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The quantification of the embodied impacts of construction projects on energy, environment, and society based on I–O LCA

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ABSTRACT

With rapid social development and large-scale construction of infrastructure in China, construction projects have become one of the driving forces for the national economy, whose energy consumption, environmental emissions, and social impacts are significant. To completely understand the role of construction projects in Chinese society, this study developed input–output life-cycle assessment models based on 2002, 2005, and 2007 economic benchmarks. Inventory indicators included 10 types of energy, 7 kinds of environmental emissions, and 7 kinds of social impacts. Results show that embodied energy of construction projects in China accounts for 25–30% of total energy consumption; embodied SO_2 emissions are being controlled, and the intensities of embodied NO_x and CO_2 have been reduced. However, given that the construction sector related employment is 17% of the total employment in China, the accidents and fatalities related to the construction sector are significant and represent approximately 50% of the national total. The embodied human and capital investments in science and technology (ST) increased from 2002 to 2007. The embodied full time equivalent (FTE) of each ST person also increased while the personal ST funding and intramural expenditures decreased. This might result from the time lag between RD activities and large-scale implementation.

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1. Introduction

The world in the 21st century faces daunting energy and environmental challenges. It confronts the continuing need to promote social development and make a better life for a growing population. Environmental, social, and economic are the three pillars for any sustainable society, whose ultimate goal lies in human well-being of both current and future generations. China is no exception, and to greatly improve living standards and quality of life, China is currently in the process of rapid urbanization and large-scale infrastructure construction, which results in an increasing amount of construction activities. Furthermore, this also results in increasing impacts in the up-stream and down-stream industrial sectors within the entire economic system.

Recent research in China has focused on energy and environmental performance of buildings in their operation phase. In the last two decades, the annual average increase in building energy consumption in China has exceeded 10%. In 2004, building energy consumption constituted 21% of the national total energy consumption (Jiang and Yang, 2006), with urban residential buildings representing 56%, rural buildings 18%, large public buildings greater than 20,000 m^2 10%, and other public buildings 16% (Cai et al., 2009). The energy sources of both residential and commercial buildings are coal-dominant, and represent 79% and 46% of the total energy use, respectively (Zhou et al., 2008; Fridley et al., 2008). In terms of overall air quality, emissions of NO_x, SO_2, PM, and greenhouse gases have been quantified and predicted with various methods, such as satellite observation, emission source analyses, national-policy-based scenario analysis, and input–output models (Zhang et al., 2007, 2008, 2009; Chen and Zhang, 2010; Zhang and Chen, 2010). For constructions projects, the embodied environmental loads of residential and commercial buildings have been analyzed with process LCA models (Gong, 2004; Liu et al., 2010; Fridley et al., 2008). In terms of carbon emissions, the potential reduction strategies for building carbon emissions have been examined at the national level (Li and Colombier, 2009; Jiang and Tovey, 2010), and a low-carbon building evaluation framework has been designed, which covers nine phases of buildings from cradle to grave (Chen et al., 2011). Generally, the analyses of building operation energy are complete and specific, while studies of the emissions of either building construction or the up-stream building sectors are comparatively unsystematic.

Compared with research on the building operation phase, exploration of the embodied energy and emissions of construction are relatively rare and scattered. Although the embodied

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energy of residential building envelopes in Hong Kong have been analyzed (Chen et al., 2001) and the embodied environmental impacts of construction materials, such as steel, glass, and cement have been quantified (Gong and Zhang, 2004), these studies focused on building component and materials, rather than complete buildings. Since an input–output model has the strength of a comprehensive national study boundary, it has been widely employed to assess energy and environmental impacts of goods or services in China. For buildings, the embodied energy and environmental emissions of construction projects were quantified based on the 2002 China economic benchmark (Chang et al., 2010), which included the top 23 sectors correlated with the construction sector. Based on multi-scale input–output analysis, a framework for building life cycle carbon accounting was designed to facilitate low-carbon planning, procurement and supply design, and logistics management (Chen et al., 2011). However, the application of I–O modeling in buildings in China is limited by the availability of comprehensive statistics. The sector divisions in the economic input–output table limit the type of products or services that can be analyzed. For example, various types of buildings and infrastructure are grouped together in the construction sector, which makes the calculation of embodied impacts by building or infrastructure type difficult. In addition, the statistics on sectoral energy consumption and environmental emissions does not exactly match the sectoral definitions in the economic I–O table, so it is difficult to develop the satellite matrix in the I–O model.

In terms of employment and occupational safety in China, the relationship between economic growth and employment has been investigated, which shows China has achieved major progress toward full employment during the past two decades (Rawski, 1979). The labor market in China demonstrated employment growth and positive structural changes in both rural and urban areas and successfully broke the myths of "zero growth of employment" and the "unchangeable rural surplus labor pool" (Cai and Wang, 2010). For occupational health and safety, the components and structure of industrial accidents in China were illustrated and compared with several countries (Liu et al., 2005). Important elements of construction safety management were found to be poor safety awareness, lack of training, and reluctance to invest in safety (Tam et al., 2004). The effectiveness of the Occupational Health and Safety Administration's (OHSA) 18001 guidelines in China's construction industry was examined and it was concluded that OSHA 18001 should be implemented with ISO 9001 so as to avoid duplicating efforts and resources and enhancing management performance (Zeng et al., 2008). However, previous research on these social impacts mainly focused on sectoral performance, and the cross-sectoral embodied social impacts of construction projects have not been analyzed yet.

To completely and comprehensively understand the embodied impacts of construction projects on energy consumption, environmental pollution, occupational health and safety, employment, and science and technology development, this study developed input–output life cycle assessment (I–O LCA) models based on the China's 2002, 2005, and 2007 economic benchmark I–O tables. The energy consumption inventories included total energy consumption, coal, coke, crude oil, gasoline, kerosene, diesel oil, fuel oil, natural gas, and electricity. The environmental pollution inventories included SO_2, NO_x, CO_2, industrial waste water discharged, industrial waste water that failed to meet discharge standards, industrial solid wastes produced, and industrial solid wastes discharged. The social impact inventories included employment, accidents, fatalities, number of ST personnel, number of full-time equivalent RD personnel, level of funding for ST activities, and expenditures on ST activities.

2. Methodology

2.1. Types of LCA models

Life cycle assessment (LCA) is a methodology for evaluating the environmental load and energy consumption of processes or products (goods and services) during their life cycle from cradle to grave (ISO, 2006). Originally developed in the late 1960s and formally defined in the 1990s, LCA has experienced 40 years of development in both methodology and research scope. More and more LCA studies with various types of modeling have been conducted in the fields of energy, environment, social politics, and economy. According to the differences in system scope and theory, LCA approaches could be categorized as process LCA, I–O LCA, and hybrid LCA.

Process LCA. The process LCA method systematically models the known energy and environmental inputs and outputs by utilizing a process flow diagram. The scope of the process model continues to the point where the flow between process and emissions is negligible. The process approach was further developed with the framework established in the ISO 14040 series with the components of goal and scope definition, inventory analysis, impact assessment, and improvement measures (ISO, 2006). By closely surrounding the life phase of certain products/services, process LCA approach has the advantages of detailed process-specific analyses, specific product comparisons, and high-precise model results. However, drawbacks like limited and subjective system boundary, time and costs intensiveness, and difficulty of results replication have also been broadly criticized.

I–O LCA. By integrating energy and environmental elements into national sector-by-sector economic input–output interaction, I–O LCA undoubtedly provides researchers with a functional assessment tool for macro-level studies (Leontief, 1970). Therefore, the model is particularly applicable to national-level studies. The economic input–output model developed by Leontief (1986) yields the economic impacts of given sector's 'total supply chain' throughout the entire social economic system. Thus, the energy and environmental emissions of a given sector could be calculated. Given that the foundation for the I–O LCA model is the sector-by-sector economic interaction, the energy and environmental results calculated by the model are the mean value of goods and services provided in a sector. This nature qualifies model's strong applicability in macro-study. The most outstanding advantage of the I–O LCA model lies in its comprehensive system boundary. In addition, attributes such as publicly available data, reproducible results, and time and cost saving are attractive (Hendrickson et al., 1998). The disadvantages of I–O LCA include rough analyses for specific and individual goods and services, time-lag in reflecting of current practices, and high dependency on data. In addition, I–O LCA is incapable of presenting a complete-life-cycle analysis on goods (except vehicles, ships, and aircrafts used in public transportation), in that the economic input–output table fails to reflect their operation.

Hybrid LCA. Since both processes LCA and I–O LCA have advantages and disadvantages, researchers proposed to find out a comparatively well-round LCA approach that gets the best of each, and a hybrid LCA was consequently raised. Hybrid LCA, which combines process and I–O LCA, reaches a balance among system boundary, specialization of model applicability as well as time and costs efficiency. With hybrid LCA models, the embodied impacts of goods could be included with economy-wide scope, and impacts in the operation and end-of-life phases could be specifically analyzed (Bilec et al., 2010). Hybrid models in this sense augment process LCA. The advantages of the integrated hybrid model are the consistent mathematical framework for the entire life cycle, avoidance of double-counting, and application in