DESIGN FOR A SUSTAINABLE FUTURE

JAY PRITZKER ACADEMY
SIEM REAP, CAMBODIA

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Introduction

Organized around a holistic design approach, this class examined the synthetic relationship between performance and design in addressing issues of sustainability in the built environment. The workshop introduced the theories behind a resource-efficient built environment and guided the design process by focusing creativity around performance goals. Workshop participants explored ways to effectively integrate considerations such as energy-efficiency, material use, structural stability, and occupant comfort into the design process.

The participants began by conducting research on resources and environmental constraints and by learning relevant tools and metrics for performance analysis, thematically applied through targeted design exercises. The workshop held focused sessions on natural ventilation, daylighting, building systems, materials, and natural resources. The class format incorporated discussions and multi-disciplinary brainstorming during the design process. Participants were asked to explore their design solutions in a synthetic manner across various scales. During the workshop, the participants worked in teams to apply this integrative design approach to a case study project.

This case study project was a second campus for the Jay Pritzker Academy in Siem Reap, Cambodia. The students worked in interdisciplinary teams to generate three different design proposals for the masterplan and various classroom structures for a new campus for 400 students with the goal of creating a truly sustainable and environmentally responsible 50,000 square foot campus. The workshop participants began by examining the Academy's first campus initiated three years ago and used new analytical computation tools to evaluate the existing campus. Based on the analysis, they used these tools to develop the design process of a new campus and its classroom structures according to the Academy program brief.

Areas that are particularly emphasized for this case study will be energy, comfort, daylighting, as well as conservation of water and material resources, as drivers for better design for the campus and the classrooms.

The goal of the workshop was to teach students that quality design, sustainability, and affordability are not mutually exclusive. By engaging the performance goals as integral to the creative design process, we hope to synthesize design and building technology in productive ways to create a more sustainable future.
The new Jay Pritzker Academy campus will be built in Siem Reap, the capital of Siem Reap province in north-west Cambodia. The hot and humid climate of Southeast Asia will be the first challenge for the new school.

Located just 12 kilometers from Tonle Sap, the largest lake in Cambodia, the site, like much of the area surrounding Cambodia’s rivers and lakes, is prone to yearly flooding, posing a challenge to any buildings in the region.

The site is also located near Siem Reap International Airport, which is experiencing an increase in traffic due to a growing tourism industry in Cambodia. Controlling noise from overhead planes will be another concern of the academy.
Siem Reap >> 2.25 km
Siem Reap International Airport >> 2.25 km
Angkor Wat >> 9 km
Tonle Sap Lake >> 12 km
Siem Reap >> 10 km
March - May

Hot/Dry

High Temp 35°C

June - August

Hot/Wet

High Temp 35°C

September - October

Cool/Wet

Lowest Temp 20°C

November - February

Cool/Dry

Lowest Temp 20°C

Clear Mornings

Monsoon Season

Rainy Afternoons
Climate Overview

The Cambodian climate is dominated by the monsoon cycle. November through May are the dry months, and June through October are rainy months. Warm and cool temperatures overlap with both periods, causing at least four distinct climatic variations: cool/dry, hot/dry, hot/wet, cool/wet. This process is fueled by cyclic pressure changes across central Asia and affects wind patterns throughout the year.

During monsoon season, rain is heavy but not constant. Periods of intense rainfall usually occur in the afternoons, while the rest of the day is clear. Still, buildings must be able to shed water quickly enough to withstand these downpours as well as must be built to resist infiltration of wind-driven rains. Precedents in Cambodia indicate that buildings should be built to resist incident rain up to 60°
Climate Data

![Graph showing monthly averages of temperature and relative humidity over the year. The temperature graph shows a general trend with slight variations, while the relative humidity graph indicates a consistent trend.](imageReference)
Thermal Comfort

ASHRAE standards look at a variety of programmatic activity and environmental conditions. In Seam Reap, there is no need for heating throughout the year, and we are not assuming conditioned spaces.

Therefore, it is only necessary to take the children's school uniforms, metabolic activity, and wet bulb temperatures into consideration.

The children wear light clothing: shorts and a short sleeve shirt. This clothing influences the shift of the ASHRAE comfort zone by a degree or two when compared with 1.0 clo, a standard western business suit. Each child wears a uniform with a clo value of approximately

0.15 clo

The children will primarily be doing desk work, so, for calculating heat loads, we assume a standard metabolic rate of

70 W/child

Finally, the following thermal comfort zone charts rely heavily on air movement. We assume a maximum of 3 degree temperature change with optimum ventilation. This increases evaporative cooling and results in overall cooler-feeling environment.
short sleeve shirt: 0.03 clo
shorts / skirt: 0.06 clo
underwear: 0.04 clo
light shoes: 0.02 clo
The psychrometric chart at the right compares the climate conditions in Siem Reap with the comfort zones as established by ASHRAE. According to the chart, there are suitable conditions available for well-ventilated classrooms for

60% of the year

High humidity is the only factor pushing Siem Reap's conditions above ASHRAE standards; considering the climate, these are in any case likely to be more acceptable in Siem Reap than they would be in the United States (whose own climate the ASHRAE standards reflect). In extreme cases, temporary measures like fans can mitigate uncomfortable conditions.

Having ruled out active systems (air conditioning) and chemical measures (dessicants), the campus design will focus primarily on creating an indoor classroom environment that resembles that of a shaded outdoor area as closely as possible.
April high: 27°C, 80% RH

April low: 25°C, 30% RH

December high: 25°C, 60% RH

December low: 21°C, 55% RH

VAPOR PRESSURE, mm Hg

OPERATIVE TEMPERATURE, °C
Water

The Mekong River enables survival for millions along its banks. From its source on the Tibetan Plateau it drops 5,000 meters and flows across six countries before reaching its delta. Over 60 million people live in the Lower Mekong Basin, using the river for drinking water, food, irrigation, hydropower, transportation, and commerce. In Cambodia, the Tonle Sap Lake, one of the world's largest freshwater fisheries, is replenished by the Mekong. Nearly half of Cambodia's people benefit directly or indirectly from the lake's resources. The Tonle Sap Great Lake is one of Cambodia's most important natural resources: over one million people rely on its fisheries and much of the country's population lives within its fertile floodplain. The lake's complex systems play a major role in the ecology of the lower Mekong River system, and much of Cambodia's economy, culture, and identity is connected to the Tonle Sap Lake.

Growing population pressures, inequality of access rights and deficient governance are aggravating conflicts over natural resources and threatening the sustainability of the lake's ecosystems and resources base. In response to this, and as part of a broader program of governance reforms, the Cambodian government is promoting integrated natural resources management for the Tonle Sap. A key feature of this strategy is the designation of the Tonle Sap Biosphere Reserve as part of the UNESCO World Network of Biosphere Reserves, according to the United Nations.
Despite high winds during storms, the overall wind resources available at Ta Chet remain in the poor to fair range. Local wind data at ground level varies significantly and accurate data is not available for the Siem Reap campus specifically. However, at a height of 30m above the ground, wind speed is, on average

**4.0-4.5 m/s**

Therefore, in calculating the potential of cross-ventilation breezes to cool the classrooms, conservative estimates of wind speed on site were used.
The campus will not require any heating, so the primary objective in dealing with the sun is to provide as much shade as possible. The average incident energy falling on the Siem Reap province is approximately \(4.0 \text{ kWh/m}^2\).

Although this energy may be used for producing electricity, the infrastructure for supporting a photovoltaic array is costly and potentially unsafe. Batteries would be needed to store the collected solar energy for use during storms. However, these batteries contain toxic chemicals, and the risk of leaks during a flood make them unpalatable for a school.
Concrete

Concrete, a mix of cement, water, and aggregate, is one of the world's most used building materials. Concrete is used extensively in the Ta Chet campus for slabs and several columns and beams. With an embodied carbon of

0.25 kg CO$_2$ per kg material

the carbon per unit area on the campus is about

220 kg CO$_2$ per m$^2$ campus

To reduce carbon investment, aggregates can be found and produced locally. Nonetheless, the production of cement is an energy-intensive process. However, the use of alternative materials in the concrete mixture can allow for up to a

63% reduction in embodied CO$_2$

Thailand's Siam Cement Group opened a new cement plant in Kampot, Cambodia in January of 2008. In its first year of operation, the plant produced 960 million kg of cement; most of this quantity would previously have been imported. Kampot Cement, Siam Cement Group's partner, has reportedly invested 200 million USD in Siam with the aim of tripling its production to meet Cambodia's growing demand for concrete.
MATERIALS
Cambodia has one of the worst deforestation rates in the world. Since 1970, Cambodia’s primary rainforest cover has decreased from over 70 percent in 1970 to 3.1 percent today. Worse, deforestation rates in Cambodia continue to accelerate. The civil war - which lasted from the 1970s to the mid-1990s - set the stage for illegal logging, as each warring faction financed its activities with timber sales.

To control the illegal harvesting and exporting of timber, the government has partnered with several organizations to establish and monitor community forests within each province. This regulation will prevent larger corporations from over-processing and exploiting the country's timber resources. Siem Reap province has 35 community forests - the highest number of any province in Cambodia.

Embodied CO$_2$ in wood of various types is low at

0.14 kg CO$_2$ per kg material

but the difficulty of sourcing wood has previously restricted its use. The Ta Chet campus uses very little wood in its buildings; while wood is used for doors and louvered shutters, there is no structural wood on the campus.

However, recently established sustainable logging operations may offer a low-carbon alternative to the steel and concrete construction model at Ta Chet.
Steel

Cambodia gets most of its steel from China, the world's number one steel producer. Other nearby suppliers include Vietnam, Indonesia, and Thailand; however, due to the worsening world economy, China is selling its overstock of steel at a reduced price that other countries cannot compete with.

Cambodia pays 0.44-0.46 USD per kg of steel from China, which is 0.10 USD less per kg than it would pay for Vietnamese steel. Cambodia does not have their own steel production facilities, though China is investing in searches for iron ore in Cambodia's Preah Vihear region.

campus as rebar in the concrete walls and as trusses supporting the roofs. As a carbon-intensive material, steel measures

0.8 kg CO₂ per kg material

On the campus, steel accounts a significant carbon load at

41 kg CO₂ per m² campus
Masonry

Apart from traditional laterite masonry, the Cambodian brick industry deals exclusively with fired bricks, whose materials are obtained locally from factory clay pits. The firing process itself is time-consuming, taking over a month in the dry season and longer in the rainy season, and requiring a workforce of up to 30 laborers.

Energy consumption and CO₂ generation vary greatly based on kiln design at the brickyard. Embodied carbon for brick, though, is generally low, with an estimate ratio of

0.18 kg CO₂ per kg material

Lately, Cambodian brick factories have gained notoriety for their use of child labor. A recent study suggested that an average of

16 child workers per factory

is a fairly low estimate. Brick prices have fluctuated wildly from 57 KHR/brick (1990) to 400 KHR/brick (2008) and back to 50 KHR/brick (2009).
Costs per kiln load (16000 bricks)

- **Preparing clay**: labor
- **Extrusion**: clay, labor, diesel
- **Drying**: labor
- **Packing kiln**: labor
- **Firing kiln**: firewood, labor
- **Cooling**: labor
- **Unpacking kiln**: cumulative total 270 USD

Total costs for firing kiln: 270 USD
Traditional Homes

Traditional Cambodian houses are raised on stilts as high as 3 meters off the ground. This helps with natural ventilation and prevents damage from annual flooding.

Houses are normally rectangular in plan and range in size from 4 by 6 meters to 6 by 10 meters. Below the floor is a shaded space for storage, animals, or retreat during the heat of the day. Two ladders or wooden staircases provide access to the house. A steep thatched roof overhanging the exterior walls protects the interior from rain.

Typically a house contains three rooms separated by partitions of woven bamboo. The front room receives visitors, the second room is the parents' bedroom, and the third is for unmarried daughters. Sons sleep wherever they can find space. Food is made in a kitchen separated from the house. Toilets are normally a pit in the ground.

Due to constant rainfall and the use of light building materials, a house can deteriorate quickly. Consequently they are generally utilitarian and not generally decorative.
Traditional Temples

The concentric walls of traditional temples are built around a central sanctuary which houses the temple's primary deity. Most temples also possess a library, which probably also acted as a shrine.

Each temple is pyramidal in shape to recall Mount Meru, the home of the gods in Hindu cosmology. The central sanctuary is located under the peak of the roof and is thus elevated above the rest of the temple.

Traditional temples are normally made out of carved masonry, brick, laterite, and wood. Sandstone, obtained from the Kulen mountains, was the only stone used. Laterite is a clay that hardens in the sun and was used for the foundations and hidden parts of the temples. The earliest Angkorian temples (for example, Preah Ko), were made of brick with a stucco finish for carved decorations.

Preah Ko, a masonry temple built in 879 CE

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Modern Construction

Many modern Cambodian buildings take advantage of global materials and styles; for example, in cities or in higher income areas, many buildings use concrete with structural rebar.

Modern houses use clay tiled roofs as a more permanent alternative to the thatched roof. Wood and concrete are used as primary structural materials; however, despite the use of new materials and technology, traditional plans are often used.
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Wood Vault

A fast-growing and strong tree that thrives in Cambodia, the eucalyptus is used primarily for furniture, finished woodwork, and wood pulp for paper making. As it is a tall, thin species, eucalyptus wood is most commonly found in long, narrow dimensions. It is used as a building material in smaller-scaled huts and stick-built dwellings.

Through simple repetition and assembly, curved eucalyptus wood members two meters in length can produce a bi-directional structural span. As this system can resist both lateral and vertical loading and follows a funicular load path, this vault is also an economical solution. Considering the low quantities of sustainable wood available in Cambodia, this material savings is especially important.
Masonry Wall Systems

Fired clay masonry products are widely available in Cambodia. These are durable and water resistant and are made primarily of locally-available materials by local labor. The firing of such materials is associated with a relatively high level of carbon emission (similar to that of concrete masonry units), but their manufacture in Cambodia provides significant local economic benefits. The adoption of low-carbon bricks which are fired at lower temperatures and with recycled materials could reduce the environmental impact of masonry production and provide a new industry in Cambodia.

Undulating walls create greater stability with less material. Patterns and openings in masonry allow for natural ventilation and visual appeal.
Steel Space Frame

A steel space frame can efficiently span large distances to support a large roof system that will provide shelter from the heavy monsoon rains. However, a second system of steel members will be needed to support the space frame. Also, the space frame will require heavy machinery (namely, cranes) to lift it into place.

Steel tube trusses: 0.14m³
Steel framing: 24.3m³
Steel girders: 2.4m³
Cable bracing: 0.004m³
Total steel: 26.8m³

Steel per classroom = 9.0m³
Embodied CO₂ per classroom: 79,000 kg
Light Steel Truss

This truss system uses narrow steel members to take vertical loading and compression in the horizontal span and cables to take tensile forces in the horizontal span and stiffen the end walls against lateral forces. The use of cables, which can be very thin, reduces the quantity of steel being used.

Steel framing: 2.1m³
Steel girders: 9.0m³
Cable bracing: 0.03m³
Total steel: 11.13m³

Steel per classroom = 5.5m³
Embodied CO₂ per classroom: 48,000 kg
Stereographic Chart for Siem Reap, Latitude 13°N (from luxal.eu)

Lightsolve rendering of typical Ta Chet classroom
Existing louvers were modeled as a lower window transmittance to simplify calculations
Existing Ta Chet Campus Analysis

Electricity is not only a concern for the new JPA campus in terms of sustainability; it is also an expensive utility whose use should be minimized for economic reasons. As such, designs need to be tested to ensure they provide adequate lighting for students to work throughout the school day.

Work began with an analysis of the existing Ta Chet campus. Computation work was done through Lightsolve, a new interactive visualization tool for advanced daylight analysis currently developed at MIT (lead faculty: Marilyne Andersen). The user interface displays a series of time-varied performance maps interactively associated to renderings and offers a comprehensive whole year analysis in terms of illuminance and glare risks, accounting for hourly climate data based on Bangkok’s weather station. The results are displayed graphically using an intuitive color scale to express how well the space responds to prescribed performance objectives.

For this analysis, there were two criteria for light levels. Acceptable light levels were from 100 to 1000 lux and optimal light levels were those that fell within the range of **300 to 800 lux**

The sensors placed at the TV and whiteboard are within optimal light range throughout the year. However, desks show some glare in the morning, which is problematic for maintaining a comfortable learning environment. It should be a goal to minimize glare at desk level while washing walls and whiteboards with light without oversaturating the room.

Two alternative strategies and building forms were explored to improve daylighting performance and visual comfort for a classroom, using one of four control options: toplighting, sidelighting with horizontal shading elements, sidelighting with vertical shading elements, and building envelope as a self-shading element.
Lightsolve Annual Image Map of Ta Chet classroom viewed from top, that reveals daylight dynamics over the day and year for the dominant weather conditions.
Vertical Louvered Classroom Design

The goal of this model is to light the classroom space from early morning through evening using diffuse lighting. The use of angled louvers will cause light to bounce around the interior, minimizing uneven lighting. Using a vertical slit at one end of the classroom will ensure that one wall is washed with light at all times. Reflective materials here could redirect diffuse, cool light to the back of the room.

Glare from January through February in the early morning, when the sun is low, will be a problem. Although it is possible to mitigate, it may be difficult to eliminate this spot entirely. Light levels become uncomfortable (too low) around 4pm-6pm local time. When this is after instructional time, however, it will not cause problems for the classrooms’ use as a teaching space.
Proposed vertical louver design to achieve daylighting performance objectives
EXERCISES
Lightsolve Annual Image Map for proposed classroom design
Test Case:  
10m x 10m classroom

The use of natural ventilation will be important in maintaining a comfortable classroom environment in the new campus. Due to the heating loads of students and teachers in the classroom, and the expense and problems arising from using active systems, the classroom will be open to the exterior environment.

The following tests look at wind flows caused by buoyancy-driven and cross-ventilated classroom ventilation options. Each looks at three different $\Delta T$ values when compared with various wind speeds and window heights to test for opening sizes needed to achieve these ventilation goals.

Simulations for ventilation were conducted using CoolVent, a natural ventilation simulation tool currently developed at MIT (lead faculty: Leon Glicksman) that allows users to visualize the effects of natural ventilation on the comfort levels of a building. It is based on the building's bulk characteristics and a coupling of multi-zone airflow and thermal analysis to predict zone temperatures and airflow rates. Energy and flow balances are solved simultaneously for combined buoyancy- and wind-driven flow, and transient simulations include detailed temperature gradients within thermal mass elements in the building.

Cross-ventilation
Windows: 4m$^2$ opening, 3m$^2$ glazing
Orientation: North, South
Height above ground: 1m

$\Delta T = 1 \, ^\circ C$
$V_{wind} = 7m/s$
$A_{eff} = 0.17m^2$
$A_{1,2} = 0.12m^2$

$\Delta T = 2 \, ^\circ C$
$V_{wind} = 7m/s$
$A_{eff} = 5.0m^2$
$A_{1,2} = 3.54m^2$

$\Delta T = 3 \, ^\circ C$
$V_{wind} = 7m/s$
$A_{eff} = 2.7m^2$
$A_{1,2} = 1.91m^2$
Buoyancy
Windows: two rows with areas $A_1$ and $A_2$
Lower height: 1m
Upper height: variable between 1m and 3m
Orientation: North, South

$\Delta T = 1 \, ^\circ C$
$h = 1m$
$A_{eff} = 14.2m^2$
$A_{1,2} = 10.0m^2$

$\Delta T = 2 \, ^\circ C$
$h = 1m$
$A_{eff} = 5.0m^2$
$A_{1,2} = 3.54m^2$

$\Delta T = 3 \, ^\circ C$
$h = 1m$
$A_{eff} = 2.7m^2$
$A_{1,2} = 1.91m^2$

$\Delta T = 1 \, ^\circ C$
$h = 2m$
$A_{eff} = 10.4m^2$
$A_{1,2} = 7.35m^2$

$\Delta T = 2 \, ^\circ C$
$h = 2m$
$A_{eff} = 3.6m^2$
$A_{1,2} = 2.55m^2$

$\Delta T = 3 \, ^\circ C$
$h = 2m$
$A_{eff} = 1.9m^2$
$A_{1,2} = 1.34m^2$

$\Delta T = 1 \, ^\circ C$
$h = 3m$
$A_{eff} = 8.2m^2$
$A_{1,2} = 5.80m^2$

$\Delta T = 2 \, ^\circ C$
$h = 3m$
$A_{eff} = 2.9m^2$
$A_{1,2} = 2.05m^2$

$\Delta T = 3 \, ^\circ C$
$h = 3m$
$A_{eff} = 1.6m^2$
$A_{1,2} = 1.13m^2$
Roof Diaphragm

By combining cross ventilation, buoyancy, and the negative pressure of a roof diaphragm, the air in the space will both be free to circulate through the room as well as be sucked out through the roof shape and secondary ventilation orientation.
General Case: Cross-ventilation and Buoyancy
Windows: 10m² opening, 9m² glazing
Height: 1m
Top opening: 2m²
Orientation: North, South
The effects of fenestrations in a building relative to ventilation and solar heat gain is crucial to creating a comfortable interior environment. Temperatures and wind directions in Siem Reap vary greatly throughout the year. When testing aperture sizes and orientations throughout a sampling of annual temperatures, a need for a hybrid system becomes apparent. No single system relying solely on cross ventilation will provide adequate cooling throughout the year. Nor will a complete reliance on buoyancy prove useful.

A hybrid strategy is thus most promising to effectively utilize cross and buoyancy ventilation combined and attain the ideal $\Delta T$ of 3 degrees. In such an extreme climate, it is also imperative to minimize solar heat gain. The most effective dispersion of apertures relative to this constraint is in the form of multiple smaller fenestrations. While allowing the same amount of air to enter the space, the breaking up of the window mitigates the intensity of the sun.
DESIGN

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ARTICULATED CANOPY
Articulated Canopy

The articulated canopy envisions a campus where maximized classroom flexibility and unified flows of students occur under one continuous roof structure.

Redefining how a campus is experienced, the canopy revitalizes the life beneath it by maximizing the potential of both interior and exterior learning spaces. It does this by providing clustered arrangements that offer gradients between interior and exterior classroom spaces. The classroom exists under this canopy as a series of operable wall panels, defining interior spaces for learning while having the flexibility to open up and welcome the operations of an exterior courtyard. By setting these elements, the classroom and the courtyard, under an articulated canopy, the campus is given shelter and a moderated climate as the canopy strategically withholds and permits the passage of direct sunlight.

In monsoon season, the shelter of the canopy not only allows for protected, usable indoor and outdoor spaces, but it manages the capture and drainage of water from its surface. Acting as a large catchment surface, the canopy channels the water to the periphery of the campus where it collects in retention ponds.

Finally, the strengths of a canopy scheme come from its ability to provide a unique learning environment which maximizes the useability of both interior and exterior spaces for learning.

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Site Planning

The planning of the school of the school is to activate the whole site equally. The High school and Junior school are separated to the east west section of the site. The main design criteria are the classroom flexibilities, multifunctional spaces, maximum use of the entire campus under any weather conditions, distribution of the educational programs, aesthetics, and relationship with nature.

The classrooms are distributed so that the students will be able to easily access the facilities such as toilets, covered outdoor spaces, and library easily. The junior high and high school campuses are laid out as a series of interlocking axis. The two major axis provide distinct campuses while minor axis allows easy access to share facilities.

Clusters and Courtyards

The classrooms are group in clusters to share the middle courtyard space as their play area, informal classroom, or study area after class. The classroom clusters and their courtyard will implement educational and communal ideals by forming micro-communities within a larger campus, leading to a more intimate setting, and allowing flexibility in the both the classroom and the courtyard. The classrooms clusters then are assembled to create two central open spaces which designate for a larger morning gathering or both schools special communal activities. Students can orient themselves to these main open spaces as a means of locating themselves in the campus.

Rich Learning Environments

Finally, the design of the new JPA campus aims for the lush, rich, textured, learning environment. The hierarchy of path ways is reflected in the differentiation of pavement and width. Attractive spaces such as waterfront spaces, docks, piers, gardens, and ecosystems are integrated in the planning. Most importantly, the relationship with nature is established by the flowing layout of the classrooms which is a play of inside-out and outside-in spaces.
ARTICULATED CANOPY
Roof outline, classrooms, and landscape

Wind circulation through the site

Paths system

Circulation system
ARTICULATED CANOPY

Pocket space and outdoor study areas

Trees and garden pockets

Water management on site

Landscape retaining walls
The main large roof is the water tight roof over the whole school. The rainwater from the roof is collected in a series of gutters and led by channels to the on-site retention ponds. The water from these ponds is then used for greywater reuse in the building's toilets and selected plumbing fixtures.

Because the main roof sufficiently overhangs the classroom (by more than 60 degrees), wind-driven monsoon rain is kept off of the classrooms and allows them to remain open and flexible, making full use of the cooling and daylighting strategies.

Additionally, the flexibility of the secondary roof and walls allow for sides of the classroom to be closed off if winds are too strong from a certain direction, while leeward sides can remain open.
Double Roof System

The primary lighting source for the classroom investigated was top daylighting; because of changeability of the wall panels a worst case was looked at to ensure adequate lighting levels would be achieved. However, general diffuse lighting would also be received from wall openings.

Panels of corrugated metal and plastic create a patchwork on the roof and vary to allow greater amounts of light in the classrooms and areas of public gathering. The plastic panels help to some diffuse of the daylight in the space.

In addition, the louvered second roof over the classroom is a patchwork of panels that allow for even, diffuse and reduced heat gain from the sun in the space. The eye shaped image shows the lighting levels that are achieved throughout the year, with blue being insufficient lighting, yellow reaching desired targets, and red exceeding targets.
Northwest view looking from the west retention pond
ARTICULATED CANOPY
The courtyard and sliding wall panels promote flexible learning and sharing cultures.

The sliding wall panels allow the private classroom to become a public, amphitheater-type gathering place for group presentations, joined classes, or small theater productions.

Courtyard Organization

Classrooms take on communal space
ARTICULATED CANOPY

Classrooms arrangement studies

Classrooms and courtyard spatial flows studies

Courtyard planning studies
Classroom interior perspective
The classrooms studies is based on the JPA school requirement which ask us to provide 14-16 classrooms; this means a classroom should accommodate a minimum of 34 students and a teacher. The proposed basic components per classroom are:

a) minimum 34 student desks
b) minimum 34 lockers for each student
c) one teacher desk
d) blackboard area
e) student works pin up area, and
f) storage space for educational equipment.
The classroom design aims to increase the pin-up space for students' works, especially in the shared classrooms such as math or science classrooms. The sliding pin-up boards are introduced to increase the pin-up area on the walls. Students can rearrange the sliders to their preference.

Paneling system

The two different types of sliding panels are a) acoustical panels made out of hollow perforated plastic with acoustical insulation inside in order to trap the sound waves, and b) louvered panels to control the light but still allow ventilation.

Sliding pin-up board

The classroom design aims to increase the pin-up space for students' works, especially in the shared classrooms such as math or science class rooms. The sliding pin up boards are introduced to increase the pin-up area on the walls. Students can rearrange the sliders to their preference.
The student lockers are designed to be the stacking unit systems. To conveniently accommodate the children of all ages, the lockers are proposed to be 35 cm tall and laid along the three sides of the classroom. The students lockers can be used as shelves or benches. The wall space above the locker can be used as pin up space.
Classroom Performance

The classrooms are made up of a series of moveable wall panels and operable louvers that can be adjusted to suite the classes needs for thermal comfort and acoustics. Because of the changeability of the wall, a variety of options were considered. The Natural Ventilation charts show the temperature difference expected from the exterior for various percent openings for average April [hottest month] winds. A less than 1 C temperature above ambient can be seen when greater than 5% of the walls and roofs are opened.

In addition to natural ventilation, the project has night time cool to help lower the temperature in the classroom during the day. When the evening temperature drops below the temperature of the ground slab, a fan flushes cooler night air through a gravel storage bed under the concrete slab an urns until the air temperature again rises above the floor slab temperature in the morning.

This thermal mass, in addition to the thermally massive rammed earth walls, use the thermal lag of the materials to stay cooler during the day when the space is occupied. The thermal mass then slowly absorbs heat from the warm daytime air, creating a cooler environment in the classrooms. As the air warms from student bodies it naturally rises up and through the classroom roof. Because of the sunlight penetration and rising hot air, the larger roof above acts as a solar chimney and increases the buoyancy ventilation of the classroom. Fans are placed between the two roofs to assist in the air flow when low wind speeds or need buoyancy do not create sufficient air flow.

The thermal mass chart shown shows the temperature of the floor slab as compared to an average April day. The floor slab is anticipated to be over 4 degrees C lower than the maximum temperature for the day. Because the students and faculty have direct contact with the floor slab, its lower temperature will both physically and mentally keep them cooler, in addition to cooling the air in the classrooms.
Daylighting Strategy

The lighting strategy proposed meets the targeted light levels for most of the occupied hours.
North-South cross section

East-West long section
# Articulated Canopy

## Material Palette

<table>
<thead>
<tr>
<th>Material</th>
<th>Performative Benefits</th>
<th>Environmental Impact</th>
<th>Notes</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rammed Earth</td>
<td>Good sound barrier, high thermal mass properties, low insulation costs</td>
<td>Green building material, manufacturing process generates little waste, minimal impact, recyclable, very low embodied energy (352, 0.36 MJ/kg) for cement reinforced rammed earth, lower without cement, embodied carbon 46 kg CO2/tonne</td>
<td>Laminate rammed earth components to prevent degradation in a tropical climate</td>
<td>China has practiced rammed earth construction for thousands of years, precedents in Thailand, buildings in Ban Rai Thai, Natural Building Project Thailand</td>
</tr>
<tr>
<td>Steel Beams &amp; Cables</td>
<td>Precise and durable construction, one of highest strengths to weight ratios of all building materials, allows for large spans, non-combustible, withstands heavy seismic and wind loads</td>
<td>Embedded energy medium to high (30 MJ/kg), recyclable material, embodied carbon 1,932 kg CO2/tonne</td>
<td>Steel lacks the social stigma of wood or the brick industry. Bricks, cement and steel are the three major contributors to energy cost of building construction. Capitalizing on steel's durability allows the other two to be minimized in design.</td>
<td>Thailand: Ban-Whitroom Steel, Bangkok Steel Industries, Pansa Steel Industries, Cheowma Steel Wire Rod—Saw-In Steel, Bangkok Industrial Steel Work, Thai Special Steel Industry (Cambodia is a major export destination)</td>
</tr>
<tr>
<td>Corrugated Metal</td>
<td>Low maintenance, high durability, good reflective qualities, good water harvesting product</td>
<td>Embedded energy medium to high (30 MJ/kg), recyclable material, embodied carbon 1,932 kg CO2/tonne</td>
<td>Stainless steel varieties (made from recycled steel products) exist, recycling process uses 11 MJ/kg, even traditional steel uses only 1/6th of the energy embodied in aluminium-based corrugated metals</td>
<td>Largest selection exists in China’s Hebei Nembest Imp. &amp; Exp., Xuzhoubest Trade Co., Zhengzhou Shangke Steel Group</td>
</tr>
<tr>
<td>Polycarbonate Panels</td>
<td>High strength to weight ratio, light weight means less energy required for transportation, allows design to maximize natural lighting</td>
<td>High embodied energy (112 MJ/kg), however, much of the energy is recoverable (PC can be used as fuel); recyclable material, embodied carbon 6,000 kg CO2/tonne</td>
<td>Material comes in varying opacities, allows for diverse light environments</td>
<td>China: Dongguan Cheyva Building Material Co., Guangzhou Yamei Plastic Industrial Co., Qian Hong Digital Materials</td>
</tr>
<tr>
<td>Concrete</td>
<td>Variety of surface finish, flexible shape/form requirements, durable, fire resistant, high thermal mass, relatively high albedo</td>
<td>Produced locally, contains some recycled material components, recyclable in theory; high embodied energy 1,090 MJ/kg, embodied carbon 100 kg CO2/tonne</td>
<td>Polishing (one time non-wax treatment) can increase reflectivity, reduce energy consumption</td>
<td>Phnom Penh (K R Ready-mixed Concrete Co., Construction Chemicals World Co., Song Enterprise Co., British Minnow Engineering (pte)</td>
</tr>
<tr>
<td>Sand-Lime Bricks</td>
<td>High dimensional stability, high albedo, higher compression strength than regular brick</td>
<td>Recyclable material form, bricks do not require firing (steam heated), lower energy than traditional clay brick, embodied energy 3.2 MJ/block</td>
<td>Potentially sustainable alternative to poured concrete and clay masonry</td>
<td>Thailand: Ban Rat Concrete Public Co Ltd, Ubon Thailand Ltd, King Group Development Co., Jango Construction, H.C. Hong/Arrow Machinery Co., Ltd.</td>
</tr>
</tbody>
</table>
Interlocking Landscapes

We think we have designed a superb academic setting for the JPA students, one where the learning environment stretches across the landscape and rests within the tree canopy; a campus that works with its natural surroundings, dispersing the classrooms and raising them up to create quiet educational spaces that capture natural breezes and offer unique views of the landscape.

Inside, our classrooms are softly lit, well ventilated work spaces beneath gently curving thatched roofs, where students can comfortably study even in the hottest months of the year. Our design combines local building traditions with innovative technologies to create a school that reflects the regional architecture while significantly out-performing the existing Ta Chet campus. Our goal is to provide the optimal learning experience for JPA students of all ages, while employing clever strategies that keep the construction cost, carbon footprint, and energy consumption to an absolute minimum.

Design Team
Adam Galletly
Julie Gawendo
Rebecca Gould
Tim Olson
Yan-Ping Wang
Planning Strategy

We raised the campus 12 feet above grade, which protects it from flooding, increases natural ventilation, and gives students the feeling that their school is a special place in a largely flat landscape.

We utilize the full area of the site to allow students to enjoy the both the noise of the playground and the quiet of the classroom on a single campus. Students can pour out onto the common area during recess and lunch, then retreat back into the landscape for concentrated study. The Lower School classrooms (grades K-8) are arranged so that it is easily accessible for the younger students and also more conducive towards lively, group-based learning. The Upper School classrooms (grades 9-12) sit out along peninsulas stretching across the site, creating insulated learning spaces for more specialized learning.
Tree Farm
Recreation Space
Administration - Security - Clinic
Cafeteria
Classroom
Junior School Library
Covered Outdoor Space
High School Library
Tree Farm
Assembly Hall
PLANTING NATIVE SPECIES IN CAMBODIA

**SMALL SCALE PLANTATIONS**
- diversify crop production
- provide valuable goods, such as, poles, fuel wood, and products for home use or sale

**NATURAL REGENERATION**
- based on principles of community succession, natural seedlings can be implemented for 1/3 of the cost of conventional reforestation

**FRAMEWORK SPECIES METHOD**
- cultivation of 20-30 native trees which produce bird dispersing fruits can serve to restore native rainforests with 80 different species within 6-10 years

The Cambodia Tree Seed Project has researched native species that will grow to 6’ in less than 1.5 years.
**Landscape: Water and Trees**

During the wet season, rainwater collects in sunken courtyards, which trickles through a system of canals and rice paddies to be retained and reused throughout the campus.

The school is populated with five different species of native trees that dot the grounds. As they grow, the trees will transform the campus into an intimate natural setting while also providing shade and shelter from the rain. The planting of trees also responds to the urgent need for reforestation in Cambodia. We hope that the new trees create a great outdoor environment on campus and also help to restore and replenish the country’s unique ecology.
**Classroom Plan**

During our research, we learned that by orienting the building at a 45 degree angle from north, we could use the same shading and window system on every side which actually optimizes both lighting and natural ventilation. This not only makes construction much faster and cheaper, but also allows us to get really creative with our roof form.
Roof System
The shape of our roof is a mathematical surface called a hypar. Although this surface is parabolic in two directions, it can be drawn using only straight lines. Therefore, to construct our roof we only need a number of thin steel rods and thatch. The lightness of the material and the strength of the arched shape allow for the long spans and large overhangs. Furthermore, this specific roof curvature has the dual functionality of focusing sunlight with its top surface while diffusing sunlight into the classroom with its bottom surface. This has enabled us to achieve nearly perfect classroom lighting conditions while collecting solar energy to power our ceiling fans.
Classroom Experience and Performance
The classroom sits lightly on the land and opens up on all sides. The design, with its gently curving thatched roof and stilts, evokes the vernacular architecture of the region while featuring a subtle technological flair. Large, crescent-shaped clerestory windows let light and air into the classroom, while the huge, arched roof overhangs block direct sunlight even in the late afternoon. The Upper School classrooms are raised on stilts an additional 12 feet, which creates the feeling that you're studying within the tree canopy. Large sliding panels on the classroom walls can be closed to shut out any noise and to keep papers from blowing off desks. Four solar powered ceiling fans increase airflow, and are especially handy on those hot, windless days.

And all this at slightly over half of the cost per student Ta-Chet. In fact, not only is it cheaper, our classroom outperforms its Ta-Chet equivalent in terms of interior lighting conditions and cooling.
Lighting Analysis

Roof Form and Light Diffusion

Sun Path Diagrams

Annual Lighting Visualization

Illuminance: Ta Chet Campus

Illuminance: Proposed
Wind Analysis

North Wind

North West Wind

Structural Analysis
## Cost Analysis

<table>
<thead>
<tr>
<th>Material</th>
<th>Interlocking Landscapes</th>
<th>Ta Chet Campus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>$281,789</td>
<td>$662,993</td>
</tr>
<tr>
<td>Steel</td>
<td>$573,763</td>
<td>$397,043</td>
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<tr>
<td>Thatch</td>
<td>$49,275</td>
<td>n/a</td>
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<tr>
<td>Masonry</td>
<td>n/a</td>
<td>$36,282</td>
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<tr>
<td>Wood</td>
<td>$68,145</td>
<td>$39,460</td>
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<tr>
<td>Tree Farm</td>
<td>$3,690</td>
<td>n/a</td>
</tr>
<tr>
<td>Earth Works</td>
<td>$309,120</td>
<td>$232,876</td>
</tr>
<tr>
<td><strong>Total Cost</strong></td>
<td><strong>$1,279,089</strong></td>
<td><strong>$1,135,778</strong></td>
</tr>
<tr>
<td><strong>Cost per Student</strong></td>
<td><strong>$1,598</strong></td>
<td><strong>$2,839</strong></td>
</tr>
<tr>
<td><strong>Cost per m²</strong></td>
<td><strong>$238</strong></td>
<td><strong>$234</strong></td>
</tr>
<tr>
<td><strong>Total Carbon Emission (kg)</strong></td>
<td><strong>821,395</strong></td>
<td><strong>1,241,765</strong></td>
</tr>
<tr>
<td><strong>Carbon Emission (kg/m²)</strong></td>
<td><strong>153</strong></td>
<td><strong>256</strong></td>
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</table>
INTERLOCKING LANDSCAPES
CHANNELS FOR LEARNING
Channels For Learning

'Channels for Learning' is a proposal for a new K-12 campus in rural Siem Reap, Cambodia which aims to manage challenging issues of water resource distribution and harness wind driven ventilation to create a zero energy school. Located in a region that experiences close to one meter of annual flooding, our design employs a robust strategy for building up the land along an elevated central ridge, dividing the site into two equal halves.

Our project proposes an affordable and sustainable new campus to accommodate the expansion of the original school by 800 students, as well as use water for both a source of recreation and cooling.

Design Team
Tiffany Chu
Lisa Hedstrom
Joseph Nunez
Lisa Pauli
Siobhan Rockcastle
Julianna Sassaman
Site Strategy

Channels for Learning splits the site in two halves and stitches it back together around shared central programs. The duality of the scheme revolves around an elevated central core and strategic views out over the flood zones on either side. Junior and high school campus are kept separate, but given access to one another through shared common spaces. Environmental considerations drive the orientation of the ridge, allowing air circulation through the classrooms and diffuse daylighting through north-facing roof skylights.
Classroom Planning

Each classroom along the ridge is staggered diagonally to provide equal access to daylight and breezes, as well as communal courtyards that adjoin each cluster of learning spaces. We optimized the roof design to channel southern and western winds across the top of the classrooms to flush out hot and stagnant air, while lifting up from the walls to allow a consistent clerestory opening for even daylight distribution down onto the desks and eliminating the need for electric lighting.

We also propose a gravity-fed channel under each terraced classroom to create a passive cooling feature beneath the vented floor, helping to create buoyancy-driven ventilation out under the angled roofs and allowing us to maintain ambient air temperature within each interior space.
Materials

Our scheme uses local and easily assembled materials such as gabion walls, clay tile, and hollow concrete brick to minimize carbon emissions while providing unique and low-cost design features.
North Wall:
The North walls on both the K-8 and high school classrooms are designed to prioritize acoustic separation. Like the east and south walls, they are constructed from CMU blocks. They are further insulated with storage: exterior lockers for the high schoolers and interior cubbies for the K-8 students.

West Wall:
The west walls optimize views toward the landscape and allow for ventilation control through the operable louver wall system. The louvers mitigate the intensity of the sun and provide a transitional light space between the exterior and interior. They can be closed to further control sound and extreme weather conditions.

East Wall:
The east wall is constructed of CMU block and permits the buoyancy flow through the classroom. The upper window, controlled by a louver, lets an escape while the lower wall provides a backdrop for pinup space and class materials.

South Wall:
The southern walls are constructed of hollow core block laid on their sides. This provides hints of views to the exterior while allowing the southern breeze to enter the classroom.

Retaining Wall:
Throughout the campus, gabion walls, or metal cages backed with rocks, retain the stepped earth to control flood lines. The walls are detailed with inlaid wood slats, creating an exterior seating area.
**Water Strategy**

Rainwater is collected off the rooftops of shared central programs into a series of large, covered cisterns located adjacent to the central street. From there, water is channeled throughout the site for three distinct uses: 1) to passively cool each classroom through underground water channels, 2) to provide a communal 'croc-washing' station for the children arriving from their muddy commute to school, and 3) to allow for special water events throughout the year, such as the annual boat racing competition.

**Water Features**

- **passive cooling** (through pipes)
- **functional water feature** (croc-washing)
- **'event' water feature** (boatracing)

**Anticipated Flooding**
Proposed Cistern System

12 CISTERNs
Dimensions: 4m tall x 2m radius
Volume: 50 m³ each

TOTAL PROPOSED CONTAINMENT VOLUME
603 m³

Mean total rainfall (mm/month)

<table>
<thead>
<tr>
<th>Month</th>
<th>Rainfall (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JAN</td>
<td>.7</td>
</tr>
<tr>
<td>FEB</td>
<td>3.5</td>
</tr>
<tr>
<td>MAR</td>
<td>26.0</td>
</tr>
<tr>
<td>APR</td>
<td>61.2</td>
</tr>
<tr>
<td>MAY</td>
<td>175.9</td>
</tr>
<tr>
<td>JUNE</td>
<td>221.3</td>
</tr>
<tr>
<td>JULY</td>
<td>236.6</td>
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<tr>
<td>AUG</td>
<td>151.0</td>
</tr>
<tr>
<td>SEPT</td>
<td>276.1</td>
</tr>
<tr>
<td>OCT</td>
<td>248.0</td>
</tr>
<tr>
<td>NOV</td>
<td>81.7</td>
</tr>
<tr>
<td>DEC</td>
<td>10.1</td>
</tr>
<tr>
<td>TOTAL</td>
<td>1494.1</td>
</tr>
</tbody>
</table>

ROOF AREAS for COLLECTION
High School  896 m²
Elem School  760 m²

TOTAL VOLUME H₂O COLLECTABLE  2474 m³
Daylighting Studies
Fall 1pm analysis
Conducted with Lightsolve
Site Airflow
Windspeed: 2.5 m/s from SW direction
Analysis conducted with PHOENICS
REVIEWS
**Future Work**

The workshop students and instructors will travel to Siem Reap, Cambodia for a period of two weeks during MIT’s Independent Activities Period (January 6-20, 2010) to fulfill three objectives:

1. **Design Development team**: Collaborate with the contractor for the existing Ta Chet campus (LBL) to further develop the design concepts and produce construction drawings — team of about 6 class students and faculty supervisor (Mee-jin Yoon).

2. **Design/Build team**: Complete a Design/Build project on the existing campus (TBD: bus shelter, meeting/study area, or other) in collaboration with Jim Adamson and two other Design/Build instructors (MIT graduate students who were involved in the El Salvador Design/Build projects) — team of about 11 class students and faculty supervisor (John Ochsendorf).

3. **Building Physics team**: Retrofit the most problematic existing structures on the Ta Chet campus (library, possibly cafeteria) in terms of comfort (light and heat/fresh air intake) — team of about 2 class students and TA with faculty supervisor (Marilyne Andersen).