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A Design Workflow Based on Life Cycle Assessment, For a Rammed Earth House in Rural Yunnan#

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ABSTRACT

Addressing global challenges such as climate change, energy crises, housing shortages, and regional inequality, this paper explores sustainable building design workflow in Yunnan's rural area. This study developed a data-driven approach to achieve climate-adaptive, affordable rammed earth house design. It assesses environmental impacts based on cradle-to-grave life cycle assessment and assesses indoor comfort and energy efficiency through dynamic building performance simulations. The study culminates in guidelines for rammed earth house design based on extensive data analysis. Several design plans for the rammed earth house project were developed and evaluated, together with a conventional brick house. The outcome of our study offers a sustainable housing design workflow that could inspire similar initiatives in regions with comparable social and climatic conditions.

Keywords: data-driven design workflow, building performance simulation, climate-adaptive, indoor climate, life cycle assessment, rammed earth house

NONMENCLATURE

Abbreviations	
BPS	Building Performance Simulation
LCA	Life Cycle Assessment
DF	Daylight Factor
PPD	Predicted Percentage of Dissatisfaction
EPD	Environmental Product Declaration
GWP	Global warming potential

1. INTRODUCTION

Against the backdrop of climate change and energy crises, architects are increasingly considering the environmental impact of their designs. Calculating carbon emissions and reducing the carbon footprint has become common practice in developed countries' architectural industry. However, in developing countries, due to a lack of awareness, technical limitations, and cost issues, this practice has not yet become an industry norm. Having this as a research gap, our study aims to explore a data-driven workflow that serves low-carbon, energy-efficient architectural design, addressing the low-carbon design needs of developing regions. Taking rural areas in Yunnan Province, China as an example, the study would conduct design practices based on this workflow.

1.1 Background - global challenges

Natural disasters are becoming more frequent worldwide, highlighting urgent global issues like the energy crisis and climate change. The building sector is a major energy consumer, using about 42% of global primary energy and contributing roughly 35% of global greenhouse gas emissions. With the global population now approaching 8 billion, the demand for affordable and sustainable housing has become urgent for countries around the world. To reduce carbon emissions, improve energy efficiency and help solve housing shortages, innovative design workflow is essential.

1.2 Background - local challenges

Narrowing the focus from global to regional perspectives reveals increasingly localized challenges in low-carbon building design. In developing countries, lower incomes and living standards result in reduced public sensitivity to climate change issues. Moreover, the modernization wave has led to psychological resistance towards traditional local building materials, with doubts about their structural performance. Therefore, cost-

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effective materials such as bricks have become a popular choice for construction. In China, for example, many villagers regard earth houses as unstable and uncomfortable, seeing them as symbols of poverty and backwardness. This view has led to houses with unique local features being replaced in rural renovations, increasing carbon emissions. Many construction project financiers do not allocate budgets for low-carbon design, which obstructs the integration of carbon emission calculations into architectural design from a market perspective. In China, the promotion of low-carbon building design is mainly a top-down government effort. However, the various design codes issued by the government currently do not have uniform and clear regulations and guidance on carbon emission calculations.

In this context, building professionals in China often struggle with managing carbon emissions in their designs. Even those aware of its importance find it hard to quantitatively assess the carbon output of their designs. In the study, a survey of 142 building professionals revealed that while 61.2% recognized the importance of calculating carbon emissions in their work, 73.2% had never actually performed such calculations. This shows a significant gap in integrating sustainability into the design process. The survey also found that professionals see the development of tools, workflows, and technical guidelines for calculating building carbon emissions as indispensable. Importantly, 59.8% of respondents believe that carbon emission considerations should start early in the design process, during project planning and conceptualization. However, despite their recognition of its importance, a lack of technical knowledge and experience prevents these professionals from effectively using these tools to perform accurate carbon emission calculations (Fig.1).

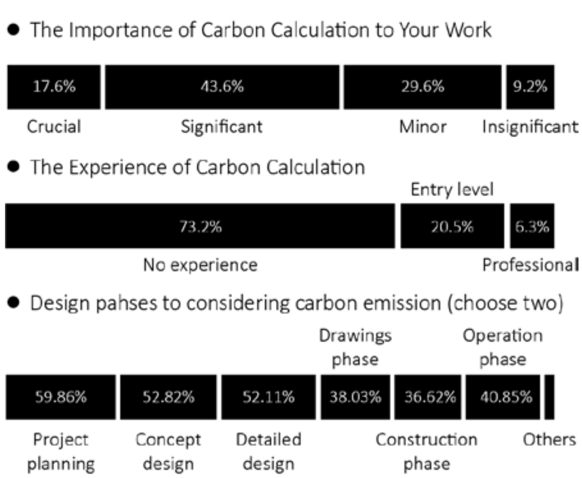

Fig. 1 Selected results of the questionnaire

1.3 Aims

Based on the background discussed, the goal of the study was set to develop a data-driven design workflow for rural areas in developing countries. This workflow integrates tools for building energy performance simulation, carbon emission calculations, and data analysis to promote low-carbon design practices in developing regions. LCA should be used as the main carbon emission measurement method.

To demonstrate the workflow, a residential project in Dashuijing Village, Yunnan was taken as an example. A rammed earth house was designed to illustrate that traditional materials can also construct a comfortable, eco-friendly, and affordable modern house.

The paper is structured as follows: Section 2 introduces the tools and methods of the workflow; Section 3 details the workflow itself; Section 4 describes its application to the design process and presents data results; Section 5 discusses the research process and its limitations; section 6 summarizes the main conclusions.

2. METHODOLOGY

2.1 LCA

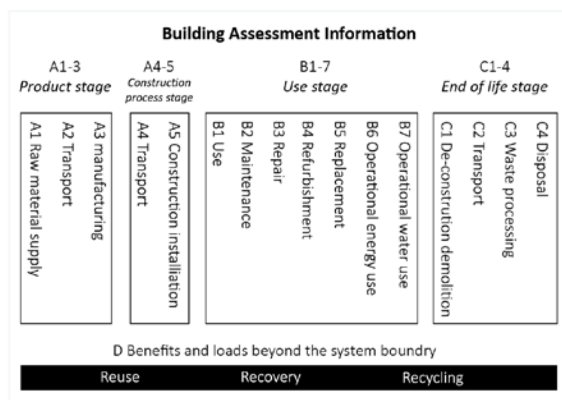

Fig. 2 Building's LCA stages according to EN 15978

To quantify the environmental impacts of a building project across its entire lifecycle, the LCA method was employed. LCA assesses the environmental impacts of products from cradle to grave. According to EN15978, it evaluates the production, construction, use, and end-of-life stages of the building (Fig.2). This methodology systematically estimates the impacts of each material and related processes. As outlined in ISO14040, LCA comprises four stages: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation.

For this study, the goal is to compare the carbon footprints of various building designs. The functional unit is defined as the construction of a single-family house, considering a 1 m² area over a 50-year lifespan. Environmental impacts are reported using the GWP indicator.

The system boundary extends from cradle to grave (A1-C4). During the usage phase, categories B1-B5 are treated as a single module, and B6 is calculated using energy simulations with relevant CO2 emission factors.

Regarding the Life Cycle Inventory, data for modules A1-A3, B4, and C3-C4 are sourced from ÖKOBAUDAT. This choice stems partly from the scarcity of local material data and partly because the LCA software CAALA, which used in the study, integrates data from ÖKOBAUDAT. The process includes creating a 3D model in SketchUp, assigning materials based on the CAALA design, and calculating material quantities. The software then merges these quantities with database data to produce the results. For A4 and C2, the local transportation modes and distance from the building material market are taken from the interviews. The emission factors are adopted from the local codes. A5 and C1 usually take up a small portion, and data collection for these modules is complex. Since the study is conducted in the early design stage, empirical formulas from local codes are adopted for assessment. During our research, One Click LCA was also used to cross-validate our computational results, which uses EPDs based on the ISO 14044 and EN15804 standards.

2.2 Building Performance Simulation (BPS)

In this study, numerous simulations of the room-scale model enable us to rapidly estimate the overall building's energy demand and indoor climate before finalizing the building's design. This approach effectively quantifies performance early on and guides design decisions. We drew significant inspiration from the "Einfach Bauen" study conducted by researchers at the Technical University of Munich.

To assess both comfort and energy efficiency, indicators such as annual total energy consumption, annual heating energy consumption, PPD, DF, and CO_2 concentration were used in the statistical and analytical evaluation of the building performance simulation results. These indicators are well-aligned with our research aims.

To run BPS, the IDA ICE 4.8 software was used. Developed by EQUA Simulation AB, IDA ICE is adept at conducting detailed, dynamic multi-zone simulations. The simulated energy consumption of the building is considered in the building's operational carbon emissions (B6), calculated based on local energy consumption and carbon emission standards.

3. WORKFLOW

For relatively simple projects like rural housing, a data-driven workflow can be summarized as follows (Fig.3).

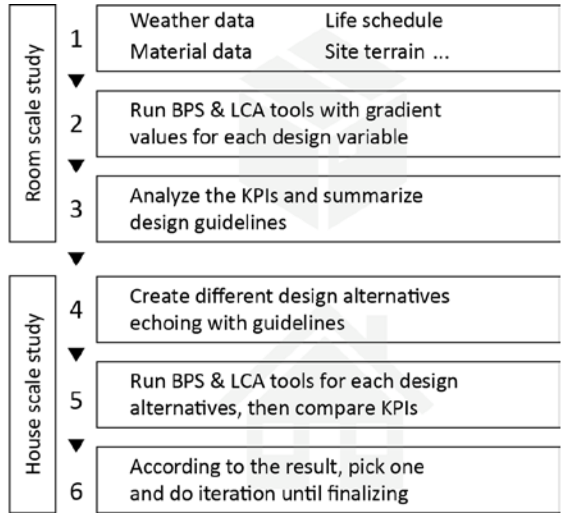

Fig. 3 Data-driven design workflow

Collect Essential Data: First, background data such as the local weather data (temperature ranges, humidity levels, local climate variations…), surrounding environmental conditions, and thermal performance data of primary materials are necessary.

Integrate Design Parameters: Combine various design parameters such as orientation, width, height, wall thickness, wall-to-window ratio, and type of window glazing. Then perform BPS and LCA at the room scale to model energy consumption and environmental impact.

Data Analysis and Insights: Summarize and analyze the output data from simulations to understand how different design parameters influence room comfort, energy efficiency, and carbon emissions. This analysis will help guide the design and identify the most effective strategies to enhance the building performance process.

Develop Design Alternatives: Using the insights gained from the data analysis, develop detailed project alternatives that adhere to identified guidelines. These should optimize the balance between aesthetic preferences, functional needs, and environmental impact.

Evaluate and Refine Designs: Perform BPS and LCA for each of the developed alternatives, focusing on key performance indicators such as energy efficiency, carbon emissions, and indoor environmental quality. Compare these indicators across different alternatives to identify the most sustainable and efficient design.

Finalize Design: Utilize the comparative analysis to refine your designs further. Ultimately, the designer can finalize a design that ensures maximum indoor comfort and minimizes carbon emissions throughout the building's lifecycle, effectively meeting both the occupant's needs and environmental sustainability targets.

4. IMPLEMENT

4.1 Context

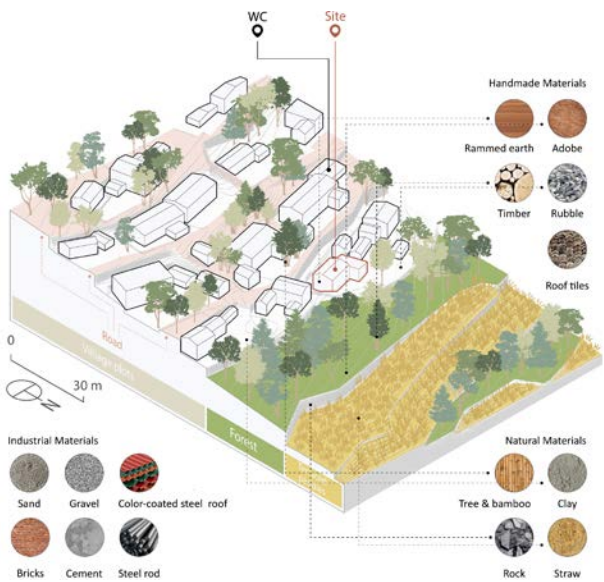

Fig. 4 Site information in the neighborhood scale

To validate the workflow, a design practice for a modern rammed earth house was conducted in Dashuijing Village, Yunnan Province, China. The process began with an understanding of the site: information about the village’s economy, infrastructure, local materials, and topography was collected. (Fig.4) Interviews and surveys were also conducted with residents and surrounding neighbors to gain insights into local living habits and the spatial needs of the residents for their houses. Data specifically related to the site’s weather, terrain, built environment, and the physical properties of rammed earth materials were collected to facilitate BPS. During this phase, the contextual information was translated into relevant values in the software, with the aim of ensuring that the simulation results accurately reflect actual conditions.

4.2 Room scale study

Next, it is necessary to understand the impact of different factors on the house's thermal performance and then develop guidelines that can assist in the design of the house. Room-scale simulations simplify the building model, enabling the quick generation of numerous simulation results. Analyzing these results with Excel is beneficial for formulating guidelines. After identifying the key output indicators for evaluating the quality of designs, multiple gradient values were assigned to each design variable, and extensive combinations of simulations were conducted during the BPS process. (Fig.5)

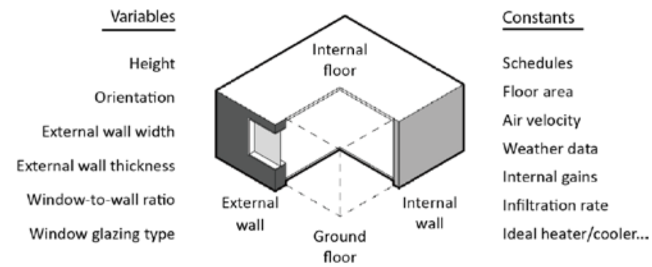

Fig. 5 Variables and constants in room scale study

We also conducted room-scale LCA to compare local materials with brick and concrete materials, to preliminarily assess their respective carbon emissions advantages and disadvantages. (Fig.6)

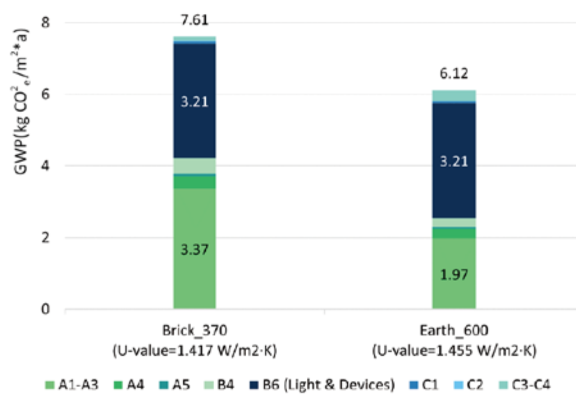

Fig.6 LCA in the room scale

After obtaining a large amount of simulation data, several analyses were conducted using Excel. Comparative analysis, regression analysis, and conditional analysis helped derive direct conclusions for each design variable. Conclusions included the impact of building orientation on the house's annual energy

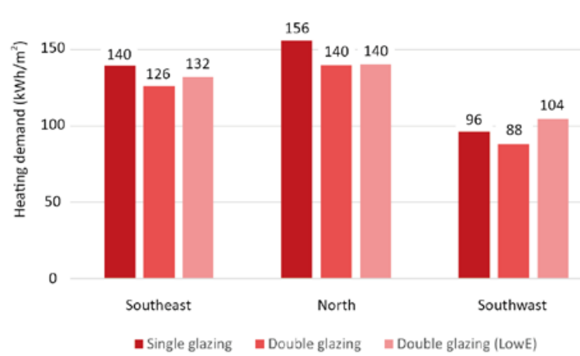

Fig. 7 An example: how orientation and window glazing types affect heating demand of a room

consumption, how wall thickness affects indoor temperature fluctuations, and how window shapes influence the distribution of DF. Additionally, the analyses highlighted the carbon emission advantages of rammed earth compared to brick-concrete structures. (Fig.7)

Further, based on these findings, several guidelines for designing rammed earth houses in the local context were summarized. (Fig.8)

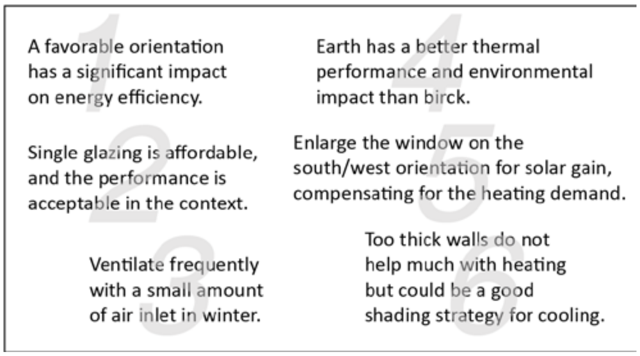

Fig. 8 Design guidelines for rammed earth house in Dashuijing village

4.3 House scale study

Following the guidelines and incorporating the actual needs of the homeowners, three design alternatives were developed. (Fig.9). To quantitatively assess and compare multiple schemes, BPS was integrated with LCA, establishing an analytical framework focused on annual energy balance and GWP per m2 of building area. The three alternatives, along with traditional brick-concrete houses, were calculated and compared using Excel charts to determine their respective strengths and weaknesses. This analysis enabled the identification of the most outstanding option among the alternatives, as well as the proposal of feasible strategies for optimizing building performance, reducing carbon emissions, and enhancing the design of a specific alternative. (Fig.10).

Fig. 9 Design alternatives

Through this workflow, a rural rammed earth housing design developed, which has been validated by data, allowing designers to convincingly inform villagers about the advantages of local materials (such as rammed earth) over brick-concrete structures, thus enhancing their acceptance of low-carbon design concepts. In the future, we will also apply this workflow in actual construction and conduct follow-up surveys and data collection after completion to verify that the building's energy consumption and carbon emissions calculated by the software align with real-world conditions. (Fig.11).

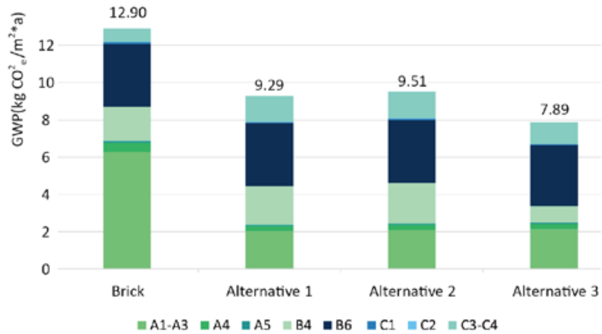

Fig. 10 An example: comparison of LCA results between different alternatives.

Fig. 11 photo by CCMCCF, rural rammed earth house construction in China

5. DISCUSSION AND LMITATION

This workflow derives guidelines and evaluates designs through data analysis. This makes the accuracy and completeness of the data critical to the credibility of the workflow. In this study, three main challenges affecting data quality also highlight areas for future improvement.

Applicability of Life Cycle Inventory: The data for materials (A1-A3, B2, B6, C3-C4) was sourced from the ÖKOBAUDAT database due to the lack of a comprehensive, transparent, and accessible LCA database in Yunnan or China. Variations in energy shares and manufacturing processes between Germany and China may introduce biases. Addressing these biases or finding more relevant data could be a future research topic.

Sample Size of Simulation: Our study involved six groups of variables across 972 cases for energy and daylight simulation, with each variable having only 3-4 values. It is uncertain whether these values adequately represent their impacts. However, the methods used, such as simulation, data collection, and standardized regression, are suitable for research employing machine learning with more cases.

Timeliness of Weather Data: The weather data used is out of date. Limited resources prevented access to more recent data. Given the global impact of climate change over the past 20 years, the specific effects of climate change in Yunnan on our simulation results are unknown. Future research should investigate the impact of climate change on energy consumption and thermal comfort.

6. CONCLUSIONS

When data is complete and accurate, this workflow offers robust guidance for design work, enabling designers to adapt various design elements to the specific local climate, terrain, and cultural practices. It emphasizes controlling the project's lifecycle carbon emissions from the earliest design stages. It promotes the adoption of low-carbon design practices domestically, providing designers with a clear and structured design roadmap.

Furthermore, this workflow not only ensures that the designs achieve outstanding building performance and low carbon emissions based on solid data but also grants architects significant decision-making power and creative freedom. Software and tools are primarily used to support architects by providing robust data backing. Additionally, this workflow plays a crucial role in architectural education, steering students towards evidence-based design and fostering more logical and pragmatic thinking in design approaches.

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DECLARATION OF INTEREST STATEMENT

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. All authors read and approved the final manuscript.

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