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Calculation of a building's life cycle carbon emissions based on Ecotect and building information modeling

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ABSTRACT

Buildings are responsible for more than 40% of global energy usage and as much as 33% of global greenhouse gas emissions in both developed and developing countries. However, the study of carbon emissions over a building's life cycle based on Ecotect and building information modeling in developing areas of Nanjing has yet to be conducted. Therefore, the results and recommendations of this paper represent a contribution to the literature on this topic. The scientific value of this paper is that Ecotect and building information modeling can be helpful in simplifying the estimation of carbon emissions over a building's life cycle because they can provide a majority of the information and calculation tools necessary for performing an life cycle assessment (LCA), which may alleviate the problem of insufficient information when executing an LCA of a building. A sensitivity analysis was performed by changing several parameters to identify the parameters that have the largest impacts on the performance a building. A comparison of the life cycle carbon emissions for each stage showed that the operational stage is the largest contributor to carbon emissions. Approximately 85.4% of the total carbon emissions were generated during operation. The construction stage accounted for 12.6% of the total carbon emissions. Approximately 2% of the total carbon emissions occurred during the demolition stage. Compared to the total carbon emissions over the entire life cycle of the building, carbon sequestration by vegetation was minimal. Thus, these findings indicate that governments can achieve the greatest reductions in carbon emissions by targeting the operational phase of buildings. However, the opportunity for addressing non-operational phases should not be ignored because the average carbon emissions per working area per year of non-operational stages are far greater than those of the use phase.

1. Introduction

A life cycle assessment (LCA) is the assessment of the environmental impact of a given product over its life (ISO, 2006a; ISO, 2006b). An LCA is able to assess energy consumption and environmental pollutant emissions by defining a scope of analysis for each type of building or fabrication method and for each type of manufacturing or building material as well as for each stage of the building or method's life cycle (Japan Resource Institute, 1996; Ardente et al., 2008; Russell-Smith et al., 2014).

LCAs have been applied to building systems on a variety of levels, including at the level of the building materials, building products, and the entire building (Erlandsson and Borg, 2003; Huang et al., 2012; Silvestre et al., 2014). Most building-related LCA studies have focused on a specific part of the building life cycle; few have addressed the entire building over its full life cycle due to the difficulties of acquiring accurate building material quantities and building performance indicators, such as energy use and indoor climate, particularly in the design stage (Ortiz et al., 2009). Building information modeling (BIM) provides an effective platform for overcoming the difficulties of acquiring the necessary building data for an LCA; therefore, such modeling provides great potential for conducting LCAs of entire buildings in the design stage. As a result, LCAs can be used to enable better early-stage decision making by providing feedback on the environmental impacts of BIM design choices (Basbagill et al., 2013). Basbagill et al.

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List of notations

A	Green area, acres
AD	Activity level
A_{gfa}	Gross floor area of buildings, m^2
C	Total carbon emissions during building life cycle, t
$\overline{C}_{At\cdot i}$	Average CO_2 emissions per working area per year of each building stage, $kgCO_2/(m^2\cdot y)$
C_b	Total carbon emissions during the construction stage, t
C_{be}	Carbon emissions produced by building material production, t
C_{bt}	Carbon emissions produced by building material transportation, t
C_{bp}	Carbon emissions of building materials used during building construction, t
C_{bp1}	Carbon emissions produced by the construction site electricity use, t
C_{bp2}	Carbon emissions produced by various construction crafts, t
C_{bp3}	Carbon emissions produced by horizontal transportation during building construction, t
C_d	Total carbon emissions produced during the demolition stage, t
C_{d1}	Carbon emissions produced by the demolition process, t
C_{d2}	Carbon emissions produced by construction waste material processing, t
C_i	Total CO_2 emissions of each building stage, tCO_2
C_u	Total carbon emissions produced during the operational phase, t
C_{u1}	Carbon emissions produced by air conditioning, t
C_{u2}	Carbon emissions produced by lighting, t
C_{u3}	Carbon emissions produced by elevator, office, and electrical equipment, t
C_t	Total carbon sequestration by vegetation, t
c_k	Carbon content
D_i	Distance building materials travel from production site to construction site, km
D_r	Distance between construction site and landfill, km
EF	Emission factor
$EF_{be,i}$	Carbon emission factor for the ith building material, t/t
$EF_{bt,i}$	Emission factor for the ith building material transportation method, t/(t·km)
$EF_{bp1,i}$	OM CO_2 emission factor for the construction site's electricity system, tCO_2/m^2
$EF_{bp2,i}$	Carbon emission factor for the ith construction process, tCO_2/m^3
$EF_{bp3,i}$	Carbon emission factor for ith building material or piece of equipment, t/(t·km)
EF_{OM}	Operating margin emission factor, tCO_2/MWh
EF_{BM}	Build margin emission factor, tCO_2/MWh
EF_{dc}	Emission factor of the demolition energy consumption for the reinforced concrete structure, kWh/m^2
EF_{dr}	Emission factor of emission due to waste transportation t/(t·km)
G_1	Carbon ratio of ground tree biomass, t carbon/t dry matter
G_2	Annual increase in the above ground biomass, t dry matter/(acres· year)
k	Types of fossil fuel used during the building material production process
n	Useful lifetime of building, years
P_{u1}	Total electricity consumption for air conditioning, MWh
P_{u2}	Total electricity consumption for lighting, MWh
P_{u3}	Total electricity consumption for elevator, office, and electrical equipment, MWh
$Q_{be,i}$	Quantity of the i th building material used in the project, t
$Q_{bp1,i}$	Construction project quantities, m^2
$Q_{bp2,i}$	Project quantity for the ith construction process, m^3
$Q_{bp3,i}$	Horizontal transportation quantity of the ith building material or equipment, t
$Q_{bt,i}$	Weight of the ith building material during the transportation stage, t
Q_r	The quantity of waste transported to the landfill, t
t_i	Duration of each building stage, years
$\eta_{i,j,k}$	Oxidation rate

(2013) presented a method for applying LCA to early-stage decision making to inform designers of the relative environmental impact importance of building component materials and dimension choices. An impact allocation scheme that showed the distribution of embodied impacts among building elements has been developed, and an impact reduction scheme illustrated which materials and thickness choices achieved the greatest embodied impact reductions (Ortiz et al., 2009).

Autodesk® Ecotect® Analysis (Autodesk, 2015) is an energy simulation tool that is compatible with BIM software, such as Autodesk Revit Architecture, and is used to perform comprehensive preliminary building energy performance analysis (Wang et al., 2011). The analysis software combines an intuitive 3-D design interface with a comprehensive set of performance analysis functions and interactive information displays. Ecotect provides thermal, lighting and acoustic analyses, including hourly thermal comfort, monthly space loads, natural and artificial lighting levels, acoustic reflections, reverberation time, project costs and environmental impact (Marsh, 2003; Crawley et al., 2008). Various studies have demonstrated that Ecotect simulations are highly accurate (Ibarra and Reinhart, 2009; Vangimalla et al., 2011; Abudallah et al., 2013). Because the operational stage is typically significant in terms of energy consumption and CO_2 emissions (Junnila and Horvath, 2003; Zabalza Bribián et al., 2009), Ecotect was used to simulate the heating and cooling loads during the operational stage of the building under its defined geometry, material properties and local weather conditions to ensure the accuracy of the results.

The life cycle energy consumption and CO_2 emissions of a university building in the midwest have been calculated using Ecotect and BIM models (Wang et al., 2011; Basbagill et al., 2013). The study compared the life cycle performance of various design configurations (in terms of CO_2 emissions and energy consumption) and their distributions over the stages of the building's lifetime. A sensitivity analysis was performed by varying several parameters to identify which parameter had the greatest impact on the building's performance. The preliminary results indicated that the whole-building life cycle performance was affected by several design parameters with different degrees of sensitivity. Adalberth presented case studies of the total CO_2 emissions of three single-unit dwellings in Sweden and found that 85% of the total energy use occurred in the operational phase, whereas the energy used in manufacturing the materials employed in construction, including erection and renovation, represented approximately 15% of the total energy use. The