Life Cycle Energy Analysis and Building Design: A comprehensive Multi-scale Framework

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ABSTRACT

Life cycle assessment can play a significant role in quantifying the overall sustainability of a building. This work describes a multi-scale life cycle energy analysis framework that considers different scales of the built environment, across the various life cycle stages of a building.. Results show that current building energy efficiency policies and environmental assessment schemes fail to provide comprehensive and quantified analyses, respectively. In addition to enlarging the environmental scope, economic and social aspects can be included in the developed framework to provide a more holistic sustainability assessment. By relying on such a multi-scale life cycle assessment framework, a more realistic measure of the sustainability of buildings can be achieved.

INTRODUCTION

The so-called 'triple bottom line' approach, which was adopted by the United Nations in 2007, emphasises the importance of the three pillars of sustainability: social, economic and environmental. Accordingly, sustainability could be summarised as balancing these three pillars in the optimal way: enhancing the economy, empowering the people and reducing environmental impact. This approach has been widely used in architectural design.

However, before trying to determine an optimal building design in regard to sustainability, each of the three pillars should be realistically and comprehensively assessed. This is essential as buildings are a core component of our society, shaping our social spaces, using our resources and playing a major role in our economic system. This chapter focuses on the environmental pillar of sustainable architecture although the inclusion of the two other pillars is discussed.

The environmental sustainability of buildings is generally measured using national schemes that are developed by so-called 'green building councils'. The most famous of these schemes are LEED (Leadership in Energy and Environmental Design, USA), BREEAM (Building Research Establishment Environmental Assessment Method, UK), the Japanese CASBEE, the German DGNB and the French HQE.[1] All these frameworks focus mainly on the environmental aspect of buildings although some include an economic component (e.g. DGNB). The main strength of these facultative certifications, often called 'building environmental assessments' (BEAs) is their comprehensiveness. For example, LEED includes criteria pertaining to material use, accessibility to public transport, building systems and others.

However, all these BEAs fail to provide a quantified environmental impact of buildings. Indeed, they rely mostly on qualitative score-based systems to award the certification, without quantifying the criterion. Therefore these certifications do not ensure a reduction of the environmental impact. For example, Scofield and Newsham *et al.* have demonstrated that LEED certified buildings do not necessarily save energy compared to normal buildings.[2,3] Another approach is therefore required to realistically measure the environmental impact of buildings.[4]

Life cycle assessment (LCA) is a method that quantifies potential environmental impacts of a product or service, across all its life cycle stages. LCA is regulated by the international standard ISO 14040 and several other standards have emerged regarding its application to buildings.[5] Examples are the European standards EN 15643-2 and EN 15978 that set the framework for the environmental assessment of buildings and its calculation procedure.[6,7] By quantifying the inputs and outputs, in terms of energy, water, waste, and other environmental indicators, at each life cycle stage of a product (e.g. raw material extraction), an LCA study can determine its environmental impacts. However, LCA is rarely used at a whole building level and often focuses on building materials or assemblies. LCA is moreover totally ignored in current building energy efficiency policies such as the European energy performance of buildings directive (EPBD). [8] Even when an LCA study is conducted at the building level, the mainstream databases often underestimate the environmental impact because of their reliance on process data.[9, 10] Therefore, while LCA is a very promising method to realistically quantify the overall environmental impact of buildings, its current use falls short of its potential. Therefore, there is a need to develop a framework that is capable of realistically measuring the environmental impact of buildings in a quantitative way.

The aim of this chapter is to demonstrate how a multi-scale LCA framework can be a key solution to better measure the environmental sustainability of buildings and potentially their socio-economic sustainability. A streamlined environmental assessment focusing solely on the energy demand of residential buildings is used to illustrate the potential of the framework. Energy is the most important indicator for the majority of existing residential buildings in Belgium. [11]A framework is proposed and apllied on two case studies to demonstrate the limits of current policies and certification schemes. Results are discussed and put in perspective regarding the role of LCA in supporting sustainable building design.

A MULTI-SCALE LIFE CYCLE ENERGY ANALYSIS FRAMEWORK FOR RESIDENTIAL BUILDINGS

Energy is used at different scales of the built environment. Building materials require significant amounts of energy for their manufacture and replacement over time (i.e. embodied energy). Infrastructures supporting the building and the related services also require energy for construction and maintenance. The embodied energy associated with infrastructures should be taken into account for a comprehensive assessment. At the building scale, occupants use energy for heating, cooling, ventilation, appliances, hot water, lighting and cooking (i.e. operational energy). At the urban scale, building occupants use energy for their mobility (i.e. transport energy).

The inclusion of embodied and transport energy has been advocated by Szalay and Garcia-Casals. [12, 13] Studies such as Stephan *et al.* and Fuller and Crawford have identified that embodied and transport energy often represent more than 50% of the total energy demand.[14, 15] It is therefore crucial to consider all these energy requirements to realistically measure the total life cycle energy demand in order to improve the sustainability of buildings.

Details regarding the quantification of the energy demand are given in Stephan and Stephan *et al.*[16, 17] To summarise, embodied energy is determined using the comprehensive input-output-based hybrid analysis that ensures a systemic completeness while using the most accurate data for known processes. [18] Embodied energy is calculated by multiplying the material quantities by their embodied energy coefficients and adding the energy demand for non-material processes. This is also done for materials contained in the infrastructure attributed to the building based on the number of occupants and population density. Operational energy is determined using static heat transfer equations for heating, cooling and ventilation and regional averages for hot water, appliances, cooking and lighting demands. These averages were obtained through the regional body IBGE for Brussels, Belgium. [19] Transport energy requirements are determined by multiplying the annual travel distance per transport mode of the household by the total energy intensity of each mode. This total energy intensity comprises both direct and indirect processes. Direct energy is associated with the process itself, such as burning fuel in a car. Indirect energy is required to support the process, such as energy for manufacturing the car, insurance, registration, etc. Total energy intensities for transport are determined using input-output analysis, such as in Lenzen. [20]

Considering life cycle energy demand at different scales of the built environment ensures that net energy savings do occur instead of being shifted between different scales or between different life cycle stages. Yet, focusing solely on energy allows possible shifts to other impact categories such as toxicity or resource depletion or others. More environmental impact categories should be considered for a comprehensive environmental assessment. However, this chapter demonstrates the relevance of a life cycle approach in the sustainability assessment of buildings instead of conducting a full environmental assessment. For this reason only energy is considered. Figure 1 shows the system boundaries of the framework. The end of life stage is not considered as Winistorfer *et al.* have demonstrated that it often represents less than 1% of the total energy demand. [21] Uncertainty in the data is taken into account through interval analysis but is not further mentioned here due to space limitations.

APPLICATION OF THE FRAMEWORK TO TWO CASE STUDIES

Two case studies are studied over 50 years to demonstrate the potential of the framework. The first is a new 300 m² passive house located 26 km outside of Brussels, in a low density neighbourhood. The four occupants use gasoline cars for their mobility and travel 28 000 km per year, in total. Being a passive house, the building is extremely insulated and airtight. The second case is a retrofitted 70 m² apartment in Brussels. Only the bearing structure is kept while all other assemblies are replaced. The apartment is highly glazed (90% of the façade) and accommodates two occupants who use a mix of tramway (2 400 km per year), subway (2 400 km per year) and car (6 000 km per year). Travel distances and modal splits are based on an interview of the inhabitants for both cases. Table 1 summarises the main characteristics of the two case studies.

Table 1 Main characteristics of the two case studies

Characteristics	Description	
	Suburban passive house	City Apartment (retrofitted)
Period of analysis	50 years	
Building useful life	50 years	
Gross floor area	300 m²	70 m²
Usable floor area	297 m²	63 m²
Number of occupants	4	2
Structure	Steel-framed on concrete slabs	Reinforced concrete structure
Façade	Glued bricks – 220 mm of polyurethane insulation – Triple glazed, argon filled, timber framed windows	Concrete blocks – 80 mm of Rockwool insulation – Double glazed windows, thermally broken aluminium frames
Roof	Terracotta tiles - 300 mm of polyurethane insulation and 100mm of rock wool insulation	N/A
Finishes	Medium standing	Medium standing
Ventilation type	Mechanical	Natural
Average *U*-value	0.19 W/(m²K)	2.2 W/(m²K)
Primary energy conversion factors	Electricity: 2.5 ;Gas: 1.0	
Total energy intensity of transport modes	Gasoline car: 3.2 MJ/pkm (adapted to Belgian conditions)[22] Tramway: 2.04 MJ/pkm [23] Subway: 1.92 MJ/pkm [24]	

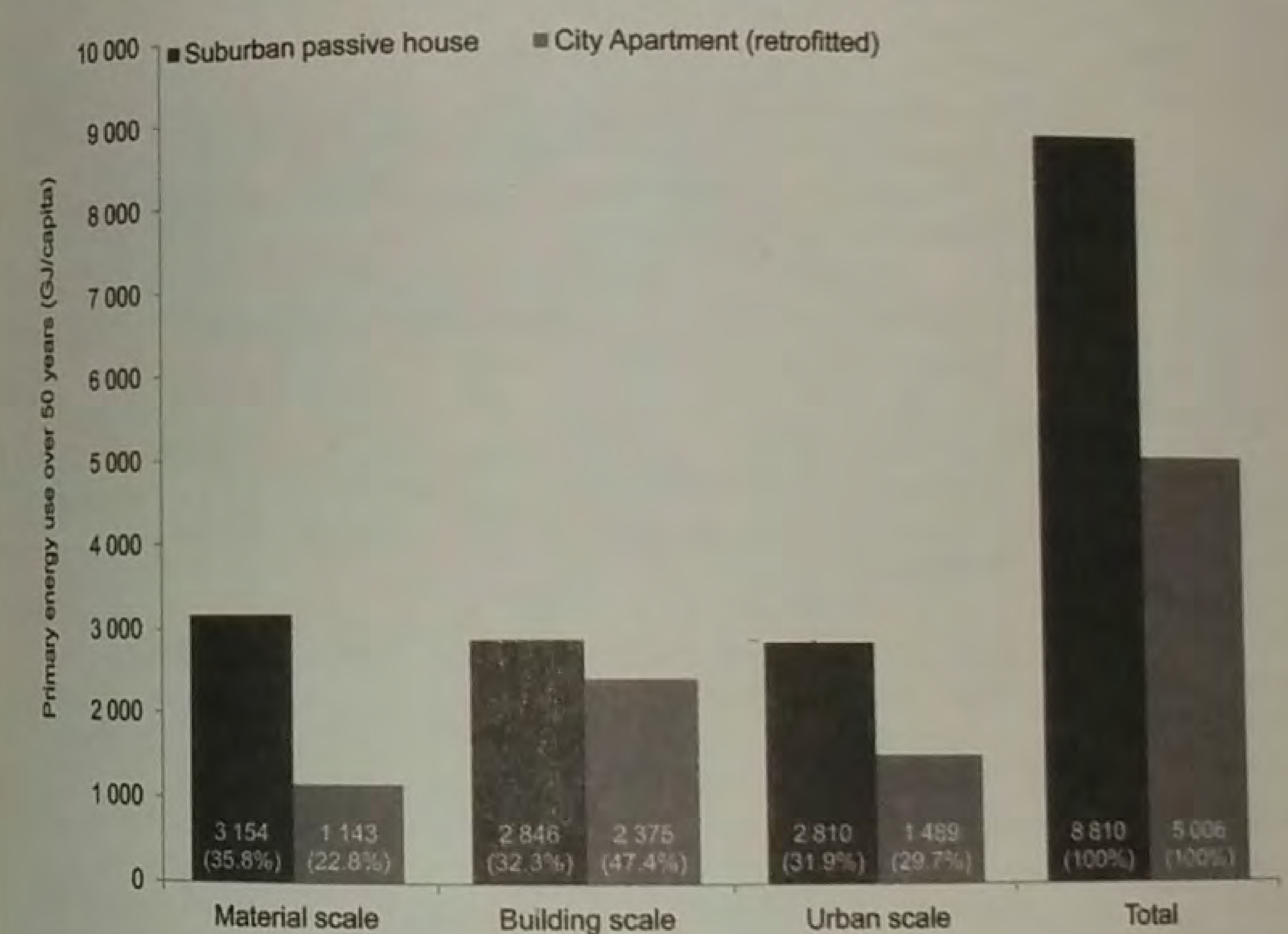

Figure 1: System boundaries of the developed framework

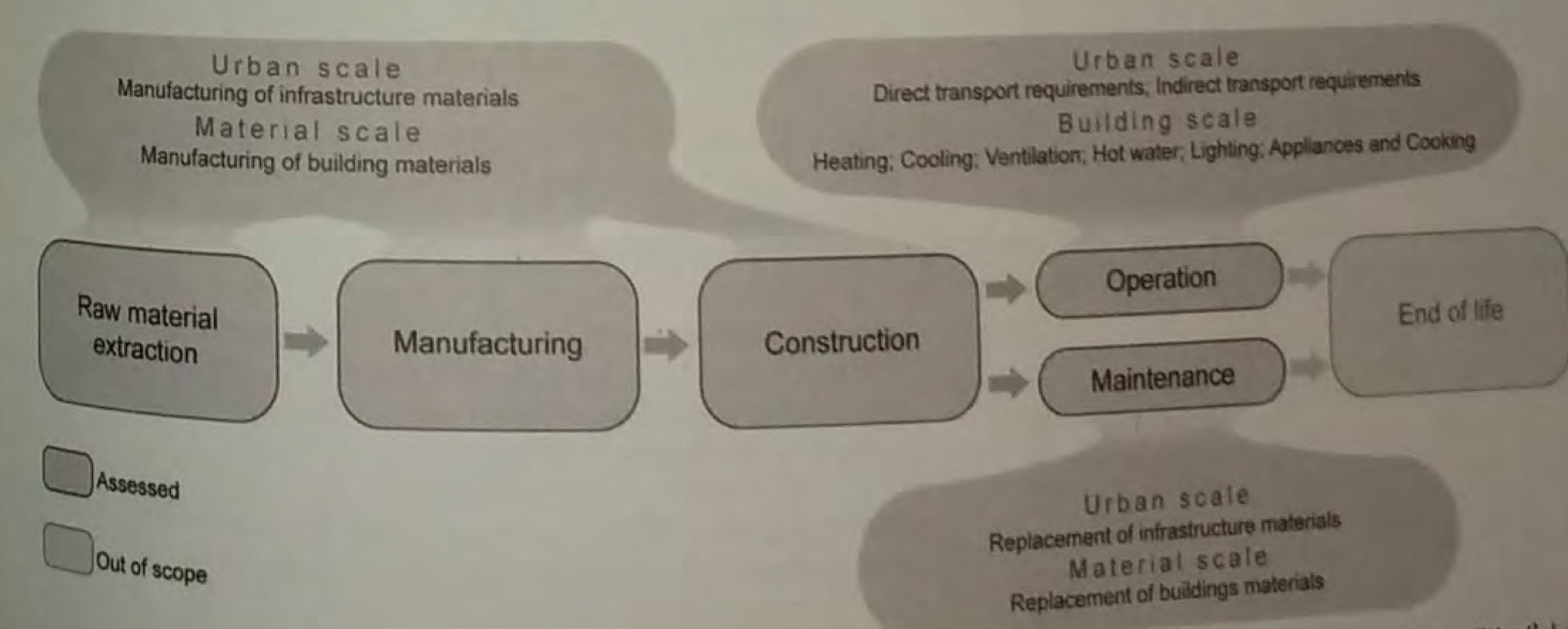

Figure 2: Life cycle energy demand over 50 years, for the suburban passive house and the city apartment (retrofitted), by scale and per capita

Figure 2 shows the life cycle energy demand of the sub-
urban passive house and the city apartment (retrofitted)
over 50 years, for each scale and per capita. Two main ob-
servations can be made. Firstly, the embodied and trans-
port energy, which are not included in current building en-
ergy policies or certifications (such as the passive house),
represent more than 50% of the total energy demand.
Secondly, despite the rather poor thermal performance of
the city apartment, its life cycle energy demand is 43.2%
lower than the demand of the passive house (per capita).
The initial embodied energy of the apartment's structure,
which is not taken into account, does not influence the
results (it represents only 124 GJ/capita). This illustrates
that, from a life cycle perspective, certified buildings can
use more energy per capita compared to buildings with
a poor operational energy performance. Other factors,
such as the living area per person, transport modes used,
travel distances and the energy sources for operational
energy play are significant contributors towards the life
cycle energy demand.

DISCUSSION AND CONCLUSION

This chapter has shown how a life cycle energy analy-
sis framework addressing multiple scales of the built
environment, can measure the overall energy demand
of a building. This comprehensiveness revealed how the
limited scope of current building energy efficiency poli-
cies and certifications cannot appropriately estimate en-
ergy use. Indeed, the passive house certification, which
is thought to be among the most stringent in the world,
focuses solely on operational energy, ignoring embodied
and transport energy requirement.

Compared to building environmental assessment
schemes (BEAs), such as LEED and BREEAM, the devel-
oped framework provides a quantified assessment and
can measure net energy benefits. Even if these BEAs are
more comprehensive through the integration of qualita-
tive parameters, a multi-scale LCA can inform the design-
er about the repercussions of choices, early in the design
process. This quantification encompasses the choice of
materials, the building operation and its location. Obtain-
ing quantified figures from a life cycle perspective can
be a game changer in informing environmental decision
making in building design.

Yet quantitative approaches such as LCA suffer greatly
from the reliability of the data used. Currently, most da-
tabases comprise so-called process figures, which can
greatly underestimate the environmental impact of a
product.[25] Comprehensive global databases, relying on
the input-output-based hybrid analysis approach should
be developed. Also, if the uncertainty margin is higher
than an observed difference between two buildings or
systems, quantitative analysis can become useless. High
quality life cycle inventory databases and the use of
frameworks for decision making under uncertainty are
both required.

The developed framework focuses on energy but can
be expanded to include environmental impacts such as
global warming or water use, as described in Stephan.
[26] By integrating a full set of environmental impact cat-
egories, the enriched framework can assess the overall
environmental sustainability of a building. If the financial
cost is considered through the use of the life cycle cost-
ing (LCC) method, another pillar of the triple bottom line
can be integrated. This is rather easy to implement be-
cause the LCC method already exists. An example com-
bining LCA and LCC is the work of Allacker.[27] Also, recent
studies have shown that LCA can be adapted to assess
social conditions.[28] The integration of social metrics is
more challenging because it can be highly subjective and
it depends on more case-specific and qualitative param-
eters. Although this may be a difficult prospect to achieve,
including both social and economic aspects alongside
environmental parameters can result in a truly compre-
hensive sustainability assessment framework, based on
a life cycle approach. Ultimately, this will help improve the
sustainability of the built environment.

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