	Sand	1.2 m³	1,476	0.3GJ/m³	360
Maintenance structure	Steel (handrail)	0.01 m³	78	36.8MJ/kg	2870.4
	Glass	0.2 m³	500	12.7MJ/kg**	6350

Total	**11,853,776 MJ**

Initial embodied energy of the glass floor (Second floor)

	Materials	Volume	Weight (kg)	Factors	Embodied energy (MJ)
Columns	Reinforced concrete	123 m^3	2623	1.9MJ/kg**	4983.7
	Cement	2.5 m^3	4500	5.6MJ/kg**	25200
	Sand	2.5 m^3	3075	0.3GJ/m^3	750
	Paint	1 m^3	0.2	61.5MJ/kg**	12.3
Beams	Reinforced concrete	136 m^3	340,000	1.9MJ/kg**	646000
	Cement	6 m^3	10800	5.6MJ/kg**	60480
	Sand	6 m^3	7380	0.3GJ/m^3	1800
Slabs	Reinforced concrete	102 m^3	255000	1.9MJ/kg**	484500
	Cement	10 m^3	18000	5.6MJ/kg**	100800
	Sand	10 m^3	12300	0.3GJ/m^3	3000
	Paint	2 m^3	0.4	61.5MJ/kg**	24.6
External maintenance structure	Steel	0.42 m^3	3276	36.8MJ/kg	120556.8
	Glass	2.05 m^3	5125	12.7MJ/kg**	65087.5
Doors	Timber	0.3 m^3	153	2.0MJ/kg **	306
	Glass	0.015 m^3	38	12.7MJ/kg**	482.6
	Paint	0.0012 m^3	0.0003	61.5MJ/kg**	0.01845
Ceiling	Plaster	10 m^3	9000	4.4MJ/kg**	39600
	Paint	2 m^3	0.4	61.5MJ/kg**	24.6
Shelves for flowers	Steel	0.7 m^3	5460	36.8MJ/kg	200928
Total	**1,754,536 MJ**				

Initial embodied energy of the pots floor (Third floor)

	Materials	Volume	Weight (kg)	Factors	Embodied energy (MJ)
Beams	Reinforced concrete	136 m^3	340000	1.9MJ/kg**	646000
	Cement	6 m^3	10800	5.6MJ/kg**	60480
	Sand	6 m^3	7380	0.3GJ/m^3	1800
Slabs	Reinforced concrete	102 m^3	255000	1.9MJ/kg**	484500
	Cement	10 m^3	18000	5.6MJ/kg**	100800
	Sand	10 m^3	12300	0.3GJ/m^3	3000
	Paint	2 m^3	0.4	61.5MJ/kg**	24.6
External walls	Plastic sheeting	0.819 m^3	197	90MJ/kg**	17730
Internal walls	Reinforced concrete	299 m^3	747500	1.9MJ/kg**	1420250
	Cement	15 m^3	27000	5.6MJ/kg**	151200
	Sand	15 m^3	18450	0.3GJ/m^3	4500
	Paint	4.3 m^3	0.9	61.5MJ/kg**	55.35
Doors	Timber	3.6 m^3	1838	2.0MJ/kg **	2676
	Glass	0.17 m^3	425	12.7MJ/kg**	5397.5
	Paint	0.001 m^3	0.0002	61.5MJ/kg**	0.0123
Ceiling	Plaster	10 m^3	9000	4.4MJ/kg**	39600
	Paint	2 m^3	0.4	61.5MJ/kg**	24.6
Total	**2,938,038 MJ**				

Initial embodied energy of the forest floor (Fourth floor)

	Materials	Volume	Weight (kg)	Factors	Embodied energy (MJ)
Columns	Timber	112 m^3	57187	2.0MJ/kg **	114374
Beams	Reinforced concrete	136 m^3	340000	1.9MJ/kg **	646000
	Cement	6 m^3	10800	5.6MJ/kg **	60480
	Sand	6 m^3	7380	0.3GJ/m^3	1800
Slabs	Reinforced concrete	102 m^3	255000	1.9MJ/kg **	484500
	Cement	10 m^3	18000	5.6MJ/kg **	100800
	Sand	10 m^3	12300	0.3GJ/m^3	3000
	Paint	2 m^3	0.4	61.5MJ/kg**	24.6
Ceiling	Plaster	10 m^3	9000	4.4MJ/kg **	39600
	Paint	2 m^3	0.4	61.5MJ/kg**	24.6
Maintenance structure	Steel (handrail)	0.01 m^3	78	36.8MJ/kg	2870.4
	Glass	0.2 m^3	500	12.7MJ/kg**	6350
Total	**1,459,824 MJ**				

Initial embodied energy of the rain floor (Fifth floor)

	Materials	Volume	Weight (kg)	Factors	Embodied energy (MJ)
Columns	Reinforced concrete	23 m^3	57,500	1.9MJ/kg**	109250
Beams	Reinforced concrete	136 m^3	340,000	1.9MJ/kg**	646000
	Cement	6 m^3	10,800	5.6MJ/kg **	60480
	Sand	6 m^3	7,380	0.3GJ/m^3	1800
Slabs	Reinforced concrete	102 m^3	255,000	1.9MJ/kg**	484500
	Cement	10 m^3	18,000	5.6MJ/kg **	100800
	Sand	10 m^3	12,300	0.3GJ/m^3	3000
	Paint	2 m^3	0.4	61.5MJ/kg**	24.6
Internal walls	Reinforced concrete	153 m^3	382,500	1.9MJ/kg**	726750
	Cement	8 m^3	14,400	5.6MJ/kg **	80640
	Sand	8 m^3	0.04	0.3GJ/m^3	2400
	Steel (decoration)	2 m^3	15,600	36.8MJ/kg	574080
Door	Timber	3.6 m^3	1838	2.0MJ/kg **	3676
	Glass	0.17 m^3	425	12.7MJ/kg**	5397.5
	Paint	0.001 m^3	0.0002	61.5MJ/kg**	0.0123
Ceiling (internal)	Plaster	4 m^3	3600	4.4MJ/kg**	15840
	Paint	0.8 m^3	0.16	61.5MJ/kg**	9.84
Maintenance structure	Steel	20 m^3	156000	36.8MJ/kg	5740800
Total	**8,555,448 MJ**				

Initial embodied energy of the windmills (Sixth floor)

	Materials	Volume	Weight (kg)	Factors	Embodied energy (MJ)
Green roof	Waterproofing PVC	2.5 m^3	138	80 MJ/kg**	11040
	Asphalt (Waterproofing layer)	2.5 m^3	25000	2.6 MJ/kg***	65000
	Mineral wool (Insulation)	2.5 m^3	50	16.8MJ/kg	840
	PVC (Drainage layer)	2.5 m^3	138	80 MJ/kg**	11040
	PVC (Substrate)	2.5 m^3	138	80 MJ/kg**	11040
	Vegetation	2.5 m^3	-	-	-
Water roof	Reinforced concrete (Structure)	205 m^3	512500	1.9MJ/kg**	973750
	Mineral wool (Thermal insulation layer)	31 m^3	620	16.8MJ/kg	10416
	Asphalt (Waterproof layer)	3 m^3	30000	2.6 MJ/kg***	78000
Slabs	Reinforced concrete	102 m^3	255000	1.9MJ/kg**	484500
	Cement	10 m^3	18000	5.6MJ/kg **	100800
	Sand	10 m^3	12300	0.3GJ/m^3	3000
	Paint	2 m^3	0.4	61.5MJ/kg**	24.6
Walls (VIP room)	Reinforced concrete (Structure)	75 m^3	187500	1.9MJ/kg**	356250
	Reinforced concrete (Internal wall)	11 m^3	27500	1.9MJ/kg**	52250
	Cement	0.01 m^3	18	5.6MJ/kg **	100.8
	Sand	0.01 m^3	12.3	0.3GJ/m^3	3
	Paint	0.006 m^3	0.001	61.5MJ/kg**	0.0615
Ceiling (VIP room)	Plaster	0.1 m^3	90	4.4MJ/kg**	396
	Paint	0.02 m^3	0.004	61.5MJ/kg**	0.246
Bridge	Timber	13.3 m^3	6791	2.0MJ/kg **	13582
	Steel (handrail)	0.66 m^3	5148	36.8MJ/kg	189446.4
Total	**2,361,479 MJ**				

Initial embodied energy of vertical circulation

	Materials	Volume	Weight (kg)	Factors	Embodied energy (MJ)
External stair	Steel (structure)	3.3 m^3	25740	36.8MJ/kg	947232
	Steel (handrail)	0.7 m^3	5460	36.8MJ/kg	200928
	Timber	77 m^3	39316	2.0MJ/kg **	78632
External lift	Reinforced concrete (Structure)	40 m^3	100000	1.9MJ/kg**	190000
	Steel	4.8 m^3	37440	36.8MJ/kg	1377792
	Timber	0.3 m^3	153	2.0MJ/kg **	306
	Glass	0.54 m^3	1350	12.7MJ/kg**	17145
Total	**2,812,035 MJ**				

Initial embodied energy of building services

Building Services	Heating, cooling, ventilation, lighting (6 levels)	6,144 m^2 (total construction area)	2,240 MJ/m^2 (Energy intensity)	**13,762,560 MJ**

Initial embodied energy of wind turbines

	Materials	Weight (kg)	Factors	Embodied energy (MJ)	
Wind turbine	Steel	6643	36.8MJ/kg	244462.4	1466774
	Cast iron	600	25 MJ/kg***	15000	90000
	Glass reinforced plastic (76% of glass fibres, 24% of epoxy resin)	495	100 MJ/kg***	49500	297000
	Copper	92	45 MJ/kg***	4140	24840
	Paint	39	61.5MJ/kg**	2398.5	14391
	Aluminium	9	170MJ/kg**	1530	9180
	PVC	7	80 MJ/kg**	560	3360
	Bronze	0.5	77 MJ/kg***	39	234
Total embodied energy	317,630 MJ				
Cable trench	Soil	110595	0.45 MJ/kg***	49768	298608
	Stone	110595	1 MJ/kg***	110595	663570
	PVC	1083	80 MJ/kg**	86640	519840
	Sand	280228	0.1 MJ/kg***	28023	168138
	Concrete	768	1.9MJ/kg **	1459.2	8755
Cable	Poly butadiene	514	83MJ/kg***	42662	255972
	Aluminium	829	170MJ/kg**	140930	845580
	Copper	289	45 MJ/kg***	13005	78030
	PVC	761	80 MJ/kg**	60880	365280
Main transformer room	Steel	14	36.8MJ/kg	515.2	3091
	Concrete	2400	1.9MJ/kg **	4560	27360
Total embodied energy	539,037 MJ				
	In all (6 wind turbines)	**856,667*6= 5,140,002 MJ**			

- Recurring embodied energy for 50 years

Recurring embodied energy of the offices floor (Ground floor)

	Materials	Embodied energy (MJ)	Useful life (years)	Recurring embodied energy (MJ) (50 years)
Pile foundations	Reinforced concrete	365750	100	0
		1458250	100	0
	Damp proof membrane	700000	100	0
Columns	Reinforced concrete	156750	50	0
	Cement (thickness: 0.005m)	14112	50	0
	Sand (thickness: 0.005m)	420	8-10	
	Paint	6.15	100	0
Beams	Reinforced concrete	646000	50	0
	Cement (thickness: 0.005m)	60480	50	0
	Sand (thickness: 0.005m)	1800	100	0
Slabs	Reinforced concrete	484500	100	0
	Cement (thickness: 0.005m)	100800	50	0
	Sand (thickness: 0.005m)	3000	50	0
	Carpet (timber)	1960704	30	1960704
	Carpet (carpet)	4100000	15-20	8200000
External walls	Reinforced concrete	973750	100	0
	Mineral wool (Insulation)	4132.8	50	0
	Cement (thickness: 0.005m)	40320	50	0
	Sand (thickness: 0.005m)	1200	50	0
	Brick (decoration)	10050	50	0
	Paint	2.46	8-10	12
Internal walls	Reinforced concrete	883500	100	0
	Cement (thickness: 0.005m)	93744	50	0
	Sand (thickness: 0.005m)	2790	50	0
	Paint	49.2	8-10	250
Doors	Timber	17768	30	17768
	Glass	26670	50	0
	Paint	0.861	8-10	5
Ceiling	Steel	172224	50	0
	Plaster	39600	50	0

Internal stair	Reinforced concrete	11875	100	0
	Brick (pavement)	1809	50	0
	Steel (handrail)	84.64	50	0
Internal lift	Reinforced concrete	3230	100	0
	Steel	2281.6	50	0
	Plastic (Decoration)	450	50	0
Total	**10,178,739 MJ**			

Recurring embodied energy of the dunes floor (First floor)

	Materials	Embodied energy (MJ)	Useful life (years)	Recurring embodied energy (MJ) (50 years)
Wall	Reinforced concrete	9728000	100	0
	Cement (thickness: 0.005m)	100800	50	0
	Sand (thickness: 0.005m)	6300	50	0
Slabs	Reinforced concrete	484500	100	0
	Cement (thickness: 0.005m)	100800	50	0
	Sand (thickness: 0.005m)	3000	50	0
	Brick	62310	50	0
Ceiling	Tile	78000	60	0
Connected bridge	Steel	152131.2	50	0
	Timber	8.4	30	8.4
Internal staircases	Reinforced concrete	1116250	100	0
	Cement (thickness: 0.005m)	12096	50	0
	Sand (thickness: 0.005m)	360	50	0
Maintenance structure	Steel (handrail)	2870.4	50	0
	Glass	6350	50	0
Total	**8 MJ**			

Recurring embodied energy of the glass floor (Second floor)

	Materials	Embodied energy (MJ)	Useful life (years)	Recurring embodied energy (MJ) (50 years)
Columns	Reinforced concrete	4983.7	100	0
	Cement (thickness: 0.005m)	25200	50	0
	Sand (thickness: 0.005m)	750	50	0
	Paint	12.3	8-10	60
Beams	Reinforced concrete	646000	100	0
	Cement (thickness: 0.005m)	60480	50	0
	Sand (thickness: 0.005m)	1800	50	0
Slabs	Reinforced concrete	484500	100	0
	Cement (thickness: 0.005m)	100800	50	0
	Sand (thickness: 0.005m)	3000	50	0
	Paint	24.6	8-10	125
External maintenance structure	Steel	120556.8	50	0
	Glass	65087.5	50	0
Doors	Timber	306	30	306
	Glass	482.6	50	0
	Paint	0.01845	8-10	0.1
Ceiling	Plaster	39600	50	0
	Paint	24.6	8-10	125
Shelves for flowers	Steel	200928	50	0
Total	**616 MJ**			

Recurring embodied energy of the pots floor (Third floor)

	Materials	Embodied energy (MJ)	Useful life (years)	Recurring embodied energy (MJ) (50 years)
Beams	Reinforced concrete	646000	100	0
	Cement (thickness: 0.005m)	60480	50	0
	Sand (thickness: 0.005m)	1800	50	0
Slabs	Reinforced concrete	484500	100	0
	Cement (thickness: 0.005m)	100800	50	0
	Sand (thickness: 0.005m)	3000	50	0
	Paint	24.6	8-10	125
External walls	Plastic sheeting	17730	50	0
Internal walls	Reinforced concrete	1420250	100	0
	Cement (thickness: 0.005m)	151200	50	0
	Sand (thickness: 0.005m)	4500	50	0
	Paint	55.35	8-10	275

Doors	Timber	2676	30	2676
	Glass	5397.5	50	0
	Paint	0.0123	8-10	0.05
Ceiling	Plaster	39600	50	0
	Paint	24.6	8-10	125
Total	**3,201 MJ**			

Recurring embodied energy of the forest floor (Fourth floor)

	Materials	Embodied energy (MJ)	Useful life (years)	Recurring embodied energy (MJ) (50 years)
Columns	Timber	114374	30	486090
Beams	Reinforced concrete	646000	100	0
	Cement (thickness: 0.005m)	60480	50	0
	Sand (thickness: 0.005m)	1800	50	0
Slabs	Reinforced concrete	484500	100	0
	Cement (thickness: 0.005m)	100800	50	0
	Sand (thickness: 0.005m)	3000	50	0
	Paint	24.6	8-10	125
Ceiling	Plaster	39600	50	0
	Paint	24.6	8-10	125
Maintenance structure	Steel (handrail)	2870.4	50	0
	Glass	6350	50	0
Total	**486,340 MJ**			

Recurring embodied energy of the rain floor (Fifth floor)

	Materials	Embodied energy (MJ)	Useful life (years)	Recurring embodied energy (MJ) (50 years)
Columns	Reinforced concrete	109250	100	0
Beams	Reinforced concrete	646000	100	0
	Cement (thickness: 0.005m)	60480	50	0
	Sand (thickness: 0.005m)	1800	50	0
Slabs	Reinforced concrete	484500	100	0
	Cement (thickness: 0.005m)	100800	50	0
	Sand (thickness: 0.005m)	3000	50	0
	Paint	24.6	8-10	125
Internal walls	Reinforced concrete	726750	100	0
	Cement (thickness: 0.005m)	80640	50	0
	Sand (thickness: 0.005m)	2400	50	0
	Steel (decoration)	574080	50	0
Door	Timber	3676	30	3676
	Glass	5397.5	50	0
	Paint	0.0123	8-10	0.05
Ceiling (internal)	Plaster	15840	50	0
	Paint	9.84	8-10	50
Maintenance structure	Steel	5740800	50	0
Total	**3,851 MJ**			

Recurring embodied energy of the windmills (Sixth floor)

	Materials	Embodied energy (MJ)	Useful life (years)	Recurring embodied energy (MJ) (50 years)
Green roof	Waterproofing PVC	11040	15-20	22,080
	Asphalt (Waterproofing layer)	65000	20-25	130,000
	Mineral wool (Insulation)	840	50	0
	PVC (Drainage layer)	11040	15-20	22,080
	PVC (Substrate)	11040	15-20	22,080
	Vegetation	-	-	-
Water roof	Reinforced concrete (Structure)	973750	100	0
	Mineral wool (Thermal insulation layer)	10416	50	0
	Asphalt (Waterproof layer)	78000	20-25	156,000
Slabs	Reinforced concrete	484500	100	0
	Cement (thickness: 0.005m)	100800	50	0
	Sand (thickness: 0.005m)	3000	50	0
	Paint	24.6	8-10	125
Walls (VIP room)	Reinforced concrete (Structure)	356250	100	0
	Reinforced concrete (Internal wall)	52250	100	0

	Cement (thickness: 0.005m)	100.8	50	0
	Sand (thickness: 0.005m)	3	50	0
	Paint	0.0615	8-10	0.3
Ceiling (VIP room)	Plaster	396	50	0
	Paint	0.246	8-10	1.25
Bridge	Timber	13582	30	13582
	Steel (handrail)	189446.4	50	0
Total	**365,949 MJ**			

Recurring embodied energy of vertical circulation

	Materials	Embodied energy (MJ)	Useful life (years)	Recurring embodied energy (MJ) (50 years)
External stair	Steel (structure)	947232	50	0
	Steel (handrail)	200928	50	0
	Timber	78632	30	78632
External lift	Reinforced concrete (Structure)	190000	100	0
	Steel	1377792	50	0
	Timber	306	30	306
	Glass	17145	50	0
Total	**78,938 MJ**			

Recurring embodied energy of building services

	Materials	Embodied energy (MJ)	Useful life (years)	Recurring embodied energy (MJ) (50 years)
Building Services	Pump, pipe …. (50%)	6,881,280	25	6,881,280
	Steel… (50%)	6,881,280	50	0
Total	**6,881,280 MJ**			

Recurring embodied energy of wind turbines

	Embodied energy (MJ)	Useful life (years)	Recurring embodied energy (MJ)
Wind turbines	5,140,002	20	10,280,004
Transportation of personnel inspection(7000kg of diesel)	3,171,00 (45.3 MJ/kg)	20	792,750
Maintenance of space parts	771,000 (15% of embodied energy of wind turbines)	20	1,542,000
Total	**12,614,754 MJ**		

Total embodied energy of Dutch Pavilion (Australian embodied energy coefficient)

Floor	Initial embodied energy (MJ)	Recurring embodied energy (MJ)
Offices floor (Ground floor)	12,338,104	10,178,739
Dunes floor (First floor)	11,853,776	8
Glass floor (Second floor)	1,754,536	616
Pots floor (Third floor)	2,938,038	3,201
Forest floor (Fourth floor)	1,459,824	486,340
Rain floor (Fifth floor)	8,555,448	3,851
Windmills (Sixth floor)	2,361,479	365,949
Vertical circulation	2,812,035	78,938
Building services	13,762,560	6,881,280
Wind turbines	5,140,002	12,614,754
Total	62,975,802	30,613,676
In all	93,589,478 MJ	

- German embodied energy coefficients

Initial embodied energy of the offices floor (Ground floor)

	Materials	Volume	Weight (kg)	Factors (MJ/kg) * ** ***	Embodied energy (MJ)
Pile foundations	Reinforced concrete	77m^3	192,500	2.54	488950
		307m^3	767,500		1949450
	Damp proof membrane	10m^3	14,000	134****	1876000
Columns	Reinforced concrete	33 m^3	82,500	2.54	209550
	Cement	1.4 m^3	2,520	4.4	11088
	Sand	1.4 m^3	1,722	0.017	29
	Paint	0.476 m^3	0.1	68 ****	6.8
Beams	Reinforced concrete	136 m^3	340,000	2.54	863600

	Cement	6 m³	10,800	4.4	47520
	Sand	6 m³	7,380	0.017	126
Slabs	Reinforced concrete	102 m³	255,000	2.54	647700
	Cement	10 m³	18,000	4.4	79200
	Sand	10 m³	12,300	0.017	209
	Carpet (timber)	1,920 m³	980,352	5.56	5450757
	Carpet (carpet)	10 m³	1,100	74.4 ****	81840
External walls	Reinforced concrete	205 m³	512,500	2.54	1301750
	Mineral wool (Insulation)	12.3 m³	246	5	1230
	Cement	4 m³	7,200	4.4	31680
	Sand	4 m³	4,920	0.017	84
	Brick (decoration)	5 m³	3,350	2.22	7437
	Paint	0.204 m³	0.04	68 ****	2.8
Internal walls	Reinforced concrete	186 m³	465,000	2.54	1181100
	Cement	9.3 m³	16,740	4.4	73656
	Sand	9.3 m³	11,439	0.017	195
	Paint	3.712 m³	0.8	68 ****	55
Doors	Timber	17.4 m³	8,884	5.56	49398
	Glass	0.84 m³	2,100	15	31500
	Paint	0.07 m³	0.014	68 ****	1
Ceiling	Steel	0.6 m³	4,680	15	70200
	Plaster	10 m³	9000	3.39	30510
Internal stair	Reinforced concrete	2.5 m³	6,250	2.54	15875
	Brick (pavement)	0.9 m³	603	2.22	1339
	Steel (handrail)	0.0003 m³	2.3	15	35
Internal lift	Reinforced concrete	0.68 m³	1700	2.54	4318
	Steel	0.008 m³	62	15	930
	Plastic (Decoration)	0.002 m³	5	80.5 ****	403
Total	**14,507,725 MJ**				

* Anon. (1994). *BEW Forschungsprojekt: Energie – und Stoffbilanzen von Gebauden.* Schlussbericht: Universitat Karlsruhe.
** Eyerer, P., Reinhardt, H., Kreissig, J., Kummel, J., Betz, M., Baitz, M., Hutter, V., Saur, K., & Schoech, H. (2000). *Okologische Bilanzierung von Baustoffen und Gebauden, Wege zu einer ganzheitlichen Bilanzierung.* Birkhauser Verlag Basel.
*** Pohlmann, C. M. (2002). *Okologische Betrachtung fur den Hausbau – Ganzheitliche Energie – und Kohlendioxidbilanzen fur zwei verschiedene Holzhauskonstruktionen.* PhD thesis. zur Erlangung des Doktorgrades, an der Universitat Hamburg, Fachbereich Biologie.
**** Hammond, G., & Jones, C. (2008). *Inventory of Carbon and Energy (ICE), Version 1.6a, Sustainable Energy Research Team (SERT).* Department of Mechanical Engineering, University of Bath, UK.

Initial embodied energy of the dunes floor (First floor)

	Materials	Volume	Weight (kg)	Factors (MJ/kg) * ** ***	Embodied energy (MJ)
Wall	Reinforced concrete	2,048 m³	5,120,000	2.54	13004800
	Cement	10 m³	18,000	4.4	79200
	Sand	21 m³	25,830	0.017	439
Slabs	Reinforced concrete	102 m³	255,000	2.54	647700
	Cement	10 m³	18,000	4.4	79200
	Sand	10 m³	12,300	0.017	209
	Brick	31 m³	20,770	2.22	46109
Ceiling	Tile	5 m³	9,000	2.29	20610
Connected bridge	Steel	0.53 m³	4134	15	62010
	Timber	0.7 m³	4.2	5.56	23.4
Internal staircases	Reinforced concrete	235 m³	587,500	2.54	1492250
	Cement	1.2 m³	2,160	4.4	9504
	Sand	1.2 m³	1,476	0.017	25
Maintenance structure	Steel (handrail)	0.01 m³	78	15	1170
	Glass	0.2 m³	500	15	7500
Total	**15,450,750 MJ**				

Initial embodied energy of the glass floor (Second floor)

	Materials	Volume	Weight (kg)	Factors (MJ/kg) * ** ***	Embodied energy (MJ)
Columns	Reinforced concrete	123 m³	2623	2.54	6662

	Cement	2.5 m³	4500	4.4	19800
	Sand	2.5 m³	3075	0.017	53
	Paint	1 m³	0.2	68 ****	14
Beams	Reinforced concrete	136 m³	340,000	2.54	863600
	Cement	6 m³	10800	4.4	47520
	Sand	6 m³	7380	0.017	126
Slabs	Reinforced concrete	102 m³	255000	2.54	647700
	Cement	10 m³	18000	4.4	79200
	Sand	10 m³	12300	0.017	209
	Paint	2 m³	0.4	68 ****	27
External maintenance structure	Steel	0.42 m³	3276	15	52416
	Glass	2.05 m³	5125	15	76875
Doors	Timber	0.3 m³	153	5.56	852
	Glass	0.015 m³	38	15	570
	Paint	0.0012 m³	0.0003	68 ****	0.02
Ceiling	Plaster	10 m³	9000	3.39	30510
	Paint	2 m³	0.4	68 ****	27
Shelves for flowers	Steel	0.7 m³	5460	15	81900
Total	**1,908,061 MJ**				

Initial embodied energy of the pots floor (Third floor)

	Materials	Volume	Weight (kg)	Factors (MJ/kg) * ** ***	Embodied energy (MJ)
Beams	Reinforced concrete	136 m³	340000	2.54	863600
	Cement	6 m³	10800	4.4	47520
	Sand	6 m³	7380	0.017	126
Slabs	Reinforced concrete	102 m³	255000	2.54	647700
	Cement	10 m³	18000	4.4	79200
	Sand	10 m³	12300	0.017	209
	Paint	2 m³	0.4	68 ****	27
External walls	Plastic sheeting	0.819 m³	197	80.5 ****	15859
Internal walls	Reinforced concrete	299 m³	747500	2.54	1898650
	Cement	15 m³	27000	4.4	118800
	Sand	15 m³	18450	0.017	314
	Paint	4.3 m³	0.9	68 ****	61
Doors	Timber	3.6 m³	1838	5.56	10219
	Glass	0.17 m³	425	15	6375
	Paint	0.001 m³	0.0002	68 ****	0.01
Ceiling	Plaster	10 m³	9000	3.39	30510
	Paint	2 m³	0.4	68 ****	27
Total	**3,719,197 MJ**				

Initial embodied energy of the forest floor (Fourth floor)

	Materials	Volume	Weight (kg)	Factors (MJ/kg) * ** ***	Embodied energy (MJ)
Columns	Timber	112 m³	57187	5.56	317960
Beams	Reinforced concrete	136 m³	340000	2.54	863600
	Cement	6 m³	10800	4.4	47520
	Sand	6 m³	7380	0.017	126
Slabs	Reinforced concrete	102 m³	255000	2.54	647700
	Cement	10 m³	18000	4.4	79200
	Sand	10 m³	12300	0.017	209
	Paint	2 m³	0.4	68 ****	27
Ceiling	Plaster	10 m³	9000	3.39	30510
	Paint	2 m³	0.4	68 ****	27
Maintenance structure	Steel (handrail)	0.01 m³	78	15	1170
	Glass	0.2 m³	500	15	7500
Total	**1,995,549 MJ**				

Initial embodied energy of the rain floor (Fifth floor)

	Materials	Volume	Weight (kg)	Factors (MJ/kg) * ** ***	Embodied energy (MJ)
Columns	Reinforced concrete	23 m³	57,500	2.54	146050
Beams	Reinforced concrete	136 m³	340,000	2.54	863600

	Cement	6 m^3	10,800	4.4	47520
	Sand	6 m^3	7,380	0.017	126
Slabs	Reinforced concrete	102 m^3	255,000	2.54	647700
	Cement	10 m^3	18,000	4.4	79200
	Sand	10 m^3	12,300	0.017	209
	Paint	2 m^3	0.4	68 ****	27
Internal walls	Reinforced concrete	153 m^3	382,500	2.54	971550
	Cement	8 m^3	14,400	4.4	63360
	Sand	8 m^3	0.04	0.017	0.0007
	Steel (decoration)	2 m^3	15,600	15	234000
Door	Timber	3.6 m^3	1838	5.56	10219
	Glass	0.17 m^3	425	15	6375
	Paint	0.001 m^3	0.0002	68 ****	0.01
Ceiling (internal)	Plaster	4 m^3	3600	3.39	12204
	Paint	0.8 m^3	0.16	68 ****	11
Maintenance structure	Steel	20 m^3	156000	15	2340000
Total	**5,422,151 MJ**				

Initial embodied energy of the windmills (Sixth floor)

	Materials	Volume	Weight (kg)	Factors (MJ/kg) * ** ***	Embodied energy (MJ)
Green roof	Waterproofing PVC	2.5 m^3	138	77.2 ****	10654
	Asphalt (Waterproofing layer)	2.5 m^3	25000	2.6 ****	65000
	Mineral wool (Insulation)	2.5 m^3	50	5	250
	PVC (Drainage layer)	2.5 m^3	138	77.2 ****	10653
	PVC (Substrate)	2.5 m^3	138	77.2 ****	10653
	Vegetation	2.5 m^3	-	-	-
Water roof	Reinforced concrete (Structure)	205 m^3	512500	2.54	1301750
	Mineral wool (Thermal insulation layer)	31 m^3	620	5	3100
	Asphalt (Waterproof layer)	3 m^3	30000	2.6 ****	78000
Slabs	Reinforced concrete	102 m^3	255000	2.54	647700
	Cement	10 m^3	18000	4.4	79200
	Sand	10 m^3	12300	0.017	209
	Paint	2 m^3	0.4	68 ****	27
Walls (VIP room)	Reinforced concrete (Structure)	75 m^3	187500	2.54	476250
	Reinforced concrete (Internal wall)	11 m^3	27500	2.54	69850
	Cement	0.01 m^3	18	4.4	79
	Sand	0.01 m^3	12.3	0.017	0.2
	Paint	0.006 m^3	0.001	68 ****	0.07
Ceiling (VIP room)	Plaster	0.1 m^3	90	3.39	305
	Paint	0.02 m^3	0.004	68 ****	0.3
Bridge	Timber	13.3 m^3	6791	5.56	37758
	Steel (handrail)	0.66 m^3	5148	15	77220
Total	**2,868,659 MJ**				

Initial embodied energy of vertical circulation

	Materials	Volume	Weight (kg)	Factors (MJ/kg) * ** ***	Embodied energy (MJ)
External stair	Steel (structure)	3.3 m^3	25740	15	386100
	Steel (handrail)	0.7 m^3	5460	15	81900
	Timber	77 m^3	39316	5.56	218597
External lift	Reinforced concrete (Structure)	40 m^3	100000	2.54	254000
	Steel	4.8 m^3	37440	15	561600
	Timber	0.3 m^3	153	5.56	851
	Glass	0.54 m^3	1350	15	20250
Total	**1,523,298 MJ**				

Initial embodied energy of building services

Building Services	Heating, cooling, ventilation, lighting (6 levels)	6,144 m^2 (total construction area)	2,240 MJ/m^2 (Energy intensity)	**13,762,560 MJ**

Initial embodied energy of wind turbines

	Materials	Weight (kg) [5]	Factors (MJ/kg) [1-4]	Embodied energy (MJ)	
Wind turbine	Steel	6643	15	99645	1285421
	Cast iron	600	25	15000	193500
	Glass reinforced plastic (76% of glass fibres, 24% of epoxy resin)	495	100	49500	638550
	Copper	92	50	4600	59340
	Paint	39	68	2652	34211
	Aluminium	9	155	1395	17996
	PVC	7	77.2	540.4	6971
	Bronze	0.5	77	39	503
Total embodied energy	173,371 MJ				
Cable trench	Soil	110595	0.45	49768	642007
	Stone	110595	1	110595	1426675
	PVC	1083	77.2	83608	1078543
	Sand	280228	0.017	4764	61456
	Concrete	768	2	1536	19814
Cable	Poly butadiene	514	83	42662	550340
	Aluminium	829	155	128495	1657586
	Copper	289	50	14450	186405
	PVC	761	77.2	58749	757862
Main transformer room	Steel	14	15	210	2709
	Concrete	2400	2	4800	61920
Total embodied energy	499,637 MJ				
	In all (6 wind turbines)	**4,038,048 MJ**			

[1] Anon. (1994). *BEW Forschungsprojekt: Energie – und Stoffbilanzen von Gebauden.* Schlussbericht: Universitat Karlsruhe.
[2] Eyerer, P., Reinhardt, H., Kreissig, J., Kummel, J., Betz, M., Baitz, M., Hutter, V., Saur, K., & Schoech, H. (2000). *Okologische Bilanzierung von Baustoffen und Gebauden, Wege zu einer ganzheitlichen Bilanzierung.* Birkhauser Verlag Basel.
[3] Pohlmann, C. M. (2002). *Okologische Betrachtung fur den Hausbau – Ganzheitliche Energie – und Kohlendioxidbilanzen fur zwei verschiedene Holzhauskonstruktionen.* PhD thesis. zur Erlangung des Doktorgrades, an der Universitat Hamburg, Fachbereich Biologie.
[4] Hammond, G., & Jones, C. (2008). *Inventory of Carbon and Energy (ICE), Version 1.6a, Sustainable Energy Research Team (SERT).* Department of Mechanical Engineering, University of Bath, UK.
[5] Ardente, F., Beccali, M., Cellura, M., & Brano, V. L. (2008). Energy Performances and Life Cycle Assessment of An Italian Wind Farm. *Renewable and Sustainable Energy Reviews*, *12*: 200-217.

- Recurring embodied energy

Recurring embodied energy of the offices floor (Ground floor)

	Materials	Embodied energy (MJ)	Useful life (years)	Recurring embodied energy (MJ) (50 years)
Pile foundations	Reinforced concrete	488950	100	0
		1949450	100	0
	Damp proof membrane	1876000	100	0
Columns	Reinforced concrete	209550	50	0
	Cement (thickness: 0.005m)	11088	50	0
	Sand (thickness: 0.005m)	29	8-10	145
	Paint	6.8	100	0
Beams	Reinforced concrete	863600	50	0
	Cement (thickness: 0.005m)	47520	50	0
	Sand (thickness: 0.005m)	126	100	0
Slabs	Reinforced concrete	647700	100	0
	Cement (thickness: 0.005m)	79200	50	0
	Sand (thickness: 0.005m)	209	50	0
	Carpet (timber)	5450757	30	5450757
	Carpet (carpet)	81840	15-20	245520
External walls	Reinforced concrete	1301750	100	0
	Mineral wool (Insulation)	1230	50	0

	Cement (thickness: 0.005m)	31680	50	0
	Sand (thickness: 0.005m)	84	50	0
	Brick (decoration)	7437	50	0
	Paint	2.8	8-10	14
Internal walls	Reinforced concrete	1181100	100	0
	Cement (thickness: 0.005m)	73656	50	0
	Sand (thickness: 0.005m)	195	50	0
	Paint	55	8-10	275
Doors	Timber	49398	30	49398
	Glass	31500	50	0
	Paint	1	8-10	5
Ceiling	Steel	70200	50	0
	Plaster	30510	50	0
Internal stair	Reinforced concrete	15875	100	0
	Brick (pavement)	1339	50	0
	Steel (handrail)	35	50	0
Internal lift	Reinforced concrete	4318	100	0
	Steel	930	50	0
	Plastic (Decoration)	403	50	0
Total	**5,746,114 MJ**			

Recurring embodied energy of the dunes floor (First floor)

	Materials	Embodied energy (MJ)	Useful life (years)	Recurring embodied energy (MJ) (50 years)
Wall	Reinforced concrete	13004800	100	0
	Cement (thickness: 0.005m)	79200	50	0
	Sand (thickness: 0.005m)	439	50	0
Slabs	Reinforced concrete	647700	100	0
	Cement (thickness: 0.005m)	79200	50	0
	Sand (thickness: 0.005m)	209	50	0
	Brick	46109	50	0
Ceiling	Tile	20610	60	0
Connected bridge	Steel	62010	50	0
	Timber	23.4	30	23.4
Internal staircases	Reinforced concrete	1492250	100	0
	Cement (thickness: 0.005m)	9504	50	0
	Sand (thickness: 0.005m)	25	50	0
Maintenance structure	Steel (handrail)	1170	50	0
	Glass	7500	50	0
Total	**23 MJ**			

Recurring embodied energy of the glass floor (Second floor)

	Materials	Embodied energy (MJ)	Useful life (years)	Recurring embodied energy (MJ) (50 years)
Columns	Reinforced concrete	6662	100	0
	Cement (thickness: 0.005m)	19800	50	0
	Sand (thickness: 0.005m)	53	50	0
	Paint	14	8-10	70
Beams	Reinforced concrete	863600	100	0
	Cement (thickness: 0.005m)	47520	50	0
	Sand (thickness: 0.005m)	126	50	0
Slabs	Reinforced concrete	647700	100	0
	Cement (thickness: 0.005m)	79200	50	0
	Sand (thickness: 0.005m)	209	50	0
	Paint	27	8-10	135
External maintenance structure	Steel	52416	50	0
	Glass	76875	50	0
Doors	Timber	852	30	852
	Glass	570	50	0
	Paint	0.02	8-10	0.1
Ceiling	Plaster	30510	50	0
	Paint	27	8-10	135
Shelves for flowers	Steel	81900	50	0
Total	**1,192 MJ**			

Recurring embodied energy of the pots floor (Third floor)

	Materials	Embodied energy (MJ)	Useful life (years)	Recurring embodied energy (MJ) (50 years)
Beams	Reinforced concrete	863600	100	0
	Cement (thickness: 0.005m)	47520	50	0
	Sand (thickness: 0.005m)	126	50	0
Slabs	Reinforced concrete	647700	100	0
	Cement (thickness: 0.005m)	79200	50	0
	Sand (thickness: 0.005m)	209	50	0
	Paint	27	8-10	135
External walls	Plastic sheeting	15859	50	0
Internal walls	Reinforced concrete	1898650	100	0
	Cement (thickness: 0.005m)	118800	50	0
	Sand (thickness: 0.005m)	314	50	0
	Paint	61	8-10	305
Doors	Timber	10219	30	10219
	Glass	6375	50	0
	Paint	0.01	8-10	0.05
Ceiling	Plaster	30510	50	0
	Paint	27	8-10	135
Total	**10,794 MJ**			

Recurring embodied energy of the forest floor (Fourth floor)

	Materials	Embodied energy (MJ)	Useful life (years)	Recurring embodied energy (MJ) (50 years)
Columns	Timber	317960	30	317960
Beams	Reinforced concrete	863600	100	0
	Cement (thickness: 0.005m)	47520	50	0
	Sand (thickness: 0.005m)	126	50	0
Slabs	Reinforced concrete	647700	100	0
	Cement (thickness: 0.005m)	79200	50	0
	Sand (thickness: 0.005m)	209	50	0
	Paint	27	8-10	135
Ceiling	Plaster	30510	50	0
	Paint	27	8-10	135
Maintenance structure	Steel (handrail)	1170	50	0
	Glass	7500	50	0
Total	**318,230 MJ**			

Recurring embodied energy of the rain floor (Fifth floor)

	Materials	Embodied energy (MJ)	Useful life (years)	Recurring embodied energy (MJ) (50 years)
Columns	Reinforced concrete	146050	100	0
Beams	Reinforced concrete	863600	100	0
	Cement (thickness: 0.005m)	47520	50	0
	Sand (thickness: 0.005m)	126	50	0
Slabs	Reinforced concrete	647700	100	0
	Cement (thickness: 0.005m)	79200	50	0
	Sand (thickness: 0.005m)	209	50	0
	Paint	27	8-10	135
Internal walls	Reinforced concrete	971550	100	0
	Cement (thickness: 0.005m)	63360	50	0
	Sand (thickness: 0.005m)	0.0007	50	0
	Steel (decoration)	234000	50	0
Door	Timber	10219	30	10219
	Glass	6375	50	0
	Paint	0.01	8-10	0.05
Ceiling (internal)	Plaster	12204	50	0
	Paint	11	8-10	55
Maintenance structure	Steel	2340000	50	0
Total	**10,409 MJ**			

Recurring embodied energy of the windmills (Sixth floor)

	Materials	Embodied energy (MJ)	Useful life (years)	Recurring embodied energy (MJ) (50 years)
Green roof	Waterproofing PVC	10654	15-20	31962
	Asphalt (Waterproofing layer)	65000	20-25	130000
	Mineral wool (Insulation)	250	50	0
	PVC (Drainage layer)	10653	15-20	31959
	PVC (Substrate)	10653	15-20	31959
	Vegetation	-	-	-
Water roof	Reinforced concrete (Structure)	1301750	100	0
	Mineral wool (Thermal insulation layer)	3100	50	0
	Asphalt (Waterproof layer)	78000	20-25	156000
Slabs	Reinforced concrete	647700	100	0
	Cement (thickness: 0.005m)	79200	50	0
	Sand (thickness: 0.005m)	209	50	0
	Paint	27	8-10	135
Walls (VIP room)	Reinforced concrete (Structure)	476250	100	0
	Reinforced concrete (Internal wall)	69850	100	0
	Cement (thickness: 0.005m)	79	50	0
	Sand (thickness: 0.005m)	0.2	50	0
	Paint	0.07	8-10	0.35
Ceiling (VIP room)	Plaster	305	50	0
	Paint	0.3	8-10	1.5
Bridge	Timber	37758	30	37758
	Steel (handrail)	77220	50	0
Total	**419,774 MJ**			

Recurring embodied energy of vertical circulation

	Materials	Embodied energy (MJ)	Useful life (years)	Recurring embodied energy (MJ) (50 years)
External stair	Steel (structure)	386100	50	0
	Steel (handrail)	81900	50	0
	Timber	218597	30	218597
External lift	Reinforced concrete (Structure)	254000	100	0
	Steel	561600	50	0
	Timber	851	30	851
	Glass	20250	50	0
Total	**219,448 MJ**			

Recurring embodied energy of building services

	Materials	Embodied energy (MJ)	Useful life (years)	Recurring embodied energy (MJ) (50 years)
Building Services	Pump, pipe …. (50%)	6,881,280	25	6,881,280
	Steel… (50%)	6,881,280	50	0
Total	**6,881,280 MJ**			

Recurring embodied energy of wind turbines

	Embodied energy (MJ)	Useful life (years)	Recurring embodied energy (MJ)
Wind turbines	4,038,048	20	8,076,096
Transportation of personnel inspection(7000kg of diesel)	317100 (45.3 MJ/kg)	20	792,750
Maintenance of space parts	605,707 (15% of embodied energy of wind turbines)	20	1,514,268
Total	**10,383,114 MJ**		

Total embodied energy of Dutch Pavilion (Germany embodied energy coefficients)

Floor	Initial embodied energy (MJ)	Recurring embodied energy (MJ)
Offices floor (Ground floor)	14,507,725	5,746,114
Dunes floor (First floor)	15,450,750	23
Glass floor (Second floor)	1,908,061	1,192
Pots floor (Third floor)	3,719,197	10,794
Forest floor (Fourth floor)	1,995,549	318,230
Rain floor (Fifth floor)	5,422,151	10,409

Windmills (Sixth floor)	2,868,659	419,774
Vertical circulation	1,523,298	219,448
Building services	13,762,560	6,881,280
Wind turbines	4,038,048	10,383,114
Total	65,195,998	23,990,347
In all	89,186,376 MJ	

- **Sensitivity analysis: embodied energy of buildings calculated using different embodied energy coefficients**

	Initial embodied energy (GJ)	Recurring embodied energy (GJ)	Total embodied energy (GJ)
Embodied energy of Crystal Palace			
UK embodied energy coefficients	184,131	164,058	348,189
Australian embodied energy coefficients	186,609	159,770	346,379
German embodied energy coefficients	218,865	160,162	379,027
Embodied energy of Shanghai Exhibition Centre			
UK embodied energy coefficients	536,979	322,103	859,082
Australian embodied energy coefficients	439,884	318,888	758,772
German embodied energy coefficients	535,757	323,167	858,924
Embodied energy of Dutch Pavilion			
UK embodied energy coefficients	65,088	27,966	93,054
Australian embodied energy coefficients	62,976	30,614	93,590
German embodied energy coefficients	65,196	23,990	89,186

Sensitivity analysis: embodied energy of buildings calculated using different embodied energy coefficients

Total embodied energy	UK embodied energy coefficients (GJ)	Australian embodied energy coefficients (GJ)	German embodied energy coefficients (GJ)	Coefficient of variation (CV)
Crystal Palace	348,189	346,379	379,027	4.2%
Shanghai Exhibition Centre	859,082	758,772	858,924	5.7%
Dutch Pavilion	93,054	93,590	89,186	2.1%