Integrative Passive Design for Climate Change: A New Approach for Tropical House Design in the 21st Century

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Abstract

This article presents a new approach to passive building design which takes into account the impacts of climate change. The approach involves considering the relative performance of a range of low-energy, passive design alternatives under a projected future climate. A low-cost housing project in the hot-humid tropics of Thailand is used herein to demonstrate the application of this new design approach. Theoretical analysis is carried out and shows that if the potential changes in the ambient temperature, solar radiation and humidity driven by climate change are taken into account, a combination of a number of passive design techniques, including passive cooling, is likely to be required to achieve interior thermal comfort and energy efficiency in these houses. To eliminate the requirement for air-conditioning, the houses should be laid out in a staggered fashion on the plot to maximize airflows between the houses. Each house would also benefit from having its service areas (e.g. kitchen and bathroom) located on the west side to act as a thermal buffer for its main spaces (e.g. bedroom and living room). A combination of a double roof and shaded double façades would also be advisable to provide effective protection from strong solar radiation. The use of thermal mass in conjunction with passive evaporative cooling and natural ventilation would help further to provide the cooling needed in more extreme weather. The analysis shows that, with all the above techniques in place, up to a 95 per cent reduction in energy use for cooling could be achieved in the passive house, compared to the energy used in a typical air-conditioned house operating in the same conditions, while achieving a comparable level of comfort. A discussion on how to generalize this new design approach to houses in different settings is provided.

Keywords: Passive design, Natural ventilation, Thermal mass, Evaporative cooling, Climate change, Tropical house

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1. Introduction

It is widely accepted that the most effective measure to mitigate the impacts of climate change is to curb the emission of green house gases (GHG), especially CO_2 from the burning of fossil fuels in energy production and use. Buildings currently consume as much as 26% of the world's energy (The Intergovernmental Panel on Climate Change [IPCC], 2007b), and are a major contributor of CO_2 emission. In 20 years' time, GHG emissions from buildings in developing regions are expected to double today's values (IPCC, 2007b), and so ensuring energy efficiency in these buildings will be key to mitigating the impacts of changing climate. However, continuing changes in temperature, humidity, precipitation and solar radiation could cause buildings which perform well today in terms of energy efficiency and comfort to underperform in the future. To ensure that this does not happen, the design of buildings today will need to take into account the potential changes in climate in the future.

Low-cost houses are a building type that has been constructed abundantly around the world, especially in developing regions. This type of building presents a challenge to the designer in terms of achieving energy efficiency and thermal comfort, owing largely to the fact that it has to be built cheaply. For example, only a few per cent of such houses can afford air-conditioning, insulation or high-performance windows, making them uncomfortable to live in most of the time. Ensuring that low-cost houses will perform satisfactorily under climate change presents an even greater challenge.

Since it is unlikely that low-cost houses will be able to incorporate expensive mechanical cooling/heating devices to cope with more extreme climates, passive design is likely to be the only viable solution for these houses. Passive design can be defined as the design that uses the prevailing climate, naturally created forces and thermal energy to condition interior spaces. A good passive building generally consumes much less energy than an active (mechanically assisted) one. However, since passive design relies heavily on the natural environment, changes in climatic conditions, such as temperature, solar radiation and humidity, could render certain passive design techniques which are effective today ineffective in the future.

Addressing this challenge, the present paper explores how passive design techniques could be developed and implemented to ensure its effectiveness under climate change. It uses a low-cost housing project in the hot-humid tropics of Bangkok, Thailand, as a case study. This housing project has been commissioned by the National Housing Authority (NHA) of Thailand, and the authors and their team have been tasked with developing, among other things, a design of a detached house that would perform satisfactorily in terms of energy efficiency and thermal comfort over the coming few decades.

In presenting our work in this paper, climate change and its impact on thermal comfort are discussed in Section 2. Then, techniques of heat gain reduction and passive cooling are investigated in Sections 3 and 4, respectively. The results of this investigation are subsequently applied to the design of the house in Section 5, and its performance is evaluated in Section 6. Section 7 then generalizes the design approach for houses in different settings, and finally Section 8 presents conclusions and discusses future research opportunities.

2. Climate change and impact on thermal comfort

It is useful to start by looking at how much of an impact climate change is likely to have on thermal comfort. The monthly average exterior air temperature and exterior relative humidity in Bangkok at present range from 26.4-30.6°C and 58-81 per cent, respectively (US Department of Energy [DOE], 2009). To estimate how comfortable these current conditions are, an adaptive comfort model which takes into account acclimatization is used (Auliciems, 1981; Auliciems & Dedear, 1986). In this model, the neutral temperature, T_n, defined as the temperature at which most people feel comfortable, is given as a function of the monthly average temperature of the exterior air, $T_{o.av}$,

$$T_n = 17.6 + 0.31\ T_{o.av} \qquad (1)$$

This neutral temperature is not to be applied as a single, precise value, however, and humans' natural tolerance to temperature should also be taken into account. It is suggested that a tolerance range of T_n +/- 2.5°C should be used (Auliciems , 1981; Auliciems & Dedear, 1986), and this is adopted in the present analysis.

In addition to the effect of temperature, the effect of humidity on thermal comfort needs to be considered. For this, a psychrometric chart is used. Figure 1 shows the present-day ranges of exterior air temperature and humidity in Bangkok in May, one of the hottest months of the year, as plotted on a psychrometric chart as a black horizontal thick line. To assess the comfort level of these exterior conditions the neutral temperature band discussed earlier is plotted onto the Standard Effective Temperature (SET) lines shown on the chart (Gagge, Fobelets, & Berglund,

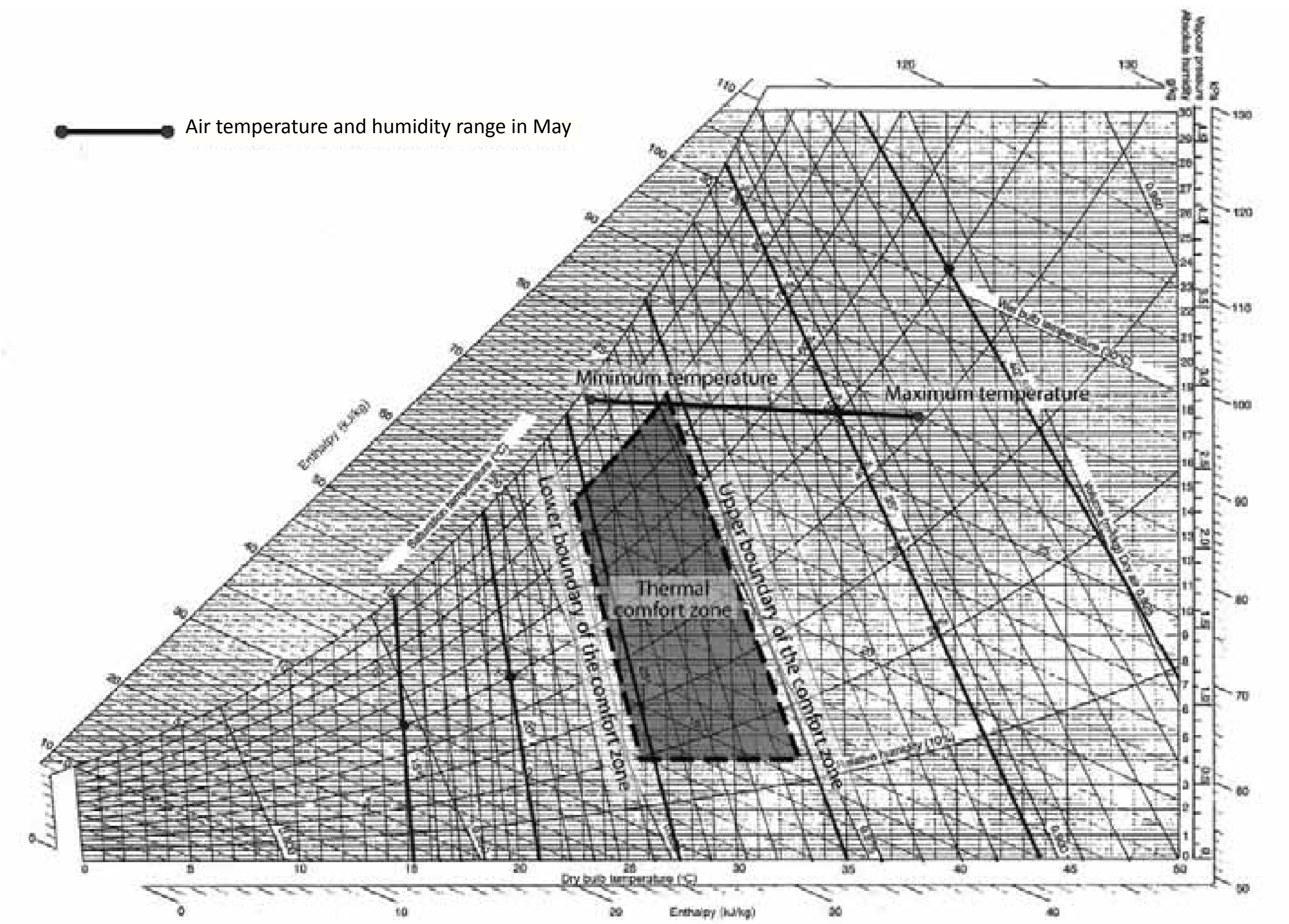
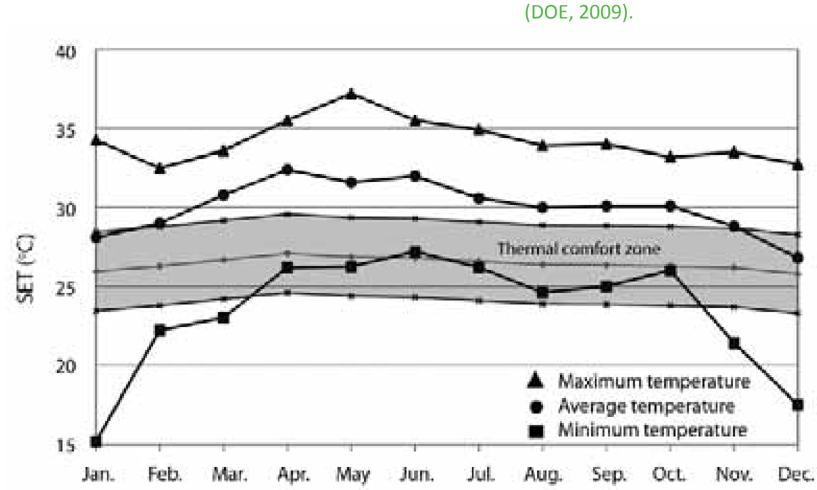


Figure 1. Example of thermal comfort zone for Thai people and air temperature range in the month of May (DOE, 2009) plotted on a psychrometric chart.

1986). To ensure indoor thermal comfort, neither should the relative humidity exceed 80% (Khedari, Yamtraipat, Pratintong, & Hirunlabh, 2000) nor should the absolute humidity be lower than 4 g/kg of dry air (Szokolay, 2004). These values thus respectively form the upper and lower boundaries of humidity for thermal comfort. A combination of the above values of the neutral temperature band and humidity then mark the present-day comfort zone for May, as indicated by the shaded area.

A series of comfort zones can be identified for all the months in the year and the results plotted in relation to today's annual profile of the exterior SET identify the period during which the exterior air becomes uncomfortable (Figure 2). It can be seen from Figure 2 that the average monthly temperatures in Bangkok lie within the comfort zone for as many as 25% of the year, with another 33%

Figure 2. Thailand's current monthly climatic conditions (DOE, 2009).



of the year seeing the average exterior temperatures just above the comfort zone. A large departure from comfort occurs relatively rarely, mainly when the exterior temperature becomes more extreme, such as during the summer months of March through July.

However, it is expected that, by the end of the 21st century, climate change will cause the temperature in the areas around Bangkok to increase on average by approximately 3°C (IPCC, 2007a). It is also predicted that precipitation will increase by 5-10% in the monsoon season (June-August) but decrease by 10-20% in the dry season (December-February) (IPCC, 2007a). In designing our prototype house, we consider a worst-case scenario for cooling, and assume that the absolute humidity will increase by 10% in the monsoon season but decrease by 10% in the dry season. This projected climate is plotted in Figure 3 along with the corresponding comfort zone shown as the shaded area. It can be seen that climate change can push the exterior temperature in Bangkok well outside the comfort zone for most of the year, and make even cooler months such as January, which is at present reasonably comfortable (Figure 2), uncomfortably warm. It is clear then that in order to bring about thermal comfort under climate change, additional cooling is unavoidable. A range of passive cooling techniques is explored in Section 3.

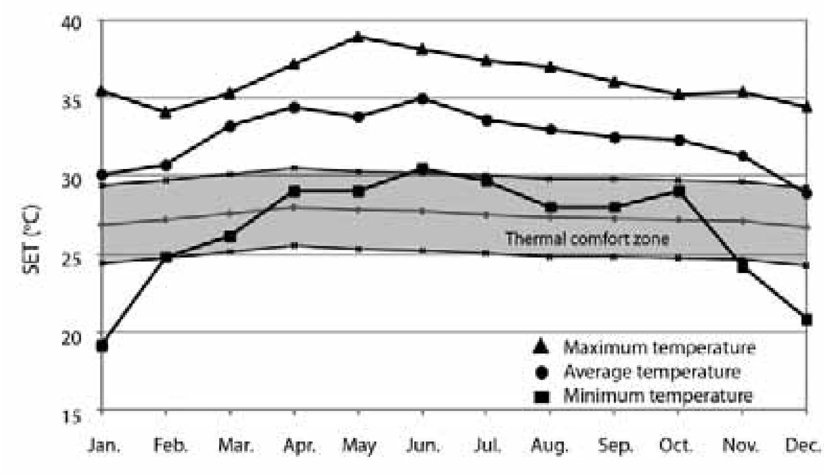


Figure 3. Thailand's projected monthly climatic conditions at the end of the 21st century (DOE, 2009; IPCC, 2007a).

3. Passive cooling techniques

A range of relatively low-cost passive cooling techniques exists which could be used to bring about thermal comfort in our house. In general, these techniques are classified according to their cooling mechanism into:

- ventilative cooling,
- evaporative cooling,
- thermal mass cooling,
- radiant cooling, and
- desiccant dehumidification.

Ventilative cooling utilizes natural air movement to remove heat and moisture from the indoor air. It generally works well in hot-humid climates during the period when the exterior air temperature and humidity are slightly above the comfort zone. Evaporative cooling extracts latent heat from the surroundings, thus reducing the temperature of the air while increasing its humidity. It is generally used in hot-arid climates but can also be applied to hot-humid regions in periods of relatively low humidity, such as during daytime in summer. Thermal mass provides cooling by delaying conductive heat gain from the exterior surface of the building into the interior space, and by absorbing internal heat gains, dampening the amplitude of the indoor temperature swing. It is generally used in areas where there are large diurnal swings in the exterior air temperature such as in hot-arid climates, although it can also be used in hot-humid areas during periods where the diurnal temperature variation is sufficiently large. Radiant cooling removes heat from the building surface by means of long-wave radiation to the night sky. Its effectiveness, however, is very limited in regions where the night sky is usually cloudy such as the tropics. Desiccant dehumidification uses a substance which absorbs moisture from the air to reduce its humidity. Dehumidification, however, usually relies on a rather complicated system which requires regular maintenance, and therefore is probably impractical for a low-cost, mass-produced house. For these reasons, only ventilative cooling, evaporative cooling, thermal mass and combinations thereof are considered in the design of our prototype house.

3.1 Ventilative cooling

Air movement increases evaporative and convective heat loss from the skin of building occupants, making them feel cooler. Thermal comfort zone is found to expand with increased air velocities according to the relation (Szokolay, 2004)

$$dT = 6\,v_e - 1.6\,v_e^2 \qquad (2)$$

where dT (°C) is the perceived reduction in the air temperature due to air movement, v (m/s) is the air velocity, and v_e = v - 0.2 is the effective air velocity.

In general, people in non-air conditioned buildings accept a wider range of indoor air temperatures and indoor air velocities than those in air conditioned buildings (Givoni, 1994). Figures 4 and 5 show how cooling by air movement can help expand the comfort zone under climate change. In both figures, a maximum air speed of 2 m/s is considered,

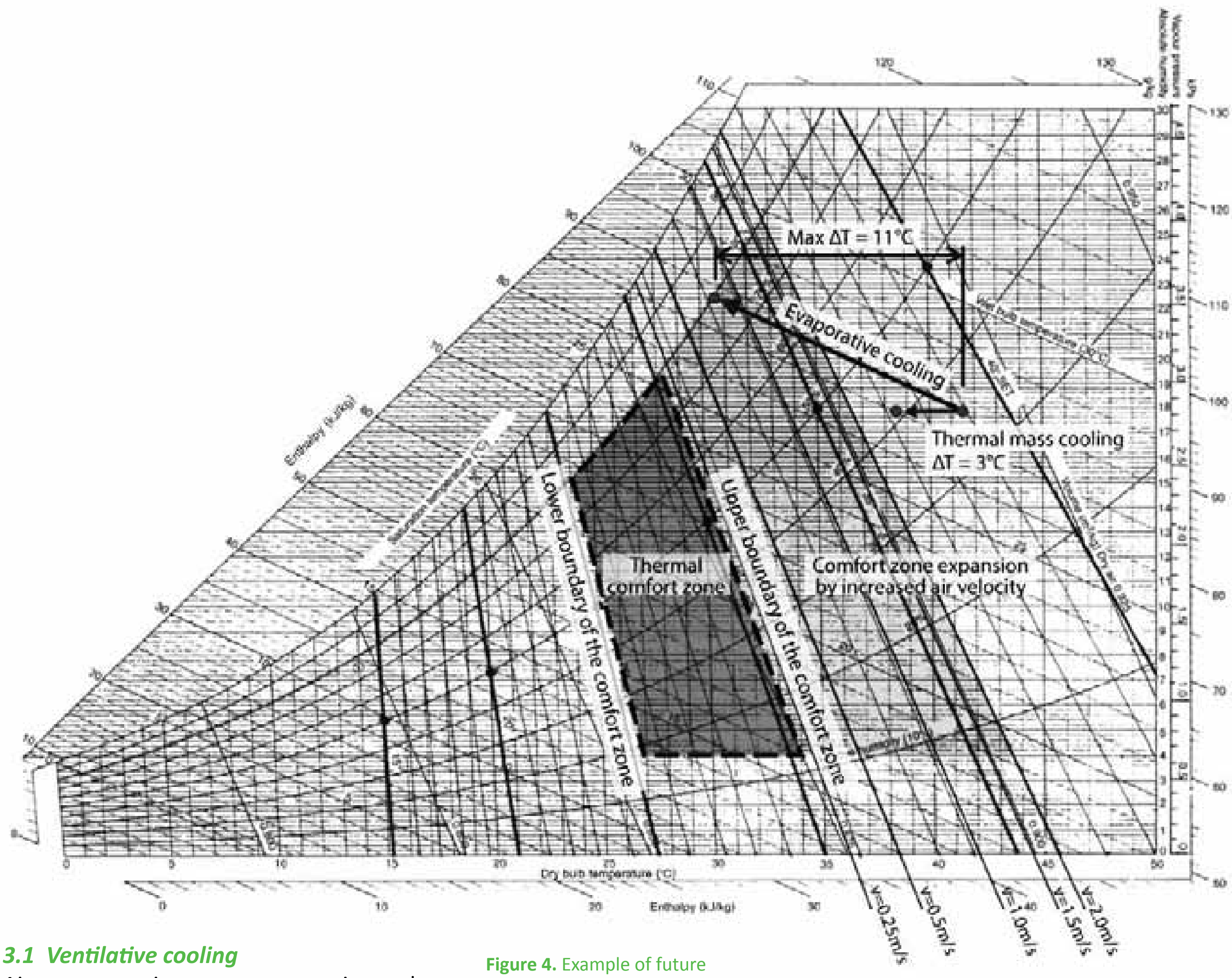


Figure 4. Example of future thermal comfort zone for Thai people in May as plotted on a psychrometric chart. The figure shows the expansion of the comfort zone due to increased air velocity and the effects of evaporative cooling and thermal mass.

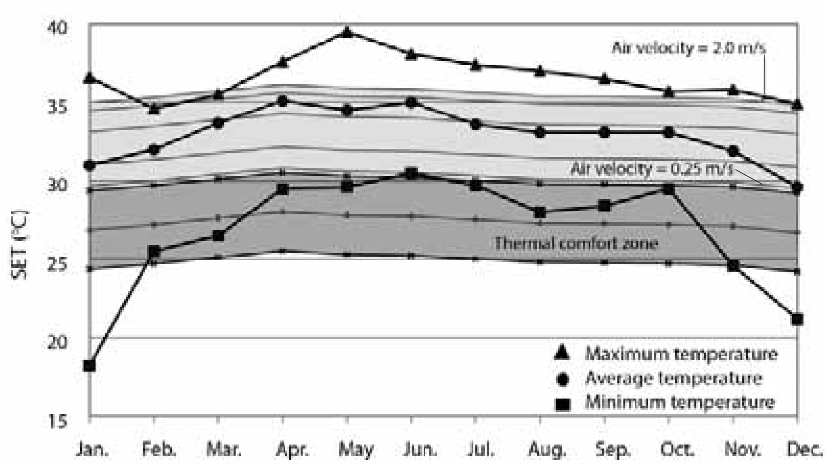


Figure 5. Thailand's climatic conditions under climate change (DOE, 2009; IPCC, 2007a) and the potential of ventilative cooling in expanding the comfort zone.

since a higher indoor air speed will generally be regarded as a disturbance (Givoni, 1994). At this air speed, the maximum cooling effect obtained, using Eq (2) is dT = 5.6°C. Figure 5 shows that, although ventilative cooling can bring the average temperatures in Bangkok to within the comfort zone for most of the year, the temperatures during the hottest months in summer are still uncomfortably high. This suggests that ventilative cooling alone cannot bring about thermal comfort under climate change, and that other passive cooling techniques are also required.

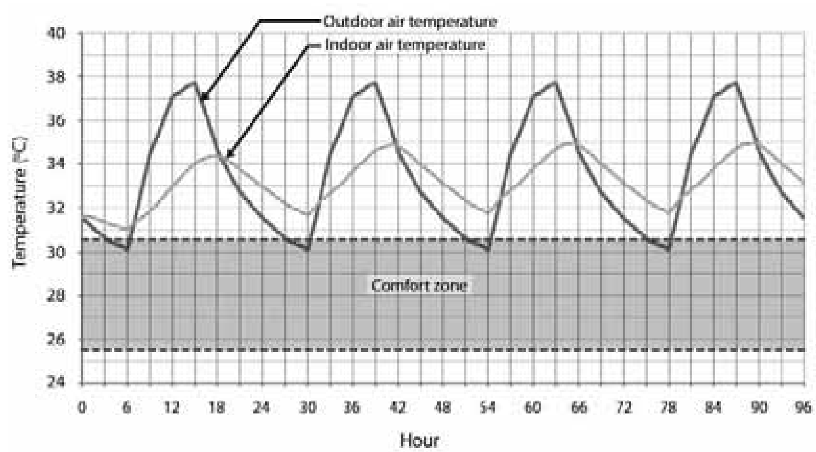


Figure 6. Simulation result using PasCal (v.1.0) showing indoor and outdoor air temperature profiles of a house with 30-cm thick concrete walls.

3.2 Evaporative cooling

When water evaporates, the latent heat of vaporization is taken from the surroundings, leading to the cooling of ambient air. The process is adiabatic, and the air temperature decreases and the humidity increases along the enthalpy line on a psychrometric chart (Figure 4). Since dry air can hold more moisture, it has higher evaporation potential than moist air, and hence greater potential for cooling. In hot-humid areas such as Thailand, evaporative cooling is therefore more effective during the day and in drier months such as January, when the relative humidity is relatively low, than at night or in other seasons such as the monsoon.
In theory, a reduction of the ambient air temperature by up to 11°C can be achieved in May, the hottest month of the year, although in practice the cooling potential is likely to be lower since the maximum efficiency of evaporation rarely exceeds 80%. Taking this into account, it can be shown that evaporation alone cannot be relied upon to bring about thermal comfort in hot-humid climates, except in the driest months in winter.

3.3 Thermal mass cooling

To study the cooling effect of thermal mass in a naturally ventilated building, PasCal (v.1.0) program (Chenvidyakarn, 2009) is used. This computer program is chosen because it can model the transient evolutions of the indoor temperature and ventilation flows in a naturally ventilated building by allowing the interior temperature, ventilation rate and the temperature of thermal mass to evolve naturally and simultaneously according to the variation in the exterior temperature and heat gains. Modeling results show that a small building of 4 m x 4 m in size with four well-shaded 30-cm thick concrete walls and a typical ventilation rate and internal gains will have its peak temperature reduced by about 3°C and shifted back by about 3-4 hours (Figure 6). The modeling also shows that daytime spaces would benefit from having a high mass envelope which cools the spaces during the day, while nighttime spaces would benefit from having a light-weight envelope which cools down quickly at night following the exterior air temperature. To remove heat stored in the massive building envelope during the day and rejuvenate it, thermal mass should be used in conjunction with nocturnal ventilation. Figure 4 shows that, due to the relatively small diurnal swing in the exterior air temperature in the hot-humid climate, thermal mass alone is insufficient to bring about thermal comfort under climate change especially during periods of more extreme weather such as in May.

3.4 Combinations of passive cooling techniques

The above analysis suggests that a combination of multiple passive cooling techniques should be used if thermal comfort is to be achieved throughout the year under climate change. Table 1 shows the effectiveness of individual cooling techniques and combinations thereof. In the table, thermal comfort

Month	1 Technique			2 Techniques			3 Techniques	
	Natural ventilation	Evaporative cooling	Thermal mass cooling	Natural ventilation + Evaporative cooling	Natural ventilation + Thermal mass cooling	Evaporative cooling + Thermal mass cooling	Natural ventilation + Evaporative cooling + Thermal mass cooling	
January	✘ v>2.0m/s	✔ SET=29.2	✘ SET=33.7	✔ v=0.0m/s	✔ v=1.5m/s	✔ SET=28.1	✔ v=0.0m/s	SET=28.1
February	✔ v=1.5m/s	✔ SET=24.7	✘ SET=32.2	✔ v=0.0m/s	✔ v=1.0m/s	✔ SET=23.4	✔ v=0.0m/s	SET=23.4
March	✔ v=2.0m/s	✔ SET=25.5	✘ SET=33.6	✔ v=0.0m/s	✔ v=1.0m/s	✔ SET=24.4	✔ v=0.0m/s	SET=24.4
April	✘ v>2.0m/s	✔ SET=29.2	✘ SET=35.4	✔ v=0.0m/s	✔ v=1.5m/s	✔ SET=28.0	✔ v=0.0m/s	SET=28.0
May	✘ v>2.0m/s	✘ SET=33.2	✘ SET=37.3	✔ v=1.0m/s	✘ v>2.0m/s	✘ SET=32.4	✔ v=1.0m/s	SET=32.4
June	✘ v>2.0m/s	✘ SET=33.5	✘ SET=36.2	✔ v=1.0m/s	✘ v>2.0m/s	✘ SET=32.7	✔ v=1.0m/s	SET=32.7
July	✘ v>2.0m/s	✘ SET=32.5	✘ SET=35.4	✔ v=1.0m/s	✔ v=2.0m/s	✘ SET=31.8	✔ v=0.0m/s	SET=31.8
August	✘ v>2.0m/s	✘ SET=30.5	✘ SET=34.4	✔ v=0.5m/s	✔ v=1.5m/s	✔ SET=24.5	✔ v=0.0m/s	SET=24.5
September	✘ v>2.0m/s	✘ SET=30.2	✘ SET=34.2	✔ v=0.5m/s	✔ v=1.5m/s	✔ SET=29.4	✔ v=0.0m/s	SET=29.4
October	✘ v>2.0m/s	✔ SET=29.5	✘ SET=33.2	✔ v=0.25m/s	✔ v=1.0m/s	✔ SET=28.6	✔ v=0.0m/s	SET=28.6
November	✘ v>2.0m/s	✘ SET=28.8	✘ SET=33.5	✔ v=0.0m/s	✔ v=1.5m/s	✔ SET=27.8	✔ v=0.0m/s	SET=27.8
December	✔ v=2.0m/s	✔ SET=24.8	✘ SET=32.6	✔ v=0.0m/s	✔ v=1.0m/s	✔ SET=23.8	✔ v=0.0m/s	SET=23.8

Comfortable | Almost | Uncomfortable

Table 1. Comfort conditions of the passive cooling techniques.

is categorized into three levels: 'comfortable' when the conditions are well within the thermal comfort zone, 'almost' when the conditions are at the borders of the comfort zone, and 'uncomfortable' when the conditions are well outside the comfort zone. In Table 1, the air velocities required to shift the exterior conditions into the comfort zone when ventilative cooling is used are shown, along with the resultant SET achievable with evaporative and thermal mass cooling. It can be seen from Table 1 that the hot-humid tropics of Bangkok requires either a combination of evaporative and ventilative cooling or a combination of all three cooling techniques to achieve thermal comfort. The table also shows that without thermal mass, the air velocities required to bring about comfort will be quite high, especially in warmer months, and mechanical fans may be needed for these periods.

4. Techniques of heat gain reduction

Passive cooling will be ineffective if heat gains are not reduced, especially in the future when solar radiation and ambient air temperature are likely to be more severe. Techniques used to minimize heat gain generally include shading and zoning. Shading can be both in the form of a landscape element such as a tree canopy and in the form of an exterior building element such as a fin and an overhang. The key is to protect the building, especially its openings, from direct sun, and since no heating is needed in the hot-humid region, complete protection from direct sun is usually advisable.

In addition to providing shading, appropriately orientating the building can generally help reduce a great deal of heat gain. In regions near the equator such as the tropics, it is usually advisable to avoid strong solar gain from the east and west in particular. This can be achieved by orientating the building so that its shorter sides face east and west. However, to achieve complete solar protection, further care should also be taken to prevent solar penetration from the north and the south by providing appropriate shading. Also, a building should be oriented and designed to capture the prevailing winds (from the north-north-east and south-south-west in Thailand) and exploit them for ventilative cooling.

Service spaces such as the kitchen and bathroom can help buffer solar gain from the east and west for primary spaces such as the bedroom and living room. A further thermal buffer can be achieved through semi-outdoor spaces such as a covered balcony between the layers of a double-skinned façade or a double roof. Our analysis using PasCal suggests that using a secondary space as a thermal buffer is generally more effective than incorporating insulation in the building envelope because the former allows conductive heat loss to take place more easily when the exterior air temperature is relatively low compared to the interior temperature, thus allowing the building to cool down at night while reducing conductive and radiative heat gains during the day.

5. Designing the low-cost house: the integrative approach

The above cooling and heat gain reduction techniques are applied, as a case study, to the design of a prototype low-cost house in Bangkok, Thailand. Since many of the deign decisions are made based on other considerations than climatic, such as social and economic, it would be useful to outline the framework of this project as set out by NHA of Thailand, the funder. Their requirements include the following:

- The house must perform well as part of a housing project as well as a stand-alone unit.
- The house must accommodate a small family of 2 adults and 2 children.
- The plot area is 200 sq.m.
- A setback of 2 m from the plot boundary must be accommodated for walls with openings, following the local building regulations.
- A total useable area of approximately 80 sq.m. must be provided, with a possibility for future extension.
- The floor should be raised to provide flood protection.
- The design must accommodate wheelchair users.
- The house must be affordable for the low- to middle-income people.

5.1 Site planning

Site planning is an important first step of passive design. In general, houses in a low-cost housing project are laid in rows, and because their plots are usually small and located adjacent to one another, ventilative cooling is generally hard to achieve. However, we have found that ventilative cooling can be encouraged by laying out rows of houses in staggered configuration to allow prevailing winds to flow through to houses located in the leeward rows (Figure 7). This layout should be used in conjunction with a compact form of house with minimal flow frontal area to minimize blockage of wind to houses in the leeward rows (Tantasavasdi, Srebric, & Chen, 2001). The distances between the houses should be as great as possible to allow wind to flow through easily. In our case, the prevailing winds in Thailand are from the north-north-east and south-south-west; therefore, each house is designed to have shorter north and south façades with a large open space on the plot along the north-south axis as a wind passage. Although such orientation contradicts to the generally accepted rules of thumb that buildings should have short east and west façades to minimize solar radiation, it allows the whole community to benefit from the prevailing wind.

5.2 Building design

The prototype house is designed by integrating all the programmatic requirements, the results from the climatic study, and passive cooling and heat gain reduction techniques into the recommended building

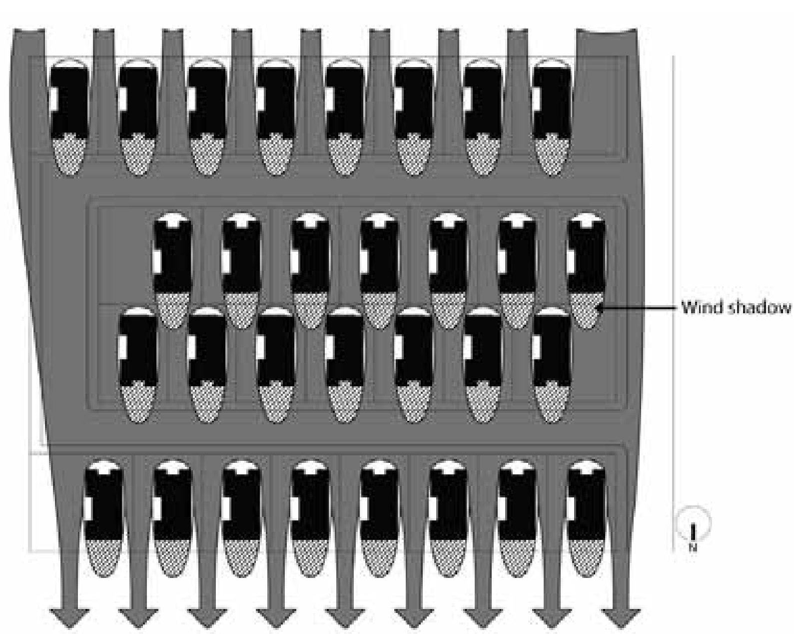


Figure 7. Recommended site planning with staggered house layout encouraging effective ventilative cooling.

form and orientation discussed in Section 5.1. All of the primary spaces, elevated to the second level for flood protection, are arranged within an oblong floor plan that is shorter on the north and south sides (Figures 8 and 9). The house is placed close to the western boundary of the plot and its plan can be mirrored along the east-west axis when the entrance to the plot is on the south side rather than on the north as shown in Figure 9. This allows the open space of every house to always be located on the east side of the plot, and in turn shaded by the house itself in the afternoon and become conducive for outdoor activities. To protect the primary spaces, namely the bedrooms and living room, from strong solar radiation, service areas, namely the kitchen and bathroom, are located on the west side of the house. Each primary area is also designed to have openings on two opposing or adjacent walls to encourage natural ventilation. Other building features include a ventilated double roof, shaded double-skinned façades, thermal mass, operable windows, and an evaporative cooling element, as described below.

Ventilated double roof

Low-rise buildings such as detached houses usually have the largest proportion of heat gain from solar radiation through the roofs. Designing a passive building that is occupied at night as well as during the day, such as a house, should take into the consideration both nighttime heat loss and daytime heat gain. A simulation study by PasCal compares four types of roof system which include a conventional non-ventilated, non-insulated roof; an insulated roof; a ventilated double

Figure 9. First and second floor plans and longitudinal section of the prototype house showing major design features.

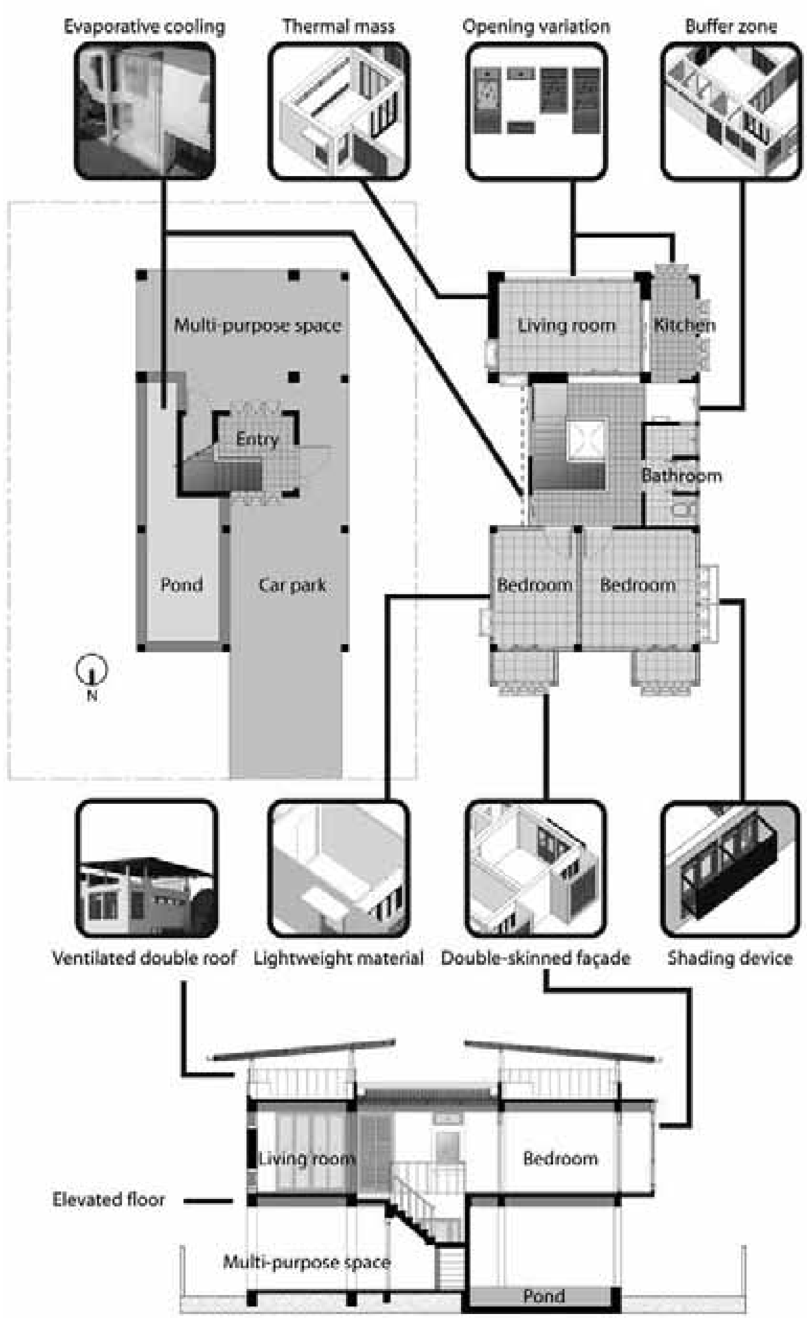


Figure 8. Exterior perspective of the prototype house.

roof with a heavyweight, non-insulated lower roof layer; and a ventilated double roof with a lightweight, non-insulated lower roof layer (Figure 10). Calculation results show that, during the day, the ventilated double roof with a massive, non-insulated lower roof layer provides the lowest indoor temperature. Therefore, it is used for the living room that is mostly occupied during the day. On the other hand, the ventilated double roof with a lightweight, non-insulated lower roof layer gives the lowest indoor temperature at night. Therefore, it is used for the bedrooms that are usually occupied during nighttime.

Double-skinned façade and shading device

A large amount of radiative heat gain can enter a building through its openings. In our prototype house, the balconies are designed so that they form another layer of the building envelope, acting not only as a thermal buffer but also as a spatial extension for the adjacent indoor spaces. Throughout the house, shading devices are designed according to the solar angle to protect openings completely from direct solar gain.

Thermal mass

The time of use of each space influences its requirement for thermal mass. A series of simulations using PasCal is carried out to compare six types of wall of typical constructions with different heat capacity and thermal conductivity values (Figure 11). Calculation results show that the room with high mass such as a reinforced concrete wall attains a lower indoor air temperature during the day, while the room with low mass such as a lightweight brick wall attains a lower indoor air temperature at night. None of the insulated rooms has better thermal performance than those equipped with appropriate levels of thermal mass, either during the day or at night. Therefore, the walls of the living room of the prototype house, which is occupied mostly during the day, are made of high-mass materials, and the walls of the bedrooms, which are used mostly at night, are made of low-mass materials.

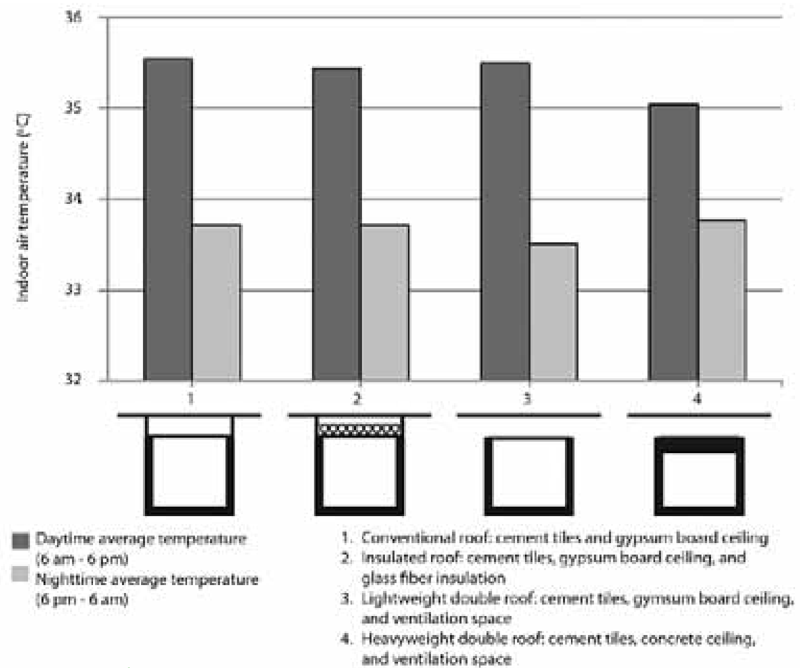


Figure 10. Indoor air temperatures as a result of different roof types as simulated by PasCal (v.1.0).

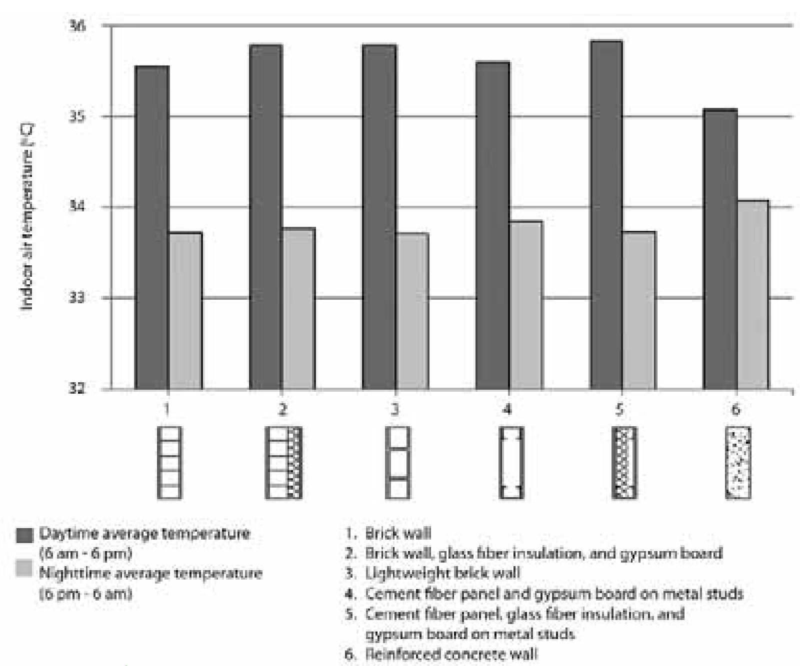


Figure 11. Indoor air temperatures as a result of different wall types simulated by PasCal (v.1.0).

Design and operation of openings

Building occupants are generally more satisfied with their environment if they have control over it. Therefore, the design of building openings, such as windows and ventilation shutters, should offer building occupants a reasonable degree of control. Shading and rain protection are mandatory for almost every opening design of our house. The ability to ventilate, daylight penetration and access to view, however, vary according to the function of each space. In our house, each opening is divided into three vertical parts, each serving its own purposes (Figure 12). A combination of ventilation openings at high and low levels will encourage buoyancy-driven ventilation. An opening at a high level will also allow good penetration of daylight, reducing the requirement for artificial lighting. An opening at a middle level will provide a view, as well as ventilation and daylight.

Evaporative cooling element

During the day when the relative humidity is not excessively high, evaporation can help cool the ambient air effectively. Our design uses falling water from the roof of the staircase in the middle of the house as an evaporative cooling device. The water can be guided into a pond via chains hung vertically from the roof to avoid splashing—an inexpensive yet effective technique borrowed from Japanese vernacular houses. This evaporative cooling method can reduce the temperature of the air that enters the living room and other daytime spaces, as well as the outdoor ambient air, creating an overall cool environment.

6. The performance

Our design takes a holistic approach, and so thermal, energy, lighting, acoustic, indoor air quality, social, and economic performance are all considered. However, the present paper focuses on thermal comfort and energy performance. Therefore, the other aspects of performance are not discussed, although they are also addressed in the actual design (for more information, please contact the authors).

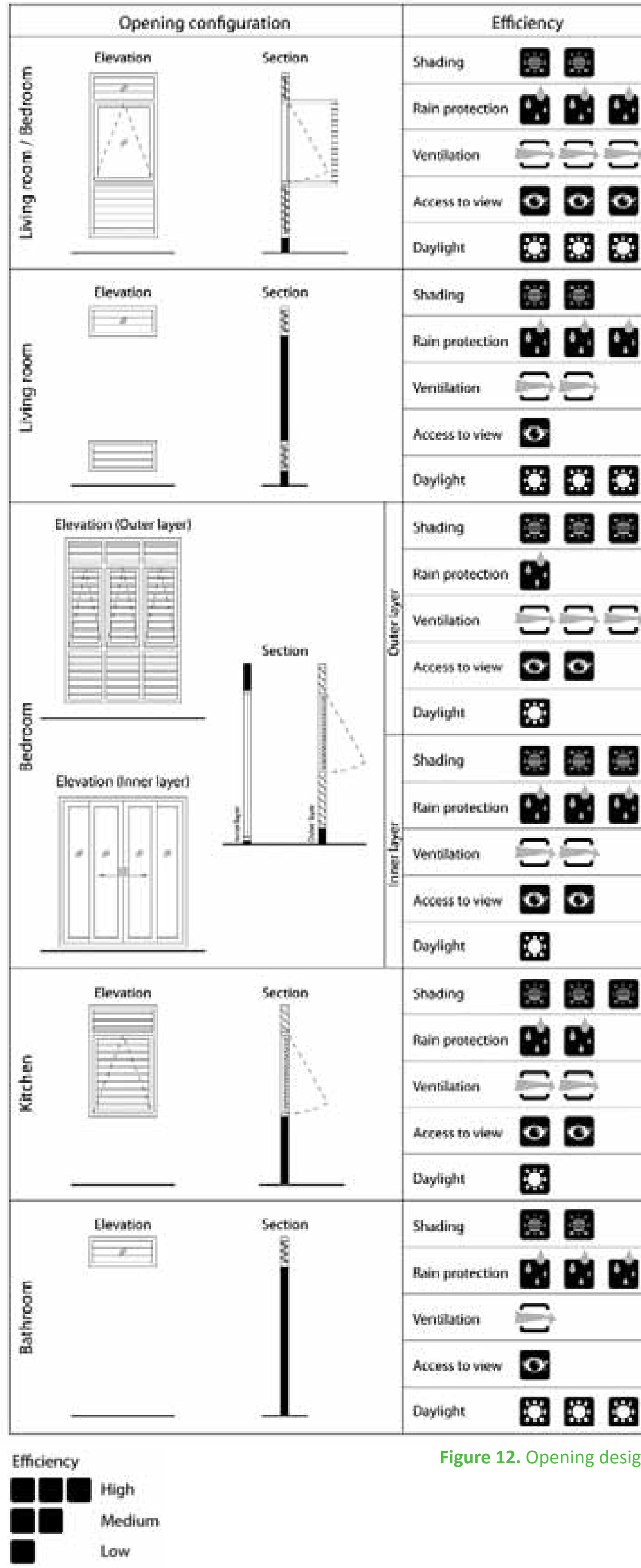


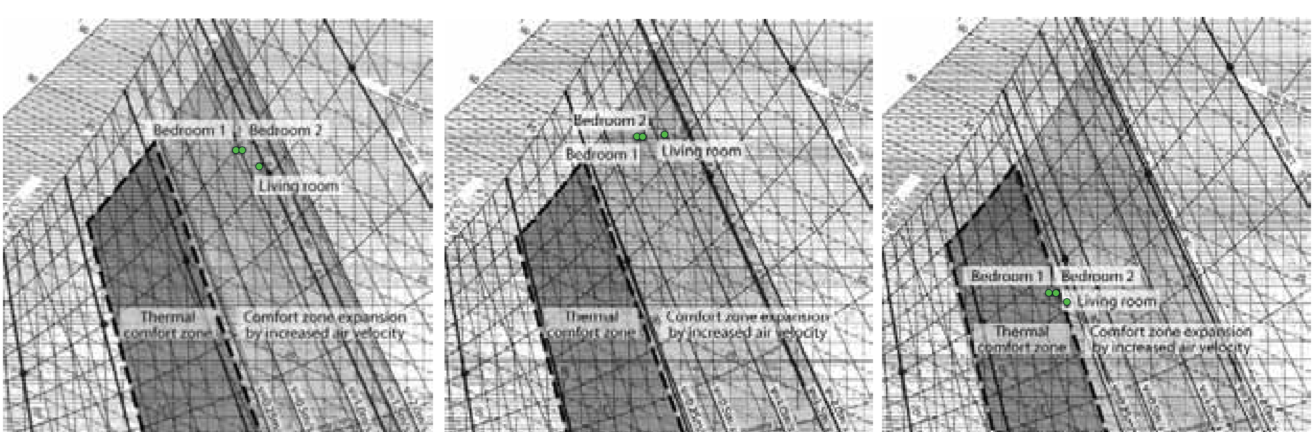
Figure 12. Opening design.

The comfort and energy performance of our house are compared with those of a conventional house found in the region. The conventional house is usually built with poor site planning which prevents effective ventilative cooling. It usually has 10 cm-thick bricks as the walls and concrete tiles as the roof. It is also poorly shaded and therefore easily overheats during both day and night, and generally requires air-conditioning to operate comfortably.

PasCal is used to assess the dynamic thermal performance of these two types of house under climate change. To simplify the calculation, all the bedrooms in both houses are assumed to be used between 6 p.m. to 6 a.m., and all the living rooms used between 6 a.m. to 6 p.m. Figures 13a-c show the thermal conditions in the three main spaces, namely the two bedrooms and the living room, in our house, as achieved in summer, the monsoon season and winter, respectively. These thermal conditions are plotted onto psychrometric charts with corresponding comfort zones. In calculating the seasonal thermal performance, the average external conditions in representative months as projected for the end of the century are used, i.e., the projected conditions in April are used for summer, those in August for the monsoon season, and those in December for winter. It can be seen in Figure 13 that although the indoor conditions achieved without cooling under climate change in our house are likely to lie mostly outside the comfort zone, they can be shifted into the comfort zone with passive cooling. In summer and the monsoon season, the rooms are likely to require air velocities of between about 1.0 and 1.5 m/s, or between about 0.5 and 1.0 m/s with evaporative cooling in place, to achieve thermal comfort. In winter, the two bedrooms are likely to be comfortable even without passive cooling, while the living room can be made comfortable with a relatively low air velocity of about 0.25 m/s or evaporative cooling.

The conventional house, due to its use of air-conditioning, which cuts their occupants off from the outside thermal environment, cannot use the same seasonal comfort zones as those used by our passive house, and must perform to a more stringent standard of comfort usually expected by occupants of air-conditioned spaces to achieve a comparable perceived level of comfort as that in our passive house. In the hot-humid climate, a temperature of 25 °C and a relative humidity of 50% are often used as a standard for indoor air temperature and humidity of an air-conditioned space, and this is also adopted in our analysis of the thermal and energy performance of the air-conditioned conventional house. Based on this standard of comfort and owing to its poor fabric and ventilation, the conventional house is likely to require air-conditioning throughout the year to achieve comfort.

The relative thermal performance between the two houses will directly affect their relative energy performance. The largest



(a) (b) (c)

Figure 13. Indoor air conditions of major rooms in (a) April, (b) August, and (c) December as simulated by PasCal (v.1.0).

proportion of energy consumed in a conventional house is for air-conditioning (about 78%, Thailand Department of Energy Development and Renewable Energy, 2008). For this reason, to obtain a general picture of the relative energy performance between the conventional house and our house, our analysis focuses on energy requirement for cooling—either by air-conditioning in the conventional house, or by fans and water pumps in our house—and ignores energy consumption in other areas such as lighting and household equipment.

In estimating the relative energy requirement for cooling between the two houses under climate change, we also assume, for simplicity, that the houses operate under each representative set of seasonal conditions for four months (i.e. under the conditions found in April for four months, the conditions found in August for four months, and the conditions found in December for four months). This leads to our passive house requiring about 14 kWh/sq.m. of energy annually (resulting from the energy requirement of about 1.4, 1.4, and 0.8 kWh/sq.m./month during each four-month period of summer, the monsoon season and winter, respectively). On the other hand, the conventional house will require approximately 300 kWh/sq.m. of energy annually (resulting from the energy requirement of 31.5, 23.6, and 19.9 kWh/sq.m./month during each four-month period of summer, the monsoon season and winter, respectively). Note that these values of energy consumption should not be taken as absolute, as they are calculated based on a limited range of climatic conditions and a set of simplifications which may or may not apply to certain real-life conditions. What these numbers essentially demonstrate is that our house may consume as little as 5% of the energy consumed in the air-conditioned conventional house under climate change, while arguably delivering a comparable perceived level of comfort.

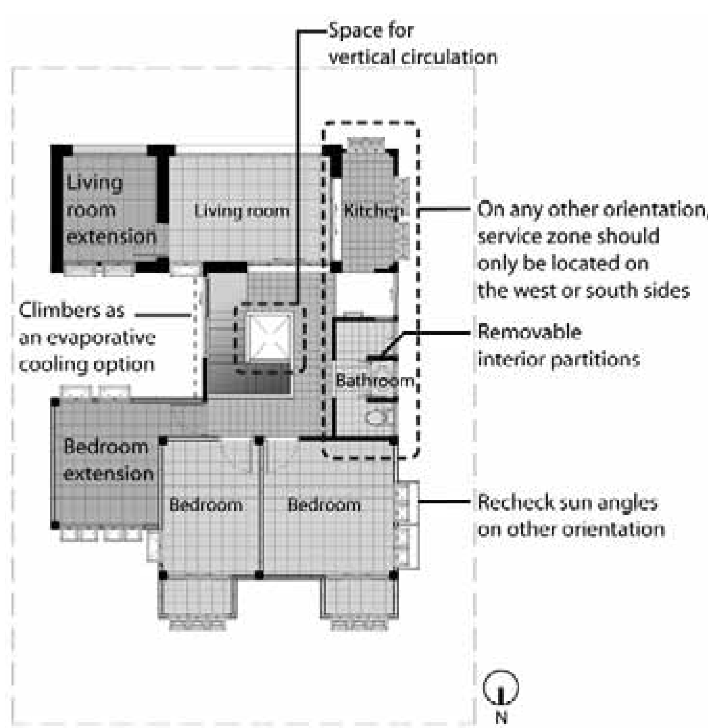
7. Generalization of design approach

The design of the prototype house presented herein is intended as a demonstration of the principles and potential of passive design under climate change. It is expected to be developed further to eventually replace conventional houses. Therefore, the design has certain inherent flexibilities which will allow it to be adapted to different locations, site constraints, specific usage requirements, etc. This section discusses the adaptability of our design along with how to operate it to achieve the best performance.

7.1 Design adaptability

The plot size and orientation may vary according to the location of the housing project and the project's site plan. The prototype design can be adapted to almost any site with little/no adjustment. In general, the house should have a north- or south-facing entry. If the orientation of the plot is such that this is not possible, then adjustment should be made to the design of the entrance of the house while keeping the service zone on the west or south side of the plot (Figure 14). The service-side façade

Figure 14. Design adaptability.



should be as close to the site boundary as possible to maximize the open space on the other side of the plot. This open space is also the area for future extension of the living room and bedrooms. In all cases, the angles of solar penetration through the windows should be rechecked and the sizes of the shading devices adjusted accordingly.

Other key adaptabilities include the raised floor, the evaporative cooling element, and the support system for the handicapped. The highest flood level in each individual location should be identified before the construction and the house elevated correspondingly for flood protection. The falling water evaporative cooling system presented earlier may be redesigned to have a series of jars instead of a pond as a water reservoir. Climber plants can also replace the falling water system with some compromise in the cooling potential. Furthermore, wheelchair access can be provided by installing a vertical stair lift in the ample space in the middle of the stairwell. The partitions in the bathroom can also be removed and handrails installed to accommodate wheelchair users.

7.2 Operation

For the house to perform well, its occupants need to operate it properly. For instance, the openings in the living room, although well shaded, should be kept largely closed during the day when the outdoor air is warmer than the inside air, to prevent convective heat gain from the warm air outside. In this case, the openings should be opened just enough to ensure sufficient fresh air for the occupants inside the room. At night, however, all the openings in the living room should be opened to allow nocturnal ventilation to rejuvenate its massive fabric which has warmed up during the day, regardless of whether the room is occupied or not. The openings in the bedroom, on the other hand, should be operated differently, because the room has a lightweight envelope and the room is occupied mainly at night. A maximum ventilation opening area should be provided any time the bedroom is occupied to maximize heat removal from the interior by natural ventilation. In extreme weather, an electric fan may also be used in conjunction with natural ventilation to increase the indoor air speed and help bring about thermal comfort. Insect screens installed to the windows should be cleaned regularly to minimize blockage of natural ventilation. Furthermore, it should also be noted that there are some limitations to the future expansion of the house. Crucially, the space underneath the roof and that on the ground floor should not be converted into an indoor space, as the former would be too hot to live in and the latter could easily be flooded. A brief guide containing information of how to operate and maintain the house such as that discussed above should be issued to the occupants to encourage energy efficiency and comfort.

7.3 Expectations

While the paper has demonstrated that a passive design solution can be developed to bring about thermal comfort under climate change, it is also important to be aware of people's expectations and behavior which are born of their familiarity with air-conditioned environments, such as offices. Key to the success of the house is the understanding of the occupants that, because the house is designed with a passive approach, it will behave differently from a typical house designed with an active approach. For example, the temperature in a passive building—although comfortable—is in general not as cool as can be expected from its actively cooled counterpart. However, a passive building generally takes in fresh air at a much higher rate than a typical air-conditioned building, while allowing physical and psychological connections with the varied outside environment, and so it will usually lead to better indoor air quality and is more conducive to physical and psychological health. Also, if air-conditioning is later added to our house, the house will consume more energy than a well-insulated house which is designed specifically for air-conditioning due to its relatively thermally conductive, more porous envelope, although it will still consume less energy than the conventional house because of its better heat protection. However, while an insulated house may become uninhabitable when the air-conditioning system breaks down or when blackout occurs, the prototype house will remain relatively comfortable in those situations.

8. Conclusions

The present paper explores an alternative, novel approach to building design under climate change, using a low-cost house in Thailand as a test bed. The study finds that with the expected average increase in the exterior air temperature of 3°C by the end of the 21st century, a house located in the tropics will require a combination of heat gain protection and passive cooling techniques to achieve thermal comfort. For the latter, judicial use of thermal mass, ventilative cooling and evaporative cooling and combinations thereof are key. For high-density housing projects, a staggered layout of houses is recommended to maximize natural ventilation. In each house, the service zone should be located on the west side and used as a thermal buffer, where possible. The use of a double roof, a shaded double façade, along with the appropriate location of thermal mass in response to the time of use of each space and careful control of ventilation openings, would also an added cooling benefit. The paper shows that a well designed and controlled passive house can save as much as 95 percent of the energy required for cooling, while providing thermal comfort for its occupants all year round. The design and analysis methodology presented herein can also be adapted to other building types in similar or different climatic conditions.

The present research has also pointed to important future research areas. Today's concern about environmental problems has prompted a number of green building evaluation measures. However, very few, if any, of these measures really provide a holistic framework for assessing the performance of passive or hybrid buildings, especially in hot-humid climates. Furthermore, although it is relatively straightforward, as shown in the present work, to measure and evaluate energy and comfort performance under climate change, performance in other areas such as social and economic are less straightforward to measure and evaluate, and there is a scope for developing measurement and evaluation indicators and methodology in those areas.

Acknowledgement

This research is supported by the National Housing Authority (NHA) of Thailand. The article is published with a written consent from the NHA. The authors thank Vichai Laopanitchakul and Sudaporn Chungloo, the co-researchers of the project. Thanks also go to Sumavalee Chindapol and Jitiporn Wongwatcharapaiboon, our research assistants.

References

Auliciems, A. (1981). Towards a psycho-physiological model of thermal perceptions. *International Journal of Biochemistry, 25,* 109-122.

Auliciems, A., & Dedear, R. (1986). Air conditioning in a tropical climate: Impacts upon European residents in Darwin, Australia. *International Journal of Biometeor, 30*(3), 259-282.

Chenvidyakarn, T. (2009). PasCal (v.1.0) [Computer software]. Retrieved October 13, 2009, from http://www.arct.cam.ac.uk/Arct/ResearchGroup.aspx?p=23&ix=99&pid=14&prcid=5&ppid=1293

Gagge, A. P., Fobelets, A. P., & Berglund, L. G. (1986). A standard predictive index of human response to the thermal environment. *ASHRAE Transactions, 92*(2), 709-731.

Givoni, B. (1994). *Passive and low energy cooling of buildings.* New York: John Wiley & Sons.

Thailand Department of Energy Development and Renewable Energy. (2008). *โครงการการศึกษาสถานภาพการใช้พลังงานและแนวทางการส่งเสริมการอนุรักษ์พลังงานในบ้านที่อยู่อาศัย* [A study on the conditions of energy consumption and guidelines to promote energy conservation in the residential sector]. Retrieved September 15, 2008, from http://www2.dede.go.th/new-homesafe/webban/actionplan.htm

The Intergovernmental Panel on Climate Change. (2007a). *Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change, 2007.* Cambridge, UK and New York, USA: Cambridge University Press. Retrieved August 10, 2009, from http://www.ipcc.ch/publications_and_data/ar4/wg1/en/contents.html

The Intergovernmental Panel on Climate Change. (2007b). *Contribution of working group III to the fourth assessment report of the intergovernmental panel on climate change, 2007.* Cambridge, UK and New York, USA: Cambridge University Press. Retrieved August 10, 2009, from http://www.ipcc.ch/publications_and_data/ar4/wg3/en/contents.html

Khedari, J., Yamtraipat, N., Pratintong, N., & Hirunlabh, J. (2000). Thailand ventilation comfort chart. *Energy and Buildings, 32,* 245-249.

Szokolay, S. V. (2004). *Introduction to architectural science: The basis of sustainable design.* Oxford, UK: Architectural Press.

Tantasavasdi, C., Srebric, J., & Chen, Q. (2001). Natural ventilation design for houses in Thailand. *Energy and Buildings, 33,* 815-824.

US Department of Energy. (2009). *Statistics for THA_Bangkok_IWEC*. Retrieved September 1, 2009, from http://apps1.eere.energy.gov/buildings/energyplus/weatherdata/2_asia_wmo_region_2/THA_Bangkok_IWEC.stat