COMPARISON OF THREE HVAC SYSTEMS IN AN OFFICE BUILDING FROM A LIFE CYCLE PERSPECTIVE

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Abstract

This study aims to explore the life cycle environmental impacts of typical heating ventilation and air condition (HVAC) systems including variable air volume (VAV) system, chilled beam system and underfloor air distribution (UAD) system through a case study based on an RMIT office building. Life cycle assessment (LCA) is employed to evaluate the environmental impacts associated with different life cycle phases of HVAC systems. Using carbon emissions as the environmental indicator, ranges of impact for each HVAC system in different life cycle stages are calculated and compared based on the information uncovered in the literature review and relevant LCA inventory database. The system designs on case study are outlined based on the characteristics of a case building. The building was originally equipped with VAV system and was then designed with the chilled beam system and UAD system for comparison purposes. The lists of materials and products used in these three HVAC systems are illustrated, forming the basis of the life cycle assessment. Inventory analyses diagrams have been established based on the activities of HVAC systems in four life cycle stages: manufacturing, construction, operation & maintenance, and demolition. Calculation methods for carbon emissions are established. In particular, inventory data have been developed for manufacturing of HVAC products as well as transportation. We found that the environmental impacts between these three HVAC systems are found to be of different magnitude in different life cycle phase. For instance, the embodied energy of UAD system is the lowest in manufacture stage while that of the chilled beam system is the highest. However, chilled beam system has much more energy saving potential than the other two air conditioning systems in operation stage, and also from a life cycle perspective, the chilled beam system has the lowest environmental impact over a 50 year time frame, and VAV system has the highest environmental impact among the three HVAC systems compared.

Keywords: life cycle assessment, carbon emissions, air conditioning systems, life cycle carbon emission

1. Introduction

In the last thirty years, indoor air quality was a major aim, as the inappropriate installation and ventilation not only fail to cope with the occupants' thermal requirements, but also directly result to poor indoor air conditions and hence to a series of syndromes and illness (Avgelis and Papadopoulos, 2009). Lately, with growing concern regarding the environment and efforts to achieve significant reductions in building energy use, many new HVAC technologies such as chilled beam and underfloor air distribution (UAD) have been invented in an aim to reduce energy consumption without sacrificing indoor thermal comfort and air quality. Also, in the days of the Kyoto protocol obligations, carbon cost factor is becoming a more and more realistic boundary condition when building owners make their purchase decisions (Balaras *et al.*, 2005;Prek, 2004). Thus, carbon emission has been chosen as a key indicator for building tenants and the HVAC practitioners from both energy consumption and environmental impact perspectives.

A variety of factors can affect the carbon emission with a HVAC system during its service life. The lifespan of HVAC is composed of a series of interlocking processes, starting from initial design and manufacture, through to actual construction, and then to annual operation and maintenance, as well as to eventual demolition or renovation. The construction of HVAC has a very important impact on the environment, and it is one of the greatest consumers of resources and raw materials in HVAC construction (Avgelis and Papadopoulos, 2009;Tae *et al.*, 2011). The manufacture and transportation of HVAC materials and products, and the installation and construction of HVAC components consume great quantities of energy and emit large amounts of carbon dioxide.

While many of these so-called green technologies have been applied in real world projects and proved to save operational energy to some extent, there is a lack of a comprehensive study, from a life cycle perspective, to compare how green these technologies are. A review of HVAC system literature indicates that even fewer studies have been conducted to understand the factors or indicator of the life cycle activates in conjunction with environmental impacts (carbon emissions) in HVAC systems. These knowledge gaps and practical deficiencies have in the past prevented practitioners from selecting lower carbon emission HVAC systems for buildings. In addition, these studies have not sought to develop a systematic approach towards the selection of appropriate HVAC systems for office building project. The lack of research inspire our research to develop a life cycle assessment model to analyse the each life cycle activates and quantify the carbon emissions in HVAC systems' service life. The specific objectives of the research in this paper are to perform the following

1) Ascertain the major factors influencing carbon emissions for HVAC systems;

2) Ascertain the calculation method of the carbon footprint in each phase of the HVAC life cycle;

3) Develop quantitative LCA models with inputs and outputs factors during the life cycle terms of HVAC systems, to evaluate the life cycle carbon emissions during the HVACs' service life.

1. Research method

The life cycle assessment (LCA) methodology has been used to obtain a comprehensive energetic and environmental picture relevant to quantify the life cycle impacts of HVAC systems. According to ISO 140140 (ISO, 2006), an LCA comprises four major stages: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation of the results. The goal and scope definition phase identifies functional units, boundaries of the study, methods and the impact categories (ISO, 2006). LCI phase involves developing an inventory of flows from and to nature for a product system. The flow models are typically illustrated with flow charts that include the activities that are going to be assessed in the relevant supply chains and give a clear picture of the technical system boundaries. The flow models are constructed using data on inputs and outputs, and the input and output data needed for the construction of the model are collected for all activities within the system boundary. LCIA phase aims at evaluating the implication of the flows from and to nature described in LCI results (Frenette *et al.*, 2010). In practice, LCIA must determine the relative significance of each of the inventory items in order to aggregate the LCI results in a small set of indicators (ISO, 2006).The results from the inventory analysis and impact assessment are summarized during the interpretation phase. The outcome of the interpretation phase is a set of conclusions and recommendations for the study.

Initially, there were six indicators considered in LCIA phase (Blengini, 2009): Gross energy requirement; Global warming potential; Ozone depletion potential; Acidification potential; Eutrophication potential; Photochemical ozone creation potential. However, due to the fact that the policy makers and building owners express their need for HVAC systems that might simplify the decision process, carbon footprint is perceived as the most important core indicator for the selection of HVAC systems. A carbon footprint is recognized as the total set of GHG emissions caused by a product. GHG emissions can be emitted through the energy consumption during materials production, fuel combustion in transportation, and energy resources consumed in products and goods manufacturing, etc. For simplicity of reporting, it is often expressed in terms of the amount of carbon dioxide.

2. LCA application to HVAC systems

The present LCA study deals with an office building in RMIT University, Melbourne, Australia. The case building is a thirteen-storey office building at the. The basement, ground floor and floors 2 to 13 are used for classrooms and offices. The total usable area of the building is 14337.57m^2 and the height from floor to floor is 4m. The geographical and weather data, orientation, infiltration, and other parameters related to building load calculations are fixed and are the same for all three HVAC systems simulated. The ventilation rate for office occupancy varies from 25 to 30 m^3/ hour-person, as suggested by the standards (ASHRAE, 2000). The heating load of the building is calculated as 660KW at 34.3°C outdoor temperature and 25°C indoor design temperature with relative humidity of 55%. The study consists of a from-cradle-to-grave LCA of three air conditioning systems: variable air volume (VAV) system; chilled beam system; UAD system. The design of these three systems is based on the characteristics of a case building. According to Blengini (2009), for comparison purpose, a standardisation is helpful. A frequently adopted functional unit is the unitary internal usable floor area, sometimes with reference to the whole building life span. The functional unit adopted in the present case study is 1m^2 net floor area, over a period of building service life.

2.1 System boundaries

Four distinct phases: manufacture, construction, operation & maintenance, and demolition are included in life cycle stages of HVAC system.

The manufacture stage is the phase of production of HVAC materials and three major activities occur in this stage. The first procedure in the material production is the extraction of raw materials, for example drilling for oil, mining for iron ore, or harvesting wood. The energy used to acquire raw materials is the initial embodied energy of the iron, copper and aluminium materials for the HVAC systems. The second procedure in the manufacture phase is the refinement of raw materials into engineered HVAC products, such as the extrusion of steel or aluminium and the injection modelling of plastics. The last procedure is the transportation, which covers shipping of HVAC materials from the source to the manufacturing site. The carbon emission from the transportation is the fuel consumption for delivering HVAC products. The embodied energy is therefore the sum of energy expended during raw materials extraction, the processes of HVAC product refinement and production, and the transportation from source to the manufacturing site.

The construction stage is the phase of installing the comprehensive HVAC products in unequipped buildings, in order to produce the mechanical service as a function of heating, cooling and ventilation. The carbon emissions in this phase comprise two parts: (1) the transportation type used to transport the HVAC products from the manufacturing factory to the construction site; (2) the electricity consumed for power tools and lighting, as well as heavy equipment at the construction site. HVAC installation work is one part of the total work-load of HVAC construction. The construction processes involve the use of construction equipment, e.g.

cranes hoist HVAC products, and hammers for pile-driving. The majority of the HVAC installation work, including the installation of ducts, air outlets, chilled beams, air diffusers, and thermal insulation, is undertaken by manual workers. However, the present study did not account for manual workers, because no actual information for this particular project was available and manual worker consumption was not included for other stages used in this study, such as the manufacture, maintenance and renewal, and final demolition stages.

The operation stage activities consist of heating, cooling and ventilating the building. Carbon emissions are mainly from the electricity consumption of HVAC services. Maintenance and renewal occur periodically over the life of HVAC systems and are assumed to involve replacing less than 100% of a HVAC product. Maintenance and renewal can be categorised into two types as follows (Cole and Kernan, 1996): Maintenance incurred during a completed life cycle of a HVAC product. For a HVAC product which completes its life cycle, the number of maintenance or repairs required is the product life divided by repair interval corrected for the possibility of forgone repairs near the end of the product's life; Renewal incurred during the incomplete life cycle of a product due to the expiration of the HVAC. The renewal rates will depend on the service life of the HVAC system.

The demolition stage is the phase for deconstruction work and the transportation of HVAC for waste disposal. HVAC deconstruction work is one part of the total work-load of HVAC deconstruction. The deconstruction processes involve the use of deconstruction equipment, e.g. hammers and drills for uninstalling the ducts, air outlets, chilled beams and air diffusers. The majority of the HVAC deconstruction work is undertaken by manual workers. Due to no primary on-site data for the electricity consumed for deconstruction equipment in demolition stage, the energy consumed in this phase is the fuel and energy consumption for transporting HVAC waste to landfill or recycling factories.

3. Inventory analysis

An LCA model of a complex system, such as a HVAC system, usually results in a network made of several process units. A description of the main inventoried activates is given in the following paragraphs.

3.1 Manufacture phase

The embodied carbon incurred in the materials manufacturing phase is influenced by three main components, which are identified as: Initial embodied carbon: the weight (in kg) of the transported raw materials; Process carbon: the electricity used in processing the raw materials; Delivery carbon: the transportation used to transport the raw material from the source to the manufacturer.

Wang (Wang, 2007) summarized the quantities of the main materials embodied in each HVAC component, refining energy in production of HVAC items, and the average transportation used. According to the database the raw materials embodied in products (Wang, 2007), the initial embodied carbon emission of each HVAC product can be calculated by the formula (1) (Yan *et al.*, 2010).

$$E_i = \sum M_j^i \times f_j^i \tag{1}$$

Where, E_i is the total initial embodied carbon emissions of all building materials (in kg CO_2-e); M_j^i is the amount of building material j (in kg); f_j^i is the carbon emission factor for building material j (in kg CO_2-e/kg).

3.2 Construction phase

Activities in the construction phase include site preparation, HVAC product installation, and mechanical and electrical equipment installation. The energy and environmental flows associated with the construction process could not be established directly, since there was no record available showing equipment usage or operational hours for HVAC installation. The most relevant work in the context of this paper is that by Honey and Buchanan who presented the life cycle energy expenditure for two office buildings in New Zealand, of two storeys (2400 m^2) and five storeys (8568 m^2). The research examined the relative orders of magnitude of the components of life cycle energy use in office buildings. An important conclusion is that construction energy accounts for 6.5-10.0% of materials embodied energy (Buchanan and Honey, 1994). The higher values in Cole and Rousseau's study (up to 12% of material embodied energy) included transportation burdens for construction workers (Cole and Rousseau, 1992). Therefore it was decided to use 8% of total embodied energy to calculate both equipment energy consumption and transportation burdens.

3.3 Operation phase

The energy used to heat, cool, and ventilate buildings represents over 30% of Australia's national energy use, with approximately 20% used in commercial buildings (NGERT, 2008). In other countries with different industrial bases, space heating or cooling in buildings can be as high as 50% of the national energy use (Zogou and Stamatelos, 2007). Since the case building is not being monitored directly, estimates of operation energy burdens are referred to the literature.

Ming and Wei (Ming and Wei, 2003) demonstrated that the energy saving potential means of VAV systems are expected to achieve 11.7% to 22.2% compared with the conventional systems in a five-storey office building. With the same nominal cooling capacity, the total electricity energy consumption of VAV systems in the operation stage is 0.08121 GJ/m^2 per year (47 kg CO_2/m^2 per year). In comparison, the Department of Energy Commercial Building Energy

Consumption Survey (DOE, 1998) shows that the bills for conventional HVAC systems are 0.3 GJ/m^2 per year for offices, and 0.1 GJ/m^2 per year for educational buildings.

Koskela et al. (Koskela *et al.*, 2010) simulated operation energy VAV, fan-coil plus fresh air and the chilled beam systems, using the Energy Plus software. The results implied that chilled beam system was the most efficient air conditioning service with the reduction by 25-30% relative to a VAV system. Fläkt Woods Group (Fläkt, 2007) also did visual inspections in a building with a chilled beam system located in Stockholm in Sweden. The site record indicates the electricity cost of the chilled beam system in operation stage is 0.056847 GJ/m^2 (32.9 kg CO_2/m^2 per year).

Raftery et al. (Raftery *et al.*, 2011) compared the performance of the UAD system to the VAV system in a real case building, with a total floor area of 5576 m^2 and aspect ratio of 1.5. The results indicated that the UAD system did not show much energy saving potential compared to the VAV system, saving 3% against the VAV system. The electricity consumed in operation stage for the UAD system can be assumed as 45.7 kg CO_2/m^2 per year.

3.4 Maintenance and renewal

The lifespan of residential buildings in Australia generally falls between 40 and 50 years (Cole and Kernan, 1996). It is assumed that the building life span used for this analysis is 50 years. The replacement factor is given by the building life divided by the product life corrected for the possibility that the replacement occurs near the end of the building life. The number of times an HVAC product is replaced is defined as the replacement time. It is determined by the replacement factor minus one. An example is as follows. A chilled beam is assumed to have a life span of 20 years (Aherne, 2009). Then calculation indicates that the chilled beam system may be exchanged (50/20)-1=1.5 times.

The basic carbon is the carbon consumed during the preliminary life cycle stages before the replacements occur. The basic carbon is composed by basic manufacturing carbon, basic construction carbon, and basic demolition carbon. The extra carbon is accounted due to the changes associated with up-keep and improvements, which are subdivided in three parts: extra manufacture carbon (extra embodied carbon from extra HVAC products); extra construction carbon (extra transportation consumption and electricity consumption); extra demolition carbon (final energy used for delivering extra demolition materials and products to recyclers or landfills).

The total extra carbon emissions outlined above can be calculated by formula (2).

$$E_{extra} = \sum_{i=1}^{n} m_i * Q_i * \left(\frac{lifespan\ of\ a\ building}{average\ lifespan\ of\ HVAC\ product\ i} - 1 \right) \tag{2}$$

Where, E_{extra} is defined as the total extra carbon emissions of extra HVAC products; n is the number of the replacement of materials and products; i is the materials concerned; m_i is the amount of the HVAC products and materials (kg); Q_i is the sum of basic carbon in manufacture, construction and demolition phases in kg CO_2-e.

3.5 Demolition phase

The conventional demolition and decommissioning process often results in landfill disposal of the majority of materials (Cochran and Townsend, 2010). However, some demolition contractors prefer to separate the disposal waste by different sources. Current demolition practices involving market price and contractors chosen, is at customer demand (Blengini, 2009). This study only evaluated the HVAC system decommissioning burdens. All the HVAC products (including steel ducts and pipes, duct iron pipes, copper tubes and wire, brass, HVAC equipment, and valves) are mostly made of iron, copper and aluminium. It assumes that all these metals can be regarded as recycling materials. Demolition data for the deconstruction of HVAC systems were not available, and the investigation of the equipment consumption was not attempted in this research. The total carbon emissions in the demolition stage accounted for the transportation distances of demolition materials, depending on shipment to recyclers. The average distance used, based on the Southern Cross Metal Recyclers, is 9.6 km for recycling materials. All of the demolition energy is assumed as a diesel fuel source. Formula (3) is used to calculate the carbon emissions from fuel combustion for the transportation of demolition waste (Yan *et al.*, 2010).

$$E_v = \sum W_j^v \times T_j \times f^v \qquad (3)$$

Where, E_v is the total carbon emission from fuel combustion for transportation of demolition waste (in kg CO_2-e); W_j^v is the amount of waste transported to landfill j (in kg); T_j is the double distance between construction site and landfill j (in km); and f^v is the carbon emission factor for transportation (in kg CO_2-e/ton km), which can be evaluated as 0.0687 (NGERT, 2008).

4. Impact assessment and interpretation of the results

The impact assessment phase is carried out to summarise the achieve results relevant to the life cycle of the HVAC systems under study, with reference to the adopted functional unit (in Table 1). In accordance with the objective outlined in the beginning stage in this study, the following interpretation steps are carried out.

Table 1: results after LCIA phase relevant to VAV, chilled beam and UAD systems (data per m^2)

System \ *Carbon Emissions*	*Manufacture*	*Construction*	*Annul operation*	*Maintenance*	*Demolition*
VAV	*19.501*	*1.596*	*47*	*13.15*	*0.363*
Chilled beam	*39.691*	*3.174*	*32.9*	*36.9*	*0.772*
UAD	*8.687*	*0.694*	*45.7*	*7.15*	*0.153*

Analysis has been conducted to reveal the varying impact of environmental burdens at different life cycle phases. The total carbon emissions during the manufacture stage are 19.501 kg CO_2/m^2 in the case of VAV systems, 39.691 kg CO_2/m^2 in the case of chilled beam systems, and 8.687 kg CO_2/m^2 in the case of UAD systems. In all three cases, between 67% and 85% of this energy is due to the materials' embodied carbon. Processing and delivery are responsible for the rest of the energy. The energy used in chilled beam systems ranks the largest of the three systems. It is approximately twice as much as that in VAV systems, and three times as much as that in UAD systems. The reason for this is that the chilled beam system is an air and water system, which contains both water pipes and air ducts. The two physical systems combined will increase the initial carbon cost of chilled beam systems. In regard to carbon emission during the construction phase, the values obtained are 1.596 kg CO_2/m^2 in the case of VAV systems, 3.174 kg CO_2/m^2 in the case of chilled beam systems, and 0.694 kg CO_2/m^2 in the case of UAD systems. It can be seen that results in the three HVAC systems are very similar. Between 85 % and 92% of these values are due to fuel combustion in transportation. A comparison with electricity consumption values of the three HVAC systems does not exhibit significant differences. The average energy use per year for the VAV system, the chilled beam system, and the UAD system is 47 kg CO_2/m^2, 32.9 kg CO_2/m^2, and 45.7 kg CO_2/m^2 respectively. The results obtained in energy use in last phase correspond to the energy consumption from the transport vehicles. The results obtained in the case of VAV systems are 0.0772 kg CO_2/m^2, compared with 0.0153 kg CO_2/m^2 for chilled beam systems and 0.00363 kg CO_2/m^2 for UAD systems. This result is greatly dependent on the distance to the closest recycler.

From these figures it can be seen that the percentages of energy use are similar in these three cases. The operation phase is responsible for the greatest environmental impact of the whole life cycle in terms of emissions. It is observed that the carbon emissions from the operation represent between 29% and 73% of total life cycle consumption. The largest proportion of the energy is used for electricity consumption in the operation stage. It occupies 57% and 73% in the total life cycle carbon burdens of the VAV and UAD systems. Manufacture ranks second in the overall life cycle. For VAV, chilled beam and UAD systems, the manufacture carbon represents 30%, 24% and 13% respectively. These figures serve to remind us to realise the significant potential of embodied energy savings by recycling and reusing waste HVAC products and materials calls for novel design concepts and innovative technologies. Maintenance work also occupies a high percentage, which is due to the replacement times changing in the service life. Improvement strategies to enhance HVAC working performance are necessary to minimize energy use and carbon emissions throughout the life cycle of an HVAC system. The environmental burdens during construction and demolition are hardly noticeable, occupying only between 2% and 4%.

5. Conclusions

The results gathered from the present LCA application to three HVAC systems demonstrated that, in a life cycle perspective, chilled beam system is feasible and profitable from the energetic and environmental point of view. In relation to the proportion of the life cycle energy from each HVAC system, some significant conclusions can be drawn. The VAV and UAD systems are shown to offer potential for initial capital savings. In addition, the maintenance costs for VAV and UAD systems are much lower than for the chilled beam system. The ease with which UAD systems can be rearranged to satisfy new office layouts improves flexibility, reducing reconfiguration costs. The simplicity of the structure and components of the VAV system mean that it does not consume large amounts of extra carbon due to the maintenance rate, compared with the chilled beam system. Active beams have a dedicated air-supply duct. Therefore, active chilled beam systems include both water pipes and air duct systems to increase the airflow through the device and thereby to increase the cooling capacity. In essence, these devices dissipate heat by using water and air as the transfer medium is more efficient than the air used in VAV and UAD systems. With the ability of both water and air to absorb hundreds of times more heat than the equivalent volumes of air (ASHRAE, 2000), the chilled beam system provides a more efficient means of transferring energy.

The environmental impacts between these three HVAC systems are found to be of different magnitude in different life cycle phase. The embodied energy of UAD system is the lowest in manufacture stage while that of the chilled beam system is the highest. However, chilled beam system has much more energy saving potential than the other two air conditioning systems in operation stage. The replacement time prioritizes evaluating carbon emissions in refurbishments and replacements so as to calculate the total life cycle carbon emission of HVAC systems in a typical office building's 50 year service life. The results indicate that UAD system may not be the best option due to its relative higher operational energy consumption compared with chilled beam system. From a life cycle perspective, the chilled beam system has the lowest environmental impact over a 50 year time frame, and VAV system has the highest environmental impact among the three HVAC systems compared.

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