Life Cycle Energy Benefit of Sustainable Design Approaches for Industrial Buildings

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Abstract: Although the construction and operation of industrial buildings represents a significant impact on the environment, their environmental performance has rarely been considered. Various techniques have been developed in order to improve building environmental performance, including design for disassembly, design for recyclability, design for durability, and design for adaptive reuse. While these approaches are increasingly being used during the building design process, the benefits they provide to the life cycle environmental performance of industrial buildings is yet to be assessed. The current study evaluates the total life cycle energy demand of a case study industrial building. The net life cycle energy benefit using the sustainable design approaches listed above is evaluated and compared to the as-built design. Results highlight the importance of a life cycle approach to sustainable industrial building design and the need to integrate sustainable design approaches during the early stages of building design, in order to achieve long term environmental benefits.

Keywords: industrial buildings; disassembly; recyclability; durability; adaptive reuse; life cycle assessment

Introduction
The industrial sector is a very important sector within society, creating economic growth and capital flows. Besides these benefits, it is also responsible for significant environmental and health impacts. Some steps for improving manufacturing processes, for prevention and control of industrial emissions have already been implemented. But the construction and operation of industrial buildings are seldom considered in the context of their environmental impacts. Sustainability assessment and design tools specific to industrial buildings are almost non-existent as environmental improvement efforts have so far been mainly focused on residential, office, commercial and retail buildings [1]. Any such efforts have been focused preliminary on the industrial buildings operational performance with little focus upon the environmental performance across their entire life cycle. Therefore, a more comprehensive understanding of the implications of key design decisions on the life cycle environmental performance of industrial buildings is needed to ensure they result in long term environmental benefits. The aim of this study is to investigate the life cycle energy (LCE) benefits of implementing key sustainable design strategies in the design of industrial buildings.
Overview of sustainable design approaches

Besides the more commonly used strategies for achieving environmental building design such as passive design and active environmental building systems, Crawford [2] identifies four key sustainable design approaches that are critical for improving the environmental performance of buildings. These are Design for Disassembly (DfD), Design for Recyclability (DfR), Design for Durability (DfDur), and Design for Adaptive Reuse (DfAR).

Design for Disassembly (DfD)
DfD is a design approach that seeks to optimise the ability to reuse materials and components after the end of a building’s life. The materials should be carefully selected according to their service life and to the life span of the building layers, minimising the number of different types of used elements. Materials should be robust, durable, lightweight, non-toxic, non-hazardous, recycled or recycling-compatible, to be worth reusing. Composite materials, where individual materials could not be detached, should be avoided. No secondary finishes are recommended as they are likely to contaminate the basic materials. Both joints and components should be designed to withstand repeated use and to allow for parallel disassembly. Prefabricated elements, open building system and modular design offer the greatest opportunities for deconstruction [3-9].

Design for Recyclability (DfR)
DfR aims for a significant increase in the opportunities for future reuse and recycling of building materials and components. The recycling potential of the selected materials should be investigated and different classes of reusability and recyclability of materials should be defined. Materials and polymers should be marked for facilitating future correct sorting and waste management. Valuable materials should be easily accessible. Critical, hazardous and environmentally harmful materials should be avoided [10-13]. DfR often goes hand-in-hand with DfD as materials become much easier to recycle if they are easy and quick to separate from other building materials on site.

Design for Durability (DfDur)
Optimising life cycle building performance and minimising on-going maintenance costs are the major benefits of DfDur. This involves taking into account the natural durability of materials including optimising maintenance and inspection activities. Materials should be physically robust, long-lasting, that resist wear and the influence of weather. It is possible for heavier materials to provide thermal mass and thus also operational benefits. While longer-lasting materials are typically ideal, materials should be carefully selected according to the life span of a building, avoiding over-specification and with regard to natural conditions such as local climate, freezing cycles, exposure to airborne salt, etc. Joints and connections should be wear resistant and long-lasting to make the most of the main materials [14-16].

Design for Adaptive Reuse (DfAR)
Constructing new buildings demands a considerable quantity of virgin resources. The building demolition process is also costly and time consuming and generates waste that is mostly
disposed of in landfill. DfAR aims to facilitate the future adaptation of buildings in order to minimise the need for new buildings and demolition of existing buildings for as long as possible. This results in reduced environmental impact, minimising land and material consumption, stimulating brownfield regeneration, and retaining the historical, social and aesthetic cultural value of existing buildings. A building designed for adaptive reuse is often much easier to adapt to other uses through minor or major refurbishment [17-19].

DfDur and DfAR design strategies are interconnected with most of their principles overlapping. In order for a building to be reused its main components must be durable enough for a period of time well beyond the time at which it is adapted in order to warrant further investment. The type of construction and appropriate foundations should be carefully selected ensuring its structural integrity, facilitating different future building uses and loading scenarios. The building system should be open and/or modular, facilitating future reconstruction and adaptive reuse.

Method
This section describes the approach used to determine the life cycle energy benefit associated with the use of sustainable design strategies for industrial buildings.

Case study building
A case study industrial building is used in order to assess the effect of the key sustainable design approaches and strategies on the LCE performance of industrial buildings. Industrial buildings are complex structures, often huge and spacious and hence they are heavy users of resources like energy, water and land. Industrial facilities account for one-third of global energy use and almost 40% of worldwide carbon dioxide emissions [20]. Compared with other types of buildings, they are typically characterised by a short service life (SL) of between 25 to 49 years [21]. One of the reasons for this is the frequent technological changes, which often lead to rapid decline, deterioration and technological obsolescence. This is why functionality, safety and flexibility for future adaptations or expansion needs are crucial.

The selected case study is a refrigerated distribution warehouse (Figure 1), chosen for this study because warehouses are responsible for the greatest share of industrial buildings – 55% [22]. The case study is located in Sofia, Bulgaria and was recently designed. It is separated

![Figure 1 Refrigerated distribution warehouse - a) Ground floor; b) Level 2; c) South façade; d) West façade](source: Diana Modeva and Dimitar Vasilev)
into two main blocks with total floor area of 1,856.5 m$^2$. The first one is a three-storey administrative block with reinforced concrete structure, external brick walls and internal plasterboard walls. The second one is a one-storey refrigerated warehouse with a service area built with reinforced concrete columns, steel roof trusses and sandwich panel walls. There is also a basement under the two blocks used as a garage and additional service area.

**Sustainable design approach scenarios**

This section details the key design changes made to the base building to reflect the four sustainable design strategies described above. As the basic strategies used within each of the design approaches often overlap, two combined scenarios have been used in this study.

Based on current construction materials and practices, a reinforced concrete structure together with brick walls are considered the most durable form of construction possible for a 75-100 years life. For this relatively long period of time some of the elements within the case study building, i.e. sandwich panels, roof insulation, paint, etc., will have to be replaced. However, the integrity of the structure is likely to remain. The partition walls could be easily dismantled and the plan could be easily changed and upgraded. For this reason, while cost and speed of construction issues are most likely the main drivers rather than the environment, the authors have assumed that the current building design is in line with the general principles of *DfDur* and *DfAR*. Some improvements are needed in order to ensure optimal thermal characteristics and building performance. Therefore, the insulation level is increased, the thermal transmittance of the glazing is improved by installing triple glazing and the efficiency of HVAC systems is improved. These changes form the basis of the first alternative design scenario (*DfAR & DfDur*).

The second alternative design scenario introduces changes to reflect the basic strategies typically used within *DfD* and *DfR*. This includes changing the types of construction, materials, components and fixings according to achieve ease of disassembly and recyclability. The type of construction is changed from a reinforced concrete to steel structure, as steel is considered to be much easier to deconstruct and is 100% recyclable. It is also much easier to recycle compared to having to separate out the steel form a reinforced concrete structure. The reinforced concrete structure is preserved only in the basement level. The brick walls are substituted with demountable prefinished external panels, eliminating the need for additional processing and finishes. In an attempt to reduce the life cycle energy demand of the building, the expanded polystyrene (EPS) insulation is substituted with fibreglass, as the embodied energy (EE) coefficient of fibreglass is much lower and the raw materials are much more abundant. In addition, the EPS is non-renewable and a heavy polluter during production, ranking just behind aluminium for energy consumption and greenhouse gases [23]. The laminate flooring is substituted with natural linoleum, made from renewable materials, and where future reuse, recycling, or reincorporation into the environment at the end of its life is possible. The curtain wall is replaced with triple glazed windows, thus decreasing the glazing area and improving thermal transmittance. Although the plasterboard is highly recyclable it was substituted with a prefabricated, prefinished and demountable particleboard partitioning.
system, made using lower impact resins and sourced from renewable raw materials as by-products from the timber industry [24].

Calculating life cycle energy (LCE)

The LCE benefit of the design changes were determined by calculating the LCE of the case study building for its original and amended designs. The LCE calculation includes energy required for initial construction (initial embodied energy), building operation, maintenance and refurbishment (recurrent embodied energy) and eventual demolition and disposal (Figure 2). The study includes the LCE associated with building materials, but excludes those associated with internal fitout, electrical wiring, plumbing and equipment. Although the average service life of an industrial building is assumed to be 38 years [21], a study period of 100 years is used for the analysis in order to quantify the long-term benefits of strategies such as DfAR and DfDur.

Initial and recurrent embodied energy

The EE is assessed using an input-output-based hybrid approach, based on hybrid coefficients for construction materials in Australia, developed by Treloar and Crawford [25]. The initial EE is determined by multiplying the hybrid coefficients and the material quantities, which are then summed. Energy requirements related to non-materials inputs upstream in the economy are accounted for with the use of additional input-output data. The initial EE of the building, which includes all of the energy associated with the processes upstream of the main construction process, may vary according to the type and quantity of the building materials used, as well as their hybrid coefficients. This method has been designed and implemented in Australia and although the applicability of Australian data to a building in Bulgaria may be questionable, because the majority of other databases are based on process-based data, the errors associated with the use of Australian data are likely to be less than the errors associated with relying on process data alone, as noted by Stephan [26].

The energy associated with the production of materials used in the maintenance and refurbishment of buildings is known as recurrent embodied energy [26-28]. The longer the building lasts, the greater the expected recurring embodied energy consumption is. However, it is still relatively not well understood and addressed in only a limited number of studies [29-31]. In this study the recurrent EE is calculated based on the average service life of materials.
used within each building scenario. These values indicate the number of replacements during the useful life of the building.

Operational energy
Computer modelling software for simulating the expected building operational energy performance, named Integrated Environmental Solution - Virtual Environment™ (IES-VE), was used in order to assess the operational energy of the case study building. Energy required for heating, cooling, ventilation, and lighting was simulated in order to understand the energy associated with the buildings use. Operational energy over an extended period of time is difficult to predict and is likely to vary due to different factors such as efficiency improvements or occupant behaviour. However the current study assumes that the results obtained from IES-VE would not vary during the building’s life.

Demolition energy
The demolition stage includes building demolition, transportation, waste management and disposal. Often, it is not considered in previous LCE studies, because most often it is considered to represent a very small proportion of a building’s life cycle energy demand [32-35]. Building demolition activities and transportation of waste may account for only 0.2% of its life cycle primary energy consumption [36]. In addition, high uncertainty in the distant future concerned with unpredictable demolition practices, transport distances, various techniques for salvaging and reprocessing of materials make it difficult to assess. Therefore in the current study it was assumed that the energy required for demolition and disposal of materials is equal to 1% of the total life cycle energy demand for the building [37].

Results and Discussion
This section presents and discusses the results of the study. The alternative design scenarios are shown to have a considerable influence over the LCE performance of the building (Figure 3). Those elements that are most significantly affected are the structure, substructure, walls and roof. The embodied energy of internal finishes is also reduced as prefabricated and prefinished materials result in a lower demand for life cycle embodied energy.

For a period of 100 years and compared to the base case scenario, the DfDur & DfAR scenario results in almost a 10% reduction in LCE. More durable materials have been used which typically, as evidenced in this case, are more energy-intensive to manufacture, and thus result in a higher embodied energy. This increase in embodied energy has been offset by a greater reduction in operational energy however. This is due to better thermally performing materials. The DfD & DfR scenario results in a 20% reduction in LCE compared to the base case due mainly to the long life of the steel structure. However, if the building was designed for a much shorter service life, there would be a significant increase in the steel-related embodied energy demand over a 100 year period due to complete structure replacement. Based on the average service life of industrial buildings of 38 years, this would equate to a 25% increase in life cycle embodied energy. This demonstrates the importance of prolonging the life of a building and utilising the most durable materials appropriate to the anticipated life of the
building to reduce life cycle embodied energy requirements. Embodied energy has been able to be reduced in this scenario by using less energy-intensive materials, while operational energy has also been reduced compared to the base case.

![Figure 3 LCE consumption of case study building designed using various sustainable design approaches](image)

**Conclusion**

The study aimed to provide a better understanding of the life cycle energy benefits associated with a range of key sustainable design strategies for industrial buildings. While a broader range of case studies is needed to draw any conclusive findings, the results of this study have shown that it is possible to significantly reduce the LCE demand of industrial buildings by employing sustainable design strategies. LCE savings of up to 20% were found to be possible. Taking a life cycle approach, as in this study, is crucial to ensuring that the environmental performance of a building is optimised across its life cycle. Designers, architects, researchers and decision makers will benefit from this knowledge, which demonstrates the advantages of some key sustainable design approaches and a useful approach for analysing the net environmental benefits of important design decisions. It can also help educate other construction stakeholders, such as contractors, investors and tenants providing them with important information for building development, investment and operational decisions.

**References**

8