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Health impact assessment from building life cycles and trace metals in coarse particulate matter in urban office environments

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ABSTRACT

This study intends to determine the health impacts from two office life cycles (St.1 and St.2) using life cycle assessment (LCA) and health risk assessment of indoor metals in coarse particulates (particulate matter with diameters of less than 10 µm). The first building (St.1) is located in the city centre and the second building (St.2) is located within a new development 7 km away from the city centre. All life cycle stages are considered and was analysed using SimaPro software. The trace metal concentrations were determined by inductively couple plasma-mass spectrometry (ICP-MS). Particle deposition in the human lung was estimated using the multiple-path particle dosimetry model (MPPD). The results showed that the total human health impact for St.1 (0.027 DALY m^{-2}) was higher than St.2 (0.005 DALY m^{-2}) for a 50-year lifespan, with the highest contribution from the operational phase. The potential health risk to indoor workers was quantified as a hazard quotient (HQ) for non-carcinogenic elements, where the total values for ingestion contact were 4.38E − 08 (St.1) and 2.59E-08 (St.2) while for dermal contact the values were 5.12E-09 (St.1) and 2.58E-09 (St.2). For the carcinogenic risk, the values for dermal and ingestion routes for both St.1 and St.2 were lower than the acceptable limit which indicated no carcinogenic risk. Particle deposition for coarse particles in indoor workers was concentrated in the head, followed by the pulmonary region and tracheobronchial tract deposition. The results from this study showed that human health can be significantly affected by all the processes in office building life cycle, thus the minimisation of energy consumption and pollutant exposures are crucially required.

1. Introduction

The building sector is a major contributor to the environmental burden as civil work and building construction account for approximately 60% of the use of raw materials extracted from the lithosphere (Arena and de Rosa, 2003; Peuportier et al., 2013; Zabalza Bribián et al., 2011). High consumption of materials was related to all processes in building, regardles of the function of the building (such as residential, commercial, factory and office purposes). Due to the development and life cycle process of all buildings, a significant amount of energy is needed. The building sector is responsible for the use of more than one-third of the total primary energy supply, which equates to 40% of the world's energy being consumed in the construction, maintenance and occupation of buildings (Shaikh et al., 2014). Office buildings have been identified as one of the highest energy consumption areas, where high energy usage is associated with heating, lighting, ventilating and air conditioning systems (Pomponi et al., 2015; Zhang et al., 2011). The large amount of energy and materials consumed throughout the building life cycle triggers environmental consequences, including human health impacts which are of high concern (Harris, 1999; Li et al., 2017).

Human health is one of the environmental impacts caused by building life cycles due to high emission of pollutants. According to Meijer et al. (2005a, 2005b), large amounts of pollutants and contaminants are emitted during all phases of the building life cycle especially in the operational phase. The operational phase generated large emissions of pollutants due to the space and water heating, lighting, and electrical equipment and appliances. Other processes in a building life cycle, such as extraction of building materials, transportation, construction, maintenance, demolition and all activities associated with building, also produce high emissions of pollutants (Ibn-Mohammed et al., 2013; Zhang et al., 2013). Gas emissions such as carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), nitrogen oxides (NOx), sulphur dioxide (SO_2), non-methane volatile organic compounds (NMVOC) and nitrous oxide (N_2O) were example of pollutants released during a building life cycle (Sim et al., 2016; Zhang et al., 2013). High emissions of pollutants during the operational phase also contributed to adverse health impacts, particularly indoor air

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quality. A study by Meijer et al. (2005a, 2005b) had found that radon and gamma-radiating elements were the major contributor to human health damage due to indoor exposure from building materials emissions. Collinge et al. (2013) studied the human health impacts by integrating indoor environmental quality with LCA and found a higher indoor cancer toxicology impact and respiratory effects compared to outdoor.

The most studied pollutant, which has the impact on human health in the indoor environment, is particulate matter (PM). Coarse and fine PM can cause adverse health impacts due to its size, as it can simply penetrate into the respiratory system and become reactive because of the large surface area of the lung (Betha et al., 2014). Among other chemical components of PM, trace elements contributed to higher potential health effects where high carcinogenic elements were determined in PM in various areas including a food stall (See and Balasubramanian, 2006), a workshop (Fang et al., 2013), a restaurant (Taner et al., 2013), a school (Mohamad et al., 2016) and an office (Othman et al., 2016). According to Huang et al. (2016), the severity of health effects produced by trace metals in PM is dependent on their total content, their bioavailability, their relative toxicity and factors related to inhalation exposure. Moreover, other routes of trace metal exposure such as dermal and ingestion were also important, where a study by Fang et al. (2013) had found that the highest exposure of trace metals was through ingestion followed by dermal and inhalation routes. All of the routes of trace metal exposure are important, especially for people who living in urban areas where airborne particulates can easily enter food and drink and fallout onto skin during indoor and outdoor activities (Hu et al., 2012).

A study by Fisk et al. (2011) found that improving indoor air quality can increase office worker work performance, reduce sick building syndrome, reduce absence, and improved the thermal comfort of workers. Thus, this study aims to investigate the human heath impact from office building life cycles and to determine the health risk of indoor workers for trace metals exposure from PM_{10} via dermal and ingestion exposure. The deposition fraction of inhalable coarse particles was also determined in the human respiratory system using a human airway deposition model (multiple-path particle dosimetry model, MPPD).

2. Methodology

2.1. Study area

Seremban city, located in Negeri Sembilan in the middle of the west coast of Peninsular Malaysia, is an urbanized and industrialized city which historically developed from a tin-mining activity. Seremban city has seen the development of industrial, commercial and residential areas, and is also affected by the high commercialisation of Kuala Lumpur city. As Seremban city is located in a very strategic location, there are tourism and national projects that were developed in this area such as the Formula One Circuit, an International Airport and a commuter rail service which connects people from Kuala Lumpur city to Seremban city.

Two office buildings located in Seremban city, Negeri Sembilan, Malaysia were studied. The first building (St.1) is located in the centre of the city and the second building (St.2) is located within a new development area which is 7 km away from the city centre (Fig. 1). Both buildings are located next to busy roads, recreational areas and shopping lots. These buildings are used for office purposes; their occupied hours are from 7.30 a.m. to 6.00 p.m. The two studied buildings were chosen because of the availability of various data such as the buildings' technical drawings and electrical bills. The daily indoor temperatures and relative humidity of St.1 and St.2 range from 23.9 to 26.6 °C and from 64.2% to 73.1%, respectively. The average outdoor ambient air temperature in the city is 27.6 °C and the relative humidity is 74.5%. The studied buildings are both ventilated using air conditioning systems, and energy equipment such as lighting is manually operated. The characteristics of the studied buildings are listed in Table S1. Two office building life cycles, which have similar crucial structural characteristics, were selected for human health impacts comparative analyses with different background areas. The two buildings can be compared to a certain extent based on the similarities of the buildings characteristics (Mao et al., 2013). The locations of the studied buildings, in urban and suburban areas with high traffic volume, are the main interest to investigate the impacts of building life cycle and urban environment towards human health, in reference to Malaysian climatic condition.

Generalizability theory (GT) was applied to evaluate the reliability of the number of PM_{10} sampling days and number of studied buildings for trace metal concentrations. The GT test was performed as followed Heitman et al. (2009) where the variance components were computed for sampling stations, sampling days and interaction between the number of sampling days and sampling stations. The results showed that the number of sampling days ($n = 48$) in the two studied buildings had both a G coefficient and an absolute coefficient of 0.85–0.94, which is higher than acceptable value (G and ϕ coefficient > 0.80). As reported by Llabre et al. (1988), G coefficients higher than 0.80 will ensure the generalizability and reliability of the measurements.

2.2. Human health impact of office building

The LCA analysis was performed according to the LCA methodology with ISO standard 14040 and ISO 14044 as reference (ISO, 2006a, 2006b). There are four main steps in an LCA study: goal and scope definition; life cycle inventory; life cycle impact assessment; and the interpretation of the results. All the elements in each step are described below:

2.2.1. Goal and scope definition

In defining the goal and scope, the aim and purpose of the study needs to be clarified. Monahan and Powell (2011) also stated that it is important to define the scope of the study, functional unit and the system boundary with details on how environmental burdens will be allocated. The goal and scope of this study is to determine the human health impact of an office building's life cycle in order to have a clear understanding of how each phase of a building's life cycle contributes to human health. This study adopts the functional unit as one square metre of the gross floor area of the buildings (m^2) over the building's lifespan. The service lifespans of the studied buildings were estimated at 50 years, as followed by previous studies (Asdrubali et al., 2013; Cuéllar-Franca and Azapagic, 2012; Dodoo and Gustavsson, 2013; You et al., 2011; Zhang et al., 2006). Using this functional unit makes the comparison between buildings of different sizes more feasible. The system boundary in this study includes all phases in the building life cycle, starting from raw material extraction and production, transportation of building materials to the site, construction, operation, maintenance and end of life of the building which is demolition phase. The input parameters include the amount of building materials (Table 1), energy and electricity, transportation, indoor PM_{10} concentration and office equipment usage during the operational phase.

2.2.2. Inventory data and modelling

The inventory data for material extraction and production, transportation and replacement were extracted from the Ecoinvent Version 3 database (Ecoinvent, Switzerland). Moreover, the obtained data was cross-referenced with the unit process in the widely-used database Ecoinvent in order to achieve a transparent and comparable analysis as recommended by Asdrubali et al. (2013). To achieve feasibility of the life cycle inventory in this study, standardization in choosing data was applied where only global data (GLO) from the Ecoinvent database was chosen. The types of GLO data in the Ecoinvent database represent average activities that are valid for all countries worldwide (Ecoinvent,