Supplementary Materials

Architectural Design: Sustainability in the Decision-Making Process

Margarida Feria [1] and Miguel Amado [2,*]

[1] GEOTPU.LAB - Laboratory of Architecture, Territory and Urban Planning Studies of IST, Lisboa, 1049-001, Portugal; margaridadcferia@gmail.com
[2] CERIS, Civil Engineering Research and Innovation for Sustainability of Universidade de Lisboa, Av Rovisco Pais 1, 1049-001 Lisboa, Portugal
* Correspondence: miguelpamado@tecnico.ulisboa.pt

Received: 08 April 2019; Accepted: 22 May 2019; Published: 27 May 2019

TABLE S1. PROGRAM AND DATA COLLECTION	LEVEL		
PASSIVE STRATEGIES			
a. Site and Climate			
> Analysis of **environmental characteristics** of the site and possibility of bioclimatic solutions.			
Additional Specifications The following parameters should be considered: - topography; - solar geometry, angle and intensity of solar radiation; - prevailing winds and breezes; - air movements; - humidity and air pressure; - range of temperatures; - levels of precipitation and snow; - soil type; - daylight availability; - effect of daylight obstructions; - outdoor air quality; - noise levels; - availability of recyclable materials taken from demolition or site stripping; - identification of pollution or contamination sources such as radon gas.			
> Definition of **energy efficiency strategies** according to the climatic context.			
> Use of **analysis techniques** (e.g., sundials, sun path diagrams, wind maps, bioclimatic charts) to collect and study relevant data.			
b. Urban Context and Conditions			
> Analysis of the possibility of implementing **harvesting and wastewater recycling** systems.			
> Analysis of the availability of **local renewable resources** to produce electricity.			
> Analysis of the most appropriate solutions to **generate or dissipate heat.**			
> Analysis of **water and heat storage** solutions.			
c. Adapting the Program to the Site			
> Adapting the program to the site to **reduce impermeabilized** areas and minimize natural resources consumption.			
Additional Specifications The following parameters should be considered: -profile of users; -number of users; -functions of the building; -typology of spaces.			
d. Internal Consumption and Needs			
> Estimates of **internal consumption and needs**.			

Additional Specifications

The following parameters should be considered:
-internal heat gains;
-electric load;
-artificial lighting needs;
-water consumption needs.

e. Other Criteria

> Analysis of other criteria including **surroundings** and **visual relations; social, historical and economic context.**

Additional Specifications

The following parameters should be considered:
-social and historical context;
-economic context;
-identification of protected areas or elements;
-integration in the urban structure;
-accessibilities;
-visual relations.

TABLE S2. FEASIBILITY STUDY	LEVEL		
PASSIVE STRATEGIES			
a. Siting			
> Site plan should be designed to balance terrain cut and filled to **reduce the need for imported or exported soil** from the site and not to damage the soil structure.			
> Positioning the building to **fit the existing topography, soil, vegetation** and **drainage context** to minimize soil erosion and preserve natural ecosystems.			
> Positioning the building to **avoid unnecessary overshading** of one building by another.			
> The **proximity of the proposal to existing buildings** should be considered according to **thermal needs.**			
Additional Specifications Building contact with adjacent constructions should be considered to increase thermal inertia and minimize heat dissipation; alternatively, it should be avoided to preserve access to breezes of each building.			
b. Orientation			
> Orienting the building according to the **geometry of the sun.**			
Additional Specifications In the northern hemisphere, the longest axis of the building should match the east-west axis facing the solar wall directly to the south.			
> Orienting the building according to **prevailing winds** and **cool breezes.**			
Additional Specifications If the effects of prevailing winds are undesirable, the longest axis of the building should be parallel or with a slight angle to predominant winds to protect it from severe air movements. If the effects of prevailing winds and cool breezes are beneficial to promote natural ventilation, the longest axis of the building should be perpendicular to air movements.			
If the two guidelines above reveal to be contradictory, a reasonable compromise should be made by adopting other possible strategies to meet daylight and thermal needs.			
c. Form			
> An **east-west**, in the northern hemisphere, **longitudinal** and **compact form** of the building is favourable to reduce heat transfer and maximize sunlight.			
> The form of the building should be suitable to **mitigate predominant wind loads,** mainly in very **tall buildings**, and allow the building's access to **cool breezes** for **natural ventilation.**			
Additional Specifications Rounded aerodynamic profiles, angled to prevailing winds or with its narrowest face turned to the wind, may be considered for tall buildings. Gradual transitions of building height, sloped in the direction of prevailing winds, may be considered to minimize strong wind movements. The building form should avoid wind turbulence effects at ground level and building's entrances should be protected from wind pressure.			
> The form of the building can be favourable for outdoor **noise control.**			

Additional Specifications

A closed form, transitional areas between the exterior and the interior of the building or the introduction of a physical barrier between the noise source and the building are example of strategies that can reduce the level of outdoor noise entering the building.

d. Envelope

> The **roof's shape** must be appropriate to regional climate conditions.

Additional Specifications

Flat roofs are appropriate for regions with a low precipitation levels while pitched roofs are appropriate for regions with high precipitation levels or snow.

> Definition of **glazing area** according to the **solar orientation** of each façade.

> Adoption of passive **shading systems** for solar protection.

> check guidelines III. d.

> Minimization of **building's skin area** (walls and roof) to **minimize heat transfer.**

e. Landscape

> Implementation of **green roofs** to collect water and increase thermal performance.

> Implementation of the most appropriate **height, density of foliage** and **spacing** between vegetation.

> Use of existing and **native species** to preserve natural ecosystems.

> Planting vegetation to **avoid overheating** of spaces exposed to excessive solar heat gains during warm periods.

Additional Specifications

Deciduous plantation provides shade during the summer and allows insolation during the winter.
Coniferous plantation provides shade year-round.

> Planting vegetation to **reduce prevailing winds' velocity** and allow cool breezes to pass through natural ventilation.

> Plantation of tall and dense vegetation can **reduce sound propagation** into the interior of the building.

> **Large bodies of water** or **water features** can be used to moderate temperature range through **evaporative cooling.**

Additional Specifications

Still water should be avoided as it can become a breeding ground for insects and microorganisms (such as legionella) that can be dangerous to human health.

TABLE S3. PRELIMINARY DESIGN	LEVEL
PASSIVE STRATEGIES **a. Structure**	
> The building design should be **compatible with a structure that is resistant to natural hazards** to assure mechanical resistance and stability.	
> A structure with an adaptable layout promotes **flexibility to the spaces**, facilitating the **future reuse** of the building and its **adaptation to new functions.**	
b. Internal Layout	
> Spaces should be **arranged within the building** according to **daylight and temperature requirements.** Additional Specifications Rooms with specific functions should be located adjacent to the most appropriate facades according to solar geometry. Clustering rooms reduce skin area and thus, heat gains. Rooms can be distributed vertically within buildings to benefit from temperature stratification.	
> **Dimensioning** rooms according to **function of the building** and **number of users**, avoid unoccupied spaces or areas greater than required. Additional Specifications Thin plan room arrangements, with a depth of less than 2.5 times the window height, ensure a minimum level and uniform distribution of daylight throughout the space and reduces heat dissipation.	
> Dividing the building into **thermal zones** with **buffer areas** (e.g., sunspaces, courtyard, atrium, balconies) that can receive temperature swings and protect rooms from undesirable heat or heat dissipation. Additional Specifications Sunspaces in cold climates can retain solar heat gain and distribute it to other spaces. Courtyards and atrium can receive sun light for heating or cooling purposes. Balconies can be considered at south and west-facing windows, in northern latitudes, to prevent overheating and, at the same time, function as a shading element for windows bellow.	
> **Areas with special air quality needs** (e.g., bathrooms, kitchens, garbage rooms) should be **separated from other living spaces** so that pollutants generated in those areas would not mix with air with better quality.	
> Internal layout should be adapted to **control noise inside the building.** Additional Specifications The overall size and volume of rooms should be adapted to acoustic requirements, particularly spaces with specific functions such as classrooms, offices, concert halls, etc. Rooms can be arranged within the building so that noisy areas are not located close to areas that require users' focused attention.	
c. Opening Elements	
> Opening elements should be planned (dimensions, exposure angle and arrangement on the façade) according to the **activities taking place, size of the room and number of occupants** to match **daylight needs and ventilation loads.**	

Additional Specifications

South-facing windows in the northern hemisphere provide maximum solar gains.
Opening elements can be planned to provide different light effects through direct or diffuse light.
Vertical windows are advisable for admitting low-level sunlight in winter and promoting natural ventilation.
The minimum area of opening elements should be about 5% of floor area to admit the most appropriate ventilation load.
Large openings of equal size placed opposite to each other increases the effect of cross ventilation.
A considerable distance between high and low openings increases the effect of stack ventilation.

> **Glare** inside rooms **should be avoided.**

Additional Specifications

A window splay can be considered to reduce glare.
Direct light should be avoided in working rooms to prevent glare.

> **Main doors** should be **located away from prevailing winds.**

d. Shading Elements

> Shading elements should be planned (dimensions, exposure angle and arrangement on the façade) according to the **solar orientation of the façade** and **daylight and thermal requirements.**

Additional Specifications

Shading elements should be considered for south and west-facing windows in northern latitudes to prevent overheating.

> **External shading elements are preferable** since the sun radiation does not reach the interior of the building.

> The **most favourable type and technology** (e.g., vertical louvers, horizontal overhangs, eggcrate, screenings) of **shading devices** should be investigated.

Additional Specifications

Overhead horizontal shading elements protect from the high sun.
Vertical shading elements protect from the low sun.
Interior light shelves can be used to reflect light to the ceiling, which reduces glare and improves daylight distribution.
Shading technology that allows diffuse light inside the building while protecting from direct light can be considered.

> **Vegetation** can be used as a seasonal shading element.

> check guidelines II. e.

> **Shading systems that maintain outside views** are preferable, to allow a visual connection with the exterior world.

e. Natural Ventilation

> **Natural ventilation** should be promoted **if outside air is not polluted.**

Additional Specifications

If outside air is polluted, air filters should be considered to reduce contaminant concentrations.

> **Cross-ventilation should be ensured** and prioritized over single-sided ventilation.

Additional Specifications

To benefit from the cross-ventilation effect, the room depth should not exceed 5 times the room height.
If cross-ventilation is not possible, the room depth should be limited to about 2.5 times the room height.

> **Stack-ventilation should be considered** to promote air circulation and cooling.

Additional Specifications

An atrium, vertical towers (windcatchers), solar chimneys, single sided double-openings and cavity ventilation are examples of solutions that can increase stack-ventilation effect.

> Dimensions and arrangement of **opening elements** on the façade should **match the ventilation loads,** according to the **activities taking place, size of the room and number of occupants.**

> check guidelines III. c.

> **Night-time breezes** should be considered to cool the building during the night.

f. Additional energy efficient strategies

> **Opaque elements of the building's envelope** (roof, walls and floors) should have **high thermal storage capacity** to reduce temperature variations.

Additional Specifications

Besides thermal insulation, other passive strategies can be used for heating or cooling the building. A Trombe Wall facing south in northern latitudes can be used as a heating strategy for cold regions.

> **Natural thermal equalizers** can be used for heating and cooling.

Additional Specifications

Passive ground-coupling or roof ponds can be used for purposes of heating and cooling air or water.
Rock beds can be used for cold or heat storage.

ACTIVE STRATAGIES
g. Heating and Cooling Solutions

> **Photovoltaic panels** should be considered to produce electricity for heating and cooling if the on-site sunlight exposure period is long.

Additional Specifications

Photovoltaic panels can be integrated on the façade and may also function as shading systems.
Photovoltaic panels should be oriented towards the sun and should be large enough to meet the building's electric load.

> If powered by renewable resources, **other heating and cooling systems** besides photovoltaic panels can be considered for **space heating and cooling and provision of hot water.**

Additional Specifications

Solar collectors can be used for space and water heating:
Glazed flat-plate collectors are recommended for domestic and commercial buildings.
Unglazed flat-plate collectors are recommended for swimming pools or to be used as a heat source for heat pumps since they have a low efficiency degree, which is a result of high thermal losses.
Evacuated-tube collectors are the most efficient but can be costly and are therefore mostly suitable for industrial buildings.
Heat exchangers can be used for heating and cooling:
Air-air heat exchangers can be considered for heating, cooling and ventilation.
Ground-coupling heat exchangers through boreholes or grid pipes can be used for heating or cooling.
Ground or surface water exchangers can be used for heating or cooling. However, great care must be taken to avoid contaminated water or the corrosion of installation components.

> Heating and cooling **storage** should be selected so that users' needs are fully met during the hours of higher consumption.

Additional Specifications

Short-term heating and cooling storage can be considered according to thermal requirements (e.g., small water tanks or tank in tank systems).
Long-term heating and cooling storage can be considered according to thermal requirements, (e.g., large water tanks, natural or enclosed aquifers, mixture of gravel and water sealed off from the surrounding soil, ground strata connected via vertical boreholes).

> Heating and cooling **distribution** should be selected.

Additional Specifications

Water pipes as a medium to distribute heat can be considered since water has a higher heat capacity than air.

> Heating and cooling **output** should be chosen.

Additional Specifications

Individual components for heating (e.g., radiator, floor outlet) or cooling (e.g., ceiling outlet or long-range nozzles) can be used for space heating and cooling.
Heated surfaces (e.g., underfloor heating, ceiling heating) can be used for space heating.

TABLE S4. DETAIL DESIGN	LEVEL		
PASSIVE STRATEGIES **a. Materials Selection**			
> Materials should be recyclable and **reusable.**			
>Whenever possible, materials should be **selected from local sources** using minimum energy in production and transport to reduce environmental impacts.			
>Finishing materials should be **selected according to the activities taking place** in each room.			
>Materials should be selected based on their **thermal performance**. >check guidelines IV. b.			
>**Finishing materials** can be selected according to their **colour**, lightness or darkness, depending on the climatic context.			
Additional Specifications Light-colored finishing materials, mostly appropriate for hot climates, reflect solar radiation, which means they reflect light and heat. Dark-colored finishing materials, mostly appropriated for cold climates, absorb solar radiation, which means they absorb light and heat.			
>**Porous absorbent materials** (e.g., fibrous materials, open-celled foam) or **resonance absorbent materials** can be considered for soundproofing depending on the frequency distribution of noise to be absorbed and the acoustic absorption profile required.			
>Materials that contain **toxic components** (e.g., VOCs, SVOCs, radon, and others) that may represent a risk for users' health or cause polluting emissions **should not be used.**			
>Exterior materials should be **resistant to temperature fluctuations, air contaminants** and **chemical agents** (e.g., airborne salt).			
>Materials should be **protected against biological agents** that might damage materials (e.g., termites and other pests, microorganisms, plants).			
>**Waterproof and moisture resistant materials** should be selected for wet areas or where condensation may occur to control moisture and prevent the growth of microorganisms.			
>Materials and components of the building should be **easy to clean and maintain.**			
>**Glass technology** can be selected to **balance daylighting and thermal needs.**			
Additional Specifications Glass coating technology can provide dynamic control of daylight and thermal needs (e.g., photochromic glass, thermochromic glass, electrochromic glass). Glass technology can scatter light evenly and avoid glare, although in some cases the outside view may be lost (e.g., light-scattering glass, diffuse glass, glass blocks). Glass technology can be selected for daylight directional control (e.g., prismatic glass, holographic glass, electrochromic glass).			
b. Thermal Insulation Materials			
>The **entire building envelope should be properly insulated** to reduce heat transfers and stabilize interior air temperature.			
>Materials with a **lower *U*-value** (thermal transmittance) [W/m^{2}K] should be selected for a better insulation performance.			
>**Exterior insulation** is advisable to control the air flow within building components and prevent condensation.			

Additional Specifications

A vapor barrier on the warm side of insulation is required to prevent condensation.

>A **low-E** (low emissivity) **glass with double or triple sheets** should be considered to improve thermal insulation capacity of glazing.

Additional Specifications

The spacing between each sheet of glass should not be too narrow (the insulating effect is then lost) neither too wide (a layer of condensation can be formed, and the low-emissivity coating loses effect)—15 to 20 mm is the recommended glazing spacing for thermal insulation.

Glazing sheets can be partially evacuated or filled with gas instead of air for better insulation performance.

>**Transparent insulation materials** (e.g., honeycombs) can be considered since they have a high transmission of solar radiation and good thermal qualities.

c. Construction Details

>**Multi-leaf facades** with an air layer should be considered to improve insulation.

>**Joints between different components** of the building should be **airtight to minimize thermal bridges.**

>**A drainage system** should be installed to direct rainwater away from the building.

d. Water Fixtures

>The **selection of low water flushing volume toilets and urinals** and **low volume taps and showerheads is recommended.**

Additional Specifications

The recommended average capacity of flushing tanks for toilets is 6, 4 or even 1 L.

The recommended water flow rate of taps and showerheads is 10L/min.

Low water flushing volume toilets include interruptible flow systems, double discharge tanks and flushing tanks with reduced capacity.

>The installation of **waterless or dry composing toilets** may be considered.

Additional Specifications

These systems require regular maintenance.

>The most favourable **type of toilet flush system** should be investigated **to reduce water consumption.**

Additional Specifications

The main types of toilet flushing systems are gravity tank, flushometer and vacuum toilets.

>**Water fixtures technology** can be used to reduce water consumption.

Additional Specifications

Aerator taps can reduce water flow but maintain water pressure.

Thermostatic taps can control water temperature and avoid excessively hot water.

Taps with solenoid valves can shut off water when not in use.

Flow rate delimiters can regulate flow rates.

e. Building Management

>An **operation and maintenance manual** with important information about the building should be provided to the users.

>A **computerized building management system** can be installed to automatically regulate energy and lighting requirements, security, lift operation and several other functions.

ACTIVE STRATEGIES

f. Low Consumption Devices

>**Energy efficient appliances** (e.g., artificial lighting, refrigerators, freezers) and equipment should be selected.			
>**CFLs, LEDs** or **other energy saving lamps** should be selected.			
>**Artificial light** should be optimized to **meet users' needs.** Additional Specifications Occupancy detection or time control systems should be installed to provide automatic light control. Daylight sensors can be considered to adjust artificial light intensity according to the incoming natural luminous flux. Artificial light control should be sectioned so that individual rows can be switched on or off as needed.			
>**The type, arrangement and number of luminaires** should be appropriate to **room functions.** Additional Specifications Task lighting is appropriate for localized activities that require focus. Amenity lighting is appropriate for overall space illumination. Spot lighting is appropriate for punctual illumination.			
>**The color of lamps** should be appropriate to **room functions.** Additional Specifications White-colored lamps are similar to natural daylight and should be chosen for rooms where focused attention is required. Warm-colored lamps should be chosen for a comfortable and relaxing atmosphere.			
>**Water efficient appliances** (e.g., dishwashers, washing machines) should be installed.			