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Life cycle assessment of stone buildings in the Taihang mountains of Hebei province: Evolution towards cleaner production and operation

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ABSTRACT

The building sector has gained significant attention due to its remarkably high energy consumption and greenhouse gas emissions. In China's rural areas, stone is a popular building material, but there are unprecedented demands to improve the life-cycle performance of stone buildings. It is essential to preserve the original architectural features while evolving towards a cleaner production and operation. This study implements a field survey in the Taihang Mountains of Hebei province. The improvement of stone extraction methods and the evolution of three stone wall styles are collected and developed. Thermal transmittances of three stone walls are measured and modeled. A cradle-to-grave life cycle assessment is conducted, and the results are compared to show their environmental performance in the embodiment and operation phases. Their life cycle inventories, including stone extraction, are developed. One representative building style sample is developed for the cooling and heating energy requirement simulation in the DesignBuilder. Based on the inventories, conducting life cycle impact assessment shows various environmental profiles in their whole life cycles. From the outcomes, the stone cladding wall (SCW) outperforms the other stone walls in both the embodiment and operation phases. However, its relatively high cost is a challenge for an individual house owner. This study proves the SCW is more sustainable, providing a basis for the choice of stone wall style in the future construction.

1. Introduction

The construction industry is one of the pillars of a country's economy (Crosthwaite, 2000), contributing to financial growth and social well-being. However, construction is also one of the highest carbon emitters (Zhou et al., 2018), and construction activities significantly impact pollution and climate change, accelerating the consumption of fossil fuels and resources. At the same time, buildings also significantly contribute to greenhouse gas emissions, with global warming, acid rain, and smog directly linked to them. According to the International Energy Agency (IEA), the building sector accounts for more than one-third of global energy consumption and nearly 40% of greenhouse gas (GHG) emissions (IEA, 2019).

To achieve the 1.5 °C and 2.0 °C temperature control targets of the Paris Agreement, countries have adopted development approaches such as emissions reduction, energy, and industrial structure reform to enhance the resilience of urban and the capability to mitigate climate change (Shi et al., 2022). China's 14th Five-Year Plan drew up a plan to achieve peak CO_2 emission by around 2030 and decarbonize the national economy by 2060 (DOS, 2021). In construction, it is crucial to reduce the environmental impact of buildings. The Chinese government has issued a series of policies and standards since 2010, such as China's 13th Five-Year Plan development guidance for the building materials industry, which proposes to promote energy-saving materials (CCMF, 2016). Standard for building carbon emission calculation unifies the life cycle evaluation method and standardizes the carbon emission calculation methods for building operation, construction and demolition, and building materials production (MHURD, 2019). China's 14th Five-Year Plan for the Development of Building Energy Efficiency and Green Building points out the promotion of new green construction methods (MHURD, 2022). Chinese policies and standards have gradually focused on the environmental footprint of the construction process and building

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materials. In addition, rural residential buildings in China account for a large proportion of the buildings, and their impact on the environment cannot be ignored (Ma et al., 2020). In 2013, Design standard for energy efficiency of rural residential buildings incorporated the building layout and thermal performance of the envelope structure for rural residential into the national standards (MHURD, 2013).

As one of the major types of rural residential buildings, stone buildings are widely distributed and numerous in China. The texture of the exterior wall of stone-built dwellings in traditional China villages were investigated because of its particular manifestation of national architectural culture (Hou et al., 2021). In the context of decarbonization, it is vital to preserve the local architectural styles while improving building environmental performance. Before performing performance studies, it is first of all essential to assess the development of stone walls and summarize typical styles. However, there is a lack of research in this field.

The development of stone building styles is inseparable from the improvement of the stone extraction technologies. Bianco and Blengini described the details of stone quarrying, cutting and finishing techniques in modern industry system and provide life cycle inventory (LCI) datasets (Bianco and Blengini, 2019). Moreover, research on the development of stone quarrying processes and technological changes in exterior wall systems has shown that it can achieve energy-saving optimization by an improved method of modeling cutting power and energy consumption during the block sawing process (Bai et al., 2021). The main procedures that cause an environmental burden are the sawing and transportation of granite slabs (Mendoza et al., 2014). The use of stone in architecture has also changed from stone blocks to stone cladding with thicknesses as small as 2–3 cm (Bortz S A, 1988; Přikryl, 2004). It means that stone buildings are shifting to be more adapted to the local natural environment and climate, showing higher energy efficiency. However, there is a lack of connection between stone building environmental impacts and the different stone processes.

Furthermore, researchers have studied structures made of stone and the thermal performance of stone, which are the basic for the environmental performance research. Morel et al. (2001) concluded that using local stone or rammed earth for structures can reduce environmental impact (Morel et al., 2001). The papers about dry-stone retaining walls (Habert et al., 2012) and stone beams (Omikrine Metalssi et al., 2013) also mentioned the advantages of using stone in structures. Tarik Ozkahraman and Bolatturk (2006) argued that the use of tuff stones for facing buildings in cold climates zones such as the Isparta region is beneficial for energy conservation (Tarik Ozkahraman and Bolatturk, 2006). Anjum et al. (2022) reviewed the thermophysical properties of rocks under the influence of moisture and temperature (Anjum et al., 2022). Medjelekh et al. (2016) studied Algeria's thermal and hygric inertia of stone houses. Its effect on the thermal comfort of indoor concludes that the passive process of building "hygric inertia" of stone walls has improved thermal comfort and humidity regulation, reducing building energy consumption (Medjelekh et al., 2016). Although there are previous studies that concerned the environmental impact of stone buildings, few attentions have been paid to the quantification of the environmental impact of stone-built dwellings. Also, few comparative studies of different stone wall systems have been carried out in the existing literature.

To better understand and reduce the buildings' environmental impact, the Life Cycle Assessment (LCA) of urban buildings has been applied under the framework of sustainability in recent years. Fluctuation caused by unstable factors can be identified through uncertainty analysis and sensitivity analysis to enhance the sustainability of buildings (Yang et al., 2021). LCA is mainly used in building materials, component assemblies, and construction processes.

Buyle et al. used LCA to determine the environmental benefits of demountable and reusable wall assemblies (Buyle et al., 2019). Alon et al. conducted a comparative LCA study of building walls made of natural and conventional materials in 6 climates (Ben-Alon et al., 2021). Evangelista et al. evaluate LAC from "cradle to grave" of four typical Brazilian dwellings. The current practices focus on LCI of stone processing and LCA of wall components for stone buildings (Evangelista et al., 2018). Bianco provides an elaborate LCI dataset about quarrying, cutting, and finishing techniques of stone (Bianco and Blengini, 2019). Mendoza et al. analyzed a detailed LCI of the production chain of granite products (Mendoza et al., 2014), and Ioannidou et al. applied LCA to evaluate three wall systems with stone cladding or massive stone (Ioannidou et al., 2014). However, no previous article applies LCA tools to assess the potential environmental benefits and burdens of stone buildings.

Herein, a series of investigations, field tests and simulations are conducted to address the aforementioned issues. The environmental performances of three stone wall systems are investigated by LCA to provide basis for the choice of stone wall style in the future. This paper is arranged as following structure. Firstly, the Taihang Mountains of Hebei province are selected because of their large stone buildings. In Section 2, a field survey in China's Taihang mountains is conducted to show the improvement of stone extraction and the development of stone walls. The stone extraction techniques for hand-made, semi-mechanized, and full-mechanized production are presented, and three typical stone wall styles are summarized. Their thermal performances are also measured and modeled for building energy consumption simulation. Then, a cradle-to-grave LCA study is conducted, and the results are compared to assess their environmental performance in the embodiment and operation phases. Section 3 presents the goal and scope definition, LCI, and LCIA based on the LCA method. It also presents constituent materials and thermal performances of three stone walls for developing LCI. The following section shows the environmental impacts of the three stone walls in the embodiment phase and operation phase. Finally, the diffusion of stone cladding walls, human labor contribution to LCA, and limitations and outlooks are discussed.

2. Field research of stone building

The Taihang Mountains are one of the vital boundary mountains between the second and third terraces of the Chinese landform and significantly influence the formation of the Chinese geographical contours (An, 2019), and are a typical representative of the rocky mountains in northern China (Jia and Luan, 1988). The Mountains start from Beijing in the North and extend southward to the Wangwu Mountains in the area between Henan and Shanxi and border the Qinling Mountains, with the Loess Plateau to the West and the North China Plain to the east. The area has thin soil layers, resulting in low vegetation coverage and a lack of timber resources. However, there is abundant in stone, producing stone buildings.

The Taihang Mountains of Hebei lay in the Southwestern part of Hebei Province in the five cities of Zhangjiakou, Baoding, Shijiazhuang, Xingtai, and Handan (Fig. 1). Due to differences in geographic location and varying degrees of stratigraphic, various rock types have been produced, such as quartz sandstone, limestone, and shale, which provide natural building materials for the area.

Based on field research, we selected 51 stone buildings in the Taihang Mountains of Hebei that are relatively well preserved, with architectural forms, structures, and techniques reflecting typical construction characteristics and historical culture, with high research value, and are still in use today as research objects. The stone walls of these stone buildings are both enclosure and load-bearing structures. The special characteristics of building materials and construction techniques are expressed through the stone walls, which become one of the most symbolic features of the Taihang Mountains of Hebei (Fig. 2). Based on field research, surveying, mapping, and craftsman interviews were conducted to collect local natural stone types, stone quarrying and processing methods, wall thickness, and wall masonry methods. Also, statistics on landforms, the local climate, cultural and historical characteristics were carried out.

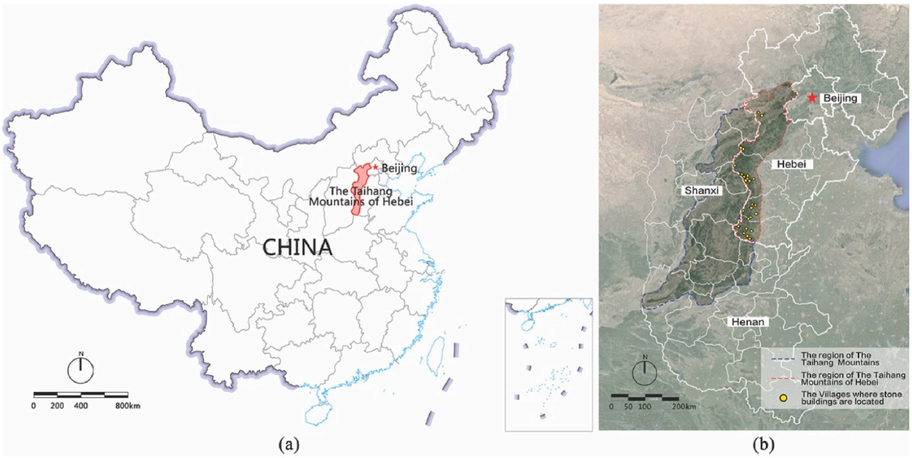


Fig. 1. Location. (a)Location of Hebei in China. (b) Location of the Taihang mountains of Hebei.

Fig. 2. Aerial view of the Stone Buildings in the Taihang Mountains of Hebei. (a)Yingtan village, Xingtai. (b)Yujia village, Shijiazhuang.

2.1. *Environment of the Hebei Taihang Mountains*

The Hebei Taihang Mountains have typical mountainous landform features, with fractures and folds, valleys and rivers cutting across the mountains, forming a landscape with thousands of ravines and gullies. The area is closed and inward-looking, reducing the possibility of living space expansion and the blockage of access to the surrounding. Meanwhile, the windward side of the Eastern Mountain is prone to flooding, making it more difficult for trees to grow, and cannot provide sufficient and good-quality timber for the buildings. However, the rock formations are directly exposed, thereby allowing stone to be extracted with hand tools without the need for deep mines. It has therefore constituted a very abundant source of stone for construction.

At the same time, with the transfer of power to Beijing during the Ming dynasty, the area gradually moved closer to the mainstream culture (Cui and Ge, 2002). The ruling class's social order advocated and regulated profoundly influenced and assimilated the region. Its thoughts and actions are relatively conservativeness, which objectively leads to the inward-looking of the Hebei Taihang Mountains, resulting in slow social development and a backward economic level in the long term. The closed geographical environment, abundant in stone and scarce in timber, and the poor economic situation have determined the characteristics of the Hebei Taihang Mountains to building a house with local materials since ancient times.

2.2. *Characteristics of natural stone*

The most common local building stone is quartz sandstone and limestone. Quartzite is produced from one of China's three major sandstone landforms, the Zhangshiyan geomorphic area, widely distributed in the southern part of the Hebei Taihang Mountains. The rock is mainly oxide mineral-based iron sandstone, showing light maroon (Wu and Xu, 2002), flesh red, purple-red, dark purple, and other colors (Tian et al., 1999). The rock is hard and thin, has sharp edges (Guo and Di, 2008), is easy to split, and the quarried stone is flat and has an intense color and noticeable impact. While Limestone is distributed in the lower hills of the Hebei Taihang Mountains and is composed of carbonates (Gong, 2006), which are gray and dark gray (Sun et al., 2011). Mostly bare rock with average hardness, large and neatly formed blocks with smooth angles.

Limestone and quartz sandstone have good physical and mechanical properties, suitable for construction applications, namely: compression resistance, durability, fire resistance, impermeability, and thermal stability (Patil et al., 2021). Coupled with the clear stratigraphic structure, quarrying of stone conditions are better and conducive to saving material costs, processing costs, and transportation costs, but also help reduce energy consumption and environmental pollution.

2.3. *Techniques of stone processing*

Based on the field survey, the development of stone extraction and processing is shown here and three methods are described as follows.

2.3.1. *Hand-made*

The quarrying industry was highly developed in ancient China, and the quarry processing methods created and defined by the quarry workers from long-term practice took into consideration the conditions of the tools at that time, but also the techniques were adapted to the local geological environment. Therefore, the traditional stone quarrying and cutting techniques of manual operation are still used today.

"Xieyan" is a standard method of quarrying in the area. Firstly, use a hand hammer and iron wedge in the rock to chisel out holes. The hole depth is 4–5 cm, and holes are about 15–20 cm apart, the number of holes according to the size of the stone used. After the holes are chiseled, in each hole, place an iron wedge, and use a hammer to pound the iron wedges in turn. Pounding should first be light and then heavy; repeat until the stone is detached from the rock mass. The block stone is uneven and rough; one piece is about 100–150 kg. To facilitate transportation of the heavy stone to the processing site, the stone will be cut further at the quarry, which can control the size of the stone to improve the efficiency of transportation and storage. Meanwhile, the scrap stone is usually backfilled or used for building the road in the surrounding area.

After being quarried, the stone needs transport to the processing site manually, which is close to a construction site. Depending on the degree of cutting and finishing, the stone is divided into three typologies: dimension stone, squared rubble, and rubble. Dimension stone involves cutting and finishing by manual or mechanical processing, forming a stone block with a regular size and flat surface. Squared rubble is roughly cut, at least two sides are flat, and the outer facade is smoothed, while the other five sides of the surface are rougher. Rubble is an irregular stone with only simple processing. Taking the squared rubble as an example. The process includes :

1. Splitting, using a hand hammer and a wedge to split the stone.
2. Chiseling, using a flat chisel and hammer to roughly repair the edges, corners, edges, and faces of the irregular stone until the stone is flat.
3. Making chisel marks, to chisel straight chisel marks on the stone's surface with a chisel and a hammer (Liu, 2015). After the stone processing is completed, the stone is usually fixed with a wooden stick and a rope and carried by two people to the construction site.

Manual quarrying and cutting techniques are more time-consuming and labor-intensive. According to Lu Shuangxiu, a craftsman in Yingtan village, processing a stone (600 mm*300 mm*300 mm) costs 200–300 RMB/block and can only process one stone per day.

2.3.2. Semi-mechanized

With the improvement of processing tools and the growing demand for raw materials, stone quarrying is now aided by modern machines to increase efficiency and reduce costs. The most common method of quarrying today is gunpowder blasting, which allows the rock to be cracked in the envisioned direction without destroying the rock mass and has a high yield. The first step of quarrying is to drill holes, usually with a drill rig at equal distances on the rock; the second step is to fill the hole with gunpowder (usually homemade gunpowder) and blast it in stages. The size of the hole and the amount of gunpowder used depends on the rock to be split.

The cutting and finishing process follows the same steps as the manual operation.

1. Splitting, using a cutter machine to roughly cut the stone to the required size.
2. Chiseling, using an angle grinder to polish off the higher part of the stone surface.
3. Separating, making chisel marks, to chisel marks on the surface with an electric hammer. After processing, the stones are transported to the construction site by cart.

2.3.3. Full-mechanized

In recent years, the application field of stone is growing, leading to the increasing requirement of stone quarrying year by year. With the development of science, technology, and modern industry, mechanical processing has gradually replaced manual operation, which significantly improves quarrying efficiency, reduces resource waste, keeps operations safe.

The quarrying phase, which is usually carried out in specialized quarries, separates the hard stone by dynamic splitting, and a primary cut is divided into blocks of dimensions better suited to truck transportation. According to the rocks' quality and characteristics, they are classified for different uses, such as slabs or tiles. While the irregular stone materials are crushed and used as backfill, secondary raw material, or abandoned (Bianco and Blengini, 2019).

During the cutting phase, the factory uses diamond mono-wire squaring/cutting to cut the stone blocks into slabs or tiles of dimensions, to suit market demands. Finally, with the finishing phase, different stone surface treatments, such as smoothing, and polishing, are performed depending on the customer's requirements (Fig. 3).

2.4. Stone wall styles

Based on the field survey, the evolution of stone buildings is shown here. Three stone wall styles are illustrated and described as follows.

2.4.1. Rough stone wall

Rough stone wall (RSW) is two-leaf stone wall which is about 500–650 mm thick, by the combination of enteral wall and internal wall, built with traditional manually quarried and processed rough stone blocks (Fig. 4). The stone wall is built by mortar, according to a laying clay content of 80%, bonding materials such as straw clay between the stones to increase the friction between the stones. Moreover, joint stones

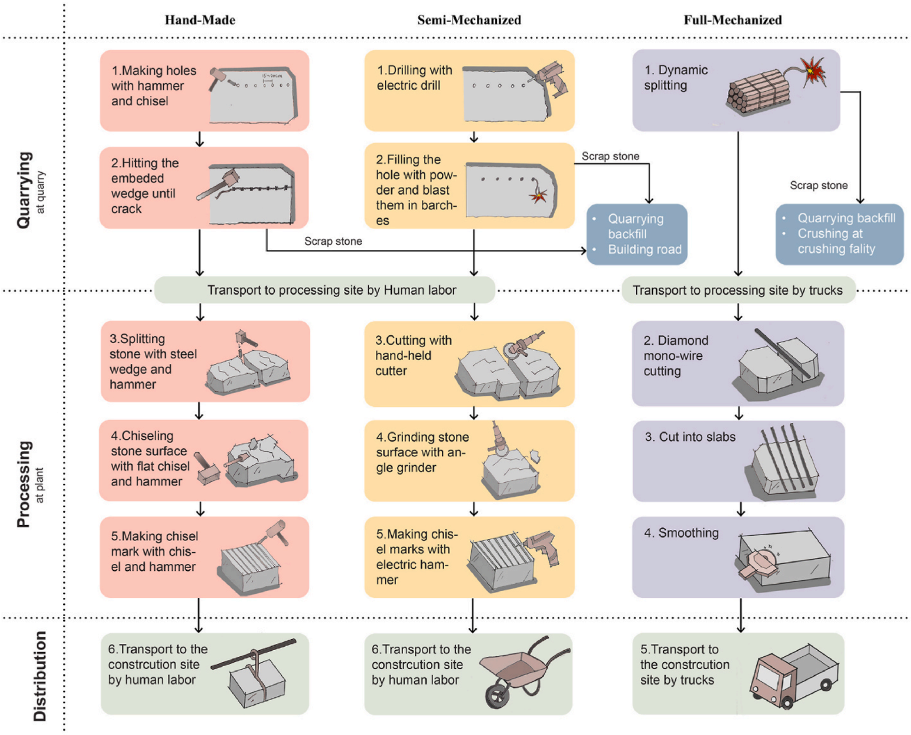


Fig. 3. The stone extraction procedures: hand-made production; semi-mechanized production; and full-mechanized production.

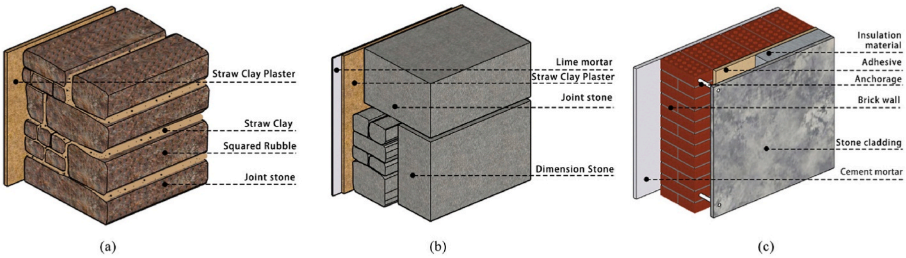


Fig. 4. Three kinds of wall construction: (a)rough stone wall, (b)dimension stone wall, (c)stone cladding wall.

are set at 2–3 levels to tie the inner and outer skins and enhance the horizontal capacity. Stones are stacked. Each stone is pressed against the vertical joints and follows the principle of larger stones at the bottom and smaller stones at the top. Despite the different shapes and sizes of the stone units, the stone blocks often present a regular texture and an excellent overall arrangement.

Based on the field survey, the wall sample images, geometric models, and sections of rough stone walls are extracted and shown in Table 1. Since there are more joints between the rough stones, the stone content of the RSW sample is between 80% and 85%, and there are smaller size stones on the wall. While the mortar (straw clay) is between 13% and 15%, according to a laying clay content of 80% mentioned above.

2.4.2. *Dimension stone wall*

Dimension stone wall (DSW) is built with stone quarried in the traditional technique by machine. The wall also follows the pattern of the alignment of horizontal joints and the misalignment of vertical joints. As the stones are flatter, increasing the contact surface between the stones, the walls are more stable, and the thickness of double-leaf walls is between 450 and 550 mm. The stones are laid in layers without mortar, performing a dry-stone construction (Li, 2016). The gaps between the stones rely on the insertion of small stones for matting and filling, and finally, straw clay or lime mortar for hooking processing.

The details of DSW are shown in Table 2. The samples of DSW have a higher stone content ranging from 92% to 95% due to the absence of filling and the more regular shape of the stone, and the rest are cracks. There is a slight error in the sampling and measurement process, which is negligible.

2.4.3. *Stone cladding wall*

Stone cladding wall (SCW) are the thin cladding tiles in the exterior façade of the building. The external wall is made of 30 mm thick limestone tiles mechanically attached to a 240 mm thick brick wall. The loadbearing function is provided by the brick wall, which also incorporates insulation materials between the brick walls and the cladding, and the interior plaster is 20 mm of cement mortar.

2.5. *Thermal performance of stone walls*

The thermal transmittance (U-value) of the stone wall constructed in

Table 1
Composition ratio of the rough stone walls.

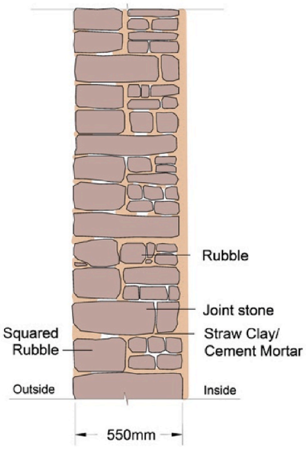
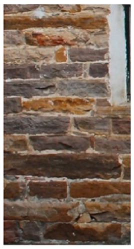
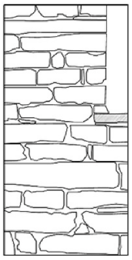
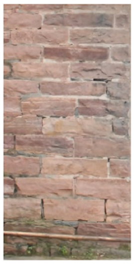
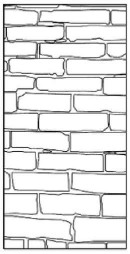
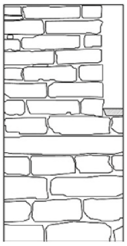
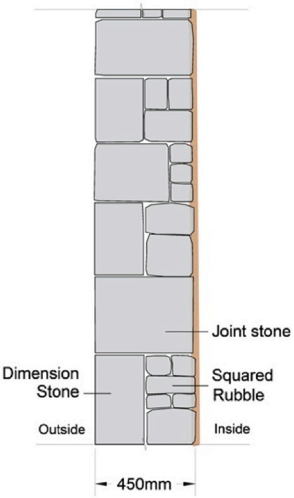
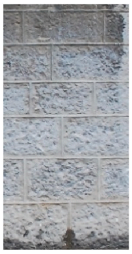
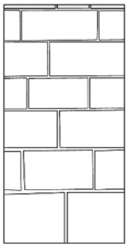
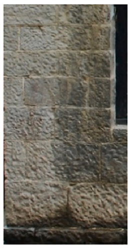
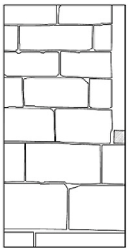
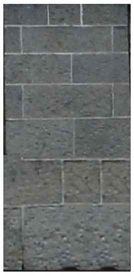
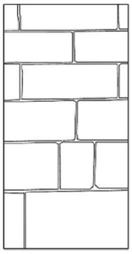
Sample wall name	Section	image	Geometric model	Stone content (%)	Crack or Filling Content (%)
RSW1				80.91%	15.27% (filling)
RSW2				83.59%	13.13% (filling)
RSW3				83.48%	13.22% (filling)

Table 2
Composition ratio of the dimension stone walls.

Sample wall name	Section	image	Geometric model	Stone content (%)	Crack or Filling Content (%)
DSW1				92.05%	7.95% (crack)
DSW2				92.52%	7.48% (crack)
DSW3				94.23%	5.77% (crack)

RSW and DSW was determined by on-site test, as shown in Fig. 5. The in-situ measurement for U-value was according to BS ISO 9869–1:2014. It was obtained by measuring the heat flow rate and the temperatures on both sides of the wall. The heat flow rate was measured by a heat flow meter, and the temperature was tested by a temperature meter and infrared thermometer. The test instruments and their specifications are shown in Fig. 5 (c). For SCW, the thermal conductivities of the materials and components are listed in Table 3. Its U-value was modeled and calculated in the software DesignBuilder. The results are shown in Table 4.

Table 3
The thermal conductivity and thickness of materials in SCW.

Material	Thermal conductivity [W/m K]	Thickness [mm]
Limestone	1.50	30
Mineral wool	0.04	50
Hollow Brick	0.30	240
Cement mortar	0.72	20

3. Methodology

3.1. Goal and scope definition

LCA is a methodology used to qualify the environmental impacts of a product, process, and service in the associated stage of the whole life and end-of-life. In recent years, LCA method has been applied in the building sector to assess the embodied carbon of building materials and the thermal performance of building insulation. This research uses LCA methodology to assess the environmental performance according to the ISO standards. There are four stages to conducting the LCA: (1) Goal and scope definition; (2) Life cycle inventory (LCI); (3) Life cycle impact


(a) (b) (c)

Fig. 5. In-situ measurement for U values of stone walls.

Table 4
U value of RSW, DSW, SCW, and other building elements.

Building elements	U value [W/m^{2}K]
RSW	1.41
DSW	1.32
SCW	0.43
Floor	3.28
Roof	0.73
Glazing	1.40

assessment (LCIA); (4) Interpretation.

This study mainly focuses on two stages: embodied and operational. The embodied stage was performed by the software SimaPro 9.3. The embodied inventory and environmental impacts of RSW, DSW, and SCW are assessed. As for the operational stage, the thermal property of the walls was simulated by DesignBuilder version 6.1 and EnergyPlus version 8.9 to calculate the heating and cooling energy demand.

This is a cradle-to-grave LCA study to compare the environmental performance of RSW, DSW, and SCW. The functional unit is set as 1 m^2 of load-bearing stone walls, which can meet the structural requirement of a two-story residential house. The lifespan of the wall is considered 70 years, as in most cases in China. The insulation properties of stone walls built in different construction methods are collected based on the field tests for the typical walls selected in the investigation. The walls built by the modern method was set based on common practice and construction standard in China. Note that the object of interest is the stone wall, not the building.

The system boundary includes the product stage, construction process, and use stage, as shown in Fig. 6. For the production phase, we are considering supplying, transporting, and manufacturing raw materials. With respect to the on-site construction stage, the transport and installation process are considered. In the use stage, the operational energy use is considered to understand the influence of wall insulation performance on the environment. End-of-life stages and benefits, and loads are not counted as system boundaries. In this paper, the whole product stage and construction process are considered as embodiment phase. B1 use and B6 operational energy use are considered as operational phase.

3.2. Life cycle inventory analysis

Life cycle inventory is essential for an LCA study. It further identifies the allocation scheme for the system. The system boundary mentioned above provides the LCI of each stone wall in this section. The embodiment phase and operation phase develop the LCI. All data for the following calculation are collected from the database Ecoinvent v3.8.

3.2.1. Embodiment phase

The environmental impacts in the embodiment phase only occurred while applying DSW and SCW. All the work in RSW is conducted by human labor. In the current LCA study, the dependence of production on human labor activities is totally ignored. Human labor is not considered to be related to the environmental impacts of production. Therefore, the manual method has no environmental impacts in the embodiment phase.

The study contains not only previously studied stone wall systems but also unstudied. As for DSW constructed in China, it is the first time to assess them in terms of LCA study. The extraction of stone block by semi-mechanized operation was investigated and summarized by field survey from the practical projects in Hebei province and previous research (Zhu et al., 2020). The LCI for extraction of 1 kg stone block by semi-mechanized production is shown in Table 5. In the construction stage, the masses of constituent materials were calculated by a geometric model, and the composition ratio of sample walls was mentioned in section 2.4. The LCI of DSW is shown in Table 7. As for the SCW, the stone cladding is extracted by full-mechanized operation, whose LCI (Table 6) was developed by (Bianco and Blengini, 2019). In the production stage, constituent materials were collected from architecture studio. The inventories were developed and provided in Table 8. The materials and components are transported by 7.5–16 metric ton lorry (Lyu et al., 2022). The framework for concrete placement is made of wood, which can be reused 4 times.

3.2.2. Operation phase

The heating and cooling energy demand was simulated to quantify the environmental impacts in the operation phase. Based on the field survey, it was found that there is a strong similarity of building layout in the villages. One typical kind of triad courtyard was summarized by typology analysis. Its layout and design are shown in Fig. 7. The typical triple courtyard faces south and consists of the main house, the eastern and western side houses, with a wall and a gate in front, giving a strong sense of enclosure. The building model developed in DesignBuilder is shown in Fig. 8.

U-values of the roof, floor, and glazing are set based on our previous research and shown in Table 4. The workdays and weekends have the same activity schedule (vacancy: 7:00 to 18:00, occupation: 00:00 to 7:00 and 18:00 to 24:00). When the room is occupied, the temperature in the room is heated by coal at 22 °C and cooled by electricity air-conditioning at 28 °C. When the room is empty, the temperature in

Table 5
LCI for extraction of 1 kg stone block by semi-mechanized production.

	Amount	Unit	Ecoinvent process
Input			
Saws	0.01	kg	Steel, low-alloyed, at plant [GLO]
Drill bits	0.04	kg	Steel, low-alloyed, at plant [GLO]
Water	5	kg	Tap water, at user [CN]
Blasting	0.04	kg	Blasting [GLO]
Electricity	0.02	kWh	Electricity, high voltage [CN]
Diesel	0.80	MJ	Diesel, burned in building machine [CN]
Output			
Ash	0.6	kg	Ash, unspecific

The items in this inventory are all secondary data.

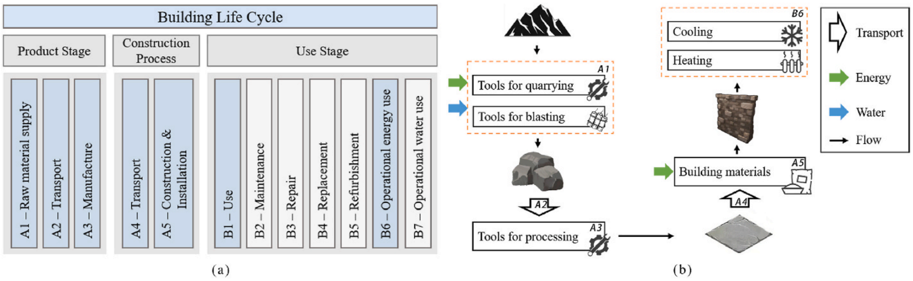


Fig. 6. The scope for LCA study. (a) Building life cycle. The box in color blue is considered in the LCA study. The box in color white is not considered in the LCA study. (b) Detailed material and energy flow. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 6
LCI for extraction of 1 kg stone cladding by full-mechanized production (Bianco and Blengini, 2019).

	Amount	Unit	Ecoinvent process
Input			
Primary data			
Diamond wire	15	mm	Created: Sintered diamond wire
Secondary data			
Drilling beam	0.01	kg	Steel, low-alloyed, at plant [GLO]
Flocculant	0.01	g	Polyacrylamide production [GLO]
Water	0.06	kg	Tap water, at user [CN]
Blasting	0.02	kg	Blasting [GLO]
Electricity	0.73	kWh	Electricity, high voltage [CN]
Diesel	1.70	MJ	Diesel, burned in building machine [CN]
Output			
Ash	0.02	kg	Ash, unspecific

Table 7
LCI for 1 m^2 DSW.

	Amount	Unit	Ecoinvent process
Primary data			
Stone block	1227.5	kg	Created: stone block
Secondary data			
Clay plaster	36	kg	Clay [GLO]

Table 8
LCI for 1 m^2 SCW.

	Amount	Unit	Ecoinvent process
Primary data			
Stone cladding	50	kg	Created: stone cladding
Secondary data			
Insulation layer	0.6	kg	EPS insulation board, at plant
Brick	192	kg	Brick [GLO]
Mould	3	kg	Wood chips, dry [GLO]
Adhesive	13	kg	Adhesive mortar [GLO]
Cement mortar	43	kg	Cement mortar [GLO]
Diesel	1.6	MJ	Diesel, burned in building machine [CN]
Electricity	0.4	kWh	Electricity, high voltage [CN]
Transport	5	tkm	Transport, freight, lorry 7.5–16 metric ton [ROW]

the room is also maintained at 18 °C by heat supply but cooled by electricity air-conditioning at 30 °C. The cooling and heating energy demands of buildings with three stone walls are shown in Table 9.

3.3. Life cycle impact assessment

Life cycle impact assessment (LCIA) is a process of translating LCI into different evaluation environmental indicators to reflect the environmental impacts of building components. Meanwhile, it can show each entry's contribution percentage to find the environmental hotspots. This study includes LCIA calculation cumulative cover energy demand, IPCC 2021 GWP 100a, CML-IA baseline, and Recipe 2016 Endpoint.

Cumulative energy demand is also called primary energy consumption. It is the sum of the primary energy that is contributed by every entry in the LCI. This study sets the electricity as China's high voltage electricity. The lifespan of the stone houses is considered more than 70 years. The IPCC GWP 100a is an important indicator that can quantify the equivalency of CO_2 emission over 100 years. The IPCC GWP 100a can show the total emissions of the stone house. So it is selected to calculate the environmental results. The assessment methods include midpoint methods and endpoint methods. Midpoint indicators focus on single environmental problems. Endpoint indicators show the environmental impact on higher aggregation levels. CML-IA baseline midpoint

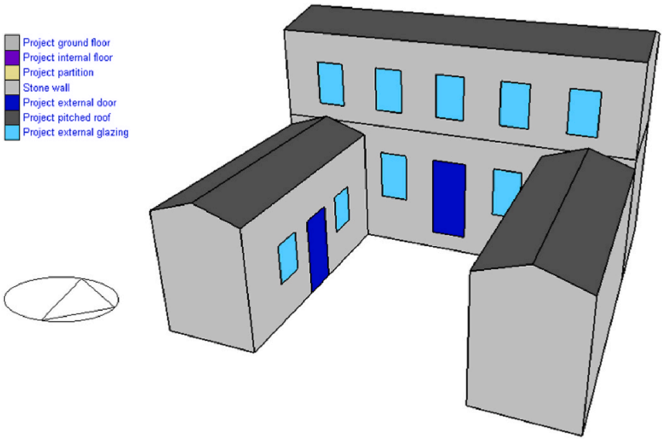
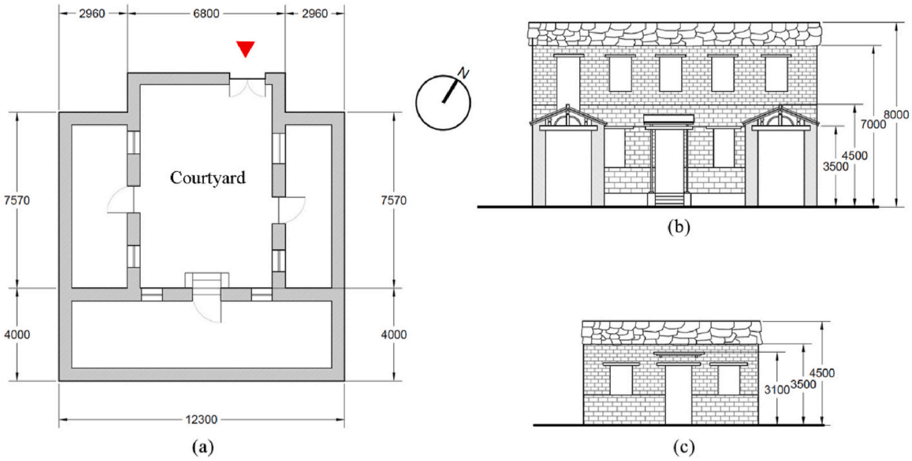


Fig. 8. Stone building model in DesignBuilder.

Table 9
Heating and cooling energy demand of the buildings with RSW, DSW, and SCW.

	Unit	RSW	DSW	SCW
Heating demand	kWh/(m^2·year)	108.1	103.5	72.4
Cooling demand	kWh/(m^2·year)	12.5	12.8	13.9



(a) (b) (c)

Fig. 7. Typical stone house layout and design in Hebei, China.

method has 10 environmental features, including abiotic depletion (AD), abiotic depletion fossil fuels (ADFF), ozone layer depletion (OLD), human toxicity (HT), freshwater aquatic ecotox (FWAE), marine aquatic ecotoxicity (MAE), terrestrial ecotoxicity (TE), photochemical oxidation (PO), acidification (AC), and eutrophication (EU). Recipe 2016 Endpoint is a method to assess the impacts. Endpoint Characterization models are applied with 22 environmental features, including Global warming/Human health (GH), Global warming/Terrestrial ecosystems (GT), Global warming/freshwater ecosystems (GF), stratospheric ozone depletion (SOD), Ionizing radiation (IR), Ozone formation/human health (OH), Fine particulate matter formation (FPMF), Ozone formation/Terrestrial ecosystems (OT), Terrestrial acidification (TA), Freshwater eutrophication (FE), Marine eutrophication (ME), Terrestrial ecotoxicity (TE), Freshwater ecotoxicity (FEC), Marine ecotoxicity (MEC), Human carcinogenic toxicity (HCT), Human non-carcinogenic toxicity (HNT), Land use (LU), Mineral resource scarcity (MRS), Fossil resource scarcity (FRS), Water consumption/Human health (WH), Water consumption/Terrestrial ecosystems (WT), Water consumption/aquatic ecosystems (WA).

3.4. Uncertainty analysis and sensitivity analysis

CED and GHG emissions' accuracies are affected by various input parameters. However, these parameters are not reliable enough, causing fluctuations in results. This problem is always because of the uncertainty of material characteristics. Therefore, this study applies the probability distribution to the material characteristics. The lognormal distribution is applied, and the geometric standard deviation is set at 1.05. The simulation is calculated in Simapro software, and 50,000 trials are applied for the Monte Carlo simulation.

4. Results

This part shows the LCA results of the stone walls in the embodiment phase and operation phase.

4.1. Environment impacts of stone block extraction by semi-mechanized production

The results of CED and GHG emissions of stone block extraction by semi-mechanized production are shown in Fig. 9. Each contributor's share is presented, where the main contributors can be identified. The contribution distributions of CED and GHG emissions show similar trends from the results. Blasting is the most dominant contributor, contributing up to 37.5% of CED and 43.3% of GHG emissions among contributors. It is higher than the contributions of other materials and processes. Among the rest contributors, the consumption of drill bits is the most influential, accounting for 29.1% of CED and 29.4% of GHG emissions. Furthermore, diesel consumption contributes a lot, up to 20.9% in the CED and 16.3% in the GHG emission. As for other contributors, the contributions are all below 10%.

The quantitative values of environmental impacts of 1 m^3 stone block extraction (raw material for the stone wall construction) are provided in Fig. 10. The results are by CML-IA method and show the amounts of ten midpoint indicators. To clearly understand the results, we use various colors in the illustration of different environmentally friendly extent. From the results, blasting and drill bits show considerably unfavorable environmental performances among the entries. The most significant factor for abiotic depletion is the Blasting, abiotic depletion fossil fuels (36.0%), terrestrial ecotoxicity (54.0%), photochemical oxidation (57.5%), acidification (91.0%), and eutrophication (82.6%). This is because Sulphur is the main ingredient of black powder, which poses significant risks to the environment and human health. For drill bits, it contributes most to human toxicity (61.9%), freshwater aquatic ecotox (66.9%), and marine aquatic ecotoxicity (56.1%). It is mainly because of coke cooling after the steel has finished baking. The wastewater of coke cooling can cause pollution in the aquatic environment. Nevertheless, diesel consumption is the largest contributor to ozone layer depletion, up to 38.4%.

4.2. Environmental performance of stone walls

4.2.1. Embodiment phase

CVD and GHG emissions are the two most crucial impact indicators among the various life cycle impact categories. The results of these two indicators with contributors were investigated according to the list presented in the previous section and are provided in Fig. 3, respectively.

It was found from the results that both CED and GHG emission of 1 m^2 DSW is far higher than those of 1 m^2 SCW. The CED of DSW is up to 6457 MJ, and the GHG emission is 565 kg CO_2 eq. DSW consumes more than three times primary energy and emits nearly six times GHG than SCW in the same size wall area.

As shown in Fig. 11, the stone block constitutes 99% of the CED in the DSW. It is not surprising that the stone block is the most influential material since it dominates the total mass of the wall. Clay plaster only contributes 1% to the CED. For SCW, the brick is responsible for 38% of CED, the most significant contributor among materials. The reason for this is that bricks dominate the total mass of the wall. As for the impacts of stone, the share decreases dramatically compared to DSW, down to 36%. It is a significant improvement while preserving the architectural style. The reason for 14% share residing in the adhesive mortar is because some chemical additives in the mortar are produced in an energy-intensive method. No other materials in the SCW contributes more than 5% of CED.

The same contribution distribution in DSW can be found in the results GHG emissions and CED (Fig. 12). Because the constituent materials are only stone block and clay plaster, and the mass of the stone block is far larger than that of clay plaster. It is not surprising that the stone block emits 99% of GHG. To SCW, the contribution distribution

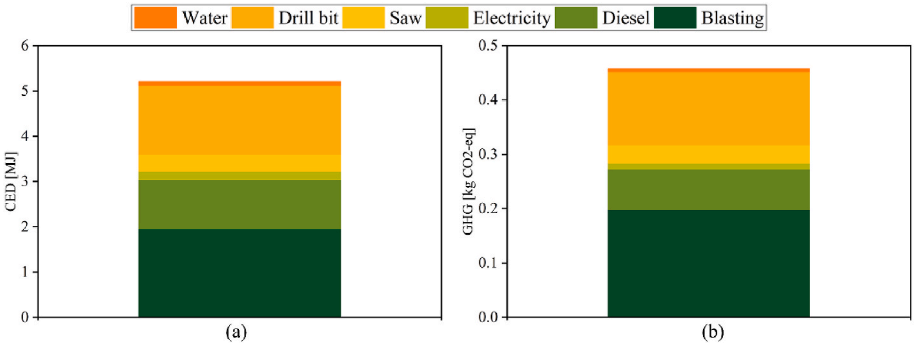
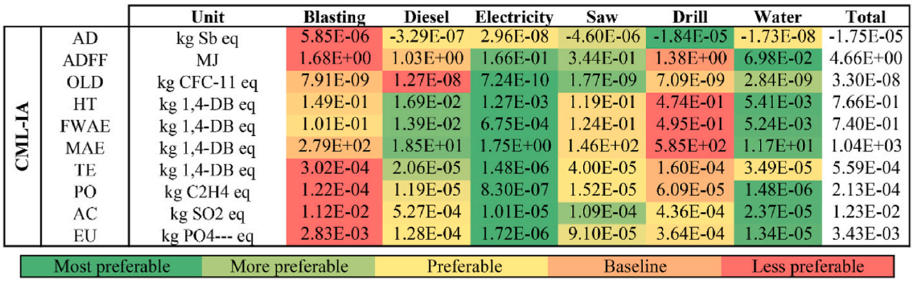


Fig. 9. CED and GHG emission of stone extraction by semi-mechanized production.



		Unit	Blasting	Diesel	Electricity	Saw	Drill	Water	Total
CML-IA	AD	kg Sb eq	5.85E-06	-3.29E-07	2.96E-08	-4.60E-06	-1.84E-05	-1.73E-08	-1.75E-05
	ADFF	MJ	1.68E+00	1.03E+00	1.66E-01	3.44E-01	1.38E+00	6.98E-02	4.66E+00
	OLD	kg CFC-11 eq	7.91E-09	1.27E-08	7.24E-10	1.77E-09	7.09E-09	2.84E-09	3.30E-08
	HT	kg 1,4-DB eq	1.49E-01	1.69E-02	1.27E-03	1.19E-01	4.74E-01	5.41E-03	7.66E-01
	FWAE	kg 1,4-DB eq	1.01E-01	1.39E-02	6.75E-04	1.24E-01	4.95E-01	5.24E-03	7.40E-01
	MAE	kg 1,4-DB eq	2.79E+02	1.85E+01	1.75E+00	1.46E+02	5.85E+02	1.17E+01	1.04E+03
	TE	kg 1,4-DB eq	3.02E-04	2.06E-05	1.48E-06	4.00E-05	1.60E-04	3.49E-05	5.59E-04
	PO	kg C2H4 eq	1.22E-04	1.19E-05	8.30E-07	1.52E-05	6.09E-05	1.48E-06	2.13E-04
	AC	kg SO2 eq	1.12E-02	5.27E-04	1.01E-05	1.09E-04	4.36E-04	2.37E-05	1.23E-02
	EU	kg PO4--- eq	2.83E-03	1.28E-04	1.72E-06	9.10E-05	3.64E-04	1.34E-05	3.43E-03

Most preferable	More preferable	Preferable	Baseline	Less preferable

Fig. 10. Environmental impacts of stone extraction by semi-mechanized production based on CML-IA method.

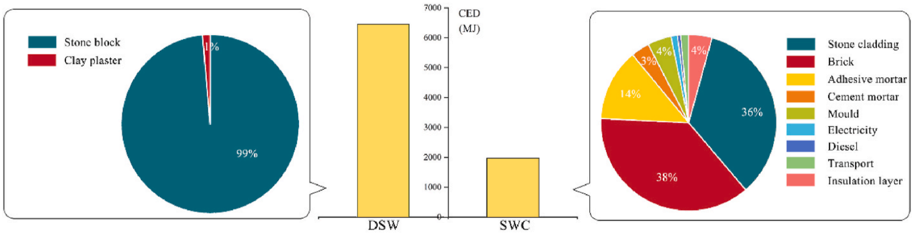


Fig. 11. CED results of 1 m^2 DSW and SCW.

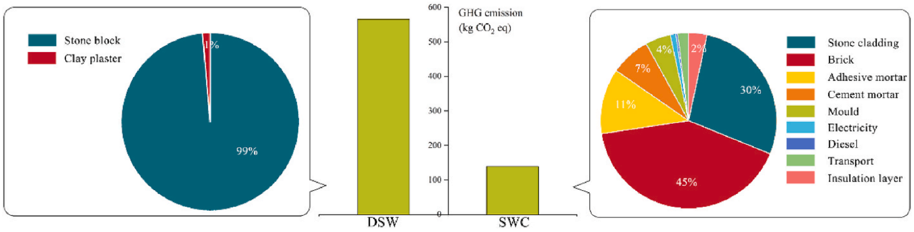
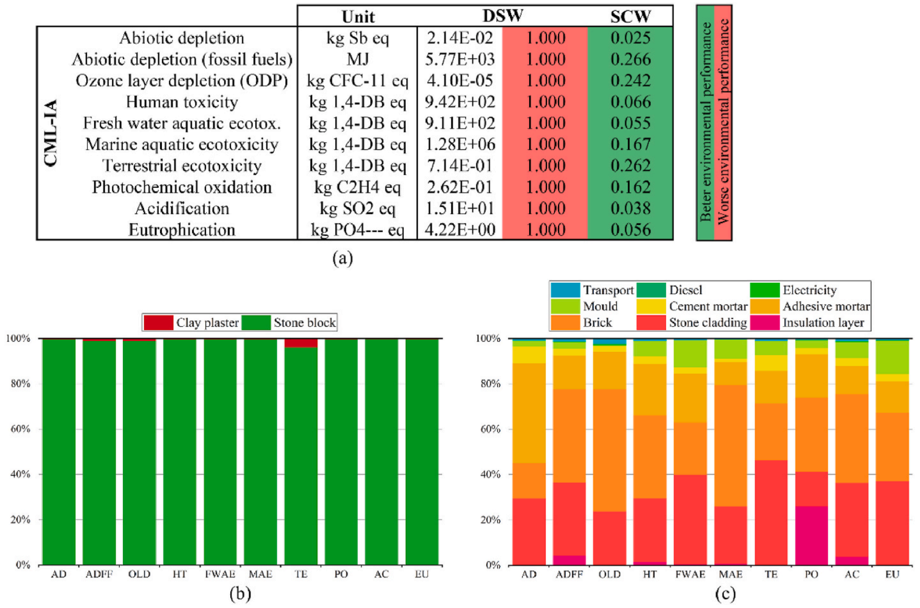


Fig. 12. GHG emission results of 1 m^2 DSW and SCW.

shows a significant change. Stone cladding and brick are the two main contributors, up to 30% and 45%, respectively. Calcination craft for brick production emits so much GHG. The third contributor is the adhesive mortar, which contributes 11% of GHG emissions. Cement is the primary driver for the emission due to its chemical process and burning fuel consumption. So, the share of cement mortar for GHG emissions also increases to 7%. Moreover, the contribution of wood mould accounts for 4%.

Fig. 13 quantifies the environmental impact of DSW and SCW based on the CML-IA method. The results of 10 midpoint indicators are shown



		Unit	DSW		SCW
CML-IA	Abiotic depletion	kg Sb eq	2.14E-02	1.000	0.025
	Abiotic depletion (fossil fuels)	MJ	5.77E+03	1.000	0.266
	Ozone layer depletion (ODP)	kg CFC-11 eq	4.10E-05	1.000	0.242
	Human toxicity	kg 1,4-DB eq	9.42E+02	1.000	0.066
	Fresh water aquatic ecotox.	kg 1,4-DB eq	9.11E+02	1.000	0.055
	Marine aquatic ecotoxicity	kg 1,4-DB eq	1.28E+06	1.000	0.167
	Terrestrial ecotoxicity	kg 1,4-DB eq	7.14E-01	1.000	0.262
	Photochemical oxidation	kg C2H4 eq	2.62E-01	1.000	0.162
	Acidification	kg SO2 eq	1.51E+01	1.000	0.038
	Eutrophication	kg PO4--- eq	4.22E+00	1.000	0.056

Beter environmental performance	Worse environmental performance

(a)

(b)

(c)

Fig. 13. The midpoint environmental impacts of 1 m^2 DSW and SCW by CML-IA method. (a) comparison of the environmental impacts. DSW is set as the reference case. Red coding indicates worse environmental performance and green coding indicates better environmental performance. (b) contributions of different components in DSW. (c) contributions of different components in SCW. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

in the figure, with the environmental friendliness of the results indicated in green and red. The value of DSW is set as 1, and the value of SCW is shown as the percentage of the DSW value. The indicators are also characterized so that the contribution share of each item can be identified in the figure. Fig. 13(a), shows all DSW values in red, which means that the environmental performances of DSW are all more unfavorable than those of SCW. From the results, it is essential to note that the highest percentage of SCW to DEW is only 0.266 in the abiotic depletion of fossil fuels. So, the SCW shows less than 30% environmental impacts than DEW. It demonstrates that wall designed with claddings and constructed in modern process can reduce the environmental impacts in the building sector.

For the DSW, it is the same as the results of CED and GHG emissions that stone block dominates the contribution. The clay plaster contributes 3.9% to terrestrial ecotoxicity, and its contributions are all less than 1% in other environmental profiles. With respect to SCW, the stone cladding is still a main contributor to each profile, in abiotic depletion (31.3%), abiotic depletion fossil fuels (32.3%), Ozone layer depletion (24.1%), human toxicity (28.1%), freshwater aquatic ecotoxicity (39.6%), marine aquatic ecotoxicology (25.4%), terrestrial ecotoxicity (46.3%), photochemical oxidation (15.4%), acidification (32.6%) and eutrophication (36.9%). Nevertheless, compared to stone blocks in DSW, the contribution share of stone cladding becomes far lower. It has led directly to a dramatic decrease in the total value of each environmental profile.

The results discussed above are all based on the midpoint methodology. Additionally, we applied endpoint indicators of ReCiPe (2016) methodology as supplements, as shown in Fig. 14. A comparison of the life cycle impact assessment result is also performed between the two modules. For most environmental assessment profiles, the DSW shows more unfavorable performances than the SCW. However, in terms of ionizing radiation, the contribution of SCW is remarkably higher. The reason is that granite cladding in the building sector is a source of potential radiation exposure. Except for ionizing radiation, the SCW contributions are all less than 60% of DSW contributions.

4.2.2. Operation phase

While applying the stone wall, the energy consumption of the sample house in the operation phase is calculated in section 3. Based on the results, CED and GHG emission of the energy consumption are provided in Fig. 15. It can be found that CED and GHG emission of SCW are both decreased compared to RSW and DSW. 138 MJ/m2/year and 97 MJ/m2/year CED can be saved, respectively. The SCW can also reduce 1.66 kg CO2-eq/m2/year and 1.17 kg CO2-eq/m2/year GHG emission.

4.3. Uncertainty analysis and sensitivity analysis

The probability distributions of the two forecasts for CED and GHG emission of DSW and SCW are shown in Fig. 16. In the distributions, the highest bars represent the values with the highest possibilities. The distributions show a symmetric profile. The results show that both CED and GHG emission are relatively robust when input materials suffer from uncertainty. For DSW, the lowest CED value in the 95% confidence regions is 6153 MJ, which is still three times larger than the highest CED value of SCW in the 95% confidence regions. This also happens in the uncertainty analysis of GHG emissions. It once more demonstrates the superiority of SCW in terms of environmental performance. Therefore, SCW can achieve environmentally sustainable stone building toward highly efficient mechanized production and cleaner operation.

5. Discussions

This section discusses the diffusion strategy of SCW, the influence of human labor in LCA, and limitations and outlooks.

5.1. Diffusion strategy of stone cladding wall

The government puts considerable resources into reducing the energy consumption and GHG emission of the building sector in rural areas. They are generally directly to reducing the U-value of building envelopes. U-value is not the only way to reduce energy consumption. However, it is also essential to consider preserving the area's original architectural features in the context of decarbonization. From the results in this paper, it was found that SCW with a far higher U value is an excellent alternative for the traditional stone house (RSW and DSW). Furthermore, the LCA performed reveals that SCW can save energy and reduce GHG emission in both the embodied and operation phases while preserving the stone building aesthetic. Similar findings were also provided by research in South-eastern Europe (Maoduš et al., 2016). The modern production and construction methods can promote cleaner built environment.

Despite the above advantages, SCW Is not widely used by the construction industry in the region. The high construction cost is considered the biggest challenge for the uptake of the SCW in rural areas. SCW can return the initial investment to the house owner in the operation phase due to the saving in cooling and heating energy requirements, but the payback period is too long, which individuals cannot accept. From the perspective of the whole society, the government should implement policies and provide subsidies to promote the evolution of sustainable stone house construction.

5.2. Insight into human labor in LCA study

The construction of RSW requires significant human labor, including quarrying, processing, and distributing. RSW should show no environmental impact in the production phase, based on the current standard attribution LCA methodology, where only activities related to and affected by changes in raw materials and function units are incorporated into the LCI. Particularly, it does not account for the contribution of human labor. Meanwhile, the existing LCA regulations and standards (Finkbeiner et al., 2006), as well as the LCA reference handbook (JRC, 2011), fail to mention how to account for human labor. The product's impact on human labor activities is usually ignored in LCA.

In fact, labor is involved in all production and service delivery processes to society, and human labor is intrinsically related to the life

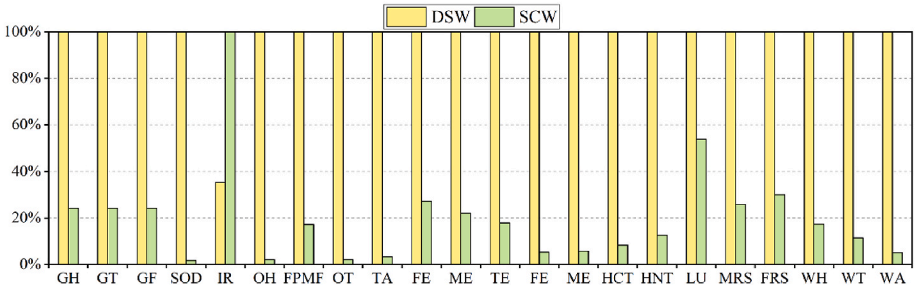


Fig. 14. The endpoint environmental impacts of 1 m^2 DSW and SCW by ReCiPe (2016) method.

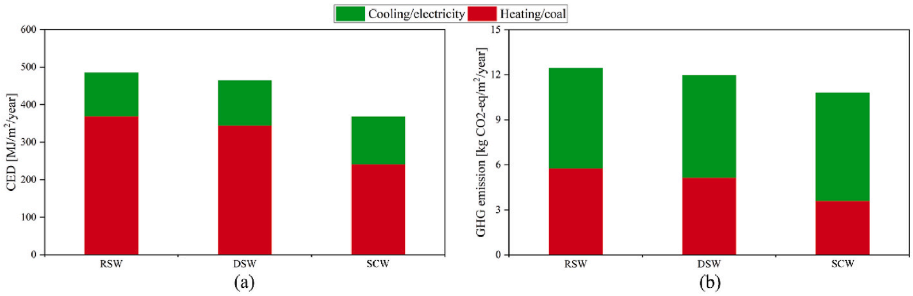


Fig. 15. CED and GHG emission results of building energy consumption with RSW, DSW, and SCW.

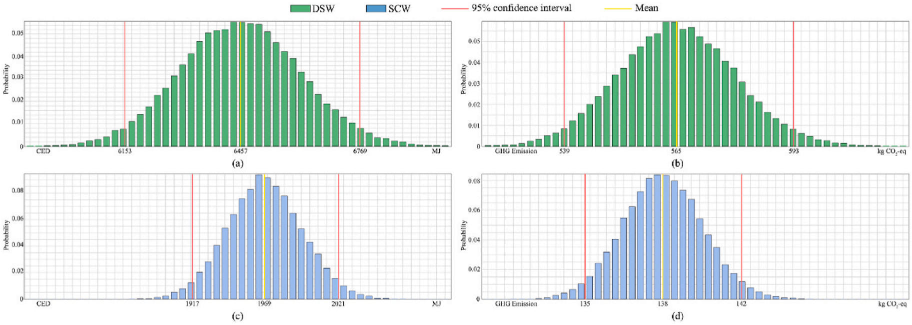


Fig. 16. Uncertainty analysis and sensitivity analysis for the CED and GHG emission of DSW and SCW.

cycle. Without human labor, there is no application of information and no mastery of matter and energy, almost all products will not be produced. Researchers have attempted to incorporate HL into LCA. Rocco and Colombo use a novel Bioeconomic Input-Output model, which illustrate the impact of human labor on energy embodied in the goods and services in a given national economy, argue the HL should be included in the supply chain in energy analysis and LCA (Rocco and Colombo, 2016). Rugani et al. assessed human labor's environmental impact through workers' services in 27 EU countries. They concluded that product LCI with HL inputs could improve the accuracy of the entire life cycle analysis (Rugani et al., 2012). Kamp and the co-author proposed that the calculation of labor UEV is divided into direct and indirect HL, making the environmental sustainability assessment (ESA) calculation method more reliable (Kamp et al., 2016).

This study also shows that human labor contributes significantly to the sustainability assessment of a system. In other words, LCA without human labor impacts may not provide a whole picture of the system. This approach in environmental impact assessments can to misjudgment of environmental conditions at various stages, especially when this production activity is labor-intensive.

6. Conclusions

Stone building is the main style in China's rural areas. Improving their environmental performances while preserving their original architectural features is essential. This study conducted a field survey on stone buildings in the Taihang Mountains of Hebei. Stone extraction methods (hand-made, semi-mechanized, and full-mechanized) are investigated. Moreover, three representative stone wall styles are summarized to show the development of stone wall design, including RSW, DSW, and SCW. The thermal performance of three stone walls was investigated, and SCW shows a lower U-value than RSW and DSW. Cooling and heating energy consumptions of building with three stone walls were simulated, respectively.

A cradle-to-grave LCA study was carried out to present their environmental performances in the embodiment phase and operation phase based on the information obtained from the field survey. Results show that SCW is more favorable in terms of environmental performance. SCW can save 138 MJ/m^2/year and reduce GHG emissions by at most 1.66 kg CO$_2$-eq/m^2/year. SCW can achieve environmentally sustainable stone building toward highly efficient mechanized production and cleaner operation. Government should therefore provide subsidies to promote the uptake of SCW to achieve environmental benefits from the perspective of the whole society. The influence of human labor on LCA was also discussed. LCA without human labor impacts may not provide an incomplete picture of the study system, especially when this production activity is labor-intensive.

In this study, there are also some limitations. The LCA did not consider the demolition phase because of the long lifespan of stone buildings. The stone block can be processed for reuse. Also, the region of the database used is not all from China, the database from [GLO] has to be used. Moreover, the limitation is also the economic costs. This study only focuses on the environmental performance of three stone house styles. Economic feasibility is also considered an essential factor for the shift to a modern and sustainable stone house. The economic feasibility and the economic payback period will be further investigated in the next stage.

CRediT authorship contribution statement

Lingege Long: Methodology, Investigation, Formal analysis, Writing – original draft. **Qingxiang Li:** Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft. **Zhenkun Gan:** Investigation. **Jun Mu:** Investigation, Supervision. **Mauro Overend:** Supervision, Writing – review & editing. **Dayu Zhang:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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References

An, J., 2019. The spirit of Taihang mountains and the nation's. Historical Geograph. J. Shanxi Univ.: Philos. Soc. Sci. 42 (1), 50–55.

Anjum, F., Yasin Naz, M., Ghaffar, A., Kamran, K., Shukrullah, S., Ullah, S., 2022. Sustainable insulating porous building materials for energy-saving perspective: stones to environmentally friendly bricks. Construct. Build. Mater. 318, 125930.

Bai, S., Qiu, H., Rabe, L., Jia, S., Elwert, T., Wang, Q.Y., Wang, Q., Sun, Y., 2021. A study on energy-saving optimization strategy for the stone processing industry—an improved method for modeling cutting power and energy consumption: a case study of block sawing process. J. Clean. Prod. 300, 126922.

Ben-Alon, L., Loftness, V., Harries, K.A., Cochran Hameen, E., 2021. Life cycle assessment (LCA) of natural vs conventional building assemblies. Renew. Sustain. Energy Rev. 144, 110951.

Bianco, I., Blengini, G.A., 2019. Life Cycle Inventory of techniques for stone quarrying, cutting and finishing: contribution to fill data gaps. J. Clean. Prod. 225, 684–696.

Bortz, S.A., E, B., 1988. Some Field Problems with Thin Veneer Building Stones. ASTM International.

Buyle, M., Galle, W., Debacker, W., 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. J. Clean. Prod. 218, 141–156.

CCMF, 2016. China's 13th Five-Year Plan development guidance for the building materials industry. https://www.ccement.com/news/content/8607590360379.html.

Crosthwaite, D., 2000. The global construction market: a cross-sectional analysis. Construct. Manag. Econ. 18 (5), 619–627.

Cui, Z., Ge, Z., 2002. On the Cultural Character of Yan-Zhao(ancient Hebei Province), 05. Journal of Hebei Normal University (Philosophy and Social Sciences Edition, pp. 99–106.

DOS, 2021. Plan of China's 14th Five-Year Plan for National Economic and Social Development and Outline of Vision 2035. http://www.gov.cn/xinwen/2021-03/13/content_5592681.htm.

Evangelista, P.P.A., Kiperstok, A., Torres, E.A., Gonçalves, J.P., 2018. Environmental performance analysis of residential buildings in Brazil using life cycle assessment (LCA). Construct. Build. Mater. 169, 748–761.

Finkbeiner, M., Inaba, A., Tan, R., Christiansen, K., Klüppel, H.-J., 2006. The new international standards for life cycle assessment: ISO 14040 and ISO 14044. Int. J. Life Cycle Assess. 11 (2), 80–85.

Gong, Y., 2006. Key Technologies for Revegetation of Limestone Areas in the Taihang Mountains of Hebei Province. Hebei Agricultural University.

Guo, K., Di, M., 2008. Theoretical study and development of the Zhangshiyan geomorphic Geography, 03 Geo Inf. Sci. 79–82.

Habert, G., Castillo, E., Vincens, E., Morel, J.C., 2012. Power: a new paradigm for energy use in sustainable construction. Ecol. Indicat. 23, 109–115.

Hou, X.W., Cheng, B., Yang, J., 2021. A quantitative study on the exterior wall texture of stone-built dwellings in traditional villages in China: a case study of the xisuo village in the Jiarong Tibetan area. J. Build. Eng. 42.

IEA, 2019. Global Energy & CO2 Status Report 2019.

Ioannidou, D., Zerbi, S., Habert, G., 2014. When more is better – comparative LCA of wall systems with stone. Build. Environ. 82, 628–639.

Jia, S., Luan, J., 1988. The Division of Land Types in Taihang Earth-Rocky Mountainous Area and its Application in Planning, 1. Journal of Hebei Forestry University.

JRC, 2011. ILCD Handbook: Recommendations for Life Cycle Impact Assessment in the European Context.

Kamp, A., Morandi, F., Østergård, H., 2016. Development of concepts for human labour accounting in Emergy Assessment and other Environmental Sustainability Assessment methods. Ecol. Indicat. 60, 884–892.

Li, L., 2016. Research on the Materials and Construction of Residential Houses in Central Hebei in the Background of Regional Characteristics. Hebei University of Technology.

Liu, D., 2015. Construction Methods of Tiles and Stones in Ancient Chinese Buildings China Architecture and. Construction Press, Beijing.

Lyu, L., Pei, J.Z., Hu, D.L., Sun, G.Q., Fini, E.H., 2022. Bio-modified rubberized asphalt binder: a clean, sustainable approach to recycle rubber into construction. J. Clean. Prod. 345.

Ma, L., Zhang, X., Li, D., Arıcı, M., Yıldız, Ç., Li, Q., Zhang, S., Jiang, W., 2020. Influence of sunspace on energy consumption of rural residential buildings. Sol. Energy 211, 336–344.

Maoduš, N., Agarski, B., Mišulić, T.K., Budak, I., Radeka, M.J.E., 2016. Life cycle and energy performance assessment of three wall types in south-eastern Europe region. Energy Build. 133, 605–614.

Medjelekh, D., Ulmet, L., Abdou, S., Dubois, F., 2016. A field study of thermal and hygric inertia and its effects on indoor thermal comfort: characterization of travertine stone envelope. Build. Environ. 106, 57–77.

Mendoza, J.-M.F., Feced, M., Feijoo, G., Josa, A., Gabarrell, X., Rieradevall, J., 2014. Life cycle inventory analysis of granite production from cradle to gate. Int. J. Life Cycle Assess. 19 (1), 153–165.

MHURD, 2013. Design standard for energy efficiency of rural residential buildings. https://www.mohurd.gov.cn/gongkai/fdzdgknr/tzgg/201301/20130105_224721.html.

MHURD, 2019. Technical Standard for Nearly Zero Energy Buildings. https://www.mohurd.gov.cn/gongkai/fdzdgknr/tzgg/201905/20190530_240712.html.

MHURD, 2022. China's 14th Five-Year Plan for the Development of Building Energy Efficiency and Green Building. https://www.mohurd.gov.cn/gongkai/fdzdgknr/zfhcxjsbwj/202203/20220311_765109.html.

Morel, J.C., Mesbah, A., Oggero, M., Walker, P., 2001. Building houses with local materials: means to drastically reduce the environmental impact of construction. Build. Environ. 36 (10), 1119–1126.

Omikrine Metalssi, O., Douthe, C., Presepi, M., Mondardini, L., Brocato, M., 2013. Experimental study on reinforced stone beams. Eng. Struct. 54, 1–8.

Patil, S.M., Kasthurba, A.K., Patil, M.V., 2021. Characterization and assessment of stone deterioration on Heritage Buildings. Case Stud. Constr. Mater. 15, e00696.

Přikryl, R., 2004. Dimension Stone 2004-New Perspectives for a Traditional Building Material. CRC Press, Prague.

Rocco, M.V., Colombo, E., 2016. Internalization of human labor in embodied energy analysis: definition and application of a novel approach based on Environmentally extended Input-Output analysis. Appl. Energy 182, 590–601.

Rugani, B., Panasiuk, D., Benetto, E., 2012. An input–output based framework to evaluate human labour in life cycle assessment. Int. J. Life Cycle Assess. 17 (6), 795–812.

Shi, C., Guo, N., Zeng, L., Wu, F., 2022. How climate change is going to affect urban livability in China. Climate Serv. 26, 100284.

Sun, Y., Hu, X., Bai, R., 2011. Distribution characteristics of limestone mining areas in Hebei Province. J. Hebei Univ. Eng.: Nat. Sci. Edition 28 (3), 75–78.

Tarik Ozkahraman, H., Bolatturk, A., 2006. The use of tuff stone cladding in buildings for energy conservation. Construct. Build. Mater. 20 (7), 435–440.

Tian, L., Hu, H., Sun, L., 1999. The stratigraphic characteristics of the Zhangshiyan geomorphic Formation and its genesis. In: Geomorphology and Quaternary Committee of the Chinese Geographical Society. Geomorphology - Environment - Development. China Environmental Science Press, Beijing, pp. 276–297.

Wu, C., Xu, Q., 2002. Scenic landforms and their evolution in the zhangshiyan geomorphic area, Hebei province. Geogr. Res. 21 (2), 195–200.

Yang, Y., Chen, S., Chang, T.X., Ma, J.R., Sun, Y., 2021. Uncertainty and global sensitivity analysis on thermal performances of pipe-embedded building envelope in the heating season. Energy Convers. Manag. 244.

Zhou, N., Khanna, N., Feng, W., Ke, J., Levine, M., 2018. Scenarios of energy efficiency and CO2 emissions reduction potential in the buildings sector in China to year 2050. Nat. Energy 3 (11), 978–984.

Zhu, L., Wang, B.H., Sun, Y., 2020. Multi-objective optimization for energy consumption, daylighting and thermal comfort performance of rural tourism buildings in north China. Build. Environ. 176.