Thermal Studies of Feasible Ecological Architecture for China’s Loess Plateau Region

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ABSTRACT: Aiming to minimize fossil fuel use and environmental impacts caused by buildings, thermal design is one of the most effective approaches to achieve ecological architecture. For any given region, building designs have to follow the principles of ecological architecture. In this context, under the poor conditions of China’s Loess Plateau region, the limitation in the budget and resources for construction is the main challenge faced by ecological design. The study presented in this paper employs a methodology based on computer simulation and analyses. Based on locally available building elements and technology the paper carries out a series of alternative techniques and feasible thermal design strategies for this region, aiming to reach the most effective ecological approach. The relationship between the cost increase and improvement on the building thermal performance resulting from each technique is presented, so as to assist locals to design and construct the feasible ecological buildings according to their individual situations in economy, resources, functions and site conditions. This illustrates an inspiring way towards an ecological architecture suitable for China’s Loess Plateau region.

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INTRODUCTION
In terms of considerable environmental and social issues caused by fossil fuel use (Houghton and Intergovernmental Panel on Climate Change. Working Group I. 2001), it is necessary and imperative to minimize human dependence on fossil fuels, such as coal, oil and gas. Buildings play a vital role in solving these issues, since they are a significant fossil fuel consumer and thus producer of environmental impacts. (E Iain et al. 1996) This can be addressed by adopting a holistic approach towards ecological architecture. (Vale & Vale 2000) In current buildings, energy needed for thermal requirements, i.e. heating and cooling, is one of the biggest sources of fossil fuel consumption. (D&R 2005; Steven and Peter 1998) Accordingly, aiming to minimize fossil fuel use and environmental impacts caused by buildings, thermal design is one of the most effective ways to achieve ecological architecture. In addition to the basic strategies in the conventional way, thermal design has to follow the principles of ecological design, which for any given region need to be conditioned to the local situation so as to achieve the most effective ecological approach.

With this background, the paper focuses on the Loess Plateau region, which is located in north-western China. (Figure 1) It is characterized by the largest deposit of loess of the world, environmental degradation and low levels of economy, resources and technology for building. Under such poor conditions, the feasibility limited by budget and conventional resources for construction is the main challenge faced in the ecological design and construction of local buildings. In this context, based on the ecologically theoretical strategies and principles concluded from analyses of local conditions, and through computer thermal simulation studies with TAS (EDSL) this paper carries out a series feasible thermal design strategies for this region so as to reach the most effective ecological approach. It illustrates a feasible thermal design for a suitable ecological architecture for China’s Loess Plateau.

1. METHODOLOGY
The methodology of the study is based on the condition analysis and computer simulation experiments, and consists of three steps. Since the thermal design study here is aimed at determining suitable ecological architecture, it first needs to outline what the suitable ecological architecture for the Loess Plateau region would be, and to highlight the principles which ecologically thermal design should follow. Therefore, in the first step the current conditions of Loess Plateau are studied. According to the analysis of local conditions and relevant literature, a series of theoretical strategies and principles of ecologically thermal design for local buildings are concluded.

In the second step, thermal simulation with software TAS is employed in the thermal design study for a prototype, a classroom designed in Xifeng, which is a representative region on the Loess Plateau. Based on the theoretical strategies and principles already concluded, locally available building elements and technology are filtered and optimized thermally in the simulation experiments, aiming to provide sustainable, effective and feasible solutions for ecologically thermal design. Accordingly, the simulation study carries out a series of feasible techniques, which can effectively improve thermal performance of the building with a maximum approach to sustainability and practical feasibility.
Finally, according to thermal performances and cost efficiencies of these techniques, the thermal design strategies towards suitable ecological architecture for the Loess Plateau areas could be concluded.

2. DEFINING THE LOCAL SUITABLE ECOLOGICAL ARCHITECTURE

In order to define the suitable ecological architecture for the Loess Plateau region so as to highlight theoretical strategies and principles that ecologically thermal design for local buildings needs to follow, three aspects of local conditions, which generally influence building design, are studied, including the economy and resource for building, climate, and vernacular architecture.

The Loess Plateau region is one of the poorest parts of China. In the rural areas in particular, the mean per capita annual net income is as low as 228USD. (China. Gu ding zi chan tou zi tong ji si. 2004) However, the local construction generally has a comparatively higher cost than that in other parts of China due to the lack of conventional resources for building. Under such poor conditions, in order to approach a feasible ecological architecture, alternative technology for building needs to be considered in this region. In comparison to conventional building technology, alternative technology emphasizes minimum use of non-renewable resources, minimum environmental impacts and regional or sub-regional self-sufficiency in material and technology. (Dickson 1974) It is evident that the strategy of alternative technology is helpful not only to realize the maximum ecological approach, but also to enhance cost efficiency and feasibility for construction. In view of this, ecological design for local buildings has to reach high cost efficiency by utilizing local technology and locally available materials.

In terms of the local climate, the Loess Plateau region has a cold winter and comparatively moderate summer. Taking Xifeng as an example, the mean monthly air temperature in winter is as cold as -8.8°C. In summer it is below 25°C averagely. It has large temperature swings not only seasonally but also daily. (Figure 2) It is noted that fossil fuel consumed in existing buildings is mainly for heating in winter. Correspondingly, the thermal performance of buildings in winter needs to be emphasized by thermal design. According to the basic thermal design strategies (Baruch 1998), fossil fuel consumption for heating in winter could be reduced by two means, minimizing heat loss and utilizing natural energy. To be detailed, thermal performance of the building could be upgraded by including insulation & thermal mass, natural ventilation systems with heat exchanger and passive solar systems.

From the study of existing local buildings, it is found that there are some useful ecological elements embodied in the local vernacular architecture. These are characterized by earth-based dwellings, which can be classified into hill-side caves, sunken caves and earth-vaulted houses. (Figure 3) According to field investigation and measurement, it is found that compared to conventional buildings, the earth-based dwelling has desirable thermal performance and is environmentally friendly. Furthermore, it is far cheaper and can be easily constructed by locals. In winter the hill-side cave, for instance, only needs 10% of fuels for heating in conventional buildings due to its more stabilized and warmer indoor thermal ambience. However, its construction cost is only around 20% of the former since relying on simple techniques even occupants can build it by themselves with raw materials. These advantages result from the local building technology based on earth materials and natural products, such as adobe, rammed earth, straw etc. Particularly, in comparison to conventional building materials such as fired bricks and concrete, the earth-based material has outstanding advantages in thermal property, environmental performance and cost efficiency. Therefore, the local earth-based technology is worth including in the study of ecological architecture. According to literature (Louis 1983), it can be utilized in the form of the building envelope based on earth and natural products (straw, reed, timber, etc), and use of the ground temperature effect, such as underground or half-buried buildings, earth-air-tunnels, etc.

It can be said that these theoretical strategies concluded from the study of the three aspects can give and outline of what suitable ecological architecture would be. It can be summarized by the hypothesis that earth-material-based buildings combined with passive heating and cooling systems utilizing natural energy and alternative technology could achieve an optimal thermal performance with minimum fossil fuel use and environmental impacts. In this process, ecological thermal design needs to follow the principles of comfortable indoor temperature, cost-effectiveness, minimum embodied energy in the building and ease of construction.
3. THERMAL STUDY BY SIMULATION EXPERIMENT

3.1 Prototype Selection for Thermal Simulation Study

Before the thermal simulation step, the prototype for the study needs to be determined first. In this study, a classroom in a real project is employed as the prototype and the basic model for all simulation series. It will be built in Maosi village near Xifeng city.

The reason why a classroom is selected as the prototype is that compared to local conventional dwellings, the classroom generally has more complex thermal and technical challenges faced by thermal design, such as larger space dimensions, bigger internal volume to be operated and higher level of requirements for indoor ventilation. If these challenges are resolved, the relevant experiences would be significant for most types of conventional buildings.

The school in which the classroom will be built is on several levels of terraces, surrounded by hills from the northwest to east, and opening to the south. In the primary design, 12 classrooms of the school are planned into 6 units at two different levels, facing the south and spreading along the west-east contour lines. Each classroom needs to be accommodated by at least 40 students. According to local codes, the classroom will be around 54m²-floor area ($6 \times 9$m on plan) and appropriately 3.2m-height. This classroom together with its dimensions and surrounding environment will act as the basic model for the coming simulation experiments. (Figure 4)

![Figure 4: Site plan of the campus (classrooms)](image)

3.2 Model Setup of Experiment Series and Analysis

Based on principles and theoretical thermal design strategies as concluded, the simulation study aims to improve the designed classroom in thermal performance with a maximum ecological approach, by filtering and optimizing locally available natural materials, building technology and their incorporations in the classroom design.

In the study, the software TAS is used for thermal simulation. By comparison of measured data with the simulated result for a local existing classroom, it is validated that by imputing relational component parameters and weather data (Figure 5), the software can basically predict dynamic indoor temperatures in the simulated building models as set up.

After validation, a series of simulation experiments are set up in two phases to study and verify available technical possibilities of improving thermal performance of the classroom. In the process, the hourly climatic data in Typical Meteorological Year (TMY) in 1995 obtained from the program, MeteoNorm V5.0 by METEOTEST, are employed. In terms of the local cold winter and moderate summer, the winter environment (the coldest two weeks in January) is
the focus for all simulation series. The indoor air temperature is emphasized to assess the building thermal performance.

![Figure 5: Software validation](image)

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The two phases of the simulation experiments are illustrated in Figure 6. In the first phase, according to the two basic strategies of thermal design, i.e. minimizing heat loss and utilizing natural energy, the simulation experiments are grouped in three parts: thermal mass & insulation, passive solar system and natural ventilation system with heat exchanger. Among them, based on the basic classroom model locally available materials, building elements and their incorporations get filtered and optimized thermally by simulation, to reach high thermal performance and cost efficiency.

![Figure 6: The experimental series of thermal simulation](image)

For thermal mass and insulation, locally available materials are examined for the building envelope in the form of wall, roof and glazing. It is found that local earth-based materials and natural products are optimal options for respectively thermal mass and insulation. With a small cost increase and less embodied energy, heat loss through the building fabric can be greatly reduced by employing natural thermal mass and insulation, such as the thick adobe wall and adding a straw layer on the local conventional pitched roof. To maximize utilization of solar energy for heating, a series of conventional passive solar systems are tested in terms of solar collector’s positions of the southern wall and roof. After optimizing their components and spatial elements, it is noted that the sunspace and roof
sunspace (the local pitched roof with a suspended ceiling straw-based-insulated, and with the southern sloping side glazed) can effectively increase indoor air temperature of the classroom, for they function as not only a solar heater but also a thermal buffer.

In addition, to reach a healthy indoor air quality for 40 students, according to ASHRAE Standard (ASHRAE 2004), an air exchange rate of at least 3.5L/s is needed. In order to minimize heat loss by such much ventilation, the natural ventilation system with heat exchanger is studied. It is noted that the passive solar system modified in air circulation mode may pre-warm or sometimes even heat fresh air from outside. Due to the terraces in the school site, the dug tunnel with 2.8-m-depth and 1.2m thick sheltered-earth is available to attach the north side of the classroom. By studying the relevant tunnel elements, such as length, section area, air flow rate, etc., the optimized earth-air-exchange tunnel can effectively moderate fresh air passing through it. From the experiments, it is found that by incorporation with the chimney; comparatively the earth-air-exchange tunnel could be the most effective and steady heat exchanger to greatly reduce indoor heat loss by ventilation. In addition, except on overcast days, only powered by a small fan the roof sunspace also has the potential to perform as a heater especially after noon, so as to further enhance the indoor temperature.

In the second phase, in order to optimize their incorporated thermal performance and then thermally improve the classroom design, the techniques obtained from the last phase are incorporated in forms of several incorporated system models. Based on thermal mass and insulation, extra components, such as a Trombe wall, sunspace and tunnels, are incorporated in several ways with different internal air circulation (Figure 7). In operation, occupants can control the indoor thermal ambience only by adjusting relevant components, such as the tunnel door and fan speed. It is found that through this incorporated system for most of the heating season, the indoor thermal environment of the classroom may achieve a desirable comfort level without any extra fossil fuel consumption.

As a result, through the two phases of simulation, based on earth-based materials and natural products, the study carries out a series of feasible techniques which can effectively upgrade the thermal performance of the classroom. According to their construction means and costs, they are grouped into three aspects: thermal mass and insulation; extra components and incorporated system. (Some of them are shown in Figure 7)

4. THERMAL PERFORMANCE PREDICTION
To further predict the thermal performance and cost effectiveness of each optimized technical option, simulation is extended for the whole heating season (Mid Nov to Mid Feb) based on the classroom model. Three cases of the ventilation modes are simulated. The first one is ventilated at 3.5L/s (6.1 ACH) and occupied by 40 students. The second is only ventilated and the last one is simulated only by infiltration without any occupant. The first and the last one can basically illustrate the thermal effects of these techniques on two types of buildings respectively, including those being able to fulfill and those not being able to fulfill the ventilation requirement. The sky condition is taken into consideration. According to the local weather record, during the heating season, fine, cloudy and overcast days account for 25%, 37% and 38% respectively. Based on the setup above, these techniques are gradually employed in the basic classroom model and simulation.

By simulation, the mean of the daily operation indoor temperatures during the heating season can be obtained from each simulation case. To compare with the thermal performance in the conventional classroom, the differences of the indoor temperature between each simulation case and conventional case are sorted out and generate in Figure 8. In this figure, the absolute indoor temperatures of the conventional classroom acting as the base line are shown by the black solid line in Y axis. The colour lines marked with letters illustrate the increase in indoor temperature resulting from the employed techniques. Meanwhile, based on the local experiences and observations, the lowest acceptable air temperature for local villagers in this season is taken as 4.3. Compared with the temperature in the conventional classroom, the difference in the lowest acceptable temperature is marked with black dotted line.
Figure 8: Comparison of the thermal contributions from the developed techniques, based on mean indoor temperatures in different sky conditions.

From the figure, it is evident that in both ventilated and non-ventilated cases, during fine and cloudy days, the indoor thermal environment may reach the lowest acceptable level only by employing thermal mass and insulation, as the blue line showing. On overcast days the indoor temperature is still colder than the acceptable range. However, in addition to thermal mass and insulation, the employment of ‘extra components’ can make the indoor temperature higher than the acceptable level. For example, for the ventilated case, as the green line showing simply by adding the earth-air tunnels, an acceptable indoor temperature can be obtained, and the indoor temperature is much higher than the lowest acceptable level. The sunspace can also bring a similar effect to the un-ventilated classroom. If replace the extra components with the incorporated system, the thermal performance of the classroom in any case could be greatly improved to a desirable level.

To further illustrate the relationship between the cost increase and improvement of building thermal performance resulting from each technique, Figure 9 is generated based on the mean indoor temperature during the whole heating season. The Y axis shows the indoor temperature increase compared to the conventional classroom. The X axis is the increase in total construction cost. The grey curve is for the ventilated and occupied case, the dot one for only ventilated case, and the solid curve for the infiltration case.

Figure 9: Relationship between construction cost and thermal performance of the developed techniques.
From the figure, it is obvious that thermal performances resulting from the adoption of these techniques are proportional to their construction costs. Meanwhile, the most basic technique, such as earth-based thermal mass and insulation, tunnels, are most effective in both cost and thermal performance. They may increase the mean indoor temperature in both the ventilated building and the building only with infiltration to the level near or even higher than the acceptable range. Beyond that, further improvement of the thermal performance would cost much more and be less effective, though the more advanced incorporated system can give a better thermal performance.

CONCLUSION
Since in the above thermal prediction the two simulated cases with ventilation and only with infiltration can illustrate the types of buildings classified with different ventilation requirements, the following ecological thermal design strategies can be concluded according to the performances of these optimized techniques in thermal effect and cost-efficiency.

For most types of buildings in the Loess Plateau region, thermal mass and insulation are necessary, and they are the most effective way to improve the thermal performance of buildings; For buildings requiring low ventilation rates, such as dwellings and offices, thermal mass and insulation could result in an acceptable thermal comfort level for most of the heating season, without any fossil fuel consumed for heating; For buildings that require high ventilation rate, such as classrooms, in addition to thermal mass and insulation, the earth-air-exchange tunnel is also highly recommended, since it can significantly improve the indoor thermal environment to a comfortable level with only a small increase in budget. However, to meet a higher thermal performance, the incorporations of passive solar system is also appreciable in spite of its higher construction cost, and hence could be selectively employed.

Based on this strategy and relevant optimized techniques for thermal design, in practice local builders may use Figure 7 and 8 as references, and selectively employ some of them according to their individual situations in economy, resources, functions and site conditions, so as to achieve their most effective ecological approach. In this case, the indoor comfort could be achieved with minimum fossil fuel consumption and expenditure for heating. Moreover, most materials recommended in these strategies are based on earth and natural products, and hence not only have much lower embodied energy than conventional materials, but also are affordable to most local villagers. Meanwhile, since these techniques are derived from local vernacular or conventional architecture, they could be manipulated easily by local builders or even inhabitants. Therefore, it can be concluded that depending on these optimized techniques and strategies, the developed architecture would be economical with desirable sustainability and constructional ease, and hence feasible and suitable for the conditions in Xifeng areas and even the whole Loess Plateau region.

However some other considerations still need to be addressed in future studies, such as thermal performance in summer, further detailed techniques in practice and feasibility in other types of buildings. After all, the developed strategies of ecologically thermal design from the study still illustrate an inspiring way towards ecological architecture suitable for Loess Plateau areas of China, and worth further developing. More importantly, though the study focuses only on the severe climate zone, the methodology based on condition analyses and simulation experiments is also significant for the tropical region with similar conditions.

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