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# Life cycle carbon-footprint calculation methods for detachable wooden cabins in the western Sichuan pastoral regions

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## Abstract

As a critical building typology in the fragile ecosystem of the western Sichuan pastoral regions, detachable buildings generate substantial carbon emissions throughout their life cycle, yet standardized assessment frameworks remain lacking. This study focuses on the widely utilized detachable wooden cabins in these areas, developing an innovative carbon emission model based on a life cycle assessment methodology tailored to detachable building structures. The model encompasses four phases: materialization, operation, circulation, and demolition and recycling. It reveals spatiotemporal distribution patterns of carbon emissions in detachable buildings and identifies the primary contributing phases. The results indicate that the life cycle carbon emissions of the modular wooden cabins amount to 172 tons of $CO_{2eq}$. Due to the building's service lifespan and the impact of biomass energy combustion on the plateau, the operational phase contributes a predominant 81.68% of total emissions. The materialization phase, influenced by cross-altitude material transportation, accounts for 10.28%, while the demolition and recycling phases represent 5.67%. Compared to conventional buildings, the lightweight yet high-strength detachable structure exhibits a unique transportation phase contribution of merely 2.38%, demonstrating no significant impact on overall life cycle carbon intensity. The detachable wooden cabins showcase substantial carbon reduction potential through lightweight design, modular configuration, and photovoltaic-enhanced energy systems, providing methodological references and practical insights for low-carbon design and assessment of detachable buildings in ecologically sensitive regions.

***Keywords:*** Life cycle assessment; Detachable wooden structures; Carbon emission calculation; Carbon footprint; Plateau sustainability

## 1. Introduction

Under the escalating urgency of global climate governance, the construction sector has emerged as a key source, contributing to over one-third of global carbon emissions (Jin *et al*., 2025). In China's pursuit of its "dual carbon goals," ecologically sensitive plateau regions have become strategic priorities for regional carbon balancing practices due to

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their dual attributes of carbon sequestration potential and emission reduction challenges (China, 2021).

The domestic construction industry currently grapples with structural contradictions between its characteristic short life cycles, high-frequency demolition and reconstruction practices, and sustainable development principles (Han *et al*., 2023). Notably, the pastoral regions of the western Sichuan plateau have achieved breakthroughs in low-carbon construction through modular, detachable wooden cabin systems that maintain nomadic economic patterns. This article establishes a life cycle carbon accounting system for detachable lightweight structures, innovatively incorporating the repeated disassembly and reassembly processes within the circulation phase into the analytical framework to systematically investigate carbon footprint characteristics and emission reduction mechanisms. The development of a carbon emission accounting framework for these cabins in the western Sichuan pastoral zones, coupled with a compositional analysis of life cycle emissions, provides a critical decision-making basis for reconciling protective development in ecologically fragile areas with carbon neutrality objectives.

This study employs the life cycle assessment (LCA) methodology (Shi *et al*., 2023) to analyze the carbon footprint characteristics of detachable wooden cabins. Since the proposal of the Dutch "industrial, flexible, and demountable building system" theory (Di Giulio *et al*., 2005), detachable construction technologies have significantly progressed in Europe, while domestic research in China remains predominantly focused on permanent structures in plain regions. For example, Wang (2017) developed a life cycle carbon emission model for industrialized pre-fabricated residential buildings. Similarly, Laurent *et al*. (2018) conducted life cycle-based carbon footprint research on modern wooden structures. Xikai *et al.* (2019) developed regression models for estimating the life cycle carbon emissions of buildings using design factors. Similarly, Ding *et al*. (2020) proposed a carbon emission measurement system for pre-fabricated residential buildings. Hao *et al*. (2020) investigated the life cycle carbon emissions of compact pre-fabricated dwellings. In addition, Islam *et al*. (2016) examined carbon emissions across the life cycle of integrated container housing units. Huo *et al*. (2022) performed life cycle analyses on detachable buildings, while Yang & Chen (2023) evaluated the feasibility of photovoltaic and energy storage systems for carbon reduction. In addition, Huang *et al*. (2024) studied the life cycle carbon emissions of insulation materials in detachable structures based on the temporary building projects of the Winter Olympics.

Present research predominantly focuses on traditional semi-manual/semi-industrial construction methods (Bayer & Pruckner, 2024), while studies on life cycle carbon emission models for detachable buildings remain limited. Notably, existing building carbon emission models continue to rely on low-altitude regional parameters (Fan *et al.,* 2013), failing to account for the specific impacts of plateau geographic heterogeneity on material transportation, energy structures, and climate adaptation technologies (Zhu *et al.,* 2023). This critical gap hinders the accurate adaptation of carbon accounting and decarbonization strategies to the unique climatic and anthropogenic conditions of western Sichuan. This study addresses this gap by establishing an LCA model tailored to plateau environments, contributing to theoretical frameworks for quantifying carbon emissions of mobile structures in ecologically fragile zones, thereby informing low-carbon habitat development in high-altitude regions.

This study investigates detachable wooden cabins in the western Sichuan pastoral regions. Building upon existing academic research, the carbon emission system boundaries are defined, and a plateau-adapted life cycle carbon emission model is developed. By integrating plateau-specific field data, a traceable carbon accounting system is established to quantify the carbon reduction efficiency of plateau-adapted technologies. Using production and processing data, this study conducts a comprehensive life cycle carbon emission analysis, providing critical references for emission control in detachable cabins and informing carbon research for other modular pre-fabricated structures.

## 2. Fundamentals of carbon emission calculation

### 2.1. Selection of research subjects

Situated between the Tibetan plateau (29°36'N – 35°38'N, 78°24'E – 104°40'E) and the Chengdu Plain (30°05'N – 31°26'N, 103°10'E – 104°50'E), China, the western Sichuan plateau spans longitudes 97°21'E – 106°03'E and latitudes 27°10'N – 34°19'N. This transitional zone covers approximately 298,300 sqkm, encompassing the Aba Tibetan and Qiang Autonomous Prefecture, Ganzi Tibetan Autonomous Prefecture, and Liangshan Yi Autonomous Prefecture. The western Sichuan plateau holds strategic significance in China's ecological landscape. Characterized by pronounced elevation gradients and climatic diversity, this region features high altitude, thin air, intense solar radiation, and substantial diurnal temperature fluctuations. Dominated by alpine meadow landforms, pastoral production has become the core industrial origin, resulting in its designation as the "western Sichuan pastoral regions" (Han *et al*., 2023), as shown in Figure 1. Detachable

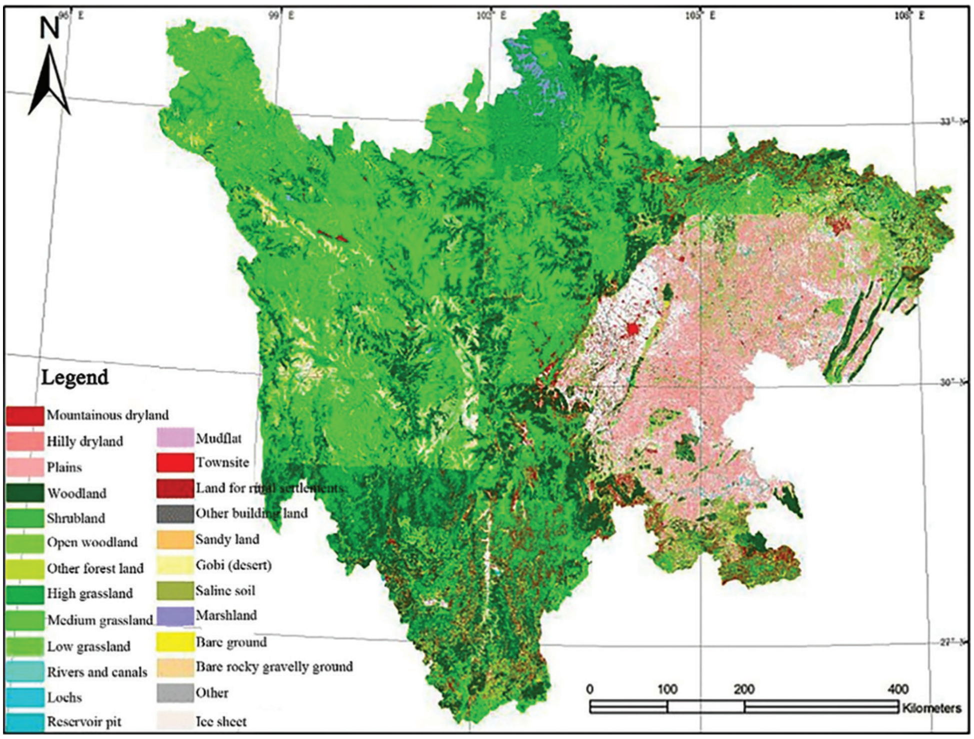


**Figure 1.** Topographic map of the Western Sichuan plateau
Source: Map by the authors

residential units have emerged and been widely adopted as a lifestyle solution for herders adapting to nomadic practices on the plateau, continuing in contemporary use.

The detachable wooden cabin (type number: QZ021, Southwest Minzu University, China) is a new type of residential unit suitable for the western Sichuan pastoral area. It explores innovative development modes for pastoral dwellings through the strategic rearrangement of materials and the feasibility of converting well-dried wooden structures into lightweight wooden structures. As of March 2025, a total of 179 wooden cabins have been put into use in this region. Modular, lightwood-structure buildings offer the advantages of low wood consumption, modularity, fast and convenient construction, and lightweight design that allows for easy lifting, incorporating the characteristics and evolving demands of traditional pastoral dwellings. This study establishes a carbon accounting framework based on the prototype modular wooden cabin developed by Southwestern Minzu University, which was assembled and displayed as the inaugural installation at the institution's branch campus in Hongyuan County, western Sichuan. The design derives its formal inspiration from traditional Tibetan dwellings, representing an optimized adaptation of log cabin construction principles into lightweight wooden framing systems, as shown in Figure 2.

The wooden cabin's floor plan retains the rectangular spatial configuration of traditional residential units, centered around a central stove with functional zones radially arranged. In conventional prototypes, spatial organization prioritizes square layouts integrated with flat roof structures clad in photovoltaic panels to support carbon-neutral design, as shown in Figure 3. The envelope system exclusively utilizes cardboard and oriented strand board (OSB) panels, while the flooring employs interlocking Siberian pine planks. All structural components conform to standardized specifications, minimizing the use of hardware. The cabin is composed of modular units, each measuring 3.00 m (L) × 2.00 m (W) × 3.22 m (H), and internally equipped with modular furniture designed for flexible assembly. When fully assembled, the cabin provides a total floor area of 13.21 m$^2$.

## 2.2. Carbon emission factors

The carbon emission factor is a coefficient used to quantify the carbon emissions of buildings at different stages by correlating energy and material consumption with carbon equivalents (Luo *et al.*, 2025). It is a fundamental basis for calculating building carbon emissions, serving as a coefficient that correlates energy and material consumption with carbon emissions, enabling standardized assessment across various life cycle stages.

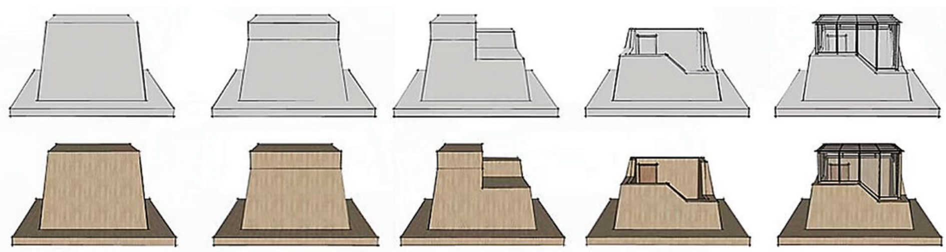

**Figure 2.** Evolution of building form
Source: Drawings by the authors

**Figure 3.** Modular wooden house construction details
Source: Photos by the authors (2024)

The methods for calculating carbon emissions are generally categorized into three types: the actual measurement method, the material balance method, and the emission coefficient method. For estimating the carbon emissions of detachable buildings, this study primarily employs the emission coefficient method, which is one of the most widely used carbon emission accounting methods (Cai *et al*., 2024; Tong *et al*., 2022).

The carbon emission factors primarily reference the *IPCC Guidelines for National Greenhouse Gas Inventories* (Eggleston *et al*., 2006), supplemented by the standard for high-energy calorific values specified in *General principles for the calculation of the comprehensive energy consumption* (GB/T 2589 – 2008) and the carbon emission factors for various construction materials and energy sources selected from China Products Carbon Footprint Factors Database (https://lca.cityghg.com/). The framework encompasses three primary categories: Construction materials, electricity, and fossil fuels, with detailed parameters presented in Table 1.

**Table 1. Carbon emission factors across various materials**

| Classification | Material | Carbon emission factor |
|---|---|---|
| Building materials | Camphor pine: CCA planing and sanding ($kgCO_{2eq}/t$) | 0.24 |
| | 0.012 m OSB board ($kgCO_{2eq}/t$) | 0.33 |
| | 0.02 m OSB board ($kgCO_{2eq}/t$) | 0.34 |
| | Low-iron glass ($kgCO_{2eq}/t$) | 1.40 |
| Power | Western Sichuan regional power grid ($kgCO_{2eq}/kWh$) | 0.70 |
| Transport | Light diesel truck (by ton) ($kgCO_{2eq}/t/km$) | 0.18 |
| | Medium-sized gasoline truck (by ton) ($kgCO_{2eq}/t/km$) | 0.12 |

Abbreviations: CCA: Chromated copper arsenate; OSB: Oriented strand board.

## 2.3. Selection of carbon emission indicators

Detachable wooden cabins, as integrated pre-fabricated wooden structures, exhibit significant differences from reinforced concrete, heavy steel, and light steel structures in terms of construction scale and design service life. These disparities lead to substantial variations in energy and material consumption during the materialization stage, resulting in considerable differences in total carbon emissions. Furthermore, service life duration substantially influences carbon accounting outcomes (Cucuzza *et al*., 2024). To ensure cross-case comparability, this study adopted "equivalent $CO_2$ emissions per square meter of floor area per year ($kgCO_{2eq}/sqm/y$)" as the carbon emission metric. This normalized indicator effectively eliminates the impacts of variations in building scale and design service life, ensuring consistency and comparability across accounting results (Tenório *et al*., 2024).

$$C_A = \frac{C_{LC}}{AY} \tag{I}$$

Where $C_A$ represents the annual carbon emissions per unit floor area ($kgCO_{2eq}/sqm$); $C_{LC}$ is the total carbon emissions of the building ($kgCO_{2eq}$); A is the floor area (sqm); and Y is the service life of the building (years).

## 2.4. Boundary and stage division of carbon emission accounting

The calculation of carbon emissions throughout the life cycle of a building refers to the total carbon emissions generated from the production of raw materials through to the end of its use and eventual demolition. The system boundary of a detachable wooden cabin is defined as a series of unit processes, including raw material extraction, production, operation, circulation, and recycling.

This study started from the perspective of the life cycle, integrating the production, installation, and usage characteristics of wooden cabins. The circulation method divides the life cycle into four stages: Materialization, operation, circulation, and demolition and recycling. Each stage involves carbon-emitting activities, with the demolition and recycling stage also involving carbon reduction processes (Hao & Ma, 2023). The carbon emission activities of the detachable wooden cabin are illustrated in Figure 4.

## 3. Carbon emissions calculation

This study calculated carbon emissions using emission factors, referencing the computational methodologies outlined in the *Standard for building carbon emission calculation* (GB/T 51366 – 2019) and the *Standard for green performance calculation of civil buildings* (JGJ/T 449 – 2018), while incorporating the characteristics of detachable wooden houses. In addition to the standardized formulas, this study introduced a supplementary carbon emission calculation method for the circulation stage unique to detachable wooden houses. This final life cycle carbon emissions calculation is expressed as follows:

$$C = C_1 + C_2 + C_3 + C_4 \quad \text{(II)}$$

Where C is the total carbon emissions over the life cycle of the detachable residential unit ($kgCO_{2eq}$); $C_1$ is the carbon emissions during the materialization stage ($kgCO_{2eq}$); $C_2$ is the carbon emissions during the operation stage ($kgCO_{2eq}$); $C_3$ is the carbon emissions during the circulation stage ($kgCO_{2eq}$); and $C_4$ represents the carbon emissions during the dismantling and recycling stage ($kgCO_{2eq}$).

According to the established life cycle inventory process, the carbon emission calculation method was determined for each stage. The total carbon emissions of the detachable wooden cabin were calculated as the sum of carbon emissions from all stages. The calculation formulas for each process are presented in Table 2.

### 3.1. Stage 1: Carbon emissions during materialization

The materialization stage included three subprocesses: Building material production, material transportation, and wooden cabin construction. The carbon emissions from the material production process are calculated using the following formula:

$$C_{sc} = \sum_{i=1}^{n} M_i F_i \quad \text{(III)}$$

Where $C_{sc}$ represents the carbon emissions during the material production process ($kgCO_{2eq}$); n is the total number of categories of materials; $M_i$ is the consumption of the i-th main material (kg); and $F_i$ is the i-th major carbon emission factor ($kgCO_{2eq}$/material quantity).

The carbon emissions during material transportation are calculated according to the following formula:

$$C_{ys} \sum_{i=1}^{n} M_i D_i T_i \quad \text{(IV)}$$

Where $C_{ys}$ represents the carbon emissions during the transportation of building materials ($kgCO_{2eq}$/sqm); Mi is the consumption of the i-th main material (kg); $D_i$ is the average transportation distance of the i-th material (km); and $T_i$ is the carbon emission factor per unit weight per transportation distance for the i-th material transportation method ($kgCO_{2eq}$/t/km).

The carbon emissions during the construction of wooden cabins are calculated according to the following formula:

$$C_{jz} = C_{ri} R_i \quad \text{(V)}$$

Where $C_{jz}$ represents the carbon emissions during the construction process ($kgCO_{2eq}$); $C_{ri}$ is the artificial carbon emission factor ($kgCO_{2eq}$/day); and $R_i$ is the i-th comprehensive manual working day operation (day).

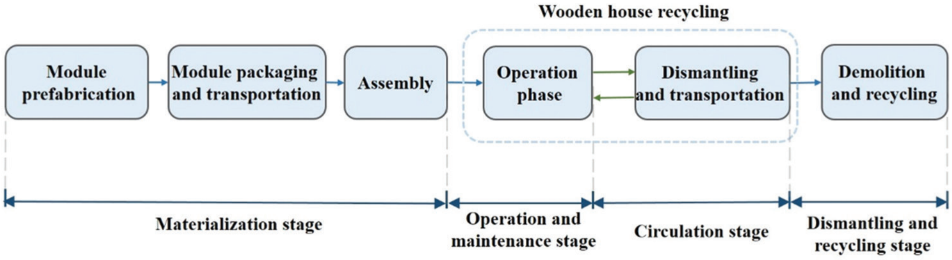


**Figure 4.** The life cycle operation process of the wooden cabin
Source: Flowchart by the authors

**Table 2. Carbon emission calculation model**

| Life cycle phase | Process | Symbol | Formula | |
|---|---|---|---|---|
| Materialization stage ($C_1$) | Material production | $C_{sc}$ | $C_{sc}=\sum_{i=1}^{n}M_iF_i$ | (III) |
| | Material transportation | $C_{ys}$ | $C_{ys}=\sum_{i=1}^{n}M_iD_iT_i$ | (IV) |
| | Wooden cabin construction | $C_{jz}$ | $C_{jz}=C_{ri}R_i$ | (V) |
| Operation stage ($C_2$) | Wooden cabin operation | $C_{yx}$ | $C_{yx}=\sum_{i=1}^{n}\left(E_iEF_i\right)Y$ | (VI) |
| | Wooden cabin maintenance | $C_{wh}$ | $C_{wh}=\sum_{i=1}^{n}\left(CM_{ri}+CM_{ti}+CM_{ci}\right)m_ir_i$ | (VII) |
| Circulation stage ($C_3$) | Wooden cabin hoisting | $C_{dz}$ | $C_{dz}=\sum_{i=1}^{n}\left(G_iP_iT_i\right)L_iY$ | (VIII) |
| | Horizontal transport | $C_{zy}$ | $C_{zy}=m_idEF_t$ | (IX) |
| Demolition and recycling stage ($C_4$) | Wooden cabin demolition | $C_{cc}$ | $C_{CC}=\sum_{i+1}^{n}E_{cci}F_i$ | (X) |
| | Outbound transportation of building materials | $C_{ys}$ | $C_{ys}=\sum_{i=1}^{n}M_iD_iT_i$ | (IV) |
| | Building material recycling | $C_{hs}$ | $C_{hs}=\sum_{i=1}^{n}\left(M_iA_iFM_i\right)$ | (XI) |
| Life cycle | Total | $C=C_1+C_2+C_3+C_4$ | | (II) |

### 3.2. Stage 2: Carbon emissions during operation

The operation phase of the wooden cabins included two subprocesses: Operation and maintenance. The carbon emissions during operation are calculated according to the following formula:

$$C_{yx}=\sum_{i=1}^{n}\left(E_iEF_i\right)Y \quad \text{(VI)}$$

Where $C_{yx}$ represents the carbon emissions during the operation of the residential unit ($kgCO_{2eq}$); n is the total number of energy categories used; $E_i$ is the annual average consumption of Class I energy in buildings (kWh); $EF_i$ is the carbon emission factor for Class I energy ($kgCO_{2eq}$/kWh); and Y is the service life of the building (years).

The calculation formula for the maintenance process is as follows:

$$C_{wh}=\sum_{i=1}^{n}\left(CM_{ri}+CM_{ti}+CM_{ci}\right)m_ir_i \quad \text{(VII)}$$

Where $C_{wh}$ represents the carbon emissions during the maintenance process of the residential unit ($kgCO_{2eq}$); CMri is the carbon emission factor for the i-th type of building materials or equipment production ($kgCO_{2eq}$/t); CMti is the carbon emission factor for the transportation of the i-th type of building materials or equipment ($kgCO_{2eq}$/km); CMci is the carbon emission factor for the i-th type of building material construction and installation ($kgCO_{2eq}$/t); mi is the weight of the i-th type of building material or equipment (kg); and ri is the number of times a material or equipment has been replaced, and is taken as an integer.

### 3.3. Stage 3: Carbon emissions during circulation

The key stage in distinguishing the carbon emission model of detachable wooden cabins from that of conventional buildings is the circulation stage. During this stage, some time was spent operating and circulating the wooden cabins in different locations, resulting in carbon emissions associated with mechanical processes, such as lifting and horizontal transportation. The carbon emission calculation formula for the lifting process is:

$$C_{dz}=\sum_{i=1}^{n}\left(G_iP_iT_i\right)L_iY \quad \text{(VIII)}$$

Where $C_{dz}$ represents the carbon emissions during the lifting process ($kgCO_{2eq}$); Gi is the i-th type of lifting machinery, and the unit of fuel consumption for lifting machinery is $kgCO_{2eq}/kWh$; $P_i$ is the mechanical power of the i-th type of lifting machinery (kW); $T_i$ is the working time of the i-th type of lifting machinery (h); $L_i$ is the number of times the residential unit has been transferred, which is taken as an integer; and Y is the service life of the building (years).

The carbon emission calculation formula for overall transportation is as follows:

$$C_{zy} = m_i dEF_t \quad \text{(IX)}$$

Where $m_i$ is the total weight of the residential unit (kg); d is the transportation distance (km); and $EF_t$ is the carbon emission factor per unit weight transportation distance ($kgCO_{2eq}/km$).

### 3.4. Stage 4: Carbon emissions during demolition and recycling

The carbon emissions during the demolition and recycling phase included those generated by the energy consumption of machinery and equipment during the demolition process, emissions from waste transportation, and emissions associated with the recycling of building materials. The total carbon emissions for this stage were calculated as the sum of emissions from demolition and transportation, minus the emissions offset by recyclable materials (Mo *et al.*, 2023). The carbon emission calculation formula for dismantling wooden cabins:

$$C_{CC} = \sum_{i+1}^{n} E_{cci} F_i \quad \text{(X)}$$

Where $C_{cc}$ is the total carbon emissions during the demolition process of buildings ($kgCO_{2eq}$); $E_{cci}$ represents the total fuel and power consumption of the i-th type in the process of building demolition (kg); and $F_i$ is the carbon emission factor of the i-th type of fuel ($kgCO_{2eq}/kWh$).

The calculation formula for the carbon emission increment of wooden cabin recycling:

$$C_{hs} = \sum_{i=1}^{n} \left( M_i A_i FM_i \right) \quad \text{(XI)}$$

Where n is the total number of classes of materials; $M_i$ is the consumption of the i-th main material (kg); $A_i$ is the recovery rate of the i-th material (%); and $FM_i$ is the recycling carbon emission factor for the i-th material ($kgCO_{2eq}/t$).

## 4. Carbon emission calculation

### 4.1. Wooden cabin specifications

Detachable wooden cabin construction, with material synergy as its technological foundation, advances pastoral residential architecture by transitioning from traditional log-based systems to lightweight wooden frameworks. The methodology employs core log-processing techniques: Crafting concave joints at both ends of full or semi-circular logs to form rectangular wooden frame units through mortise-and-tenon connections. Load-bearing walls are assembled by horizontally stacking these modular units, followed by systematic roof structure installation, as shown in Figures 5 and 6. Comparative analyses against conventional techniques demonstrate the system's technical superiority across multiple parameters: reduced wooden consumption, enhanced pre-fabrication rates, increased on-site assembly efficiency, and optimized structural weight for transportation. This architectural innovation preserves traditional pastoral construction wisdom while addressing contemporary functional requirements.

The detachable wooden cabin's envelope system integrated interior OSB panels (0.012 m and 0.02 m) with exterior Siberian pine planks. Cardboard and wooden elements were adhesively bonded using eco-friendly glue, while a 0.02 – 0.03 m foam insulation layer was installed between the interior and exterior cladding layers. Windows were fitted with float glass possessing certified fire-resistant properties. Roof-integrated solar photovoltaic panels were strategically positioned during the design phase, with pre-embedded wiring, as illustrated in Figure 7. To optimize spatial efficiency, foldable furniture modules with base dimensions of 0.3 m × 0.3 m × 0.2 m (Farhan & Nasar, 2021; Joensuu *et al.*, 2022) were implemented, utilizing 0.3 m modular units for configurable assembly.

### 4.2. Analysis of actual case scenarios for computation

#### *4.2.1. Stage 1: Materialization stage*

The materialization stage of the detachable wooden cabin comprises three processes: building material production, packaging and transportation, and construction assembly. Carbon emissions generated during this stage primarily originated from the use of construction machinery. The emissions from the production phase were calculated using Equation III. Based on manufacturer-provided drawings and the material configuration list of the detachable wooden cabin, the calculation scope encompasses roof modules, floor modules, columns, beams, grille strips, interior and exterior wall cladding panels, and other components—covering 37 categories in total. These materials accounted for over 95 percent of the total building material mass.

The carbon emissions in the transportation phase were calculated using Equation IV, which integrates energy consumption parameters with region-specific emission factors derived from the China Products Carbon Footprint

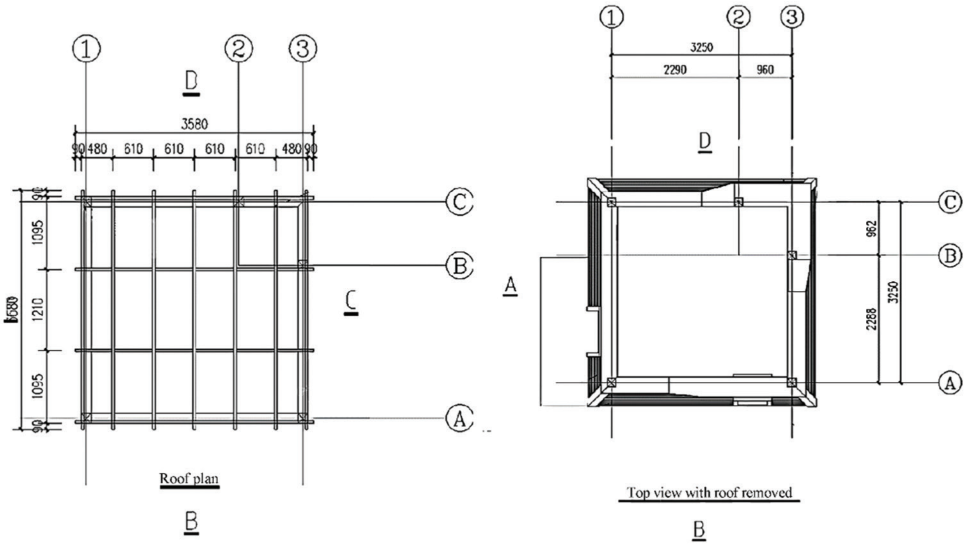


**Figure 5.** Roof plan with top view of the house
Source: Drawings by the authors

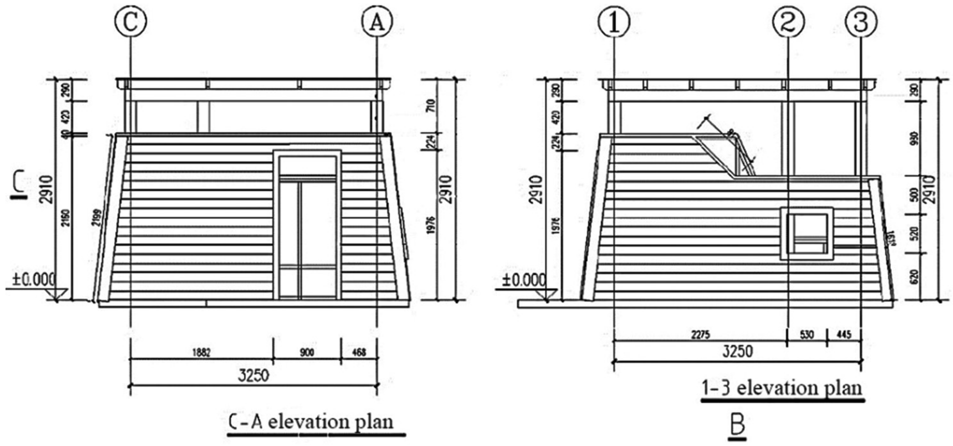


**Figure 6.** Elevation of a wooden cabin
Source: Drawings by the authors

Factors Database. This database provides granular emission coefficients for light-duty trucks and medium-duty trucks operating under high-altitude terrain conditions, as validated by road freight studies conducted in Sichuan province (Cai *et al*., 2024).

For the case study, the building materials of the wooden cabins were transported from Chongzhou city, Chengdu – a region exhibiting 12.3% higher construction-related carbon intensity compared to Sichuan provincial averages, as quantified through geospatial life cycle analysis – to Barkam city, Ganzi Prefecture (Cai *et al*., 2018). The route prioritizes light-duty trucks over heavy-duty vehicles, aligning with optimization models demonstrating an 18.7% reduction in per ton-kilometer emissions for mountainous logistics. Subsequent distribution across pastoral areas employed real-time GPS monitoring of vehicle operating hours, a methodology proven to reduce route deviation emissions by 9.2% in comparable rural freight networks (Zhao *et al*., 2025).

The carbon emissions in the construction phase were calculated using Equation V. These emissions primarily stemmed from the use of mechanical equipment during construction. The on-site installation process primarily utilized bench-type electric saws, electric planers, pneumatic nail guns, handheld sanders, glass cutters, small forklifts, crawler cranes, and other machinery.

#### 4.2.2. Stage 2: Operation phase

The operational phase consists of two components: Operation and maintenance. The energy consumption during the operation of the detachable wooden cabin primarily stems from heating, cooling, and equipment systems (Li *et al*., 2020). Carbon emissions in this phase were calculated using Equation VI. The wooden cabin was equipped with a photovoltaic glass roof, which cumulatively generates 26,000 – 35,000 kWh of electricity annually, sufficient to meet basic lighting energy demands (Frischknecht *et al*., 2015). Carbon emissions during building operations were computed by incorporating meteorological parameters based on the altitude of the pastoral area into Trnsys software (Thermal Energy System Specialists, LLC, United States), as shown in Figure 8.

The carbon emissions during the maintenance phase were calculated using Equation VII. The design service life of the detachable wooden cabin typically ranges from 5 to 10 years (Mazur & Olenchuk, 2023). However, certain components, such as insulation materials and equipment, such as distribution boxes, battery packs, and electric heaters, generally have shorter lifespans than the structure. These components may require replacement during the building's life cycle, resulting in associated carbon emissions.

#### 4.2.3. Stage 3: Circulation stage

The "circulation" phenomenon of the detachable wooden cabin refers to the process of transporting the structure through integral hoisting to another location for reuse after its service period at the original site ends. Carbon

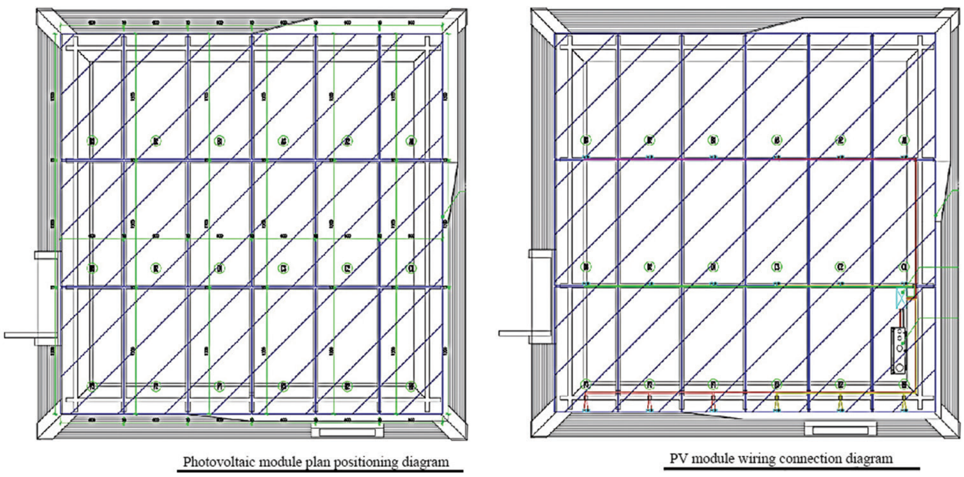


**Figure 7.** Photovoltaic (PV) module planar positioning connection diagram
Source: Drawings by the authors

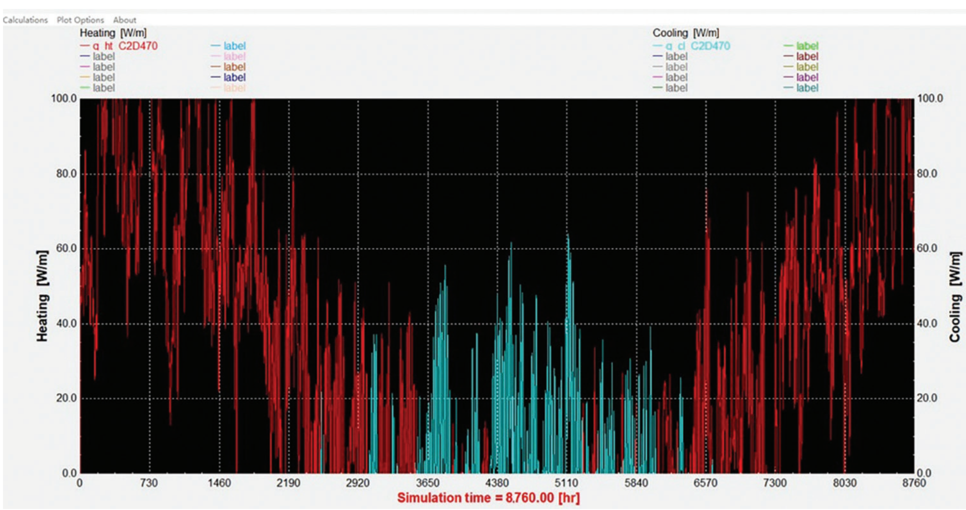


**Figure 8.** Software simulation of the annual energy consumption of a detachable wooden cabin
Source: Screen capture by the authors

emissions during this phase primarily arise from the energy consumption of machinery used in installation, dismantling, and transportation. The circulation phase encompasses the installation, dismantling, and transportation processes that components undergo from factory delivery to the end of the wooden cabin's service life.

The carbon emissions during the circulation process were calculated according to Equations VIII and IX. The installation process during the circulation stage is relatively simple, usually using equipment, such as a truck crane for installation. Disassembly is the reverse operation of the installation process, so the carbon emissions during disassembly and installation are essentially the same. The turnover frequency for disassembling and assembling wooden cabins is at least 5 times, and this study assumed five cycles. Considering uncertainties in usage, the overall transportation was set at 3 times per year, with a service life of 10 years. Therefore, the overall lifting frequency was also 3 times per year (the last lifting transportation was placed in the demolition and recycling stage). Parameters for lifting machinery were based on a specific engineering list. The weight of a wooden cabin was approximately 1.9 tons. This study selected horizontal transportation vehicles and corresponding machinery shifts based on the actual weight. According to the distances between pastoral areas, the single transportation distance per trip was 180 km, utilizing light-duty trucks with a five-ton load capacity.

#### *4.2.4. Stage 4: Demolition and recycling stage*

The dismantling and recycling stage primarily comprises three components: Demolition, external transportation, and material recycling. Carbon emissions from demolition processes were calculated using Equation X. Emissions from external transportation were referenced from the transportation calculations in the materialization stage, with an average distance of 300 km for transporting building material. For material recycling, only partially recyclable main components were considered: Mongolian pine (recycling coefficient = 0.15), OSB boards (0.43), and low-iron glass (0.82), while the remaining materials were treated as construction waste (Mayer *et al.*, 2021; Olumo & Haas, 2024; Zboinska & Göbel, 2025). Due to the recycling of low-iron glass, carbon emissions in the demolition and recycling phase were reduced by 0.45%.

Detachable wooden cabins achieve carbon reduction objectives primarily through enhanced material recovery rates during recycling processes, effectively lowering carbon emissions and mitigating environmental impact. Given the unique environmental conditions of the Western Sichuan plateau, optimizing recycling pathways requires coordinated consideration of material properties and regional constraints. Adoption of the *Production LCA specification for float glass (Product category rules)* (GB/T 29157 – 2012) enabled precise measurement, while compliance with the *Technical Code for Recycled Building Materials in Plateau Regions* (DB51/T 2987 – 2022) facilitated adaptive retrofitting. These approaches established a classified, gradient-based recycling system.

Field validation indicates that the system elevated single-cycle demolition recycling carbon reductions to 1,237.9 kg $CO_2$ per cabin, representing a 36% improvement over conventional methods. Material-specific analysis shows that wooden recycling accounts for 15% and glass recovery for 8% of the total emission reduction, as shown in Table 3.

### 4.3. Result analysis

In summary, the total life cycle carbon emissions of a detachable wooden cabin were calculated to be 172,479.86 $kgCO_{2eq}$ or approximately 172 tons. The carbon emissions during the materialization, operation, circulation, and dismantling and recycling stages were 17,722.87 $kgCO_{2eq}$, 140,877.96 $kgCO_{2eq}$, 4,105.35 $kgCO_{2eq}$, and 9,773.68 $kgCO_{2eq}$, respectively. The contributions of each stage were 10.28%, 81.68%, 0.24%, and 5.67%, respectively (Table 4). The operation stage contributed the most to the carbon emissions, followed by the materialization stage and the demolition and recycling stage. Although the contribution of carbon emissions from the circulation stage was relatively small, it should not be overlooked throughout the life cycle (Figure 9).

Based on the preceding analysis, the operation stage of the detachable wooden cabin and the initial transportation and outbound logistics of building materials are the key phases for targeted carbon emission reduction, as shown in Figure 10. Modular wooden cabins achieved a 22% reduction in operational emissions through passive heating strategies, comparable to the insulation-oriented design proposed here. When studying low-carbon strategies, emphasis should be placed on factors affecting carbon emissions during the operational phase. While

**Table 3. Emission reduction rates for optimized building material recovery**

| Types of building materials | Original recovery rate (%) | Optimized recovery rate (%) | Emission reduction rate during the recycling process (%) |
|---|---|---|---|
| Camphor pine board | 13 | 44 | 17.70 |
| OSB board | 33 | 62 | 13.65 |
| Low-iron glass | 72 | 88 | 8.20 |

Abbreviation: OSB: Oriented strand board.

**Table 4. Life cycle carbon emissions of the detachable wooden cabin**

| Life cycle stages | Process | Carbon emissions ($kgCO_{2eq}$) | Carbon emissions per unit area ($kgCO_{2eq}$/sqm) | Proportion (%) |
|---|---|---|---|---|
| Materialization stage | Material production | 1,244.18 | 94.16 | 0.72 |
| | Material transportation | 16,204.95 | 1,226.44 | 9.40 |
| | Wooden cabin construction | 273.74 | 20.72 | 0.16 |
| | Subtotal | 17,722.90 | 1,341.32 | 10.28 |
| Operation stage | Wooden cabin operation | 138,226.08 | 10,461.40 | 80.14 |
| | Wooden cabin maintenance | 2,651.87 | 200.70 | 1.54 |
| | Subtotal | 140,877.96 | 10,662.10 | 81.68 |
| Circulation stage | Wooden cabin hoisting | 3,299.85 | 249.74 | 1.91 |
| | Horizontal transport | 805.50 | 60.96 | 0.47 |
| | Subtotal | 4,105.35 | 310.71 | 2.38 |
| Demolition and recycling stage | Wooden cabin demolition | 72.75 | 5.51 | 0.04 |
| | Wooden cabin transportation | 10,432.50 | 789.56 | 6.05 |
| | Wooden cabin recycling | 731.57 | 55.37 | 0.42 |
| | Subtotal | 9,773.68 | 850.44 | 5.67 |
| Life cycle | Total | 172,479.86 | 13,164.50 | 100 |

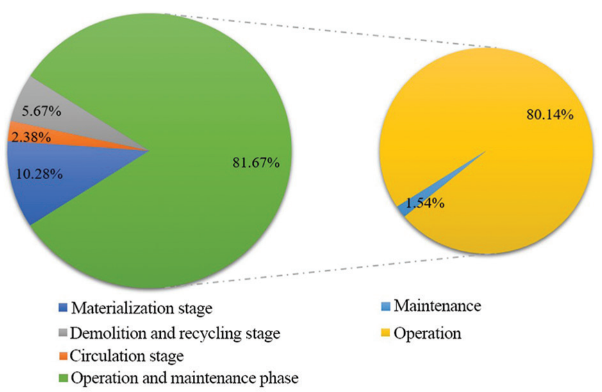


**Figure 9.** Proportion of each stage in the life cycle carbon emissions of the detachable wooden cabin
Source: Charts by the authors

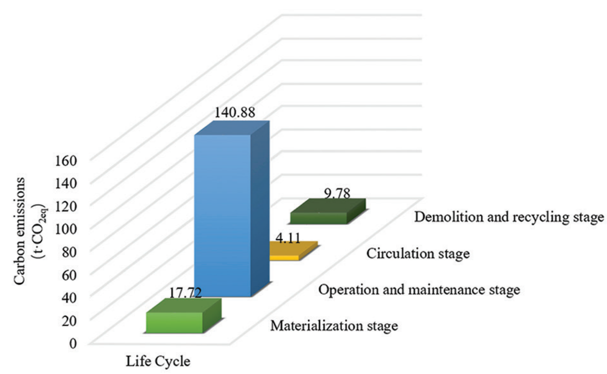


**Figure 10.** Carbon emissions of the detachable wooden cabin during the four stages of the life cycle
Source: Graph by the authors

Scandinavian thermal regulation codes require insulation layers 30% thicker than those in this case study, the use of aerogel-enhanced composite panels enables the enclosure structure to achieve equivalent thermal resistance with 40% less material, demonstrating its adaptability to a range of climatic conditions, including polar and temperate zones.

In addition, emission reduction analysis should be conducted from the perspective of a life cycle, such as selecting natural, lightweight, and high-strength building materials during the production process. For example, cross-laminated wood, widely used in Swiss zero-carbon projects, offers a 40% higher strength-to-weight ratio than materials used in the present project, suggesting potential for further optimization. Besides, transportation strategies should prioritize proximity to production facilities and incorporate site-specific factors, such as building orientation and enclosure insulation performance. This echoes Norwegian logistics models, where local material sourcing reduced transport-related emissions by 35%. During the end-of-life phase, priority should be given to materials with high recycling rates to maximize emission reduction benefits through recovery and reuse.

## 5. Conclusion

This study develops a carbon emission accounting framework for detachable wooden cabins in the Western Sichuan pastoral regions, based on LCA theory. It innovatively incorporates cyclic processes within the circulation phase and divides the life cycle into four stages: materialization, operation, circulation, and demolition/recycling. Using a carbon emission factor methodology, computational models were developed for each stage. The results indicate that the operation and materialization stages dominate life cycle emissions at 81.67% and 10.28%, respectively, correlating with the operation phase's extended temporal span. The materialization phase is influenced by cumulative effects from material production, transportation, and construction processes. By contrast, the circulation and demolition/recycling stages contribute minimally at 2.38% and 5.67%, attributable to the lightweight and modular characteristics of detachable structures.

Decarbonization priorities differ across life cycle stages. In the materialization stage, key strategies involve optimizing plateau transportation modes and implementing clean energy substitution, complemented by low-carbon material selection. The operation stage requires a focus on managing energy demand through reduced heating-season consumption, alongside solar and geothermal energy integration and durability-enhanced lifespan extension. The circulation stage necessitates minimizing machinery usage during disassembly-reassembly cycles and rationalizing operational frequency. The demolition/recycling stage should prioritize material circularity through advanced recycling protocols to achieve carbon offsetting.

As green and environmentally friendly detachable cabins, these structures play pivotal roles in achieving carbon peaking and neutrality goals in plateau regions. Future research should prioritize developing hybrid renewable energy systems and plateau-adapted building materials to enhance mitigation robustness. The modular design principles and sustainable material selection criteria established here are already informing policy updates in Central Asian pastoral zones, where 35 percent of new housing developments now mandate renewable energy integration and mobile dwelling standards. This study not only provides tailored technical paths for low-carbon architectural transitions in pastoral areas but also offers interdisciplinary theoretical support and data-driven decision-making foundations for improving green building standards, advancing recycled material policies, and implementing dual-carbon goals in ecologically vulnerable zones.

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## Conflict of interest

Xianmin Mai is an Executive Editor of this journal, but was not in any way involved in the editorial and peer-review process conducted for this article, directly or indirectly. Separately, other authors declared that they have no known competing financial interests or personal relationships that could have influenced the work reported in this article.

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## Ethics approval and consent to participate

Not applicable.

## Consent for publication

Not applicable.

## Availability of data

The data presented in this study are available on request from the corresponding author or the first author.

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