Lowland Technology International 2020; Volume 22(2): 268-279
International Association of Lowland Technology (IALT): ISSN 1344-9656

Research Paper

Effects of external wall composition on embodied CO_2 emission and economic cost in hot summer and cold winter zone of China

J. Lu [1] and J.T Weng [2]

ARTICLE INFORMATION

Article history:

Received: 19 November, 2019
Received in revised form: 24 May, 2020
Accepted: 27 May, 2020
Publish on: 06 September, 2020

Keywords:

External wall
Self-insulation
Embodied CO_2 emission
Economic cost

ABSTRACT

External walls make up the main components of the building envelope. Numerous standards were proposed addressing the thermal performance, whereas the embodied CO_2 emission and economic cost of different external walls lack further study. Four typical types of external walls, i.e., external insulation (Wall 1), internal insulation (Wall 2), self-insulation (Wall 3), and combined internal and external insulation (Wall 4), are designed. The thermal performance of Walls 1–4 is set to be the same by adjusting the thickness of insulation. The four walls are considered to be part of a typical residential building located in Hangzhou, China. The embodied CO_2 emissions and economic costs of Walls 1–4 are quantitatively compared based on life cycle assessment and life cycle cost. Wall 3 performs optimally on both reducing embodied CO_2 emission and economic cost. Although Wall 4 does not have an obvious advantage on reducing embodied CO_2 emissions, the total economic cost of Wall 4 is 14.9% and 9.5% lower than that of Wall 1 and Wall 2 respectively, which indicates its potential in possessing a certain amount of the market share. This study provides helpful data and evaluating procedures for establishing standards in future carbon reduction of buildings.

1. Introduction

China vowed to peak CO_2 emission by 2030 and achieve a 60%–65% reduction by 2030 compared with 2005 (Niu et al., 2020). The CO_2 emissions of China's building industries account for 20% of the country's total emissions (China Association of Building Energy Efficiency, 2018). Thus, to achieve this commitment, it is imperative to reduce the CO_2 emission in the building industry. The whole building lifecycle directly or indirectly generates CO_2 emissions, including the production and transport of building materials, construction, operation, and demolition of buildings. The consumption of materials and energy occurs during the entire lifecycle of the building, generating CO_2 emissions. The external wall has a significant effect on the building energy consumption. Previous studies (Fan, 2008; Najjar et al.,2019) show that heat loss from external walls accounts for 20%–25% of energy consumption by air-conditioning. Therefore, improvement of the thermal performance of external walls is one of the important measures to promote the sustainable development of buildings.

The insulation material used in the external wall determines the thermal performance of the external wall. Four typical external wall compositions, depending on the position of insulation in the external wall, exist in the hot summer and cold winter (HSCW) zone of China. These include external walls with external insulation, internal

---

[1] Associate Professor, School of Civil Engineering and Architecture, Zhejiang University of Science and Technology, Hangzhou, 310030, China; 13858019381@139.com
[2] PhD student, Department of Architecture, Zhejiang University, Hangzhou, 310058, China; arc_wjt@163.com

Note: Discussion on this paper is open until March 2021 insulation, self-insulation, and combined internal and external insulation.

The external wall with external insulation is widely applied in the majority of new buildings in the HSCW zone of China. The extruded polystyrene (XPS) board is commonly used as the insulation layer, placed on the outside surface of the main structure. The insulation layer protects the main structure and extends the service life of the external wall. However, the external wall with external insulation has a high requirement with regards to durability and fire resistance of the thermal insulation material, and the installation of external insulation is difficult in high-rise buildings.

Alternatively, the insulation layer can be set on the inside surface of the external wall, which is referred to as internal insulation. This setup is also commonly used in the HSCW zone of China. The internal insulation is easier to install compared to the external insulation. The requirements of pressure strength and durability for the insulation material in internal insulation are lower than that for external insulation. The insulation layer coats the indoor area, and hence it is easily destroyed during the building's operation.

In the past decades, traditional insulation materials, i.e., XPS, have been widely accepted as thermal insulation at both internal and external insulation (An et al., 2017). However, most of these materials are flammable and prone to causing fire during their installation. The external wall with combined internal and external insulation, first put forward by the Shanghai Institute of Construction Science and Technology in 2009 (Ye and Zhao, 2009), is a type of external wall with inorganic insulating mortar, used to replace flammable insulation materials. The insulation layers are set both on the inside and outside of the external wall. Inorganic insulating mortar is used as the insulation material, which reduces the fire risk. This type of external wall not only protects the main structure, but also has the advantage of quickly raising or lowering the indoor temperature by air-conditioning (Ruan, 2017). However, the construction process of this external wall is complex, and unqualified construction can easily cause the mortar layer at the external wall to fall off.

With the improvement in manufacturing technology, the thermal performance of the building blocks in the external wall is likewise improved. Material with good thermal insulation performance, such as the autoclaved aerated concrete block, is used as the main structure in the external wall, which is referred to as self-insulation. The service life of self-insulation is as long as the service life of the entire building, and no additional insulation layer is required.

The embodied CO_2 emission is restrained by large uncertainties in the composition designs and material selections at the design stage (Röck et al., 2018). A careful selection of building materials can help reduce CO_2 emissions (González and Navarro, 2006). The application of life cycle assessment (LCA) (International Standard Organization, 2006) is widely accepted and used at the building (Ge et al., 2015) (Lu et al., 2017) and envelope scale (Paik et al., 2018) for the comparison of CO_2 emissions of different construction solutions. This provides guidance for the selection of design composition in buildings. Li et al. (2014) for example, established an assessment framework to quantify the embodied CO_2 emission of residential buildings in China. Ingrao et al. (2016) conducted energy and environmental assessments of four types of external walls in Italy, and the results documented that ventilated facades performed better in comparison to the standard external wall. Azari (2014) examined the energy and environment performance of different envelope enclosures by LCA. The results showed that the operation phase accounted for most of the CO_2 emission. Jin and Ling (2015) examined the performance of an ecological wall based on the LCA and ecological footprint, which indicated that the ecological wall provided a better indoor environment and more economic benefits than the traditional external wall. López-Mesa et al. (2009) conducted a life cycle analysis to evaluate the environmental impact of two types of slab systems, and found that the environmental impact of the precast concrete floors was 12% lower than in situ cast floors. Wen et al. (2016) explored differences in CO_2 emissions of different building structures, and the results indicated that wood structures achieved the lowest CO_2 emission.

The economic cost is an unavoidable issue when selecting the optimal construction scheme. The application of the life cycle cost (LCC) (Kim et al., 2014) is widely conducted to select the best construction method. Udawattha and Halwatura (2017) conducted the LCC analysis of a basic dwelling unit in Sri Lanka, and found that mud concrete block performed best in the long run. Buyle et al. (2019) evaluated seven alternative wall assemblies using a multi-model of LCA and LCC, and the results showed that the cost of the demountable and reusable wall was lower than the conventional wall. Reza et al. (2011) in Tehran utilized an analytical hierarchy process (AHP)-based LCC for the selection of flooring systems, and indicated that the expanded polystyrene (EPS) block was the best solution.

Based on the existing studies, the insulation materials and composition design directly influence the embodied CO_2 emissions and economic costs of external walls. The embodied CO_2 emissions and economic costs of different types of external walls are still not clear in the HSCW zone of China. Therefore, the purpose of this study is to quantify the embodied CO_2 emissions and economic costs of four typical external walls, and make an in-depth comparison of the advantages and disadvantages of external wall compositions. In this study, four external walls, i.e., external insulation (Wall 1), internal insulation (Wall 2), self-insulation (Wall 3), and combined internal and external insulation (Wall 4), are designed and analyzed. The thermal performance (thermal transmittance) of Walls 1–4 is set to be equal across the walls by adjusting the thickness of the thermal insulation layer. These four walls are considered to be a part of a typical residential building located in Hangzhou, China. An embodied CO_2 emission procedure for the external wall is established based on the LCA. In the meantime, the economic costs are calculated based on the LCC method. Detailed methods are introduced in Section 2. The embodied CO_2 emissions and economic costs of four external walls over the life cycle are analyzed in Section 3. Finally, conclusions are drawn in Section 4.

2. Methods

2.1 Research object

According to the classification of the thermal climate in China (Ministry of Housing and Urban-Rural Development of the People's Republic of China and General Administration of Quality Supervision Inspection and Quarantine of the People's Republic of China, 2016), Hangzhou belongs to the HSCW zone. A previous study (Weng et al., 2017) in Hangzhou showed that 82% of the residential buildings' layouts are rectangular; the average floor area of each household is less than 90 m^2 in 73% of the existing residential buildings. Therefore, a typical residential building in Hangzhou was selected. The surface area to volume ratio of the sample building is 0.33. This sample building has seven floors, and each floor has four households. Each household consists of six rooms, including two bedrooms, a living room, a kitchen, a dining room, and a bathroom. The layout of the standard floor is shown in Fig 1. The floor height is 3 m, and the floor area of each household is about 80 m^2. The window-to-wall ratio (WWR) of the east and west facade is 0.02. The WWR of the south facade is 0.50, and the WWR of the north facade is 0.34.

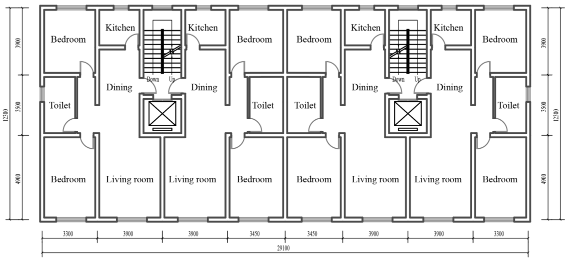


Fig. 1. Layout of standard floor of sample building.

2.2 Four external walls

Four typical external walls, including external insulation (Wall 1), internal insulation (Wall 2), self-insulation (Wall 3), and combined internal and external insulation (Wall 4) were designed as presented in Table 1. According to the design standard for the energy efficiency of residential buildings in the HSCW zone JGJ 134-2010 (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2010a), the thermal transmittance of the external wall is generally less than 1.2 W/(m^2·K) in the HSCW zone of China. In this study, the thermal performance (thermal transmittance) of Walls 1–4 is set to be 0.89 W/(m^2·K) by adjusting the thickness of the thermal insulation layer. The detailed description of studied walls is as follows:

1) Wall 1: Wall 1 consists of an insulation layer, a layer of perforated concrete brick, and a layer of cement mortar on the inside and outside surface (China Institute of Building Standard Design & Research, 2010a). The XPS board is used in the insulating layer, placed on the outside surface of the perforated concrete brick.

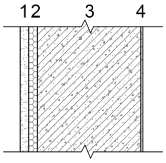
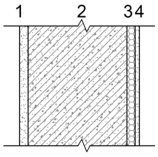
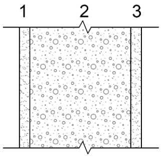
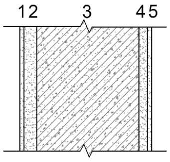
2) Wall 2: the building materials used in Wall 2 are the same as Wall 1, however the insulation layer is set on the inside surface of the external wall (China Institute of Building Standard Design & Research, 2011b).

3) Wall 3: autoclaved aerated concrete block is used as the main structure in the external wall of the self-insulation. According to the recommended atlas (Hubei Bureau of Quality and Technical Supervision and Hubei Provincial Department of Housing and Urban-rural Development, 2012), a layer of cement mortar is placed on both sides of the main structure.

4) Wall 4: Wall 4 consists of an outside layer of cement mortar, an outside insulation layer, perforated concrete brick, an inside insulation layer, and an inside layer of cement mortar (China Institute of Building Standard Design & Research, 2011c). The inorganic insulating mortar is used in the insulation layer. In this study, the inorganic insulating mortar is made of glazed hollow beads. The thickness of the insulation layer is determined according to the requirement of thermal performance.

These four walls are considered to be a part of the sample building in Hangzhou. Four scenarios (Scenario 1–4) are established by changing the design of external walls (Wall 1–4), as shown in Table 1. Apart from the external walls, other parts of the sample buildings are consistent across the four scenarios. The interface layer and the decorative finishes of external walls vary greatly among the projects, hence they are not considered in this study.

Table 1. Characteristics of studied walls.

Scenario	Studied walls	Detailed drawing*	Composition of external wall	Thermal transmittance W/(m^2•K)
Scenario 1	Wall 1 External insulation		1) 20-mm cement mortar 2) 20-mm XPS 3) 240-mm perforated concrete brick 4) 5-mm cement mortar	0.89
Scenario 2	Wall 2 Internal insulation		1) 20-mm cement mortar 2) 240-mm perforated concrete brick 3) 20-mm XPS 4) 5-mm cement mortar	0.89
Scenario 3	Wall 3 Self-insulation		1) 25-mm cement mortar 2) 240-mm autoclaved aerated concrete block 3) 25-mm cement mortar	0.89
Scenario 4	Wall 4 Combined internal and external insulation		1) 5-mm cement mortar 2) 30-mm inorganic insulating mortar 3) 240-mm perforated concrete brick 4) 20-mm inorganic insulating mortar 5) 5-mm cement mortar	0.89

* From the outside (left) to the inside (right).

2.3 Scope and function unit

The scope of this study is to evaluate embodied CO_2 emissions and economic costs of the above-described four walls over their life cycle. As this study is conducted at the envelope scale, CO_2 emission and costs in operation stage are not included. The embodied CO_2 emission and economic costs per floor area are not adequate indexes to explain results. Therefore, the embodied CO_2 emission and economic costs per external wall area are used in the following text.

2.4 Calculation procedure for embodied CO_2 emission of external wall

The total embodied CO_2 emission of the external wall mainly consists of four parts: the production phase, transport phase, construction phase, and demolition phase (Ahmed and Tsavdaridis, 2018). The formula is as follows:

$$E = E_\mathrm{p} + E_\mathrm{t} + E_\mathrm{c} + E_\mathrm{d} \qquad [1]$$

where E_p, E_t, E_c, and E_d represent the CO_2 emission per external wall area in the phases of production, transport, construction, and demolition (kg CO_2/m^2).

2.4.1 Production phase

The production phase of the external wall comprises the mining, transport, and production of raw materials. According to the standard for building carbon emission calculation GB/T 51366-2019 (Ministry of Housing and Urban-Rural Development of the People’s Republic of China, 2019b), the calculation formula is as follows:

$$E_\mathrm{p} = \sum\nolimits_{i=1}^{n} e_i V_i \Big/ A \qquad [2]$$

where n is the total number of building materials used in an external wall; V_i is the consumption of material i (m^3); e_i is the CO_2 emission factor of material i (kg CO_2/m^3); A is the area of the external wall of sample building (m^2).

The sample building of this study belongs to the type of ordinary constructions with a service life of 50 years (Ministry of Housing and Urban-Rural Development of the People’s Republic of China, 2018c). The CO_2 emission factors and service lives of different building materials are summarized in Table 2.

2.4.2 Transport phase

Materials used in the external walls need to be transported from the manufacturers to the construction site by different transports. During the transportation process, vehicles consume gasoline, diesel, electricity and other

Table 2. CO_2 emission factors of materials and service lives of different building materials.

Materials	CO_2 emission factors (kg/m³)	Service life (year)
Cement mortar	311 *	50
XPS board	161 **	25
Inorganic insulating mortar	268 *	50
Autoclaved aerated concrete block	299 *	50
Perforated concrete brick	336 **	50

* Data is derived from Zhou (2017).
** Data is derived from Ministry of Housing and Urban-Rural Development of the People's Republic of China (2019b).

Table 3. Shipment distances of different building materials.

Building materials	Average shipment distance (km)
Cement mortar	53 (Zhou, 2017)
XPS board	26 (Zhou, 2017)
Inorganic insulating mortar	60 (Zhou, 2017)
Autoclaved aerated concrete block	50 (Zhu and Chen, 2010)
Perforated concrete brick	15 (Zhou, 2017)

energy, thus generating CO_2 emissions. The formula is as follows (Zhu, 2015):

$$E_t = \sum_{i=1}^{n} p_i m_i L_i / A \qquad [3]$$

where p_i is the CO_2 emission factor of transport used for material i (kg CO_2/ton/km); m_i is the mass of material i (ton); L_i is the shipment distance of material i (km).

Different building materials were purchased based on the proximity principle. When data in Hangzhou were missing, statistical data were selected from cities nearby (see Table 3). In this study, building materials were transported by road. The CO_2 emission factor of road transport was 0.169 kg CO_2/ton/km (Zhu, 2015).

2.4.3 Construction phase

The CO_2 emission during the construction phase includes CO_2 emission from the use of machinery and the consumption of manpower. The formula depicting CO_2 emission in the construction phase is as follows:

$$E_c = E_{c1} + E_{c2} \qquad [4]$$

where E_{c1} is the CO_2 emission caused by the use of machinery (kg CO_2/m^2), and E_{c2} is the CO_2 emission from the use of manpower (kg CO_2/m^2).

The lighting energy consumption during construction was insignificant. Only CO_2 emissions generated using lifting equipment were included. The calculation of CO_2 emission from the use of machinery is as follows (Zhu, 2015):

$$E_{c1} = EF_e P_{eq} T / A \qquad [5]$$

where EF_e is the CO_2 emission factor of regional electricity (t/MWh); P_{eq} is the operation power of lifting equipment (kW), which is 32.9 kW (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2019b) in this study; T is the total operation time of lifting equipment (h).

Hangzhou is located in East China. The comprehensive CO_2 emission factor of the East China power grid in 2016 was 0.6131 t/MWh (China Association of Building Energy Efficiency, 2018), which was used to represent the value of EF_e in Eq. (5).

The operation time of lifting equipment was calculated based on Eq. (6).

$$T = kh(k-1)\sum_{i=1}^{n}\left[V_i / kQ_i + 1\right] / 3600 S_{ave} \qquad [6]$$

where k is the number of floors, h is the house height (m); Q_i is the maximum transport volume of lifting equipment (m³), which is assumed as 2.0 m^3 for bricks and blocks, and 5.8 m^3 otherwise; S_{ave} is the average speed of lifting equipment (m/s), which is 0.25 m/s in this study.

The CO_2 emissions assigned to the use of manpower were obtained based on manpower consumption. The construction process of the external wall consists of wall masonry, external plastering, internal plastering, and insulation installation. The manpower quotas in different construction processes are different, hence manpower consumption of different processes needs to be calculated separately. The formula is as follows:

$$E_{c2} = \sum_{j=1}^{r} W_j X_j / A \qquad [7]$$

where r is the number of processes in an external wall; W_j is the manpower CO_2 emission factor of process j (kg CO_2/person-day); X_j is the total manpower consumption during process j (person-day).

$$X_j = P_j x_j \qquad [8]$$

where P_j is the construction quantity of process j (m^3), and x_j is the manpower quota of process j (person-day/m^3).

Based on the physical work intensity classification GB 3869-1997 (China State Bureau of Technical Supervision,

Table 4. Manpower CO_2 emission factors under different work intensities.

Grade of work intensity	Wj (kg CO_2/person-day)
I	1.35
II	2.09
III	2.42
IV	2.83

1997), there are four grades of work intensity. The corresponding CO_2 emission factors are depicted in Table 4 (Jiao et al., 2012). The work intensity of wall masonry (Chen et al., 1992) is assumed as grade II, while the work intensity of plastering and insulation installation (Chen et al., 1992) is grade III.

2.4.4 Demolition phase

The blasting method is commonly used to demolish disused buildings in China. The building materials used for the external walls are assumed not recycled in this study. The demolition process of the external wall is regarded as the reverse process of construction. CO_2 emissions during the demolition account for about 10% of CO_2 emission in the construction phase (Ge et al., 2015), and the calculation is as follows:

$$E_d = 0.1E_c \qquad [9]$$

2.5 Calculation procedure for economic cost of external wall

The method of LCC was adopted to evaluate economic costs. The LCC mainly includes the initial, operation, and maintenance costs at their present value (*PV*). As this is a building envelop scale study, the energy consumptions during the operation of buildings are not included. The initial and maintenance costs were calculated to represent the economic cost. The calculation is as follows:

$$C_e = C_i + C_m \qquad [10]$$

where C_e is the total economic cost ($\$/m^2$), C_i is the initial construction cost ($\$/m^2$), and C_m is the maintenance cost ($\$/m^2$).

The method of composite cost used in the bidding process was adopted to calculate the initial cost, including manpower and material costs. The cost data were obtained from actual projects in the HSCW zone of China and local specifications. The official currency used in China is Renminbi (RMB). All costs were converted into US dollars (USD). The exchange rate was set as 7 RMB to 1 USD in this study.

As maintenance costs are predicted, future costs were calculated by Eq. (11) considering inflation (Ahmed and Tsavdaridis, 2018). Eq. (12) was adopted to determine the present value of future costs considering the influence of the interest rate (Ahmed and Tsavdaridis, 2018). The calculations (Ahmed and Tsavdaridis, 2018) are as follows:

$$FC = PV\left(1+f\right)^y \qquad [11]$$

$$DPV = FC/\left(1+d\right)^y \qquad [12]$$

where *FC* is the future cost; *PV* is the present value; *DPV* is the discount present value; *f* is the inflation rate, which is 3% in this study; *d* is the discount rate, which is 3.5% in this study; *y* is the number of years.

3. Results and discussion

This section presents the results of embodied CO_2 emissions and economic costs of four studied walls. The consumptions of building materials in the four scenarios are presented. Subsequently, the corresponding CO_2 emissions in different phases are obtained based on the LCA method. The total CO_2 emissions of four external walls are summed and analyzed. Finally, the economic costs of four external walls are assessed for over 50 years. The initial and maintenance costs are presented separately. Wall 1 is regarded as a reference for evaluating the embodied CO_2 emissions reduction and economic savings.

Table 5. Consumption of building materials and CO_2 emissions in production phase.

External wall	Building materials	V_i (m^3)	Density (kg/m^3)	CO_2 emission ($kg\ CO_2$)	In total ($kg\ CO_2$)
Wall 1	Cement mortar	63	1800	19602	159040
	XPS	56	32	9022	
	Perforated concrete brick	336	1600	112987	
	Masonry mortar	56	1800	17428	
Wall 2	Cement mortar	42	1800	13071	152509
	Perforated concrete brick	336	1600	112987	
	XPS	56	32	9022	
	Masonry mortar	56	1800	17428	
Wall 3	Cement mortar	70	1800	21789	139762
	Autoclaved aerated concrete block	336	500	100545	
	Masonry mortar	56	1800	17428	
Wall 4	Cement mortar	14	1800	4354	153543
	Inorganic insulating mortar	70	300	18773	
	Perforated concrete brick	336	1600	112987	
	Masonry mortar	56	1800	17428	

Table 6. Comparison of CO_2 emissions in transport phase.

External wall	Building materials	CO_2 emission (kg CO_2)	In total (kg CO_2)
Wall 1	Cement mortar	1016.21	3291.5
	XPS	7.88	
	Perforated concrete brick	1363.91	
	Masonry mortar	903.51	
Wall 2	Cement mortar	677.63	2952.9
	Perforated concrete brick	1363.91	
	XPS	7.88	
	Masonry mortar	903.51	
Wall 3	Cement mortar	1129.55	3453.8
	Autoclaved aerated concrete block	1420.74	
	Masonry mortar	903.51	
Wall 4	Cement mortar	225.72	2706.2
	Inorganic insulating mortar	213.09	
	Perforated concrete brick	1363.91	
	Masonry mortar	903.51	

3.1 Embodied CO_2 emissions of four external walls

3.1.1 Production phase

The total area of the external wall in the sample building was 1401 m^2. The amount of masonry mortar used was estimated to be 0.04 m^3 per 1 m^2 of external wall (Du, 2013). The total volumes of building materials were calculated based on the design of external wall compositions. CO_2 emission of the production phase was obtained according to Eq. (2). The consumptions of building materials and CO_2 emissions are summarized in Table 5.

The results show that the main structural materials, such as perforated concrete brick and autoclaved aerated concrete block, dominate CO_2 emission in the production phase. The CO_2 emission of Wall 3 is the lowest in the production phase. There is no big difference in CO_2 emissions among Wall 1-4.

Table 7. Comparison of CO_2 emissions from use of machinery.

External wall	CO_2 emission in total (kg CO_2)
Wall 1	87.5
Wall 2	87.5
Wall 3	81.9
Wall 4	84.7

3.1.2 Transport phase

CO_2 emissions in the transport phase were obtained using Eq. (3). The results are depicted in Table 6. There are obvious differences in the CO_2 emissions among four scenarios, which results from the change in consumption of cement mortar. The CO_2 emission of Wall 4 is the lowest in the transport phase, whereas that of Wall 3 is the highest.

The insulation materials have little effect on CO_2 emission during transport. They account for only about 0.3% of the total emissions for Wall 1 and Wall 2. For Wall 4, inorganic insulating mortar accounts for about 8% of the total emission.

3.1.3 Construction phase

In the construction phase, CO_2 emissions caused by the use of machinery (E_{c1}) were obtained using Eq. (4-6), and the results are presented in Table 7. The CO_2 emissions from manpower consumptions in different construction processes are calculated separately. According to Eq. (7-8), the manpower consumptions in different processes and the corresponding CO_2 emissions are summarized in Table 8. Wall masonry is more difficult to perform than plastering and insulation installation. The manpower quota during the process of wall masonry is

Table 8. Comparison of CO_2 emissions from manpower consumption.

External wall	Process	P_j (m^3)	x_j (person-day/m^3)	CO_2 emission (kg CO_2)	In total (kg CO_2)
Wall 1	External plastering	56	0.175 *	20.5	791.5
	XPS installation	56	0.206 **	24.1	
	Wall masonry	336	0.915 ***	744.6	
	Internal plastering	7	0.154 *	2.3	
Wall 2	External plastering	28	0.175	10.2	778.2
	Wall masonry	336	0.915	744.6	
	XPS installation	42	0.206	18.1	
	Internal plastering	14	0.154	5.2	
Wall 3	External plastering	35	0.175	12.8	768.7
	Wall masonry	336	0.915	744.6	
	Internal plastering	35	0.154	11.3	
Wall 4	External plastering	7	0.175	2.6	773.8
	Inorganic insulation mortar	70	0.166	24.3	
	Wall masonry	336	0.915	744.6	
	Internal plastering	7	0.154	2.3	

* Data were derived from an actual project in Jiangsu province, China.

** Data were derived from Ministry of Human Resources and Social Security of the People's Republic of China and Ministry of Housing and Urban-Rural Development of the People's Republic of China (2008a).

*** Data were derived from Ministry of Human Resources and Social Security of the People's Republic of China and Ministry of Housing and Urban-Rural Development of the People's Republic of China (2008b).

Table 9. Comparison of embodied CO_2 emissions in different phases (kg CO_2/m^2).

External wall	Production phase	Transport phase	Construction phase	Demolition phase	In total	Difference compared with Wall 1
Wall 1	113.52	2.35	0.63	0.06	116.6	/
Wall 2	108.86	2.11	0.62	0.06	111.7	–4.9 (–4.2%)
Wall 3	99.76	2.47	0.61	0.06	102.9	–13.7 (–11.7%)
Wall 4	109.59	1.93	0.61	0.06	112.2	–4.4 (–3.8%)

Table 10. Comparison of initial costs of four external walls.

External wall	Process	Consumption (m^2)	Composite cost ($\$/m^2$)	C_i ($\$/m^2$)
Wall 1	Plastering	2802	5.62 **	54.7
	XPS installation	1401	13.44 *	
	Wall masonry	1401	29.97 **	
Wall 2	Plastering	2802	5.62	52.4
	Wall masonry	1401	29.97	
	XPS installation	1401	11.18 *	
Wall 3	Plastering	2802	5.62	40.4
	Wall masonry	1401	29.12 **	
Wall 4	Plastering	2802	5.62	60.9
	Inorganic insulating mortar	2802	9.82 ***	
	Wall masonry	1401	29.97	

* mean value of two actual projects in the HSCW zone.
** Data were derived from Zhejiang Construction Engineering Cost Management Station (2019).
*** Data were derived from Mou (2016).

Table 11. Comparison of maintenance costs of four external walls.

External wall	Process	Consumption (m^2)	Composite cost ($\$/m^2$)	C_m ($\$/m^2$)
Wall 1	Plastering	1401	5.62	16.9
	XPS installation	1401	13.44	
Wall 2	Plastering	1401	5.62	14.9
	XPS installation	1401	11.18	
Wall 3	/	/	/	/
Wall 4	/	/	/	/

0.915 person-day/m^3, and it is 0.175, 0.154, 0.206, and 0.166 person-day/m^3 for external plastering, internal plastering, XPS installation, and inorganic insulation mortar, respectively.

CO_2 emissions from the manpower consumptions are nine times that from the use of machinery. Total CO_2 emissions in the construction phase of the four walls are almost the same. In order to reduce the CO_2 emission, it is important to reduce the manpower consumption in construction phase.

3.1.4 Comparison of embodied CO_2 emissions in different phases

The CO_2 emissions of four external wall compositions in different phases according to Eq. (1–9) are summarized in Table 9. The differences in total embodied CO_2 emissions are calculated compared with Wall 1. Negative numbers represent the corresponding reductions in total embodied CO_2 emissions, compared to Wall 1.

The production phase dominates the total embodied CO_2 emission of the external wall. The construction and demolition phases account for less than 1% of the total embodied CO_2 emission. The embodied CO_2 emission of Wall 1 is the highest. Compared with Wall 1, Wall 2 achieves a 4.2% reduction of CO_2 emission. Wall 3 achieves a 11.7% reduction of CO_2 emissions, as no additional insulation material is used. The embodied CO_2 emissions of Wall 4 are 3.8% lower than those of Wall 1. This indicates that Wall 4 does not provide a significant advantage regarding CO_2 emission reduction compared to Wall 1.

3.2 Economic cost of four external walls

The initial and maintenance costs of external walls were obtained according to Eq. (10–12) and shown in Table 10 and Table 11, respectively. The total economic costs are summarized in Table 12. The differences in total economic costs are calculated in comparison to Wall 1. Negative numbers represent the corresponding reduction in total economic costs compared to Wall 1.

The service lives of materials have a significant influence on the economic cost. The total economic cost rises in the following order: Wall 3＜Wall 4＜Wall 2＜Wall 1 (Table 12). The total economic cost of Wall 3 is the lowest. Because the service lives of building materials used in Wall 3 are equal to the service life of the sample building, and no additional insulation is used. The service life of XPS in Wall 1 and Wall 2 is only half the service life

Table 12. Comparison of total economic costs of four external walls.

External wall	Ce ($\$/m^2$)	The differences in price compared with Wall 1 ($\$/m^2$)
Wall 1	71.6	/
Wall 2	67.3	-4.3(-6.0%)
Wall 3	40.4	-31.2 (-43.6%)
Wall 4	60.9	-10.7 (-14.9%)

of the sample building. Hence, the replacement of insulation material is required, which makes the total economic costs of Wall 1 and Wall 2 much higher than those of Wall 3 and Wall 4. In comparison to Wall 1, Wall 3 achieves a 43.6% reduction in the total economic cost. The total economic cost of Wall 4 is 14.9% and 9.5% lower than that of Wall 1 and Wall 2, respectively.

Economic costs increase with the increase of construction difficulty. Wall masonry is significantly more difficult than other processes, and hence the economic cost of wall masonry is the most expensive. The construction process of Wall 4 is the most complex, and the initial cost of Wall 4 is the highest. The construction process of Wall 2 is easier than that of Wall 1, thus Wall 2 has a 6% lower cost compared to Wall 1.

4. Conclusions

In this study, four typical types of external walls, i.e., external insulation (Wall 1), internal insulation (Wall 2), self-insulation (Wall 3), and combined internal and external insulation (Wall 4), were designed according to the relevant standards. These four walls were assumed to be installed and operated in a residential building in Hangzhou, China. The thermal performance was set to be equal across the four walls by adjusting the thickness of the thermal insulation layer. The embodied CO_2 emissions and economic costs of four typical external walls were investigated and analyzed by LCA and LCC methods. The conclusions are as follows:

1) The production phase dominates the embodied CO_2 emission of the external wall. Construction and demolition phases account for less than 1% of total embodied CO_2 emission. Wall 3 performs best in reducing the total embodied CO_2 emission, because no additional insulation material is applied. Wall 4 does not have a significant advantage regarding embodied CO_2 emission reduction in comparison to Wall 1.

2) The life of insulation materials and the difficulty of the construction process have an evident influence on the total economic cost. The economic costs of Wall 3 and Wall 4 are much lower than those of Wall 1 and Wall 2. The construction process of Wall 2 is easier than that of Wall 1, and Wall 2 is 6% cheaper than Wall 1.

3) Wall 3 performs best regarding the reduction of both embodied CO_2 emissions and economic costs. The results indicate that a proper selection of building materials can significantly help reduce CO_2 emissions and economic costs. The evaluation of CO_2 emission and economic cost should be conducted in the design stage.

4）Wall 4 can reduce the total economic cost by 14.9% without increasing embodied CO_2 emission compared with Wall 1. This indicates its potential in taking a portion of the market share.

In this study, due to the data limitations, only four typical external walls are considered. However, there are many existing external walls with different kinds of building materials, i.e., rock wool board and burned shale perforated brick. Furthermore, the construction method of buildings is continuously changing. Recently, an increasing number of buildings in China have been constructed by the prefabricated method. Many new types of external walls are designed, and they are manufactured on a large scale in factories. The embodied CO_2 emission and economic costs will change accordingly. Therefore, further external wall compositions could be included in the analysis of future studies.

It is recommended to conduct the sensitivity analysis in the future, as many variables including the building layout, window-to-wall ratio, floor height directly influence the results. These citation data, such as CO_2 emission factor of material and shipment distances, vary greatly in different projects. Therefore, the results of the case study need to be verified in actual projects. And more specific and local data are needed to get more convinced results.

Even the transmittance of four walls is the same, the energy consumptions are different in operation stage. It is necessary to extend the CO_2 emission and economic costs to cover all stages at the building scale in the future.

Acknowledgements

This research was funded by the China National Key R&D Program, grant number 2016YFC0700302.

References

Ahmed, I.M. and Tsavdaridis, K.D., 2018. Life cycle assessment (LCA) and cost (LCC) studies of lightweight composite flooring systems. Journal of Building Engineering, **20**: 624–633.

An, W., Sun, J., Liew, K.M. and Zhu, G., 2017. Effects of building concave structure on flame spread over extruded polystyrene thermal insulation material. Applied Thermal Engineering, **121**: 802–809.

Azari, R., 2014. Integrated energy and environmental life cycle assessment of office building envelopes. Energy and Buildings, **82**: 156–162.

Buyle, M., Galle, W., Debacker, W and Audenaert, A., 2019. Sustainability assessment of circular building alternatives: consequential LCA and LCC for internal wall assemblies as a case study in a Belgian context. Journal of Cleaner Production, **218**: 141–156.

Chen, X., Bai, S., Zeng, Z., Yi, Y., Lin, Q and Zhang, Z., 1992. Survey on grading of physical labor intensity of construction workers. Chinese Journal of Industrial Hygiene and Occupational Diseases. **10** (6): 375–377. (in Chinese)

China Association of Building Energy Efficiency, (2018). China building energy consumption report 2018; Available online: http://www.sohu.com/a/281166569_99895902/ (accessed on 26 October 2019). (in Chinese)

China Institute of Building Standard Design & Research, 2010a. Design atlas for external wall with external insulation 10J121. (in Chinese)

China Institute of Building Standard Design & Research, 2011b. Design atlas for external wall with internal insulation 11J122. (in Chinese)

China Institute of Building Standard Design & Research, 2011c. Design atlas for building structures with ZL combined internal and external insulation 11CJ25. China. (in Chinese)

China State Bureau of Technical Supervision, 1997. Physical work intensity classification GB 3869-1997. (in Chinese)

Du, J., 2013. Preliminary analysis of comprehensive energy consumption and carbon emission in production of masonry. Build. Building Blocks and Block Buildings. **5**: 9–12. (in Chinese)

Fan, W., 2008. Energy-saving technology and economic analysis of the structure envelope in hot summer and cold winter zone, Master Thesis, Zhejiang Univ. Hangzhou, China. (in Chinese)

Ge, J., Luo, X., Hu, J. and Chen, S., 2015. Life cycle energy analysis of museum buildings: a case study of museums in Hangzhou. Energy and Buildings, **109**: 127–134.

González, M.J. and Navarro, J.G., 2006. Assessment of the decrease of CO_2 emissions in the construction field through the selection of materials: practical case study of three houses of low environmental impact. Building and Environment, **41**: 902–909.

Hubei Bureau of Quality and Technical Supervision and Hubei Provincial Department of Housing and Urban-rural Development, 2012.Technical specification for blocks engineering of autoclaved aerated concrete DB42/T268-2012. (in Chinese)

Ingrao, C., Scrucca, F., Tricase, C. and Asdrubali, F., 2016. A comparative Life Cycle Assessment of external wall-compositions for cleaner construction solutions in buildings. Journal of Cleaner Production, **124**, 283-298.

International Standard Organization., 2006. 14040: Environmental management - life cycle assessment - principles and framework. Switzerland.

Jiao, S., Du, Q. and Hou, C., 2012. A life cycle road carbon measurement method and its application. (in Chinese)

Jin, H. and Ling, W., 2015. External wall structure of green rural houses in Daqing, China, based on life cycle and ecological footprint theories. Frontiers of Architectural Research, **4**: 212–219.

Kim, S., Kim, G.H. and Lee, Y.D., 2014. Sustainability life cycle cost analysis of roof waterproofing methods considering $LCCO_2$. Sustainability, **6**: 158–174.

Li, X., Yang, F.; Zhu, Y. and Gao, Y., 2014. An assessment framework for analyzing the embodied carbon impacts of residential buildings in China. Energy and Buildings, **85**, 400–409.

López-Mesa, B., Pitarch, Á., Tomás, A. and Gallego, T., 2009. Comparison of environmental impacts of building structures with in situ cast floors and with precast concrete floors. Building and Environment, **44**: 699–712.

Lu, J., Wu, J.J, Zhou, Y., 2016. Analysis on green technology system and LCA CO_2 emission reduction of phase II construction project of JDXG. Lowland Technology International, **18**(3):231-238.

Ministry of Housing and Urban-Rural Development of the People's Republic of China and General Administration of Quality Supervision Inspection and Quarantine of the People's Republic of China, 2016. Code for thermal design of civil buildings GB 50176-2016. (in Chinese)

Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2010a. Design standard for energy efficiency of residential buildings in hot summer and cold winter zone JGJ 134-2010. (in Chinese)

Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2019b. Standard for Building Carbon Emission Calculation GB/T 51366-2019. (in Chinese)

Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2018c. Unified standard for reliability design of building structures GB 50068-2018. (in Chinese)

Ministry of Human Resources and Social Security of the People's Republic of China and Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2008a. Manpower quota for construction projects construction engineering - anticorrosion, heat insulation, heat preservation LD/T 72.11-2008. (in Chinese)

Ministry of Human Resources and Social Security of the People's Republic of China and Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2008b. Manpower quota for construction projects construction engineering masonry construction LD/T 72.4-2008. (in Chinese)

Mou, L., 2016. Analysis on effect of internal and external thermal insulation applied in residential buildings in hot summer and cold winter areas. Master thesis, Zhejiang Univ. Hangzhou, China. (in Chinese)

Najjar, M.K., Figueiredo, K., Hammad, A.W.A., Tam, V.W.Y.; Evangelista, A.C.J. and Haddad, A., 2019. A framework to estimate heat energy loss in building operation. Journal of Cleaner Production, **235**: 789–800.

Niu, D., Wang, K., Wu, J., Sun, L., Liang, Y., Xu, X. and Yang, X., 2020. Can China achieve its 2030 carbon emissions commitment? Scenario analysis based on an improved general regression neural network. Journal of Cleaner Production, **243**: 118558.

Paik, I., Na, S. and Yoon, S., 2018. Assessment of CO_2 emissions by replacing an ordinary reinforced concrete slab with the void slab system in a high-rise commercial residential complex building in South Korea. Sustainability, **11**, 82.

Reza, B., Sadiq, R. and Hewage, K., 2011. Sustainability assessment of flooring systems in the city of Tehran: an AHP-based life cycle analysis. Construction and Building Materials. 2011, **25**: 2053–2066.

Röck, M., Hollberg, A., Habert, G. and Passer, A. 2018. LCA and BIM: Integrated assessment and visualization of building elements' embodied impacts for design guidance in early stages. Procedia CIRP, **69**: 218–223.

Ruan, F., 2017. Theoretical research on envelope insulation effect for residential buildings with compartmental and intermittent energy consuming method, Doctoral Thesis, Zhejiang Univ. Hangzhou, China. (in Chinese)

Udawattha, C. and Halwatura, R., 2017. Life cycle cost of different walling material used for affordable housing in tropics. Case Studies in Construction Materials. **7**: 15-29.

Weng, J., Ge, J. and Chen, S., 2017. On-site measured summer indoor environment in residential buildings in hangzhou based on architectural typology. Procedia Engineering. **205**: 3353–3358.

Wen, R., Qi, S. and Jrade, A., 2016. Simulation and assessment of whole life-cycle carbon emission flows from different residential structures. Sustainability, **8**: 807.

Ye, B. and Zhao, L., 2009. Nonflammable Type of Composite Thermal Insulating System of Internal and External Walls. New Building Materials, **5**: 60-63. (in Chinese)

Zhejiang Construction Engineering Cost Management Station, 2019. Norms for preliminary estimate of building construction and decoration works of Zhejiang Province 2018. (in Chinese)

Zhou, Y., 2017. Research of CO_2 emission of building external wall insulation system in materialization procession Zhejiang Province, Master Thesis, Zhejiang Univ, Hangzhou, China. (in Chinese)

Zhu, S., 2015. Research on Life cycle CO_2 emission of typical external wall insulation system of building in Chongqing area. Master Thesis, Chongqing Univ. Chongqing, China, (in Chinese)

Zhu, Y. and Chen, Y., 2010. Cases for Life-cycle energy consumption and environmental emissions in residential buildings. Journal of Tsinghua University, **50**(3): 330–334. (in Chinese)

Symbols and abbreviations

A	Area of the external wall of sample building (m^2)
C_e	Total economic cost ($\$/m^2$)
C_i	Initial construction cost ($\$/m^2$)
d	Discount rate
DPV	Discount present value
E_c	CO_2 emission per external wall area in the construction phase (kg CO_2/m^2)
E_{C1}	CO_2 emission caused by the use of machinery (kg CO_2/m^2)
E_{C2}	CO_2 emission from the use of manpower (kg CO_2/m^2)
E_d	CO_2 emission per external wall area in the demolition phase (kg CO_2/m^2)
E_i	CO_2 emission factor of material i (kg CO_2/m^3)
E_t	CO_2 emission per external wall area in the transport phase (kg CO_2/m^2)
EF_e	CO_2 emission factor of regional electricity (t/MWh)

f	Inflation rate
FC	Future cost
h	House height (m)
k	Number of floors
L_i	Shipment distance of material i (km)
m_i	Mass of material i (ton)
n	Total number of building materials used in an external wall
P_{eq}	Operation power of lifting equipment (kW)
p_i	CO_2 emission factor of transport used for material i (kg CO_2/ton/km)
P_j	Construction quantity of process j (m^3)
PV	Present value
Q_i	Maximum transport volume of lifting equipment (m^3)
r	Number of processes in an external wall
S_{ave}	Average speed of lifting equipment (m/s)
T	The total operation time of lifting equipment (h)