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# Energy and carbon performance evaluation for buildings and urban precincts: review and a new modelling concept

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ABSTRACT

With the accelerating pace of urbanisation around the world, the planning, development and operation of buildings and precincts have become increasingly important with respect to energy use and the associated carbon footprint of the modern built environment. Over recent decades, much effort, both in research and in practice, has been devoted to building construction and urban planning for the improvement of energy efficiency and greenhouse gas emissions. However, the accuracy of modelling and evaluation of energy and carbon performance for buildings and urban precincts remains limited, affected by inadequate energy intensity data and highly integrated building systems, as well as the complex interactions between buildings and the urban eco-system. This paper presents a critical review of current measures and models for representing and assessing life cycle energy as well as associated emissions profiles at both the building and the precinct levels. It also identifies influential factors and explores interactions among buildings, surrounding environment and user behaviours at the urban precinct level by taking a systems perspective. Based on such a review, this study maps out some key challenges for integrating energy and carbon metrics, and finally proposes a precinct-level system boundary definition and an integrated model following systems thinking. The proposed model can facilitate a critical thinking approach about the evaluations of global energy and emissions, and support the quantification of energy consumption and associated emissions for building precinct systems.


## 1. Introduction

As a highly active sector in both developed and developing countries, building and urban development holds great potential for sustainable development in terms of reducing natural resource consumption and greenhouse gas (GHG) emissions, as well as delivering economic and social benefits to the community (Cabeza et al., 2014; Tuominen et al., 2014). Current research and investigations indicate that nearly 40% of the raw materials consumption, 40% of the global energy consumption, 25% of solid waste, 25% of water use, 12% of land use and about 33% of GHG emissions are attributed to the building sector (Fumo et al., 2010; Monahan and Powell, 2011; Chang et al., 2012). In Australia, approximately 20% of energy is consumed within buildings, and commercial buildings account for about 10% of Australia's total GHG emissions (Australia Government Report, 2012). Buildings consume energy and contribute to GHG emissions both directly and indirectly throughout their life cycle phases. Direct energy use and emissions are related to the processes of construction, operation, renovation and demolition, whereas indirect energy consumption and associated emissions are caused by production and transportation of materials, as well as technical installations.

Although a building is often designed and assessed as a self-contained system consisting of various materials and components, it is inevitably dependent on and influenced by the surrounding natural, built and socio-economic environments in which it is established, occupied and operated. An urban form that integrates these environments with buildings to realise certain predefined functions is often represented in forms of a precinct, regarded as ‘a system of many interconnected systems’. Since the 1970s, greater attention has been devoted to the observation of energy and emissions performance affected by land use, urban planning and urban formation. Some early research work (e.g.

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Kurtzweg, 1973; Arens and Williams, 1977; Taha et al., 1988) indicated that the urban environment can have significant impacts on the energy and emissions performance of individual buildings. Therefore, it is worth devoting more effort to energy efficiency improvement and emissions reduction through planning and design optimisation, and material selection, as well as policies formulation and implementation at both the building and the precinct levels.

The energy intensity and carbon performance of a building are quite complex phenomena, as they are influenced by many factors such as building types, construction materials, built-in appliances, urban precinct forms, local climate, user/occupant behaviours, energy sources, and retrofitting and maintenance strategies (Zhao and Magoulès, 2012; Abanda et al., 2013). Accurate modelling and estimation of energy consumption and associated emissions requires detailed data input of building and environmental parameters. A comprehensive understanding coupled with a systems-based consideration of interactions among urban forms, buildings and the environment are critical to the formulation of strategies and policies for urban development to meet sustainable development targets. Therefore, the main focus of this study is to present a critical review of current research on energy and carbon performance of buildings (Section 3) and of precincts (Section 4), which leads to the identification of the main gaps and challenges in extant modelling and evaluation approaches (Section 5). Then, a new integrated modelling concept based on the systems perspective is proposed (Section 6). Finally, the paper concludes with a summary of the review findings and an outline of the future research directions (Section 7).

## 2. Life cycle assessment in environmental impacts evaluation

Life cycle assessment (LCA), also known as life cycle analysis, is an important tool developed to identify and evaluate a range of, or some specific environmental loads and impacts of a particular product, process or service over its entire life 'from cradle to grave'. According to Crawford (2011), LCA approaches can be classified into three types depending on the application in various cases: baseline (or conventional) LCA, comparative LCA and streamlined LCA. Generally, baseline LCA aims to identify the most significant areas; those contributing the greatest to the overall environmental impacts over a product's life cycle. Comparative LCA, however, is employed for environmental performance optimisation of products by selecting the best solution with the lowest environmental impacts from a number of feasible solutions. In comparison to the other two approaches, streamlined LCA is often applied in the assessment of environmental impacts with a scope that is limited in depth, breadth and detail. In the built environment, because buildings are always related to energy consumption, a streamlined LCA approach appears more appealing and also fit for use when the focus of the assessment is largely on energy-related environmental impacts.

Since the 1990s, a series of standards such as ISO 14040, ISO 14041, ISO/TR 14049, EN 15643-2 and EN 15978 have been published by the International Organization for Standardization (ISO) and the European Committee for Standardization (CEN) to support environmental management and LCA development. In ISO 14040:2006, four phases are defined for a general LCA process (see Fig. 1):1) *Goal and scope definition*—functional units, system boundary and quality criteria settings; 2) *Life cycle inventory analysis*—information integration and processing for various life cycle stages; 3) *Life cycle impact assessment*; and 4) *Life cycle interpretation* for Phases 2 and 3.

As the first phase of an LCA, the goal and scope definition involves the determination of research objectives, as well as the

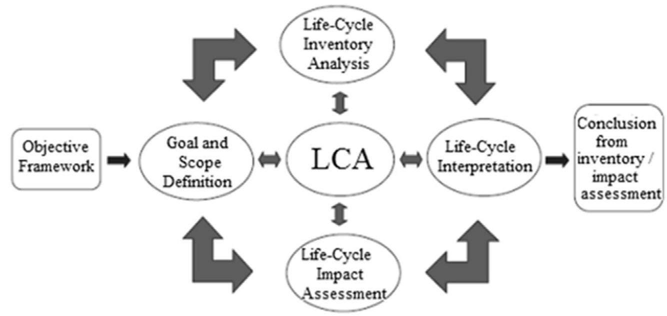


**Fig. 1.** Stages of life cycle assessment (adapted from Sharma et al., 2011).

identification of life cycle stages and boundaries for the product system. The standards released by ISO and CEN, along with current LCA practices indicate that system boundary selection employed to define the inputs, outputs and processes of a product system is a complex and important issue in LCA implementation. The accuracy and completeness of a system boundary is the major contributor to the precision of modelling and evaluation. In addition, from the systems perspective, a fair comparison between different systems can only be guaranteed when similar completeness or the same boundary is applied (Raynolds et al., 2000; Dixit et al., 2013). Padgett et al. (2008) performed a comparative analysis on ten US-based carbon calculators, concluding that estimates of carbon footprints produced by different calculators can vary by as much as several metric tons per annum per individual activity, due to a lack of consistency and clear boundary setting. Kenny and Gray (2009) supported this through a comparative study on six carbon footprint models used in Ireland.

Three types of methods have also been developed for life cycle inventory analysis: input–output (IO) analysis, process analysis and hybrid analysis, with each having their own benefits and limitations. IO analysis is an economic technique that uses sectoral monetary transactions to describe and explain the complex independences of industrial activities within a given national or regional economic system (Suh et al., 2004). Since all the physical relationships among the analysed industrial sectors are linked directly with capital expenditure, IO analysis can simplify modelling, and explain the spatial distribution and consumption in complicated multi-regional and dynamic scenarios (Leontief, 1970). Another benefit of IO analysis is that the data are regularly compiled as part of national statistics (Suh et al., 2004). However, this approach is often limited by uncertainties arising from basic source data, proportionality, imports and homogeneity assumptions, as well as incompleteness of sectoral environmental statistics. Such a notion is supported by some earlier studies (e.g. Treloar, 1997; Lenzen, 2000). In addition, IO analysis can distort the physical flow relationships between industries, and fail to guide technological and consumer choices, because IO data are blind to individual processes (Majeau-Bettez et al., 2011).

In comparison with IO analysis, process-based analysis can provide more recent, accurate and detailed process information, as well as a deeper understanding of the nature of construction and consumption activities at the product level. This detail-oriented bottom-up approach has attracted the growing attention of practitioners and academia, and contributed significantly in some recent research on the evaluation of building energy and carbon performance over its lifespan (see Abanda et al., 2013; Karimpour et al., 2014). Although giving more accuracy and relevance to the product being analysed, as argued by Treloar et al. (2003) and Han et al. (2013), the process-based analysis typically suffers from system boundary incompleteness and truncation errors, depending on