Life cycle assessment for three ventilation methods

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Abstract

A sustainable ventilation method is one of the possible solutions to mitigate climate change and carbon emission. This method shall involve an analysis of the environmental impact, energy performance, and economical cost-effectiveness. There are still few studies concerning the life cycle assessment (LCA) of various alternative ventilation systems incorporating the combined effect of life cycle cost (LCC) and carbon emission in the supply-and-installation phase, as well as energy performances in the operation phase. The supply-and-installation phase of the system materials and components has a significant contribution to the total energy consumption and environmental loads of buildings. This paper covers a systematic approach to estimate their environmental impact, which was counted in terms of energy demand and CO_2 emission in the two phases. This approach has been applied to an actual typical classroom served by mixing ventilation (MV), displacement ventilation (DV) and stratum ventilation (SV). The results show that SV has the least environmental impact and life cycle cost (LCC). Results of this analysis demonstrated that by adopting DV and SV, it is possible to reduce the CO_2 emission up to 23.25% and 31.71% respectively; and to reduce the LCC up to 15.52% and 23.89% respectively, in comparison with an MV system for 20 service years. This approach may be generally applied to a sustainability analysis of ventilation methods in various scales of air-conditioned spaces.

Keywords

LCA; LCC, CO_2, mixing ventilation, displacement ventilation, stratum ventilation.

Nomenclature

AHU	Air handling Unit
BREEAM	Building research establishment environmental assessment method
CE	Carbon emission (kg-CO_2)
CO_2	Carbon dioxide
DDC	Direct digital controller
DV	Displacement ventilation
ELCD	European life cycle database
EMSD	Electrical and Mechanical Services Department
HKEPD	Hong Kong Environmental Protection Department
F	Future value occurred in the *n* years (HK$)
GHG	Greenhouse gas
HK$	Hong Kong dollar
HVAC	Heating, ventilation and air conditioning
i	Annual discount rate (%)
IC	Initial cost (HK$)
ICE	Inventory of carbon & energy
k	Inflation rate (%)

LCA	Life cycle assessment
LCA (Yr-*n*)	Life cycle assessment in the *n* service years (kg-CO_2)
LCC	Life cycle cost
LCC (Yr-*n*)	Life cycle cost in the *n* service years (HK$)
LCI	Life cycle inventory
LEED	Leadership in energy and environmental design
n	Number of years
P	Multiplying factor of energy use
PV	Present value
P_f	Equivalent present worth of *F*
SAG	Supply air grille
SC	Salvage cost (HK$)
SV	Stratum ventilation
SV/MV	Carbon emission ratio of SV and MV in LCA (Yr-*n*)
SV/DV	Carbon emission ratio of SV and DV in LCA (Yr-*n*)
TEFC	Totally enclosed fan cooled
RAL	Return air louver
MC	Maintenance cost (HK$)
m	Multiplying factor of ductwork size
NPV	Net Present value
OC	Operation cost (HK$)
TRNSYS	TRaNsient system simulation
USEPA	United states environmental protection agency
$MV/$SV	Cost ratio of MV and SV in LCC (Yr-*n*)
$SV/ $DV	Cost ratio of SV and DV in LCC (Yr-*n*)

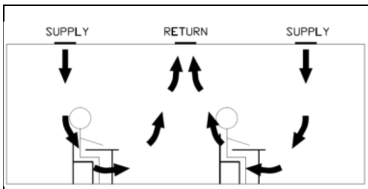
1. Introduction

Human-induced climate change has become a dramatically urgent and serious problem. The 195 countries that met at Paris in 2015 agreed to hold the increase in the global average temperature to well below 2°C above pre-industrial levels and also make efforts to limit the temperature increase to 1.5°C [1]. Several developed countries have a long-term policy of reducing global GHG emission by at least 50 percent by 2050 [2, 3]. In order to achieve the long-term temperature goal, the countries aim at reducing global peaking of greenhouse gas emission as soon as possible, says the agreement. Excessive greenhouse gas (GHG) emission have been recognized as the root causing the anthropogenic climate change. In general, the major operational energy consumer in building is the HVAC system [4-6]. For example, all energy end-uses account in Hong Kong commercial sector, space air-conditioning and electrical lighting installations are counted for 30% and 16% of the total electricity energy use respectively. A practical instrument for predicting CO_2 emission that is undergoing rapid development is life cycle assessment (LCA), which is used internationally as an environmental management technique for the industry and authorities [7]. A lot of building environmental assessment methods and tools have been developed for appraising the environmental impact of buildings [8], such as Leadership in Energy and Environmental Design (LEED) of the USA [9], the Building Research Establishment Environmental Assessment Method (BREEAM) of the UK [10], Green Star of Australia [11], Green Mark of Singapore [12] and the Hong Kong Special Administrative Region (HKSAR) [13]. These tools have some useful attributes to analyze building performance [14-16], but they are unable to quantify energy use in all phases, including embedded energy used by air conditioning systems. Every key entry of life cycle inventory of energy going in and CO_2 emission coming out of the entire process in the preparation of the various ventilation system components are considered in this study.

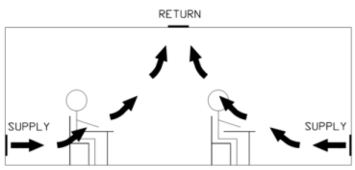
The specific inventories' values are regionally referenced from the Life Cycle Assessment tool's inventory databases. The Life Cycle Inventory (LCI) database in different countries and regions has respected to their defined system boundary, including Cradle to Gate, Cradle to As-built and Cradle to Grave. Those are involved the Ecoinvent [17], European reference Life Cycle Database (ELCD) [18], eBalance [19], Inventory of Carbon & Energy (ICE) [20], as well as Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) Tool developed for Hong Kong commercial buildings [13, 21-23].

The total life cycle energy of a building includes both embodied energy and operating energy: (1) Embedded energy: sequestered in building materials during all processes of production, on-site construction, and final demolition and disposal; and (2) Operational energy: expended in maintaining the inside environment through processes such as ventilation method in heating and ventilation, air conditioning (HVAC) system. The three ventilation systems studied are mixing ventilation, displacement ventilation and stratum ventilation. They have different supply and return configurations as those illustrated in Figure 1. In planning stage, the decision-maker should consider both embodied energy in supply-and-installation phase and operational energy of alterative ventilation systems in order to reduce the carbon emission.

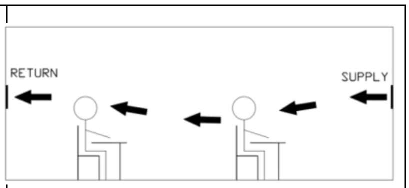
To produce useful information concerning carbon emission in the building operation system, many researchers studied energy consumption at different stages of the building life cycle and concluded that each stage has different effects [16, 24-30] Carbon emission is commonly expressed in terms of the life cycle stages involved: planning, design, construction, installation, test, commissioning, operation and disposal [31]. United States Environmental Protection Agency (USEPA) categorizes these stages into the three consecutive phases, namely Cradle to gate, Cradle to as-built and Cradle to grave [32].



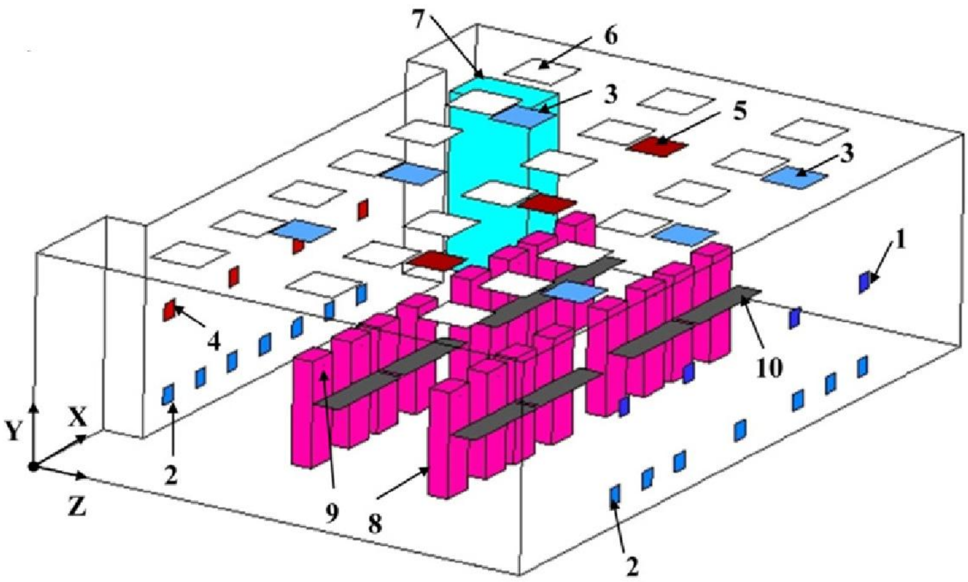
1(a) Mixing ventilation (MV) with ceiling supply and return



1(b) Displacement ventilation (DV) with front & rear wall supply at low level and ceiling return



1(c) Stratum ventilation (SV) with front wall supply at mid-level and rear wall return at same level



1 (d) The Classroom

1 Supply diffusers for SV
2 Supply diffusers for DV
3 Supply diffusers for MV
4 Return diffusers for SV
5 Return diffusers for MV & DV
6 Lighting panels
7 BMS workstation
8 Seated occupants
9 occupant's nose
10 desk

Figure 1 Three alternative ventilation systems for typical classroom

In this paper, these are presented in three distinct phases: (a) Supply-and-installation phase: covering the content of materials in the construction process; (b) Operation phase: the operation and maintenance of the ventilation systems; and (c) End of life impact: the deconstruction process to waste materials [33]. The result of LCA is of paramount importance for reducing the carbon emission in supply-and-installation phase and also influential on their operational efficiency with equal thermal comfort provision of the three ventilation methods [34]. Reducing the demand for operational energy appears to be the most important aspect for the design of buildings that are energy efficient throughout their life cycle.

A good ventilation method design would not only increase the potential for emission reductions over the building system life cycle, but should also provide a comfort environment during the operation phase. For instance, carbon emission may be reduced by means of cutting down electricity consumption in the entire centralized air conditioning system by the elevated indoor enthalpy and also facilitates better air quality in the breathing zone [35-37]. Furthermore, the correct selection of materials, equipment and air distribution technology during the planning and design phase can provide an opportunity to reduce carbon emission [38, 39].

2. Research methodology

Through the case study to evaluate the economic benefits of adopting the alternative ventilation methods, including mixing ventilation, displacement ventilation and stratum ventilation in the typical air conditioned three-row seating pattern classroom with the sizes of 6.1 m (width) × 8.8 m (length) × 2.4 m (height) during the supply-and-installation and operation phases. This LCA is a quantitative method to evaluate the environmental impacts of building ventilation components and equipment, and requires the use of LCC to access the environmental and financial viability of investments based on equal thermal comfort conditions for alternative ventilation methods. LCA and LCC are used to derive environment and investment decisions in the interest of sustainable development of ventilation technologies. The three ventilation methods including mixing ventilation, displacement ventilation and stratum ventilation are used to assess their years of cost investment, energy consumption, and greenhouse gas emission, making reference to the local industry practices. The prediction of operation performance and operational energy of the three ventilation systems is based on the all-year-round energy simulation software TRNSYS [40], industrial data interpretation, with the scope of energy saving restricted to the life-long electricity saving for the support of the ventilation system design.

2.1 System boundary of LCA

The focus of this study is to compare a full-scale stratum ventilation and displacement ventilation, with reference to conventional mixing ventilation during supply-and-installation and operation phases under the specific thermal comfort condition. Figure 2 presents the full boundary of study, including the processes from raw material extraction to the system fabrication, and to the final disposal stage at the end of system service life.

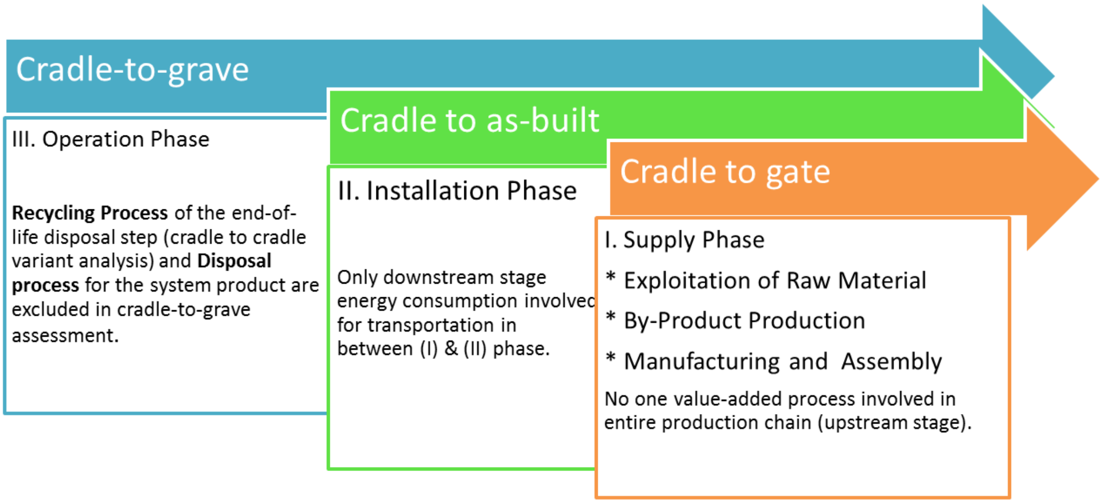


Figure 2 System boundary of the LCA study

Using the cradle-to-gate approach compiled the life cycle inventory. This allows the LCA to collect all of the impacts due to the resources being purchased. The raw materials for the fabrication of the various ventilation system components, which are tabulated in Table 1, have been mainly mined in the Chinese Mainland with the rest imported from other places worldwide.

Table 1 Initial cost of mixing ventilation, displacement ventilation and stratum ventilation during supply-and-installation phase

Item	Description of each construction details	Qty	Unit	HK$ /Unit	HK$
1	Supply and install air handling unit completed with double skin 50mm thickness panels, 50mm polyurethane insulation, 50mm aluminum filter, 450 L/s supply air fan.	1	no.	50,000	50,000
2	Supply and install a framework support for ceiling mounted air handling unit (AHU)	1	lot	6,000	6,000
3	Supply and install duct silencer	2	no.	4,000	8,000
4	Supply and install 50mm diameter mild steel chilled water pipework completed with phenolic foam thermal insulation and connection to air handling unit	30	m	450	13,500

5	Supply and install 32mm diameter galvanized steel condensate drain pipework completed with phenolic foam thermal insulation	20	m	320	6,400
6	Supply and install electrical power supply and control including starter panel, switch and wiring	1	lot	50,000	50,000
7	Supply and install Direct Digital Controller (DDC) control equipment including control valve, temperature sensor, relative humidity sensor, pressure sensor, flow sensor, actuator for monitoring and control of the air handling unit	1	lot	70,000	70,000
Initial cost of the identical AHU (IC_{AHU}) = sum of items 1 to 7: $203,900					
Ductwork and its accessories (IC_{Duct}) of MV = sum of items 8_{MV} to 11_{MV}					
8_{MV}	Supply and install galvanized iron air ductwork with accessories for mixing ventilation (MV)	45	m^2	300	13,500
9_{MV}	Supply and install 25mm thickness, 40 kg/m^3 phenolic foam thermal insulation for air ductwork for MV	45	m^2	180	8,100
10_{MV}	Supply and install aluminum supply air grille (SAG) completed with volume control damper 200×200mm wall mounted SAG, 600 × 600mm ceiling mounted SAG for MV	6	no.	450	2,700
11_{MV}	Supply and install aluminum return air louver (RAL): 200 × 200mm wall mounted RAL, 600 × 600mm ceiling mounted RAL for MV.	3	no.	450	1,350
Ductwork and its accessories (IC_{Duct}) of DV, = sum of item 8_{DV} to 11_{DV}					
8_{DV}	Supply and install galvanized iron air ductwork with accessories for displacement ventilation (DV)	30	m^2	300	9,000
9_{DV}	Supply and install 25mm thickness, 40 kg/m^3 phenolic foam thermal insulation for air ductwork for DV	30	m^2	180	5,400
10_{DV}	Supply and install aluminum supply air	8	no.	350	2,800

	grille (SAG) completed with volume control damper 200 × 200mm wall mounted SAG, 600 × 600mm ceiling mounted SAG for DV				
11_{DV}	Supply and install aluminum return air louver (RAL), 200 × 200mm wall mounted RAL, 600 × 600mm ceiling mounted RAL for DV	3	no.	350	1,050
Ductwork and its accessories (IC_{Duct}) of SV, = sum of item 8_{SV} to 11_{SV}					
8_{SV}	Supply and install galvanized iron air ductwork with accessories for stratum ventilation (SV)	43	m^2	300	12,900
9_{SV}	Supply and install 25mm thickness, 40 kg/m^3 phenolic foam thermal insulation for air ductwork for SV	43	m^2	180	7,740
10_{SV}	Supply and install aluminum supply air grille (SAG) completed with volume control damper: 200 × 200mm wall mounted SAG, 600 × 600mm ceiling mounted SAG for SV	4	no.	350	1,400
11_{SV}	Supply and install aluminum return air louver (RAL): 200 × 200mm wall mounted RAL, 600 × 600mm ceiling mounted RAL for SV	4	no.	350	1,400
Initial cost, *IC* (HK$) for three ventilation systems					
IC_{MV}	Items of 1 + 2 + 3 + 4 + 5 + 6 + 7 + 8_{MV} + 9_{MV} + 10_{MV} + $11_{MV:}$ =				229,550 (Base)
IC_{DV}	Items of 1 + 2 + 3 + 4 + 5 + 6 + 7 + 8_{DV} + 9_{DV} + 10_{DV} + 11_{DV} =				222,150 (3.22% less)
IC_{SV}	Items of 1 + 2 + 3 + 4 + 5 + 6 + 7 + 8_{SV} + 9_{SV} + 10_{SV} + 11_{SV} =				227,340 (0.96% less)

For this study on the classroom, the data of embedded energy and carbon emission of each material is mainly extracted from the website of the Electrical and Mechanical Services Department of the HKSAR Government (EMSD) [13] and other databases in the Chinese Mainland [19]. The initial cost of each construction detail is provided by the local contractors. All the main parts and sub-parts of the ventilation systems are considered to be fabricated in the Chinese Mainland. Hence, the transportation of raw materials within China and from worldwide to the by- or main-product fabrication factories in China takes place. All the components of the ventilation systems are fabricated and assembled in China and are delivered from the main factory in the Chinese Mainland to the installation site in the HKSAR. The ventilation systems are finally installed in the classroom. Each component of the systems, the electrical wiring works and the water piping works are considered in the supply-and-installation phase. The disposal of the ventilation systems is excluded from this LCA due to the current waste reduction target in HKSAR. The target is to reduce the per capita disposal rate of municipal solid waste by 40% by 2022 using 2011 as the base [41, 42]. The Hong Kong landfills used for disposal of solid waste are being filled up at an alarming rate. All construction and demolition material is not allowed for disposal at landfills unless approval has been issued at the planning stage by the Environmental Department of HKSAR [43]. If such a process is considered, the energy demand and greenhouse gas emission for reuse, recycling, landfill and incineration have to be added in the total inventories summation. This part is not including due to the lack of information on the case-by-case disposal treatment and their inventories data. Life cycle impact assessment usually follows the LCI analysis without applying any weighting factors and impact indicator of the life cycle energy uses including embedded and operational energy use.

2.2 Data adopted in supply-and-installation and operation phases

In the supply-and-installation phase, the mass, embedded energy and embedded carbon of each component of the air handling unit (AHU) are tabulated in Tables 2 and 3 respectively. The embedded energy and embedded carbon values are extracted from the eBalance [19] and LCI data developed by the EMSD [21, 23]. The "eBalance" LCA software encompasses the Chinese Life Cycle Database (CLCD) which is developed by Sichuan University and IKE Environmental Technology. This database is tailor-made to represent the average technology in the Chinese market. The Life Cycle Inventory (LCI) database also includes the information in the Ecoinvent database and the European Reference Life Cycle Database (ELCD). Since the free version of the "eBalance" software only provides limited data from the CLCD, some of the embedded energy data is referenced from the Ecoinvent and (ELCD) database stored in the "eBalance" software. The Ecoinvent and ELCD databases support the inventory data of materials that are imported to China and provide referencing inventory values that are not yet available in the CLCD database. LCI data developed by the EMSD is based to evaluate the direct and indirect impact of the material manufacturing process using the life cycle assessment technique. Inventory of this study is based on the surveyed LCA and LCC data which are conducted based on components and materials used in 28 completed commercial buildings in the HKSAR adopted in the life cycle energy analysis (LCEA) study software [13], which can identify the range of components and materials that would dominate the total environmental impacts of buildings, such as . Other well-known life cycle assessment programs for buildings include: Athena LCA software tools of Canada [44], Building for Environmental and Economic Sustainability software of US [45] and Envest 2 of UK [46], etc. The cumulative embedded energy of different installed accessories for the three ventilation systems to be used in this study are tabulated in following Section 3.1.2.

In the operation phase, the energy use for mixing ventilation, displacement ventilation and stratum ventilation has been evaluated under their thermal neutral temperature in thermal sensation model [47]. These neutral temperatures have been estimated from the actual votes of a large group of human subjects based on the heat balance of the human body. According to the ASHRAE 7-point thermal sensation scale, it concerns the thermal sensation vote of -3, -2, -1, 0, +1, +2, and +3 representing cold, cool, slightly cool, neutral, slightly warm, warm, and hot, respectively [48-50]. The neutral temperature is not only affected by the combinations of activity level, clothing insulation, metabolic rate, air speed, humidity and other possible environmental parameters [50], but also each of air distribution methods is being adopted [30, 47]. This thermal sensation model with varied air distribution methods is based on the regression analysis of the votes results from the forty-eight subjects of ASHRAE 7-point scale under the same conditions in the classroom. It can directly find out the thermal balance of the internal heat production in the body equaling to the loss of heat to the environment in mixing, displacement and stratum ventilation systems. In mathematic expression of this model, the neutral temperature is defined in a thermal comfort context as the room temperature for which the actual vote of a sample occupant group is equal to zero “neutral” in the thermal sensation model. As result, the thermal neutral temperature under stratum ventilation is approximately 2.7 °C higher than that under mixing ventilation and 2.2 °C higher than that under displacement ventilation at the supply air flow of 10 air change per hour [30, 47]. The respective neutral temperatures of 24.6 °C, 25.1 °C & 27.3 °C for MV, DV & SV respectively are matched with the earlier publications by the other researchers [51, 52].

The all-year-round energy consumption for the three ventilation systems including primary and secondary sides of central air conditioning system was estimated using TRNSYS [40]. All-year-round energy consumptions of the three ventilation systems have been analyzed under their respective neutral temperatures. System simulations are made for one year based on the TMY weather data of Hong Kong [53] using a simulation time step of three minutes. The total primary energy consumption and system performance for the various cases with the part-load control are compared. The primary data used for estimating the energy use related to CO_2 emission are the estimated energy consumption figures, which for each ventilation system, based on territory-wide emission factor of CO_2, i.e., utility power generation is 0.7 kg-CO_2-eq/kWh.

LCA analysis of the study utilizes the costs of each ventilation method in the supply-and-installation phase plus the energy consumption as the initial data for the assessment of carbon emission. The initial and maintenance costs are provided by the local contractors. Costs of maintenance plus amounts of energy consumed in the operation phase of the three ventilation systems have been used as initial data for the operation phase. In order to make a comprehensive assessment, different time perspectives have been used. The chosen time periods have been 5, 10, 15 and 20 years.

3. Case studies for three ventilation systems using LCA

This study of CO_2 emission of alternative ventilation systems, including mixing ventilation, displacement ventilation and stratum ventilation (as illustrated in Figure 1), are divided into the supply-and-installation phase and operation phase. The CO_2 emission of the supply-and-installation phase consists of the emission embedded in the materials utilized to construct the ventilation systems. This classroom is located in an interior zone of an air conditioned building. Thus, the energy is mainly used to tackle for the internal and ventilation loads.

3.1 Supply-and-installation phase

3.1.1 Life cycle cost

The first step is to acquire relevant cost data for the evaluation of the three alternative ventilation systems. The focus of the LCC analysis is to compare different components of each ventilation method. Each initial cost is tabulated in Table 1. The results of initial cost (*IC*) for mixing ventilation, displacement ventilation and stratum ventilation are HK$ 229,550 (base), HK$ 222,150 (3.22% less) and HK$ 227,340 (0.96% less) respectively. These costings are used for incorporating with embedded energy and carbon emission studies in the following sections.

3.1.2 Cumulative embedded energy

The CO_2 emitted in the supply-and-installation phase of the alternative ventilation systems have assessed using the same model of air handling unit (AHU). Its overall mass weight of 222 kg and each component inside air handling unit are tabulated in Table 2.

Table 2 Mass of each component inside air handling unit (AHU)

Section	Component	Material	Size	Mass (kg)
Frame and panel section	Corner	Rubber	40mm (W) × 5 mm (thickness) × 50 mm (L)	0.09
	Double skin type panel	Polyurethane layer (density>45)	Top: 830mm × 1110 mm × 8.8 mm	0.24
			Bottom: 830mm × 1110 mm × 8.8 mm	0.24
			Left: 1110 mm × 560 mm × 8 mm (need to exclude pipe area)	0.16
			Right: 1110 mm × 560 mm × 8 mm	0.16
			Front: 830 mm × 560 mm × 8 mm (need to exclude duct area)	0.11
		Blue color painted steel	Top: 830mm × 1110 mm × 8.8 mm	8.62
			Bottom: 830mm × 1110 mm × 8.8 mm	8.62
			Left: 1110 mm × 560 mm × 8 mm (need to exclude pipe area)	5.80
			Right: 1110 mm × 560 mm × 8 mm	5.82
			Front: 830 mm × 560 mm × 8 mm (need to exclude duct area)	3.90
		Aluminum frame	Top: 830mm × 1110 mm × 8.8 mm	1.48
			Bottom: 830mm × 1110 mm × 8.8 mm	1.48
			Left: 1110 mm × 560 mm × 8 mm (need to exclude pipe area)	1.56
			Right: 1110 mm × 560 mm × 8 mm	1.56
			Front: 830 mm × 560 mm × 8 mm (need to exclude duct area)	3.74
			No panel at the back	0.00
	Panel gasket	Rubber		3.68

		(40mm thickness)		
	10 nos. washers for motor, fan and panel handles installation	Steel		0.10
				0.15
	10 nos. M8 screw for motor, fan and panel handles installation			10.71
				2.69
	Electrical wire	Copper	Core Area 1.5mm^2, length: 6.65m	0.09
		PVC	Length: 6.65m, 1mm insulation	0.27
	Insulation	Fiber glass (chiller water pipe)	Pipe dia. = 25.4 mm, thickness 13mm, total length = 13.38m	0.42
		Aluminum foil	Pipe dia. = 25.4 mm, fiber glass thickness = 13 mm, thickness = 0.1mm, length = 8.58m	0.10
	6 handles	Rubber	160mm (L) × 25mm (W) × 10mm (D)	0.36
	16 locks		10mm (L) × 5mm (W) × 5mm (D)	0.01
	M8 screw framework for mounting AHU	Galvanized iron	Thickness = 3mm width = 40mm extra length for screw connection =8cm	16.51
Motor and fan section	Fan	Hot-dip galvanized steel sheets	No panel at the back Core Area 1.5mm^2, length:6.65m	76.89
	Fan wheel	Cast iron		1.29
	11kW TEFC Motor	Stainless steel		0.08
		Stainless steel		9.82
		Copper		6.74
		Cast iron		4.51
		Stainless steel		0.21
	Motor bell wheel	Cast iron		8.70
	Spring × 4	Galvanized steel	Diameter = 30mm, thickness = 2mm, number of rounds = 4	0.04

	Bell	Rubber	1000mm(L) × 20mm (W) × 2mm(D)	0.06
Coil section	Coil with connection points	Black steel	25.4 mm (Dia.) × 3.14 × 4290 mm (L) × 0.2 mm (thickness)	0.54
		Black steel	25.4 mm (Dia.) × 3.14 × 4460 mm (L) × 0.2 mm (thickness)	0.56
		Cast iron	25.4 mm (Dia.) × 3.14 × 4630 mm (L) × 0.2 mm (thickness)	0.59
		Copper	12.7 mm × 3.14 × 400 mm (L) × 0.15 mm (thickness), Number of tube rows : 4, 8 parallel tubes in each row	1.23
	Exchange tubes	Aluminum	0.1524 mm (W) ×140 (L) × 400 (H) × 284 (No. of fins = 610/(0.1524 +2)	6.54
	Fins	Copper	$(((22 + 1.5 + 1.5)/2)^2 - (22/2)^2) \times 3.14 \times 400 \times 4 / (1000^3)$, thickness = 1.5 mm, diameter = 22mm	3.81
	Header (inlet)	copper	$(((22 + 1.5 + 1.5)/ 2)^2 - (22/2)^2) \times 3.14 \times 400 \times 4/(1000^3)$	3.81
	Suction (outlet)	Galvanized iron	980mm (L) × 860mm (W) × 1mm (thickness)	6.63
	Condensing panel	Aluminum	670(L) × 460 (H) × 140 (D)	21.64
	Coil Frame	Aluminum	$(46/2)^2 - (22/2)^2) \times 3.14 \times 400 \times 4/(1000^3) \times 455 \times 400$	8.91
Filter section	Filter	Galvanized iron	80 mm (H) × 900 mm (D) × 25 mm (thickness)	28.33
			Total mass weight (kg) :	**222.34**

The calculation has considered the amount of material used in AHU. It needs to point out that the peak cooling load of stratum ventilation is about 70% of that of mixing ventilation [30]. The peak cooling loads of various ventilation systems were determined using the load simulation software of E20 [54]. The same AHU was adopted because a smaller AHU of exactly-needed capacity is unavailable on the market. Therefore, the analysis is disadvantageous to stratum ventilation to certain extent. The numbers of each assemble component are determined in accordance with the manufacturer's catalogue and installation guideline. The embedded energy of all connection accessories and the components are estimated by their mass (in kg) multiplying the embedded energy per unit mass (in MJ/kg). The embedded energy inventories in this database are for the supply-and-installation phase, which is equivalent to Cradle to As-built stage. All the values have included all the processes across the entire LCA boundary. The total cumulative energy and carbon emission for the air handling unit are 14,482 MJ and 1,101 kg-CO_2 respectively as shown in Table 3. Table 4 presents the embedded energy and carbon emission of each raw material consisted of different installed accessories for mixing ventilation (41,408 MJ and 3,057 kg-CO_2), displacement ventilation (31,953 MJ and 2,364 kg-CO_2) and stratum ventilation (36,346 MJ and 2,639 kg-CO_2).

The components of the three systems, listed in Tables 3 and 4, are manufactured in the Pearl River Delta region in Guangdong province of China. The vehicle travel distance between Dongguan in the region and HKSAR is about 150 km. From the Chinese Life Cycle Database stored inside "eBalance" [19], the embedded energy for an eight-ton lorry is 2.474 MJ per ton-kilometer. The embedded energy in transportation of all components is summarized in Table 5 for the three ventilation systems. The total CO_2 emission for the three ventilation systems during the supply-and-installation phase is summarized in Table 6.

Table 3 Cumulative embedded energy in AHU

Chamber	Description of each assemble component	Material	Embedded energy (MJ) [Mass, kg × Energy intensity, MJ/kg]	Embedded carbon (kg-CO_2)
Enclosure	Corner	Rubber	9.15	0.29
	Double skin type panel	Polyurethane layer (density>45)		
		Top	17.54	0.91
		Bottom	17.54	0.91
		Left (connect to water pipes)	11.83	0.62
		Right	11.83	0.62
		Front (supply)	7.93	0.41
		Blue color painted steel		
		Top	454.45	29.58
		Bottom	454.45	29.58
		Left (connect to water pipes)	305.87	19.91
		Right	306.62	19.96
		Front (supply)	205.47	13.37
		Aluminum frame		
		Top	324.03	26.78
		Bottom	324.03	26.78
		Left (connect to water pipes)	341.18	28.20
		Right	341.18	28.20
		Front (supply)	820.13	67.78
	Panel gasket	Rubber	374.21	11.70
	Washer	Steel		
		Motor: 4	5.27	0.34
		Fan : 6	7.91	0.51
	M8 screw	Steel		
		Motor: 4	564.18	36.72
		Fan : 6	141.95	9.24
	Electrical wire	Copper	2.02	0.17
		PVC	24.15	0.60

	Insulation	Fiber glass (chiller water pipe)	13.34	1.04
		Aluminum foil	20.93	1.73
	6 handles	Rubber	36.61	1.14
	16 locks	Rubber	0.61	0.02
	Framework for mounting AHU			
	Framework	Galvanized iron	234.80	13.56
	M8 screw × 7		1.23	0.07
Supply fan & coil section	Fan	Hot-dip galvanized steel sheets	4052.30	263.75
	Fan bell wheel	Cast iron	18.41	1.06
	TEFC Motor (1.1 kW)			
	Motor bell wheel	Cast iron	124.47	7.19
	Bearing	Stainless steel	4.37	0.28
	Rotor	Stainless steel	517.38	33.67
	Stator	Copper	152.27	12.94
	Controller	Cast iron	64.52	3.73
	Shaft	stainless steel	11.33	0.74
	Spring × 4	Galvanized steel	2.08	0.14
	Bell	Rubber	6.10	0.19
	Chilled water connection pipe in	Black steel	28.36	1.85
	Chilled water connection pipe out	Black steel	29.49	1.92
	Condensing water drain pipe	Cast iron	8.38	0.48
	Exchange tubes	Copper	27.76	2.36
	Fins	Aluminum	1380.82	118.45
	Header (inlet)	Copper	34.44	2.93
	Suction (outlet)	Copper	34.44	2.93
	Condensing panel	Galvanized iron	94.85	5.48

	Coil frame	Aluminum	4566.21	391.70
Filter	Filter section	Aluminum	1879.51	161.23
	Slide in guides for filter	Galvanized iron	405.15	23.40
	Total cumulative value:		**14482.46**	**1100.71**

Table 4 Cumulative embedded energy of different installed accessories for three ventilation systems

Ventilation systems	Description of Major Components	Mass (kg)	Embedded energy (MJ) [Mass, kg × Energy intensity*1, MJ/kg]	Embedded carbon (kg-CO_2)
(1) Air Handling Unit for the three ventilation systems		222 (*from Table 2)*	14,482 *(from Table 3)*	1,101 *(from Table 3)*
(2) Accessories of mixing ventilation (Base)	Ductwork , 45m² × 2mm thickness of galvanized iron	708	10,129	585
	Insulation, 45m² × 13mm thickness of fiber glass	281	8,901	694
	Insulation for ductwork, 45 m² × 0.1mm thickness of aluminum foil	12	2,564	220
	Supply & return diffuser, 3.24 m² × 3 mm thickness of aluminum	26	5,332	457
(1) + (2): Cumulative energy of mixing ventilation		1,249	41,408 (Base)	3,057 (Base)
(3) Accessories of displacement ventilation	Ductwork , 30m² × 2mm thickness of galvanized iron	472	6,752	390
	Insulation, 30m² × 13mm thickness of fiber glass	187	5,934	462
	Insulation for ductwork, 30 m² × 0.1mm thickness of aluminum foil	8	1,709	147
	Supply & Return Diffuser, 1.8 m² × 3 mm thickness of aluminum	15	3,076	264
(1) + (3): Cumulative energy of displacement ventilation		904	31,953 (22.83% less)	2,364 (22.68% less)
(4) Accessories of	Ductwork , 43m² × 2mm thickness of galvanized iron	679	9,678	559

stratum ventilation	Insulation, 43m² × 13mm thickness of fiber glass	268	8,505	663
	Insulation for ductwork, 43.12 m² × 0.1mm thickness of aluminum foil	12	2,450	210
	Supply & return diffuser, 0.72 m² × 3 mm thickness of aluminum	6	1,231	106
(1) + (4): Cumulative energy of stratum ventilation		1,187	36,346 (12.22% less)	2,639 (13.69% less)

[*1] The energy intensities of galvanized iron, fiber glass, aluminum foil and aluminum are 14, 32, 214 and 205 MJ/kg respectively.

Table 5 LCA cumulative embedded energy in transportation of the equipment/material/parts

Transportation method by 8 tons lorry.	Total mass of ventilation system (kg or Ton)	Distance (km)	Embedded energy factor (MJ/Ton.km)	Embedded energy (MJ)
Mixing	1,249 or 1.249	150	2.474	464
Displacement	904 or 0.904	150	2.474	336
Stratum	1,187 or 1.187	150	2.474	441

Table 6 CO_2 emission for three ventilation systems during supply-and-installation phase

Vent. system	Cumulative energy in AHU and Accessories (Table 4) + Transportation (Table 5), MJ	Total Cumulative Embedded energy, MJ	Total Cumulative Embedded energy, kWh (= 3.6 × MJ)	CO_2 emission, kg-CO_2 (= 0.7 × kWh)
MV	41,408 + 464	41,872	150,739	105,517 (Base)
DV	31,953 + 336	32,289	116,241	81,368 (22.89% less)
SV	36,346 + 441	36,787	132,433	92,703 (12.14% less)

3.2 Energy consumption in the operation phase

This LCA analysis is based on their estimated thermal neutral temperature of each ventilation method. The neutral temperatures of young HKSAR Chinese under mixing ventilation, displacement ventilation, and stratum ventilation are found to be 24.6 ℃, 25.1 ℃, and 27.3 ℃ at 10 Air Change per Hour (ACH) through regression analysis [22, 30, 47]. The energy consumption in operation phase studied has been evaluated with same base case along with alternative options, where alternative ventilation systems are combined under their respective neutral temperatures. It has involved 2,686 W of total internal heat sources generated by 25 occupants (1190 W), a projector (220 W), lamps (1176 W), a teaching computer set (100 W) and a portable electronic device per each students (24 × 80 W) as well as ventilation load based on 10 L/s per person. The energy simulation is based on the existing HVAC system, including air-cooled constant-speed-driven chiller, variable-speed circulation pump, ceiling-mounted AHU, variable speed fan, provided in this education area. All components associated with the all-year-round energy consumption for various cases in the TRNSYS simulation are illustrated in Figure 3. Energy consumption for a space conditioned by air conditioning systems respectively adopting mixing ventilation, displacement ventilation and stratum ventilation, the all-year-round total energy consumptions of 21,529 kWh (base); 16,495 kWh (23.38% less); 13,228 kWh (38.56% less) are tabulated in Table 7.

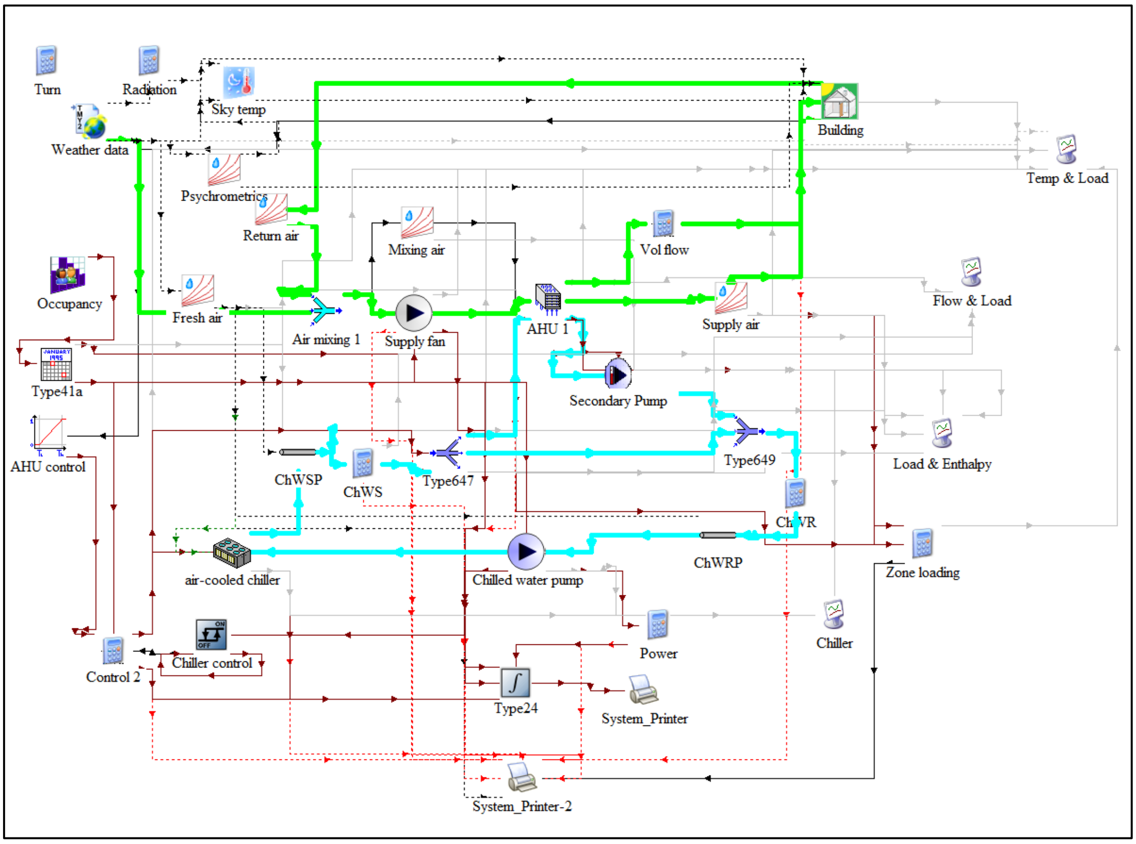


Figure 3 Components associated with all-year-round energy consumption in TRNSYS simulation

Table 7 All-year-round energy consumption simulated using TRNSYS for MV, DV and SV

Vent. system	Room temp. [*1] (°C)	Supply air temp. (°C)	Chilled water temp.		Chiller (kWh)	Fan and Pump (kWh)	Total power [*2] (kWh)	% of saving
			Lower (°C)	Upper (°C)				
MV	24.6	13.5	7	12.5	12,103	9,426	21,529	Base
DV	25.1	15.4	10	15.5	7,798	8,697	16,495	23.38% less
SV	27.3	17.5	12.5	17.5	4,709	8,519	13,228	38.56% less

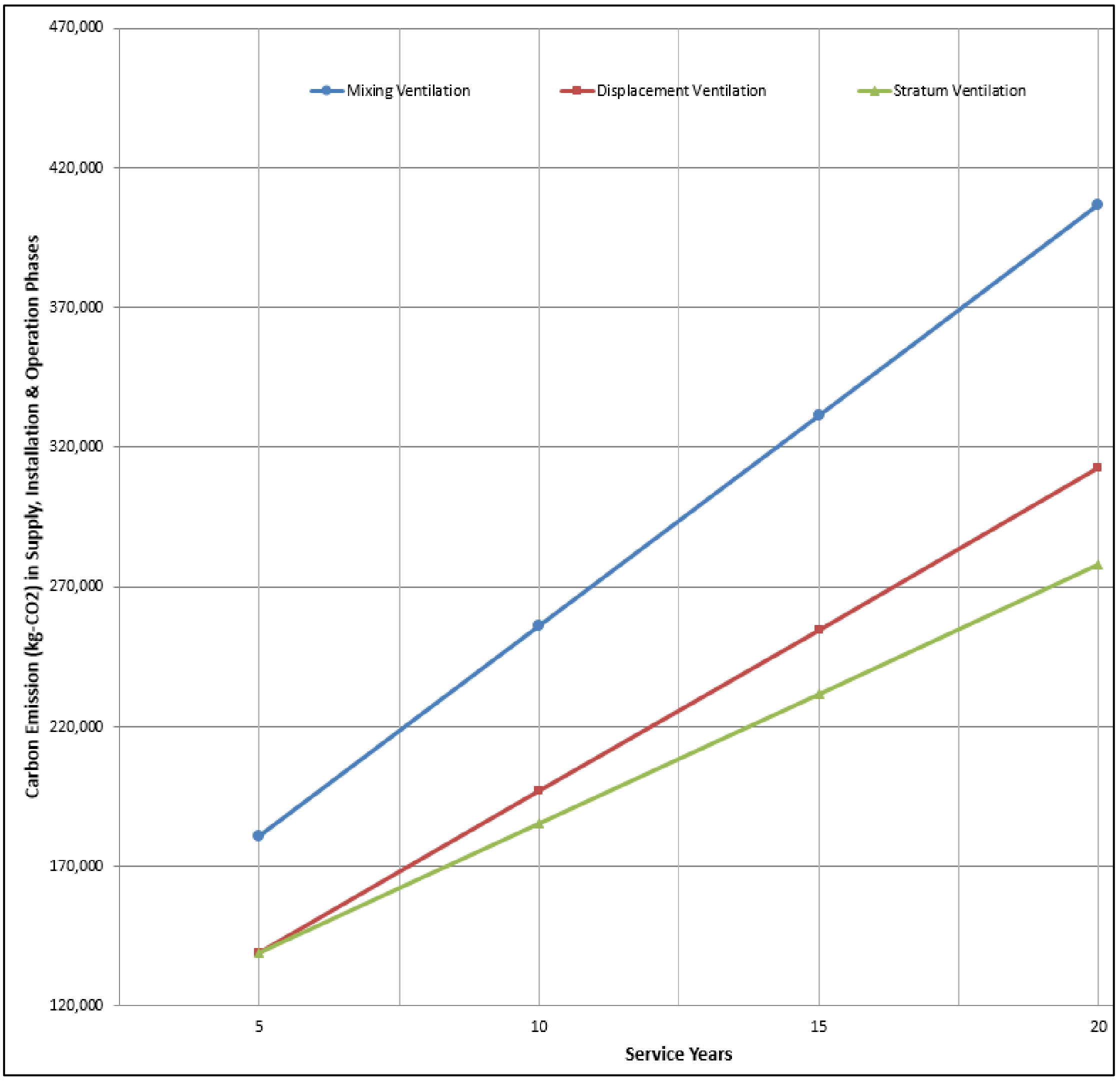
[*1] The room temperature is at the neutral temperature for the respective ventilation systems [30,47]

[*2] The all-year-round power consumed by the chiller, fan and pump

3.3 LCC and LCA result

As a result, the operational energy consumption for systems with mixing ventilation, displacement ventilation and stratum ventilation can be estimated by the all-year-round total energy consumption multiplying the concerned service years and emission factor of CO_2. The analysis of carbon emission combined with (1) supply-and-installation phase and, (2) operation phase of the three ventilation systems, including their annual energy consumption with their respective neutral temperatures during LCA in 5, 10, 15 and 20 service years are presented in Figure 4. In 20 service years, the estimated carbon emission of 406,923 kg-CO_2 (base) for mixing ventilation, 312,298 kg-CO_2 (23.25% less) for displacement ventilation and 277,895 kg-CO_2 (31.71% less) for stratum ventilation.

Table 8 presents the life cycle cost (LCC) in term of net present value (NPV) of the three ventilation systems in 5, 10, 15 and 20 service years. Operation costs for three ventilation systems are based on the all-year-round energy consumption as shown in Table 7. Maintenance Costs for the three ventilation systems are assumed to be 6% of their initial costs. The other parameters and formulas used for NPV estimation are shown in the remarks under Table 8. At the end of 20 service years, the life cycle cost results at HK$308,900 (base) for mixing ventilation, HK$260,966 (15.52% less) for displacement ventilation and HK$235,104 (23.89% less) for stratum ventilation.



Service Years / Ventilation systems	5	10	15	20
Mixing Ventilation (Base)	180,869	256,220	331,572	406,923
Displacement Ventilation	139,101 23.09% less	196,833 23.18% less	254,566 23.22%less	312,298 23.25% less
Stratum Ventilation	139,001 23.15% less	185,299 27.68% less	231,597 30.15% less	277,895 31.71% less

Figure 4 CO_2 emission, kg-CO_2 in mixing-, displacement- and stratum-ventilated classroom during supply-and-installation and operation phases

Table 8 Net Present Value, NPV (HK$) of LCC of three ventilation systems in 5, 10, 15 and 20 service years

Net present value (NPV)	Service Years			
Life Time	5	10	15	20
Present value (PV) factor [(a)]	4.4995	6.9363	8.1479	8.7502
(i) Present value of *IC* (from Table 1)				
PV of IC_{MV}	229,550 (base)			
PV of IC_{DV}	222,150 (3.22% less)			
PV of IC_{SV}	227,340 (0.96%less)			
(ii) Present value of *OC* & *MC* [(b)]= (*OC*+*MC*) × *PV* factor				
PV of OC_{MV} & MC_{MV}	158,841	244,865	287,637	308,900
PV of OC_{DV} & MC_{DV}	134,193	206,868	243,003	260,966
PV of OC_{SV} & MC_{SV}	120,894	186,367	218,921	235,104
(iii) Present value of salvage cost =$SC \times P_f$				
Equivalent present worth of F, P_f [(c)]	0.4972	0.2472	0.1229	0.0611
" a" % of initial Cost [(d)]	50%	25%	10%	0%
SC_{MV}	57,066	14,186	2,821	0
SC_{DV}	55,226	13,729	2,730	0
SC_{SV}	56,517	14,050	2,794	0
Life cycle cost (i) + (ii) – (iii), HK$				
LCC_{MV}				
MV as reference case	331,325	230,679	284,816	308,900
LCC_{DV}	301,117 9.12% less	193,139 16.27% less	240,273 15.64% less	260,966 15.52% less
LCC_{SV}	291,718 11.95% less	172,318 25.30% less	216,127 24.12% less	235,104 23.89% less

Remarks for Table 8:

(a) By substituting annual discount rate, i = 0.15 (i.e.15%) and inflation rate, k = 0.043 (4.3%) into $(n,k,i) = \sum_{j=1}^{n} \frac{(1+k)^{j-1}}{(1+i)^{j}}$; if $i \neq k$, $PV\ \text{factor}(n,k,i) = \frac{1}{i-k}\left(1-\frac{(1+k)^{n}}{(1+i)^{n}}\right)$; if $i = k$, $\text{PV factor} = \frac{n}{1+k}$ to determine the equivalent present value (PV) factor occurring in the "nth" years in the future.

(b) Operation Costs (OC_{MV}, OC_{DV} & OC_{SV} for mixing ventilation, displacement ventilation and stratum ventilation respectively) are based on electricity cost of HK$1/kWh multiplying with the all-year-round total energy consumption as shown in Table 7; Maintenance Costs (MC_{MV}, MC_{DV} & MC_{SV} for mixing, displacement and stratum ventilation respectively) are assumed as 6% of their initial costs.

(c) By substituting annual discount rate, i = 0.15 (i.e.15%) to find out the equivalent present value of F, then using it in the formula $P_f = \frac{F}{(1-i)^n}$ to determine cash flow occurring in the "nth" years in the future.

(d) Salvage cost (SC) in this NPV analysis is equal to initial cost (IC) × a % for each ventilation system in the NPV analysis, where "a%" is the assumed percentage of initial cost after different service years.

4. Discussion

4.1 LCA and LCC analysis

This LCA analysis of the air-conditioning equipment and each component covers the supply-and-installation phase and operation phase. The total cumulative energy of the three ventilation systems in the supply-and-installation and operation phases, shall be evaluated in order to quantify the environmental impact of the embedded energy of the product in each ventilation system.

In the supply-and-installation phase, the initial costs of displacement ventilation and stratum ventilation are 3.22% and 0.96% less than that of mixing ventilation as shown in Table 1. The savings in initial costs for DV and SV are due to less material use in the air ductwork, such as their ductworks are smaller compared with the mixing ventilation system.

Taking into considering of the operation phase, the carbon emission, embedded energy, neutral temperature, all-year-round energy consumption and LCC of mixing ventilation, displacement ventilation and stratum ventilation, through a methodological LCA framework in terms of 5, 10, 15 and 20 service years, are summarized in Tables 7, 8 and Figure 4. It is found that stratum ventilation has the least energy consumption (38.56% less than that of MV in Table 7), least carbon emission (31.71% less than that of MV in Figure 4) and least LCC (23.89% less than that of MV in Table 8) in 20 service years. The material used by SV or DV is less than that by MV. Also less energy is consumed by SV and DV annually compared with that of MV. Therefore, the embedded energy and carbon emission of SV and DV are less than those of MV. The trends of carbon emission for the three ventilation systems, which is MV > DV > SV, during the supply-and-installation and operation phases are illustrated in Figure 4. This result is consistent with the recent study on annual energy performance with different ventilation systems for cooling [55, 56].

4.2 Data used in assessment framework

The selections of different construction methods, material and size of equipment for the air conditioned area could significantly affected the environmental impact of the ventilation system. For example, scaffolding work is a crucial method to establish a high-ceiling mounted ductwork and AHU during the installation phase. Further reduction for stratum ventilation is expected because it is installed at the occupant level.

Besides, LCI of the embedded carbon may be affected by the regional factor and transportation distance at product level during LCA. The difference in embedded energy has been given in different LCI database. The life cycle inventory data are region-specific because the energy fuel mixtures and methods of production often differ from region to region. The LCI database examples include UK LCI, Ecoinvent v.2, and NIST, each of these is country-specific. The final decision on the alternative ventilation systems coming from LCA shall be based on an agreed framework to assess the carbon emission of construction materials from different locations of supply at product level of “cradle to as-built”, which include the processes of cradle to gate, gate to gate and gate to site. In pursuit of low carbon construction of ventilation systems, the fundamental issues on how to assess the carbon emission of air distribution systems, especially in the supply-and-installation phase, need to be further investigated. Carbon emission embedded in a constructed facility at the supply phase, or "cradle-to-gate", is an important but often neglected issue. The assessment framework serves to provide specific requirements according to the production process of various imported ventilation systems as well as those stipulated in the existing local and international best practices. The benchmarking LCI mechanism should be designed for local requirements. More comprehensive modeling for estimating the technical and economic performance of various ventilation systems incorporating with particular architectural design, energy simulation result, as well as the thermal comfort shall be further developed and extended to other places in a global context. It is similar to the rationale behind the recent study on adopting various finite element models in various building systems [57, 58]

4.3. Sequential analysis

More comprehensive modeling is studied in accordance with the above discussion on LCC and LCA results. Throughout the LCC analysis presented in this paper, the savings in initial costs for DV and SV are due to less material use in the ductwork, those ductworks used are smaller compared with that of the mixing ventilation system. Their ductwork of different sizes with the accessories of the three ventilation systems are indicated in the items 8 to 11 of Table 1. To generalize this analysis, the multiplying factor "*m*" is used to represent the variation in ductwork size. The generalized LCC for different service years can be expressed as follows:

$$LCC\ (Yr\text{-}n) = IC_{AHU} + m.IC_{Duct} + \sum_{n=1}^{20} n.OC + m\sum_{n=1}^{20} n.MC \qquad (1)$$

Where

- *LCC (Yr-n)*: is the life cycle cost during *n* service year(s)
- IC_{AHU}: is an initial cost of the identical AHU used in the current study (i.e. sum of cost items 1 to 7 in Table 1)
- IC_{Duct}: is an initial cost of ductwork size plus its accessories for the selected ventilation system (i.e. sum of cost items 8 to 11 in Table 1)
- *m: is a* multiplying factor for the current studied sizes of ductwork and its accessories during 5,10,15,20 service years
- *OC*: is an annual energy cost to maintain indoor comfort within the air-conditioned space for the selected ventilation system. It is equal to annual operational cost. It is equal to the all-year-round power consumption in term of kWh (Table 7) multiplying by the energy cost of HK$1/kWh
- *MC*: is an annual maintenance cost and assume as 6% of the initial cost for the selected ventilation system

The trends of LCC ratio of SV and MV for 5, 10, 15 and 20 service years are illustrated in Figure 5. It is found that the LCC ratio of $SV/$MV is always less than unity and the trends of *LCC (Yr-n)* is overlapping at the inserting point when *m* is less than one. This means that the most expensive system is MV, though the number of service year and ductwork size affect the slope of the trend of *LCC (Yr-n)*. The trend of the LCC ratio of $SV/$DV is presented in Figure 6, which illustrates that the *LCC (Yr-n)* of $SV/$DV is also greater than unity. Thus, the LCC of SV is less than that of MV. But this trend would be reversed if *m* is less than one.

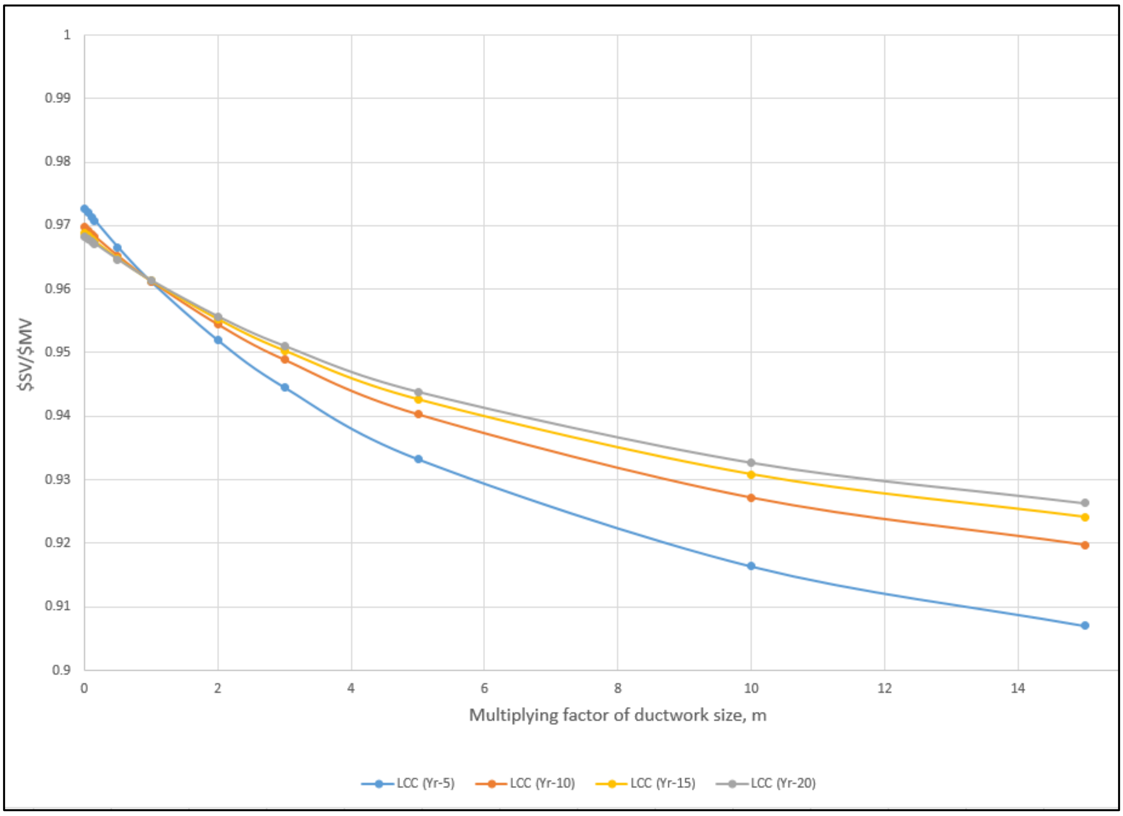


Figure 5 The LCC ratio of \$SV/\$MV against multiplying factor (*m*) of ductwork size in 5, 10, 15 and 20 service years

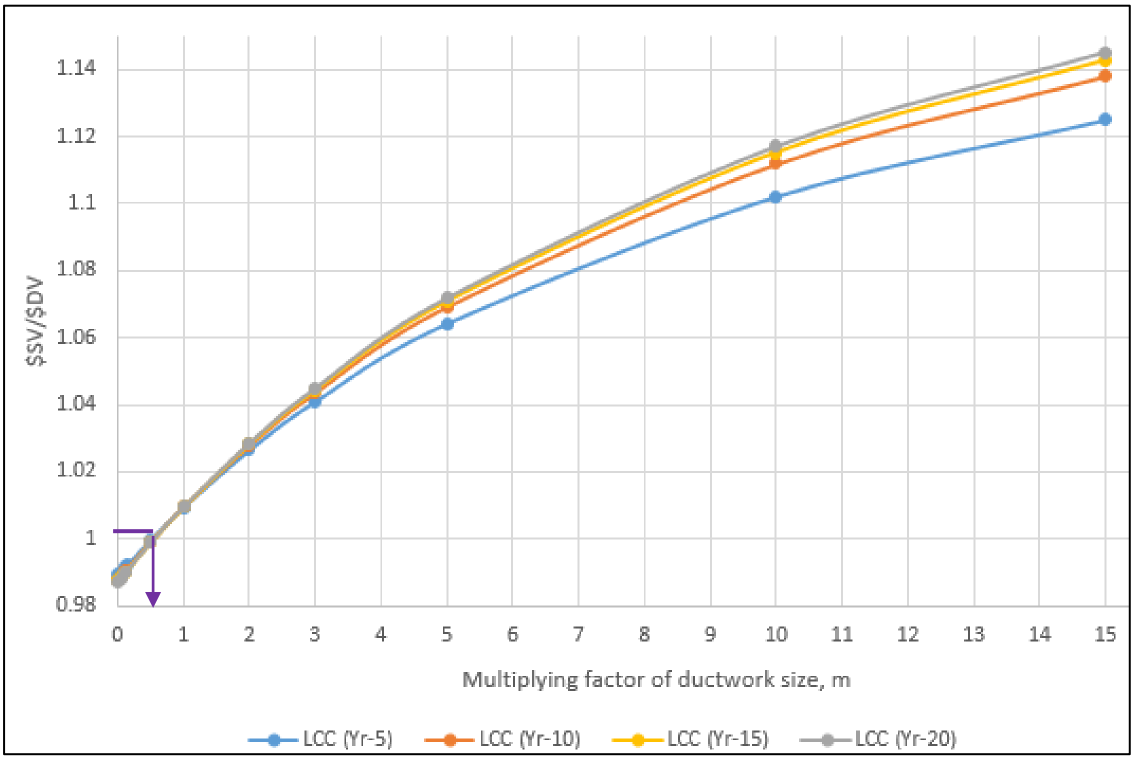


Figure 6 The LCC ratio of \$SV/\$DV against multiplying factor (*m*) of ductwork size in 5, 10, 15 and 20 service years

For the results presented in Figure 4, the life cycle assessment (LCA) function is defined as:

$$CE_{total} = (CE_{supply} + CE_{installation}) + P \sum_{n=1}^{20} n.CE_{operation} \quad (2)$$

Where

- CE_{total} is total carbon emission, kg-CO_2 in concerned service years
- CE_{supply} is the first-year carbon emission during the supply phase
- $CE_{installation}$ is the first-year carbon emission during the installation phase
- $CE_{operation}$ is an annual carbon emission during the operation phase. It is directly proportional to the all-year-round energy consumption in the operation phase
- n is the number of the service years
- P is the multiplying factor due to different cooling demand. P = 1 for the current requirement

The embedded energy and carbon emission of SV and DV are less than that of MV. It is due to less energy consumed by SV and DV. If the cooling demand is different for anther air-conditioned space, the multiplying factor should be applied in Equation (2). The CO_2 emission of SV and MV when applying the multiplying factor "*P*" during 5, 10, 15 and 20 service years are compared in Figure 7. The trend of LCA ratio of carbon emission of SV/MV is less than one according to the different cooling demand for various service years. It is found that the carbon emission of SV is always less than MV. Figure 8 shows a shadowed zone of CO_2 emission ratio of SV versus DV. The carbon emission of SV is greater than DV only if the cooling load is unrealistically low. This unrealistically low cooling supply cannot achieve the expected thermal comfortable environment. Apart from this zone, the carbon emission of SV is less than DV in various service years. It is found that the LCA of SV is less than DV while more cooling demand is required for the air-conditioned space (i.e. $P > 1$).

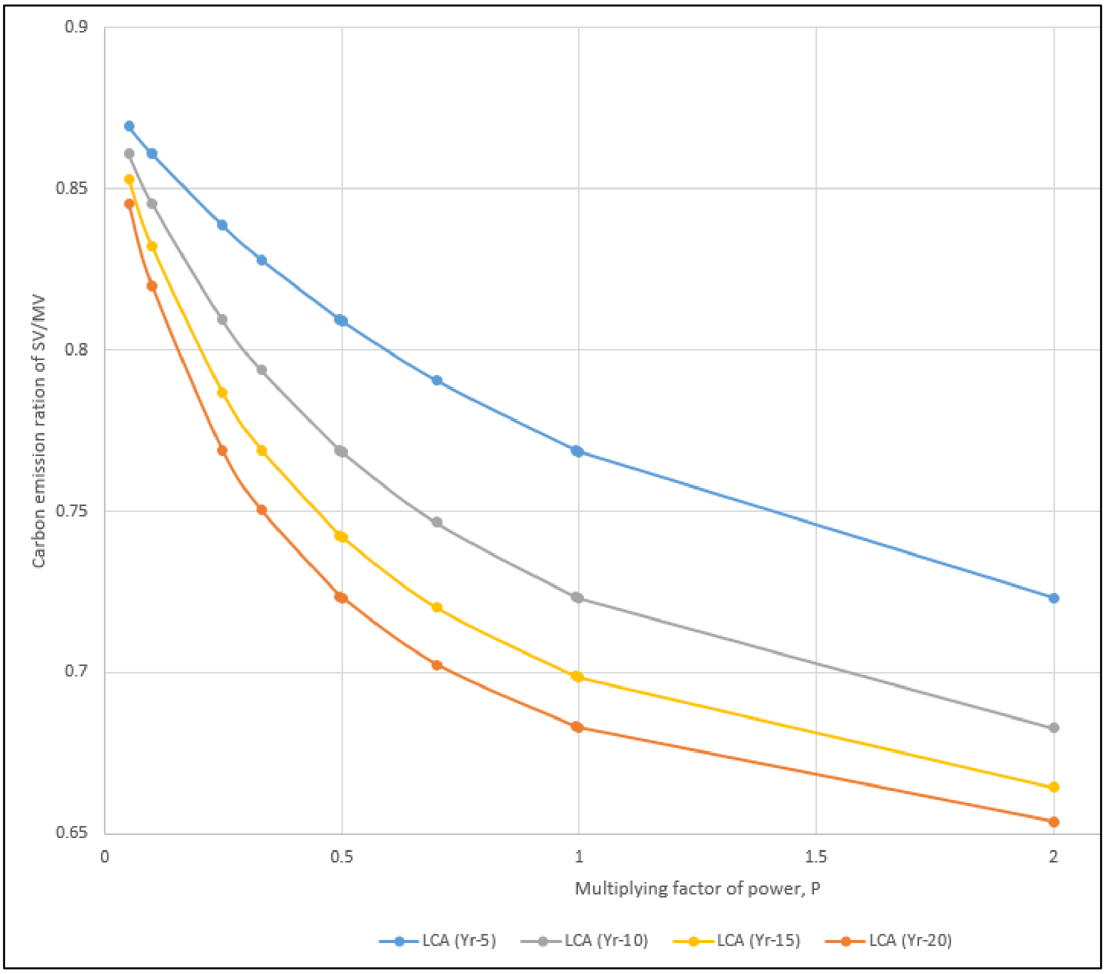


Figure 7 The carbon emission ratio of SV/MV against multiplying factor (*P*) of power consumption in LCA during 5, 10, 15 and 20 service years

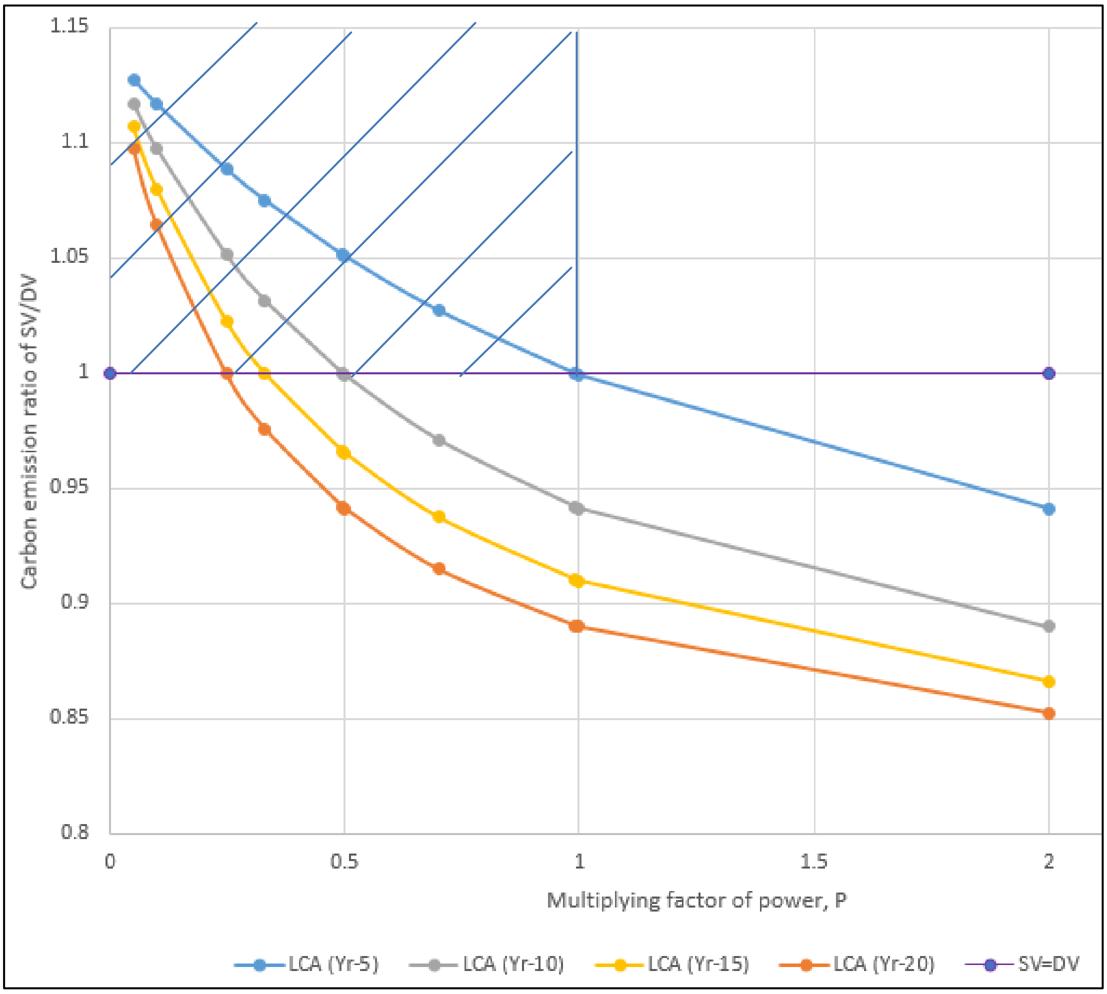


Figure 8 The carbon emission ratio of SV/DV against multiplying factor (*P*) of power consumption in LCA during 5, 10, 15 and 20 service years

Apart from the two sensitive variables of ductwork size and all-year-round energy consumption, the LCC & LCA results are also affected by climate adjustment of the energy use data. In terms of the performances of the three alternative ventilation systems, thermal comfort is one of important factors applying to various geometry of space [59]. For example, the design guidelines for SV shall be followed, such as the application is limited the thermal length of the supply air jets [60]. However, in the broader context the analysis is, as stated, dependent on regional-specific data hence the approach is, more effectively regarded as a template which should be followed where the use of other regional data is appropriate.

In term of mathematic expression to reflect these trends of curves in Figures 5 to 8, the LCC and LCA modeling equations with the corresponding variables are tabulated in Table 9. The corresponding LCC and LCA results for particular service years can be estimated based on the relative multiplying factor of ductwork size "*m*" and power "*P*".

Table 9: LCC and LCA modeling equations for "*m*" and "*P*" in 5, 10, 15 and 20 service years

LCC / LCA modelling equations in *n* service years		R-squared value
Figure 5: "y = \$SV/\$MV" and "x = *m*"		
LCC (Yr-5)	$y = -1E\text{-}05x^3 + 0.0005x^2 - 0.007x + 0.9682$	0.9998
LCC (Yr-10)	$y = -1E\text{-}05x^3 + 0.0005x^2 - 0.0075x + 0.9686$	0.9998
LCC (Yr-15)	$y = -2E\text{-}05x^3 + 0.0006x^2 - 0.0085x + 0.9696$	0.9998
LCC (Yr-20)	$y = -2E\text{-}05x^3 + 0.0008x^2 - 0.0116x + 0.9724$	0.9998
Figure 6: "y = \$SV/\$DV" and "x = *m*"		
LCC (Yr-5)	$y = 3E\text{-}05x^3 - 0.0013x^2 + 0.0228x + 0.9876$	0.9999
LCC (Yr-10)	$y= 3E\text{-}05x^3 - 0.0013x^2 + 0.0225x + 0.9878$	0.9999
LCC (Yr-15)	$y = 3E\text{-}05x^3 - 0.0013x^2 + 0.0225x + 0.9878$	0.9999
LCC (Yr-20)	$y = 3E\text{-}05x^3 - 0.0013x^2 + 0.0228x + 0.9876$	0.9999
Figure 7: "y = Carbon emission of SV/MV" and "x = *P*"		
LCA (Yr-5)	$y = -0.0168x^3 + 0.0822x^2 - 0.1743x + 0.8777$	0.9999
LCA (Yr-10)	$y = -0.0464x^3 + 0.1937x^2 - 0.2972x + 0.8738$	0.9996
LCA (Yr-15)	$y = -0.0714x^3 + 0.2806x^2 - 0.3775x + 0.868$	0.9986
LCA (Yr-20)	$y = -0.0903x^3 + 0.3436x^2 - 0.4299x + 0.8614$	0.9970
Figure 8: "y = Carbon emission of SV/DV" and "x = *P*"		
LCA (Yr-5)	$y = 0.0417x^2 - 0.1784x + 1.1325$	0.9976
LCA (Yr-10)	$y = -0.0588x^3 + 0.2457x^2 - 0.378x + 1.1333$	0.9996
LCA (Yr-15)	$y = -0.0907x^3 + 0.3566x^2 - 0.4805x + 1.126$	0.9986
LCA (Yr-20)	$y = -0.1148x^3 + 0.4371x^2 - 0.5477x + 1.1176$	0.9970

5. Conclusion

In conclusion, the trends of LCC and LCA for the three alternative ventilation systems in downward order are MV > DV > SV. If the cooling load of the room is substantially lower, which is unrealistic, the trends would change to MV > SV > DV in the sequential analysis. Results of the study indicate that there is a strong case for stratum ventilation which is the best option for small-to-medium sized rooms to mitigate the LCC and CO_2 emission in Hong Kong over a service period of 20 years. The result was found through taking account of the carbon emission into both the supply-and-installation and operation phases, using the accepted data available for the Hong Kong region. Other cases can be easily extended on ductwork size, power demand, as well as any regional concern by the sequential analysis.

This study prevents overlooking of the embedded energy in the supply-and-installation phase that definitely leads to significant amount of carbon dioxide generation and the different enthalpy values of the room air and different energy consumptions of chilled water in the operation phase for the alternative ventilation methods. The enthalpy values should be based on the respective neutral temperature of particular ventilation methods. For the same token, the energy consumptions of the cooling media should also be based on the respective neutral temperatures (corresponding to the supply air temperatures) of particular ventilation methods. The approach described in the paper represents a methodical template for the evaluation of the overall implication on the environment prior to the selection of a ventilation method.

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