ABSTRACT
Over the last hundred years the booming exhibition industry has promoted development, which in turn has led to environmental damage. The construction of exhibition buildings has been part of this phenomenon. At first sight improvement in energy efficiency techniques would seem to offset the increased energy demand from both exhibitions and exhibition buildings. However, whether energy efficiency technologies truly help to improve building performance to the point where a building is ‘environmentally friendly’ throughout its whole life-cycle is uncertain. This research is part of investigating whether energy efficiency technologies are really the easiest means to lower costs and energy requirements when the whole useful life of an exhibition building is considered. This article investigates the energy use of three case study buildings based on their operating and embodied energy flows. The results suggest that modern technologies for making exhibition buildings more sustainable may not be as effective as the simpler strategies used over 100 years ago. This suggests a different approach may be needed for sustainable development in the twenty first century.

KEYWORDS
sustainability, energy efficiency, exhibition buildings, embodied energy, operating energy, whole life-cycle energy analysis

1. INTRODUCTION
The aim of international expositions, such as World Expo 2010, is to stimulate economies (Bachman 2003, p.246). As such, they continue to display an impressive power of attraction for both visitors and participating countries and can have considerable influence on the development of the local economy where the exhibition occurs (Findling and Pelle 2000, p.1-2). The Global Association for the Exhibition Industry (UFI) (2007) has demonstrated...
that the available exhibition space of the entire world is expanding. Expanding economic activity and further development of the built environment have led to environmental damage over the last hundred years, especially in terms of global warming and resource depletion. As a result, 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 these problems, and lowering carbon footprint has become a key target globally (Figueres and Philips 2007; Kneifel 2010). 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). Torcellini et al. (2006) found that high-performance commercial buildings can help to decrease energy use by 25-70% below code, and Griffith et al. (2008) have reported that improvement of building envelopes, lighting controls and HVAC systems should decrease energy use to 43% below an ASHRAE 90.1-2004 compliant design.

Currently, 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). However, any reduction in energy use has to be measured over the whole life of the building, and needs to include the two largest energy components in a building Life Cycle Analysis, operating energy and embodied energy. The sustainable design of buildings must be concentrated on reducing overall energy usage, rather than just focusing on mitigating GHG emissions. This is because the functions the existing stock of natural capital performs cannot be duplicated by manufactured capital, setting this research in the context of strong sustainability (Neumayer 2010; Brekke 1997 p. 91).

This research aims, therefore, to estimate whether modern energy efficiency technologies, such as low-energy and renewable energy technologies as found in the Dutch Pavilion, built in 2000 for the Hannover Expo, are truly the easiest means to lower the energy requirements of modern exhibition buildings significantly. Comparison is, therefore, made with the energy usage of a historic exhibition building, the 1851 Crystal Palace, which was constructed at a time when buildings used less energy for their operation. A third exhibition building from the 1950s, the Shanghai Exhibition Centre, is added as an example of a building that uses modern technologies and energy systems but, unlike the Dutch Pavilion, without being designed to be sustainable. The three case study buildings, all exhibition buildings with comparable functions, are detailed and quantified and then compared in terms of their energy intensity from embodied and operating energy use, using the Life Cycle Assessment method. As clarification, the discussions and conclusions in this paper are made in the context of the environmental aspect of sustainability, this being the most significant aspect for energy flows in the construction industry in the triple bottom line of sustainability (environment, economy, and society). The economic aspects of sustainable exhibition buildings will be estimated and discussed in further research. The results not only help in understanding whether modern technology makes exhibition buildings more sustainable, but also suggest potential approaches to sustainable development in the twenty first century from the past.

2. SUSTAINABLE EXHIBITION BUILDINGS

Current World Expos show both technological innovations and concern for the sustainable development of the human community (Findling and Pelle 2000, p.2). “Sustainable development” has also been the main theme for recent World Expositions. Expo 1974 was the first
exposition to have an environmental theme (ExpoMuseum 2009). 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 Achai, 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). Expos can, therefore, be a platform on which to implement and enact sustainability measures (Findling and Pelle 2000, p.2).

Many exhibition halls for World Expositions, especially in recent and current expositions, have been described as sustainable buildings. The Expo Centre in Expo 2010 has reached the international standard (LEED Gold rating) for green buildings (EXPO2010 2010). The Dutch Pavilion in Expo 2000 is another typical example. This building had six storeys. Each storey had a different character or theme (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 building. MVRDV concluded that this building not only saved space, but also saved energy, time, water and infrastructure. However, the useful life of this building was just 5 months and it was not reused after the World Exposition.

This phenomenon raises the problem embodied in the “sustainable buildings” of expositions, which is whether “sustainable exhibition buildings” are truly creating a sustainable environment and saving natural resources over the whole life cycle. Some results from research into other building types suggest differently. Sartori and Hestnes (2007), in a study of a variety of building types, state that the design of low-energy buildings induces both a net benefit in total life cycle energy demand and an increase in the building’s embodied energy. 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. Moreover, 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).

Although, some studies show that reduction in the operating energy for buildings 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. First, is the assumption that buildings have a long and useful life (at least 50 years). However, not all exhibition buildings achieve this. For example, most of the pavilions built for Expo 2010 in Shanghai will be demolished after the event (EXPO 2010). 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 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. 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 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. This research uses comparisons to avoid some of these problems, and concentrates on the two major impacts from a building, operating energy and embodied energy.

3. METHODS OF ENERGY ANALYSIS
This study is based on a detailed energy analysis of three buildings, located in the UK, China and Germany respectively (Table 1). The historic exhibition building, the Hyde Park Crystal Palace, was finished in 1851, and had a total usable floor area of 92,000 m² 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. The original building components were reused in the construction of the Sydenham Crystal Palace (Phillips et al. 1860). The Shanghai Exhibition Centre, the conventional modern exhibition building, was built in 1955 using a concrete structure in the city centre of Shanghai, China. The total usable floor area of this building is 80,000 m². It was structurally reinforced and renovated with the main elevation redecorated and two exhibition halls added in 2001. The Dutch Pavilion, the sustainable exhibition building with its six attached wind turbines, was designed as the exhibition hall of The Netherlands for World Expo 2000 in Germany. The total construction area of this building is much smaller at approximately 6,144 m². It has a hybrid steel – concrete structure, with the latter the main structural material. Although these three exhibition buildings use different construction materials, they were designed for a similar function (displaying exhibits) and had similar internal layouts (mainly large column-free space) and similar structures (beam and column grid) (Table 1).

**TABLE 1.** The case study buildings.

<table>
<thead>
<tr>
<th>Buildings</th>
<th>Hyde Park Crystal Palace</th>
<th>Shanghai Exhibition Centre</th>
<th>Dutch Pavilion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor area (m²)</td>
<td>Hyde Crystal Place: 92,000 Sydenham Crystal Palace: 138,000</td>
<td>Original floor area: 54,108 Extension floor area: 25,892 Total floor area: 80,000</td>
<td>6,144 (each floor has an area of 1024 m²)</td>
</tr>
<tr>
<td>Number of visitors</td>
<td>6,039,195 (1 May–15 Oct, 1851)</td>
<td>7,500,000/year</td>
<td>2,700,000 (1 Jun–31 Oct, 2000)</td>
</tr>
<tr>
<td>Number of floors</td>
<td>Hyde Crystal Place: 3 Sydenham Crystal Palace: 6</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Part of typical floor plan</td>
<td><img src="https://example.com/image1.png" alt="Image" /></td>
<td><img src="https://example.com/image2.png" alt="Image" /></td>
<td><img src="https://example.com/image3.png" alt="Image" /></td>
</tr>
</tbody>
</table>
The useful life of the Crystal Palace was from 1851-1852 and 1854-1936 (it was destroyed by fire), making 82.5 years in total. The useful life of the Shanghai Exhibition Centre has been taken as 50 years (1955-2005) although the building is still in use. The real life of the Dutch Pavilion was 5 months (June - October, 2000) and although it was designed to be moved and re-used after the Expo this has not happened. To gain a fairer comparison between the different approaches of these three buildings, this study also looks at the performance of the Dutch Pavilion over an assumed longer useful life of 50 years.

The energy analysis of these case study buildings is based on a simplified Life Cycle Analysis (LCA), which is a quantitative assessment of resource uses and waste discharges for every step of the life of products, services, activities and technologies (Chevalier and LeTeno 1996, p.488; Mithraratne et al. 2007, p.23). The quantification of life-cycle energy generally includes the estimation of embodied energy (initial and recurring), operating energy and demolition-related energy use. In this paper, the embodied energy and operating energy for the buildings are the focus for assessment and discussion, because these two factors are the main influences on the whole life-cycle energy consumption of a building (Cole and Kernal 1996; Fernandez 2008; Energy Assessment 2010). The assessment of energy usage for building demolition is not included because it accounts for a very small percentage of the total energy in a conventional building’s whole life cycle (Camilleri and Jaques 2001, p.41). The inclusion of demolition-related energy use would be an area for further research.

3.1 Embodied energy
The assessment of initial and recurring embodied energy for construction and maintenance of the case study buildings is based on quantifying all construction materials by volume or weight (detailed in Appendix 1). The initial or recurring embodied energy of the buildings is calculated by multiplying the embodied energy coefficients with the weight or volume of the component and its useful life.

The embodied energy coefficients for different countries vary slightly because the energy mixes for manufacturing materials are different in each country. However, between 1994 and 2008 embodied energy coefficients from different countries have not changed very much, as shown in Table 2. As explained below, 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. However, the data were checked by applying all three sets of coefficients to all three buildings, but the overall differences were very small (maximum 9%). This justified the selection of the relevant coefficients.

No data on the energy mix for the materials of the Crystal Palace could be found. Many industrial goods had a higher hand-made component in the mid-nineteenth century meaning the energy consumption should be lower than now. However, much of the energy for most industries came from coal, which might result in higher values than those for modern manufacturing. Based on this, the energy coefficients from Hammond and Jones’s research in the UK were used for the Crystal Palace (Hammond and Jones 2008). For the Shanghai Exhibition Centre, the energy intensities of materials were taken from typical Australian data (Treloar 1994) as, like China, coal is still an important part of the national energy mix. This is because the establishment of the Chinese embodied energy database (Sino Centre) is ongoing. Other research which has applied Australian data has demonstrated appropriate results in terms of embodied energy for case study buildings in China (Chen and Chau 2001; Wang and Cai.
TABLE 2. Embodied energy coefficients of the selected materials in different countries.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Kiln dried sawn softwood</td>
<td>3.4</td>
<td>2.5</td>
<td>1.6</td>
<td>1.5</td>
</tr>
<tr>
<td>Particleboard</td>
<td>8.0</td>
<td>8.0</td>
<td>9.5</td>
<td>5.7</td>
</tr>
<tr>
<td>MDF</td>
<td>11.3</td>
<td>11.9</td>
<td>11.0</td>
<td>10.5</td>
</tr>
<tr>
<td>Gypsum plaster</td>
<td>2.9</td>
<td>4.5</td>
<td>1.8</td>
<td>2.5</td>
</tr>
<tr>
<td>Plasterboard</td>
<td>4.4</td>
<td>6.1</td>
<td>6.8</td>
<td>3.4–8.5</td>
</tr>
<tr>
<td>Fibre cement</td>
<td>4.8</td>
<td>9.5</td>
<td>10.9</td>
<td>5.3</td>
</tr>
<tr>
<td>Cement</td>
<td>5.6</td>
<td>7.8</td>
<td>4.6</td>
<td>4.4</td>
</tr>
<tr>
<td>Precast steam-cured concrete</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.5</td>
</tr>
<tr>
<td>Clay bricks</td>
<td>2.5</td>
<td>0.1</td>
<td>3.0</td>
<td>2.2</td>
</tr>
<tr>
<td>Concrete blocks</td>
<td>1.5</td>
<td>0.9</td>
<td>0.6*</td>
<td>0.6–0.8</td>
</tr>
<tr>
<td>Glass</td>
<td>12.7</td>
<td>15.9</td>
<td>15.0</td>
<td>15.0</td>
</tr>
<tr>
<td>Steel</td>
<td>36.8</td>
<td>32</td>
<td>24.4</td>
<td>15</td>
</tr>
</tbody>
</table>

*8MPa concrete block

2006). For the Dutch Pavilion, the relevant coefficients are from modern German data as this is where the Dutch Pavilion was built (Anon 1994; Eyerer et al. 2000; Pohlmann 2002).

In addition, in this paper the energy used for producing the original construction materials of the Hyde Park Crystal Palace is defined as the initial embodied energy, while the energy for manufacturing the new construction components of the Sydenham Crystal Place and for the maintenance of this building is defined as the recurring embodied energy.

3.2 Operating energy

Building operating energy basically means the energy consumed in the building operating phase, such as energy usage for lighting, and HVAC system. The Shanghai Exhibition Centre consumes electricity for lighting, heating, air conditioning and ventilation. As it has not been possible to obtain figures for the energy to run this building, its operating energy consumption is calculated on the basis that it is a conventional commercial building in Shanghai. The operating energy is taken as 888 MJ/m²/year, found by looking at comparable buildings (Shen et al. 2009).

The Hyde Park Crystal Palace achieved almost zero energy consumption in its operating phase, owing to there being no artificial lighting, heating, cooling and ventilation in the building. The internal lighting entirely depended on natural light, and the cooling and ventilation systems were elaborately designed to work on the natural buoyancy of air. The only energy requirement was for the internal heating system of the later Sydenham Crystal Palace. This consisted of 22 boilers and associated pipe work, each boiler holding 11,000 gallons (42m³) of water (Crystal Palace 2009). Again, it was not possible to find data relating to the energy used to run this system. However, glasshouses are still heated using coal fired boilers. A study of the energy used to heat modern glasshouses suggests an appropriate energy use figure is 1,120 MJ/m²/year (Wass and Barrie 1984; Cock and Lierde 1997; Nederhoff and Houter 2007).
For the Dutch Pavilion, as it 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. Nearly half the floor area (42.7%) is space open to the outside and without HVAC systems. The calculation of the operating energy of the Dutch Pavilion is separated into the different floors and is shown in Table 6. The office level can be assumed to be the level with the highest energy consumption, while the forest floor and dunes floor have no heating, cooling and ventilation systems. Because of the special operating performance (such as using natural ventilation), the enclosed floors of the Dutch Pavilion have been assumed to act as an efficient office building in terms of energy use. 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/m²/year, based on the fact that generally a conventional air-conditioned office uses 200–400kWh/m²/year in Germany (IEA PVPS 1999). Energy for lighting the unenclosed floors is calculated from unit lighting energy consumption. However, no German lighting data for sustainable commercial buildings was available for this study. After comparing unit lighting energy consumption data from different countries (Table 3), a figure of 30kWh/m²/year has been used for the lighting intensity of the floors without HVAC installed, which is also the average lighting energy requirement for a typical German house (Gauzin-Müller and Favet 2002).

In addition the energy generated by operation of the wind turbines attached to the Dutch Pavilion helps to reduce the net electricity consumption of this building. It can be assumed that the electricity generated by a small windmill of this type (10 kW) is around 10,000kWh/year (Jimenez 2010). However, the distance between the small wind turbines installed in the Dutch Pavilion is less than 15m, and this will reduce the generating capacity of the turbines (David 2002). The total electricity production of the windmills of the Dutch Pavilion, therefore, is assumed to be reduced by half because of their less than optimal installation (Encraft 2009).

### 4. ARE MODERN BUILDINGS MORE SUSTAINABLE?

#### 4.1 Results

The quantified results for the three case study buildings over their actual lives are shown in Tables 4 – 6. The total energy consumption is 13,022,741 GJ or 1.2 GJ/m²/year for the Crystal Palace (1851–1936) and 4,317,272 GJ or 1.1 GJ/m²/year for the Shanghai Exhibition Centre (1955–2005). The total energy consumption of the Dutch Pavilion (for its real useful life of 5 months) is 65,817 GJ or 25.7 GJ/m²/year. For an assumed 50 year life, the total energy requirement would be 163,616 GJ or 0.5 GJ/m²/year.

### Table 3. Lighting energy for different types of buildings in different countries.

<table>
<thead>
<tr>
<th>Country</th>
<th>Type of building</th>
<th>Lighting (kWh/m²/year)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany</td>
<td>Typical house</td>
<td>30</td>
<td>(Gauzin-Müller and Favet 2002)</td>
</tr>
<tr>
<td>Portugal</td>
<td>Office/commercial building</td>
<td>30–70</td>
<td>(EPE 2009)</td>
</tr>
<tr>
<td>Denmark</td>
<td>General office building</td>
<td>26</td>
<td>(Kristensen 1991)</td>
</tr>
<tr>
<td>India</td>
<td>Commercial building</td>
<td>37–60</td>
<td>(Kumar 2008)</td>
</tr>
<tr>
<td>U.S.</td>
<td>Commercial building</td>
<td>59.6</td>
<td>(Archer 2008)</td>
</tr>
</tbody>
</table>
### TABLE 4. Energy consumption of the Crystal Palace (1851-1936, 82.5 years).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>Main building, Colonnade</td>
<td>6,120</td>
<td>8,175</td>
<td>12,673,920</td>
</tr>
<tr>
<td>Iron</td>
<td>Columns, Girders, Pipes, Connection collars, Metal louvers, Roof trusses</td>
<td>157,928</td>
<td>83,125</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Boilers</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Colonnade</td>
<td>-</td>
<td>-</td>
<td>1,500</td>
</tr>
<tr>
<td>Wood</td>
<td>-</td>
<td>13,592</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Concrete</td>
<td>Foundations (footing)</td>
<td>1,710</td>
<td>1,438</td>
<td></td>
</tr>
<tr>
<td>Brick-work</td>
<td>Foundations</td>
<td>-</td>
<td>38,243</td>
<td></td>
</tr>
<tr>
<td>Paint</td>
<td>Components made of iron and wood (Durability: 5 years)</td>
<td>5,416</td>
<td>31,577</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>-</td>
<td>184,763</td>
<td>164,058</td>
<td></td>
</tr>
<tr>
<td>In all</td>
<td>-</td>
<td>13,022,741 GJ (1.2 GJ/m²/year)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### TABLE 5. Energy consumption of the Shanghai Exhibition Centre (1955-2005, 50 years).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Foundations</td>
<td>Reinforced concrete, Damp proof membrane</td>
<td>110,638</td>
<td>52943</td>
<td></td>
</tr>
<tr>
<td>Columns</td>
<td>Reinforced concrete, Cement mortar, Granite, Paint</td>
<td>13,758</td>
<td>8051</td>
<td></td>
</tr>
<tr>
<td>Beams</td>
<td>Reinforced concrete, Cement mortar</td>
<td>14,244</td>
<td>7431</td>
<td></td>
</tr>
<tr>
<td>Floors</td>
<td>Reinforced concrete, Cement mortar, Terrazzo</td>
<td>22,587</td>
<td>11910</td>
<td></td>
</tr>
<tr>
<td>Walls</td>
<td>Reinforced concrete, Rockwool, Cement mortar, Paint</td>
<td>116,053</td>
<td>59010</td>
<td></td>
</tr>
<tr>
<td>Windows</td>
<td>Float glass, Steel, Timber</td>
<td>9,853</td>
<td>11801</td>
<td></td>
</tr>
<tr>
<td>Doors</td>
<td>Timber, Glass, Copper</td>
<td>2,697</td>
<td>3226</td>
<td></td>
</tr>
<tr>
<td>Ceiling</td>
<td>Plywood, Plaster, Plasterboard, Paint</td>
<td>11,084</td>
<td>20324</td>
<td></td>
</tr>
<tr>
<td>Staircases</td>
<td>Reinforced concrete, Cement mortar, Terrazzo</td>
<td>2,926</td>
<td>1449</td>
<td></td>
</tr>
<tr>
<td>Roof</td>
<td>Reinforced concrete, Rockwool, Asphalt, Cement mortar, Paint</td>
<td>20,594</td>
<td>15766</td>
<td></td>
</tr>
<tr>
<td>Arch structure</td>
<td>Reinforced concrete, Cement mortar, Paint</td>
<td>5,022</td>
<td>2769</td>
<td></td>
</tr>
<tr>
<td>Galleries</td>
<td>Reinforced concrete, Asphalt, Cement mortar, Paint</td>
<td>22,446</td>
<td>34152</td>
<td></td>
</tr>
<tr>
<td>Services</td>
<td>Steel, Plastic, Paint</td>
<td>87,977</td>
<td>90054</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>-</td>
<td>439,883</td>
<td>318,889</td>
<td></td>
</tr>
<tr>
<td>In all</td>
<td>-</td>
<td>4,317,272 GJ (1.1 GJ/m²/year)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*The two parts of recurring embodied energy come from repairing and redoing finishes and from the extensions in 2001.
With the figures derived in Tables 4 ~ 6, it is possible to look at which elements of the three buildings consume more energy in the building construction phase, as shown in Table 7. The results show that producing the columns for the Hyde Park Crystal Palace accounts for around 43% of total energy, or 860 MJ/m\(^2\). This is because the columns were made from a high embodied energy construction material, iron. For the Shanghai Exhibition Centre, the single largest part of the initial embodied energy is used for the foundations, amounting to 2,045 MJ/m\(^2\). For the Dutch Pavilion, building services and relevant appliances are the highest energy-consuming components in the total initial embodied energy, amounting to 2,897 MJ/m\(^2\).

Obviously, the Dutch Pavilion, the experimental sustainable building, has the highest initial embodied energy compared with the historic and conventional buildings (10,611 MJ/m\(^2\)). Most of the initial embodied energy is consumed in the building structural members for the historic and conventional buildings, while for the experimental sustainable building it is in the high-tech appliances and systems.

To compare the energy used in maintenance and refurbishment (recurrent embodied energy) in a reasonable manner, the useful life of the Dutch Pavilion is assumed to be 50 years. The Sydenham Crystal Palace has the lowest recurring energy embodied (14.4 MJ/m\(^2\)/year), because a large number of components were recycled from the Hyde Park Crystal Palace (Table 8). Because the foundations (concrete footings) could not be moved and reused, the recurring embodied energy of the foundations forms the highest percentage of recurrent energy consumption (24%) for the Sydenham Crystal Palace. In the comparison, it is interesting to find that building services including the wind turbines and relevant appliances for the

### TABLE 6. Energy consumption of the Dutch Pavilion (over 5 months and 50 years).

<table>
<thead>
<tr>
<th>Floors</th>
<th>Real useful life: June ~ October, 2000, 5 months</th>
<th>Assumed useful life: 2000~2050, 50 years</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial embodied energy (GJ)</td>
<td>Recurring embodied energy (GJ)</td>
</tr>
<tr>
<td>Offices floor</td>
<td>14,508</td>
<td>0</td>
</tr>
<tr>
<td>Dunes floor</td>
<td>15,451</td>
<td>0</td>
</tr>
<tr>
<td>Glass floor</td>
<td>1,908</td>
<td>0</td>
</tr>
<tr>
<td>Pots floor</td>
<td>3,719</td>
<td>0</td>
</tr>
<tr>
<td>Forest floor</td>
<td>1,996</td>
<td>0</td>
</tr>
<tr>
<td>Rain floor</td>
<td>5,422</td>
<td>0</td>
</tr>
<tr>
<td>Windmills</td>
<td>2,869</td>
<td>0</td>
</tr>
<tr>
<td>Vertical circulation</td>
<td>1,523</td>
<td>0</td>
</tr>
<tr>
<td>Building services</td>
<td>13,763</td>
<td>0</td>
</tr>
<tr>
<td>Wind turbines</td>
<td>4,038</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>65,196 GJ</td>
<td>0 GJ</td>
</tr>
<tr>
<td>In all</td>
<td>65,817 GJ (25.7 GJ/m(^2)/year)</td>
<td>0 GJ</td>
</tr>
</tbody>
</table>

*Operating energy based proportionally on that for enclosed and unenclosed floors.
Dutch Pavilion are not just a high initial embodied energy component but also remain a very high recurring embodied energy requirement, even if the building uses its wind turbines for 50 years. This means that producing and maintaining the wind turbines over 50 years is the equivalent of constructing several floors of a commercial building in Germany.

Looking at the life cycle energy consumption of the three case study buildings over their actual useful life, the Dutch Pavilion, as expected, has the highest energy requirement (25.7 GJ/m²/year) for construction, maintenance and operation, although less energy is consumed in the building operation, because it had a very short life and nearly half the floor area is not enclosed but open to the external environment (Table 9). The Crystal Palace, the site of a world-scale exposition with 6,039,195 visitors (this excludes visitors to the Sydenham Crystal Palace), although it was built in the 19th Century, consumed a similar amount of energy over its whole useful life to the much more modern Shanghai building. The total energy consumption of the Crystal Palace is around 22 times less than that of the experimental sustainable building, the Dutch Pavilion, although the heating system at Sydenham required much more energy to operate that the corresponding systems for the Shanghai and Dutch buildings.

<table>
<thead>
<tr>
<th>Elements</th>
<th>Hyde Park Crystal Palace</th>
<th>Shanghai Exhibition Centre</th>
<th>Dutch Pavilion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial embodied energy (MJ/m²)</td>
<td>Percentage (%)</td>
<td>Initial embodied energy (MJ/m²)</td>
</tr>
<tr>
<td>Foundations</td>
<td>18.6</td>
<td>0.9</td>
<td>2044.8</td>
</tr>
<tr>
<td>Columns</td>
<td>860.0</td>
<td>42.8</td>
<td>254.3</td>
</tr>
<tr>
<td>Beams</td>
<td>457.6</td>
<td>22.8</td>
<td>263.3</td>
</tr>
<tr>
<td>Floors</td>
<td>90.8</td>
<td>4.5</td>
<td>417.4</td>
</tr>
<tr>
<td>External walls</td>
<td>32.6</td>
<td>1.6</td>
<td>1357.3</td>
</tr>
<tr>
<td>Internal walls</td>
<td>90.8</td>
<td>4.5</td>
<td>787.6</td>
</tr>
<tr>
<td>Windows</td>
<td>14.2</td>
<td>0.7</td>
<td>182.1</td>
</tr>
<tr>
<td>Doors</td>
<td>0.7</td>
<td>0.03</td>
<td>50.0</td>
</tr>
<tr>
<td>Ceiling</td>
<td>0.0</td>
<td>0.0</td>
<td>204.9</td>
</tr>
<tr>
<td>Vertical circulation</td>
<td>0.0</td>
<td>0.0</td>
<td>54.1</td>
</tr>
<tr>
<td>Roof</td>
<td>188.2</td>
<td>9.4</td>
<td>380.6</td>
</tr>
<tr>
<td>Affiliated structure</td>
<td>0.0</td>
<td>0.0</td>
<td>507.7</td>
</tr>
<tr>
<td>Services</td>
<td>254.9 (Drainage)</td>
<td>12.7</td>
<td>1626.0</td>
</tr>
</tbody>
</table>

Total 2,008.3 MJ/m² 100 8,129.7 MJ/m² 100 10,611.3 MJ/m² 100
TABLE 8. Component recurring embodied energy of the three case study buildings.

<table>
<thead>
<tr>
<th>Elements</th>
<th>Sydenham Crystal Palace (1854 ~ 1936, 82 years)</th>
<th>Shanghai Exhibition Centre (1955 ~ 2005, 50 years)</th>
<th>Dutch Pavilion (Assumed from 2000 ~ 2050, 50 years)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Recurring embodied energy* (MJ/m²/year)</td>
<td>Percentage (%)</td>
<td>Recurring embodied energy* (MJ/m²/year)</td>
</tr>
<tr>
<td>Foundations</td>
<td>3.6</td>
<td>24.2</td>
<td>13.2</td>
</tr>
<tr>
<td>Columns</td>
<td>2.4</td>
<td>16.8</td>
<td>2</td>
</tr>
<tr>
<td>Beams</td>
<td>1.2</td>
<td>8.5</td>
<td>1.9</td>
</tr>
<tr>
<td>Floors</td>
<td>0.7</td>
<td>5.3</td>
<td>3</td>
</tr>
<tr>
<td>Walls</td>
<td>1.1</td>
<td>7.2</td>
<td>14.8</td>
</tr>
<tr>
<td>Windows</td>
<td>1.2</td>
<td>8.2</td>
<td>3</td>
</tr>
<tr>
<td>Doors</td>
<td>0.02</td>
<td>0.2</td>
<td>0.8</td>
</tr>
<tr>
<td>Ceiling</td>
<td>0</td>
<td>0</td>
<td>5.1</td>
</tr>
<tr>
<td>Vertical circulation</td>
<td>0</td>
<td>0</td>
<td>0.4</td>
</tr>
<tr>
<td>Roof</td>
<td>1.2</td>
<td>10.0</td>
<td>3.9</td>
</tr>
<tr>
<td>Affiliated structure</td>
<td>0.1</td>
<td>1.1</td>
<td>9.2</td>
</tr>
<tr>
<td>Services</td>
<td>2.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Drainage)</td>
<td>18.5</td>
<td>22.5</td>
<td>28.2</td>
</tr>
<tr>
<td>Total</td>
<td>14.4 MJ/m²/year</td>
<td>100</td>
<td>79.8 MJ/m²/year</td>
</tr>
</tbody>
</table>

*The two parts of recurring embodied energy come from repairing and redoing finishes and from the extensions.
** The recurring embodied energy come from repairing and redoing finishes.

TABLE 9. Total energy consumption of three case study buildings.

<table>
<thead>
<tr>
<th>Case study buildings</th>
<th>Number of visitors</th>
<th>Embodied energy (MJ/m²/year)</th>
<th>Operating energy (MJ/m²/year)</th>
<th>Total energy consumption (MJ/m²/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystal Palace (82.5 years)</td>
<td>6,039,195 (Hyde Park)</td>
<td>36</td>
<td>1,116</td>
<td>1,152</td>
</tr>
<tr>
<td>Shanghai Exhibition Centre (50 years)</td>
<td>7,500,000/year</td>
<td>192</td>
<td>888</td>
<td>1,080</td>
</tr>
<tr>
<td>Dutch Pavilion (5 months)</td>
<td>2,700,000</td>
<td>25,440</td>
<td>240</td>
<td>25,680</td>
</tr>
</tbody>
</table>
4.2 Further discussions
The question needing further discussion is whether the performance of a building with high levels of technological equipment would reach a state of sustainability if these are used for long time. Winther and Hestnes (1999) did research on five buildings in Norway. Although these were row houses and, therefore, do not compare directly with exhibition buildings, the results are indicative. These show that by reducing the energy use for operation to a very low level, the total energy used during the lifetime of the building is also reduced. These five cases are simulated, based on 50 years of useful life.

The Dutch Pavilion, as an experimental sustainable building for Expo 2000, shows a different story from the results of this study because it was only used during the Expo and abandoned afterwards. If it is assumed that the Dutch Pavilion has a useful life of 50 years life the total energy use reduces from 25,680 to 540 MJ/m²/year (Table 10). This would give it the lowest life-cycle energy of the three case study buildings, thus verifying Winther’s earlier results.

Another comparison can be made by examining the total energy usage of the three case study buildings (Table 11), in order to look at the changes over the different periods of useful life. For the Crystal Palace, there was no operating energy in the first five months in the Hyde Park, while after moving to Sydenham the operating energy was raised to 93MJ/m²/month because a heating system was installed. If it is assumed that the Hyde Park Crystal Palace was not moved and used for 50 years, the total energy consumption would at the very low level of 4MJ/m²/month. This comparison shows the operating energy for exhibition buildings has

<table>
<thead>
<tr>
<th>TABLE 10. Total energy consumption of the Dutch Pavilion over different useful lives.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Embodied energy</strong></td>
</tr>
<tr>
<td><strong>(MJ/m²/year)</strong></td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>Dutch Pavilion (5 months)</td>
</tr>
<tr>
<td>Dutch Pavilion (50 year life)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE 11. Comparison of total energy usage for three case study buildings for assumed 5 month and 50 year useful lives.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Useful life of 5 months (MJ/m²/month)</strong></td>
</tr>
<tr>
<td>Initial embodied energy</td>
</tr>
<tr>
<td>Recurring embodied energy</td>
</tr>
<tr>
<td>Total embodied energy</td>
</tr>
<tr>
<td>Operating energy</td>
</tr>
<tr>
<td>Total energy consumption</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Useful life of 50 years (MJ/m²/month)</strong></th>
<th><strong>Initial embodied energy</strong></th>
<th><strong>Recurring embodied energy</strong></th>
<th><strong>Total embodied energy</strong></th>
<th><strong>Operating energy</strong></th>
<th><strong>Total energy consumption</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Shanghai Exhibition Centre</td>
<td>9</td>
<td>3</td>
<td>2</td>
<td>16</td>
<td>90</td>
</tr>
<tr>
<td>Hyde Park Crystal Palace</td>
<td>7*</td>
<td>1</td>
<td>1*</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Actual Crystal Palace</td>
<td>74</td>
<td>0</td>
<td>93</td>
<td>3</td>
<td>96</td>
</tr>
<tr>
<td>Dutch Pavilion</td>
<td>7</td>
<td>0</td>
<td>7</td>
<td>2</td>
<td>45</td>
</tr>
</tbody>
</table>

* The two parts of recurring embodied energy come from repairing and redoing finishes and from the extensions.
a large influence on the total energy consumption, which is mainly affected by the design of the building services systems. Secondly, the comparison of the energy consumption of the three buildings used for a hypothetical 5 months demonstrates that the short useful life makes the Dutch Pavilion (designed as the sustainable exhibition building) even worse than a conventional building. In addition, if the Dutch Pavilion, were used for 50 years, the recurring embodied energy (mainly for maintaining the turbines) is higher than in normal buildings.

However, on closer examination nearly half of the exhibition space of the Dutch Pavilion is external exhibition area (42.7%), including the open space of the top floor (Table 12), which means it is not the equivalent of a general commercial building or of either of the two other case study exhibition buildings. The dunes, forest and windmills floors of the Dutch Pavilion are all open covered space but without external walls. To make a fairer comparison, if the total floor area of the Dutch Pavilion is assumed to use energy at the rate of the closed in parts of the building, the equivalent total energy consumption would be increased from 25.7 to 38.5 GJ/m²/year over its actual useful life (5 months). This means that if similar sustainable technologies as used in the Dutch Pavilion were used for a commercial building its energy consumption would be higher than that of a conventional commercial building. In addition, the unit embodied energy and operating energy are increased 1.5 times (Table 13). Furthermore, if the Dutch Pavilion has a useful life of 50 years and 100% indoor floor area, making it similar to a general exhibition building, its total energy consumption would be 792 MJ/m²/year. Compared to the Shanghai Exhibition Centre, the total energy consumption of the Dutch Pavilion (50 years, 100% indoor floor area) would then be 26% lower than that of the Shanghai building and the Crystal Palace. However, whether such an experimental sustainable exhibition building would be used for long time cannot be guaranteed, as this depends on the sponsors and users, rather than the designers.

Further discussion concerns the effect of using or not using the renewable energy systems for the sustainable exhibition building. The study found that the maintenance of the wind turbines and the relevant equipment would potentially use a significant amount of energy (10,383 GJ). Different assumptions are made about the use of wind turbines for the Dutch Pavilion in Table 14. It shows that the Dutch Pavilion would consume less energy over its whole life if the high-tech equipment had not been installed. The energy generated by the non-optimally sited wind turbines is not equal to the energy of manufacturing and maintaining them.

**TABLE 12.** Different types of floor area in the Dutch Pavilion.

<table>
<thead>
<tr>
<th>Floor</th>
<th>Floor area (m²)</th>
<th>Open covered floor area (m²)</th>
<th>Enclosed floor area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offices floor</td>
<td>1,024</td>
<td>0</td>
<td>1,024</td>
</tr>
<tr>
<td>Dunes floor</td>
<td>1,024</td>
<td>1,024</td>
<td>0</td>
</tr>
<tr>
<td>Glass floor</td>
<td>1,024</td>
<td>0</td>
<td>1,024</td>
</tr>
<tr>
<td>Pots floor</td>
<td>1,024</td>
<td>0</td>
<td>1,024</td>
</tr>
<tr>
<td>Forest floor</td>
<td>1,024</td>
<td>1,024</td>
<td>0</td>
</tr>
<tr>
<td>Rain floor</td>
<td>1,024</td>
<td>0</td>
<td>1,024</td>
</tr>
<tr>
<td>Windmills</td>
<td>1,024</td>
<td>1,015</td>
<td>9</td>
</tr>
<tr>
<td>Total Exhibition area</td>
<td>7,168</td>
<td>3,063 (42.7%)</td>
<td>4,105 (57.3%)</td>
</tr>
</tbody>
</table>
TABLE 13. Total energy consumption of the case study buildings with Dutch Pavilion having different useful life times and different percentages of covered floor area

<table>
<thead>
<tr>
<th>Case study buildings</th>
<th>Useful life</th>
<th>Percentage of covered floor area</th>
<th>Embodied energy (MJ/m²/year)</th>
<th>Operating energy (MJ/m²/year)</th>
<th>Total energy consumption (MJ/m²/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dutch Pavilion</td>
<td>5 months</td>
<td>57.3 %</td>
<td>25,440</td>
<td>240</td>
<td>25,680</td>
</tr>
<tr>
<td></td>
<td>(real useful life)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5 months</td>
<td>100%</td>
<td>38,112</td>
<td>360</td>
<td>38,484</td>
</tr>
<tr>
<td></td>
<td>(Assumed)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>50 years</td>
<td>57.3 %</td>
<td>288</td>
<td>240</td>
<td>528</td>
</tr>
<tr>
<td></td>
<td>(Assumed)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>50 years</td>
<td>100%</td>
<td>432</td>
<td>360</td>
<td>792</td>
</tr>
<tr>
<td></td>
<td>(Assumed)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shanghai Exhibition Centre</td>
<td>50 years</td>
<td>100%</td>
<td>190</td>
<td>888</td>
<td>1,080</td>
</tr>
<tr>
<td>Crystal Palace</td>
<td>82.5 years</td>
<td>100%</td>
<td>36</td>
<td>1,116</td>
<td>1,152</td>
</tr>
</tbody>
</table>

TABLE 14. Energy consumption of the Dutch Pavilion with and without wind turbines (assumed to be used for 50 years).

<table>
<thead>
<tr>
<th></th>
<th>Embodied energy</th>
<th>Operating energy</th>
<th>Total energy consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>With wind turbines</td>
<td>89,186 GJ</td>
<td>74,430 GJ</td>
<td>163,616 GJ</td>
</tr>
<tr>
<td></td>
<td>(300 MJ/m²/year)</td>
<td>(240 MJ/m²/year)</td>
<td>(540 MJ/m²/year)</td>
</tr>
<tr>
<td>Without wind turbines</td>
<td>74,766 GJ</td>
<td>83,430 GJ</td>
<td>158,196 GJ</td>
</tr>
<tr>
<td></td>
<td>(240 MJ/m²/year)</td>
<td>(376 MJ/m²/year)</td>
<td>(516 MJ/m²/year)</td>
</tr>
</tbody>
</table>

5. CONCLUSIONS

This study set out to investigate whether the use of modern energy efficiency technologies for exhibition buildings is really the easiest means to lower life cycle energy requirements based on a study of three buildings with the same function. These three buildings are quantified and their energy intensities from embodied and operating energy use are compared.

Firstly, the results show that the short lived Dutch Pavilion has the highest energy requirement for construction and maintenance over its whole life cycle. The Dutch Pavilion, as the experimental sustainable building, also has the highest embodied energy compared to the historic and conventional buildings used for a long life. Most this embodied energy is consumed for the high-tech and energy generating appliances (wind turbines). On the other hand, if the Dutch Pavilion were used for 50 years, its total energy consumption would be reduced and would then be lower than both the conventional and historic exhibition buildings studied. It can be seen that the true useful life of a building is a significant point in terms of its overall sustainability. Sustainable exhibition buildings will only reach the goal of sustainability, if they are used continuously for a long time. The problem with buildings for events like Expos is that this long life cannot be guaranteed. In addition, using sustainable technologies, such wind turbines, for exhibition buildings does not seem the best approach for reducing their energy consumption. A further investigation showed the Dutch Pavilion only achieved its
low life cycle energy by having some of its covered exhibition space un-serviced. Therefore, the two comparisons were not equal in terms of building function. This also suggests that life cycle analysis has to be used carefully when comparing buildings of this type.

Secondly, the case study of the Crystal Palace shows that flexibility in the construction approach, such as the ability to recycle building components, is an appropriate approach to decreasing the environmental impact. Other studies demonstrate that recycling would be a potential way for reducing embodied energy requirements (Adalberth 1999; Adalberth et al. 2001; Thormark 2002). Power (2008) suggests that upgrading the building stock to high environmental standards is cheaper than demolishing it and building new for a similar carbon reduction. The environmental aspects of exhibition buildings with demountable components thus become an important area for further research. In fact it was the building services installed in the Sydenham Crystal Palace that led to its higher energy consumption in the operating phase. Had the original design been retained when the building was moved, the Crystal Palace would be the building of three studies with the lowest life cycle impact. This brings into question whether modern building servicing systems are having a significant impact on the natural environment friendly recently.

Thirdly, the Shanghai Exhibition building with its city centre location shows that a well constructed building in the right place can have a long useful life, and this will also result in a lower lifecycle energy use than a purpose designed sustainable exhibition building with a short life.

Finally, the boundaries of environmental analysis for large-scale exhibition building need standardization. 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.

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Power, Anne. (2008). “Does demolition or refurbishment of old and inefficient homes help to increase our environmental, social and economic viability?” Energy Policy, 36, 4487-4501.


