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Evaluation of energy consumption during production and construction of concrete and steel frames of residential buildings

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ABSTRACT

There is a growing attention to energy consumption (EC) of buildings during their life cycle. The construction phase has been less considered due to its small share of the EC in buildings life cycle, as well as the lack and inconsistency of data, especially in developing countries. The purpose of this research is to evaluate the EC during production and construction (PAC) of concrete and steel frames of residential buildings. To address the mentioned purpose, the EC during PAC of frames of 14 concrete and steel framed buildings in Iran's capital city, Tehran, is studied. The findings show that the EC during PAC of concrete frames is about 27% less than steel frames. Comparison of EC during various PAC processes shows that production of steel is the most energy consumed process. As an example, considering total area of residential buildings constructed in Tehran in 2014, replacing steel frames by concrete could lead to 13% energy saving. Moreover, with respect to optimistic and pessimistic evaluated values of EC during PAC of concrete and steel frames of buildings constructed in the mentioned year, about 43% of energy can be saved.

1. Introduction

Nowadays, the optimized EC would be one of the most important human priorities around the globe, due to energy resources' limitation and environmental issues. The construction industry is a highly active industry in both developed and developing countries, so the social, economic and environmental indicators of sustainable development are drawing attention [1]. For example, 40% of EC in Europe is related to buildings [2]. In Iran, the equivalent amount is even more than 40% of the total EC [3]. In this regard, the management of EC related to buildings is more critical than other facilities.

A building uses energy throughout all phases of its life cycle including raw material extraction, manufacturing, transportation, construction, operation, demolition, and recycling. Energy in buildings can be categorized as either operational energy (OE) or embodied energy (EE). The OE includes all energy requirements for lighting, heating, and cooling so as to provide a required comfort level. The EE is the energy used in the mining and resource extraction, resource transportation, building product manufacturing and component manufacturing, subassemblies or building systems, and also energy required to demolish the building and transport the material to landfill sites [4,5]. Focusing only on the usage phase forgoes the opportunity to reduce other building-related emissions [6], and even if the environmental impacts from construction are small compared to other phases, these impacts may be large when looked at on a national level [7].

This research aims to evaluate EC during PAC of concrete and steel frames of residential buildings. To address the mentioned purpose, the EC, included electricity and fossil fuels, by considering major PAC processes of concrete and steel frames of 14 buildings in the developing country of Iran is studied. The results of this study are validated by using Athena EcoCalculator software, and comparing with some previous studies. This research, also, studies the EC and potential energy saving, regarding the under construction areas of the residential buildings in Iran's capital city, Tehran, in 2014. Eventually, cost of EC is evaluated and discussed to highlight its importance.

2. Literature review

Due to importance of energy around the globe, many studies were carried out to evaluate the EC in buildings. For many years

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most of the studies focused on the operational energy. For example Balaras et al. [8] evaluated the thermal EC and environmental impacts of that in European apartments. Dodoo and Gustavsson [9] explored the thermal performance of Swedish multi-story residential buildings with different construction including a prefab concrete-frame, a massive timber-frame and a light timber-frame building. They explored energy efficiency configurations under different climate scenarios. Heravi and Ghaemi [10] identified several measures for reducing EC and determined the most applicable renewable energy system in building industry in Iran.

In recent years, aim to help optimization of OE, the importance of considering EE has increased and studied in some research. Gustavsson and Joelsson [11] showed that the primary energy for the production of conventional and low-energy residential buildings can be up to 45% and 60% of the total EC, respectively. Devi and Palaniappan [12] concluded that depending on variation in the OE systems, EC in construction phase could be different from 10% to 70% of the life cycle energy. Monahan and Powell [13] estimated EE of a house constructed with two alternative construction scenarios in the UK using a life cycle framework. They suggested that increasing offsite manufacturing of components and selection of materials with reduced environmental impact can save EE. Han et al. [14] evaluated the EE of six commercial buildings in Beijing. The results showed that steel sector, cement and plaster sector, and construction sector have the highest contribution in EC. Guan et al. [15] developed an input–output based hybrid life cycle analysis model to quantify the EE of a building.

Choice of building materials is one of the major decisions which have to be made in the early design stages. Life cycle approach can help to make appropriate choices. Several researchers have investigated the influence of the material selection on the EC of buildings. Thormark [16] investigated the effect of choosing materials on both the EE and recycling potential in an energy efficient apartment block in Sweden. His study revealed that changing building materials can decrease and increase the EE up to 17% and 6%, respectively. Bansal et al. [17] compared the EE for the residential houses with different construction materials, in India. Gustavsson and Sathre [18] identified factors that have a particularly strong influence on the energy and CO_2 balances resulting from building material production and use. In this regard key parameters in the manufacture and use of the materials comprising a wood- and a concrete-framed building was studied. The result showed that the use of wood building material instead of concrete can reduce fossil fuel usage. Praseeda et al. [19] analyzed the EE of 16 urban dwellings of India and showed that different types of construction materials had various EC. Basbagill et al. [20] presented a method to evaluate the relative environmental impact of materials and dimensions of building components. They revealed which material and thickness of a building component lead the greatest embodied impact reductions. Takano et al. [21] demonstrated the relationship between material selection and the life cycle energy balance of a building. They found that between three building component categories (structural-frame, surface components and inner components), the selection of the structural-frame materials has larger influence than the other two components categories. Zhang et al. [22] evaluated adverse environmental impacts, including EC, during a full building life cycle. They analyzed an inventory of all the construction materials and examined the five top building materials of a two-story residential building located in Vancouver, Canada. The result showed after the operating energy, the most significant life cycle phase was manufacturing, with a share of approximately 7% to 51%.

Due to the less share of environmental impacts and EC during construction phase compared to other phases of the life cycle and the lack and inconsistency of data supplied by the construction industry [7], the construction phase has been less considered during the past decades. However, in recent years, the construction phase is taken into consideration, among them are: Sharrard et al. [23] analyzed the environmental impacts of construction phase of buildings. They focused on energy and environmental implications of the construction process, specifically on site EC. Chen et al. [24] identified a total of 33 sustainable performance criteria for the selection of construction method in concrete buildings to compare the use of prefabricated construction and on-site construction method. Wen et al. [25] studied the assembly phase of industrialized building system and cast in situ for low rise apartment residential buildings in Iskandar, Malaysia. The results of the life cycle analysis indicated that the industrialized building system has better performance in terms of reducing EE (MJ) and global warming potential (GWP) (kg CO_2-Equiv). Comparing different common types of building frame, Hemström and et al. [26] assessed the Swedish architects' perceptions, attitudes and interest towards steel, concrete and wood frames in both residential and non-residential buildings of three to eight stories. The result showed although the interest towards use of wood was large, the concrete and steel were considered more suitable frame materials in multi-story buildings.

Guggemos and Horvath [6,27] in their studies presented process diagrams of the critical construction processes of steel and cast in place concrete buildings and identified and quantified energy usage during the construction phase of two typical office buildings. The results indicated that more energy consumed during the construction of concrete structures, because more formwork used, larger transportation impacts, larger mass of materials, and longer installation process. Later, Xing et al. [28] compared the EC and environmental emissions during all life cycle phases of steel and concrete frames of two typical office buildings in Shanghai, China. They showed that the EC during construction of buildings with concrete structures is lower than buildings with steel structures. Foraboschi et al. [29] assessed the EE of tall building structures including concrete central core and either concrete or steel rigid frames. The result showed that concrete frames cause the building to consume less EE than steel frames.

3. Methodology

Life Cycle assessment (LCA) is a systematic approach for evaluation of the environmental impacts of a product or service system throughout its life cycle. A typical LCA includes the major stages of raw material extraction, manufacturing, use, and end-of-life scenarios for a product or process [7]. The EE and GWP are two main indicators of the LCA. The GWP *is* an equivalence measure with carbon dioxide as the common reference standard for global warming or greenhouse gas effects (all other greenhouse gases are referred to as having a "CO2 equivalence effect"). Due to some limitation to access the authentic data related to GWP, this research focusses only on the EE. Guidelines for performing an LCA are delineated by the International Organization of Standardizations (ISO). Of its 14,000 standards series, 14,040 series focus on establishing methodologies for LCA. According to the ISO 14040, the LCA shall include definition of goal and scope, inventory analysis, impact assessment and interpretation of results [34]. In fact, ISO 14040 improved a systematic approach to study entire life cycle. So, the four-stage iterative framework of ISO used in this study, and needed information gathered from available sources or interviews. The methodology of this research is shown in Fig. 1.

3.1. The scope definition

The cradle-to-gate impacts associated with buildings are those from mining and material extraction, manufacturing, transport to site, and on-site construction [35]. In this study, EC during PAC of structural-frames of buildings from cradle-to-gate with exception