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Advances in Passive Cooling Design: An Integrated Design Approach

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Abstract

Incorporating passive cooling devices within building design requires analysis of device variables and actions to improve cooling performance, maximize efficiency, and integrate with building elements. Improving devices performance requires understanding the relation of devices to design stages, building elements, and working mechanism, and actions performed by devices to enhance cooling process and effectiveness. Therefore, designers could integrate passive devices as intrinsic design elements. The current research introduces SARS as an innovative classification of passive devices based on cooling actions that are performed by a device like *storing, avoidance, removal* or *slowing* (SARS). All actions, devices, and variables were discussed and analyzed to help integrate them within design stages: analysis, designing, and performance. Understanding actions will help maximize the performance of the devices, combine two or more devices together, and integrate the devices' design in design process. Combining more devices together to perform more than one function will move passive design to a new level to become as whole building design approach and to be a core design element.

Keywords: passive cooling, storing, avoidance, removal, slowing, design matrix, shading, ventilation

1. Introduction

The integration of passive systems in the architectural design process requires many considerations on all levels of design stages. The aim of this integration is to achieve and provide high-efficiency thermal comfort or natural lighting. Passive system performances depend mostly on natural and environmental elements like the sun, wind, earth, and water. It is, therefore, significant to study and analyze how passive systems interact with natural elements and their relationship to a building site. Passive cooling systems, thereafter, need to be integrated within the design process, as their performance requirements are affected by orientation, height, materials, form, and characteristics of many architectural elements.

The main two innovative ideas of this chapter are, first, to provide analysis of passive devices based on one or more of the cooling actions (store, avoid, remove, and slow (SARS)) and, second, to develop a design matrix based on SARS actions and analysis of examples of integrated passive systems.

2. Passive cooling systems

Passive cooling systems were the main design driver in low energy architecture and vernacular architecture especially in hot climate regions. Buildings were designed and built to adapt to local environmental conditions and to use natural elements to provide occupants with the required thermal comfort around the year. However, the discovery of fossil fuels and the development of new construction materials the building industry became less respect to the surrounding environment and less dependent on passive techniques. Buildings become heavily dependent on energy to provide the indoor environment with the required thermal comfort. The use of fossil fuels on a large spreader scale resulted on many environmental and health problems that associated with the greenhouse emissions. These problems shifted architects' awareness to environmental and climatic variables to be key drivers of the building design to provide the required thermal comfort and reduce energy consumptions.

Passive cooling or heating approaches play a major role in bringing architecture closer to the original green, environmental, and vernacular architecture by using surrounding environmental elements such as solar radiation and natural ventilation. Passive cooling is an approach that focuses on providing thermal comfort by controlling heat gains and heat dissipation without involving mechanical or electrical devices. The performance quality of this approach depends totally on the interaction of the building's design and devices with the surrounding environmental factors, such as sun rays, ambient air temperature, wind, and humidity, to achieve energy balance for occupants. Therefore, conducting a thorough analysis of a building's local climatic conditions is essential for any passive cooling approach to successfully fulfill its purpose and to maximize a specific action of SARS.

Heat gain sources include internal and external sources. The internal heat gains are produced from human activities, artificial lights, equipment, and appliances used by the occupants, while the external heat gains result from the interaction of the building with the outdoor environment. Heat gain or loss has four forms: *first*, heat gains caused by solar radiation passing through opaque envelope materials and heating the interior spaces with the greenhouse effect, *second*, heat gain caused by direct sun rays transmitted through windows and transparent surfaces into the interior spaces, *third*, heat gains caused by conduction between the building envelope and the surrounding environment, and, *fourth*, heat gains through convection caused by air infiltration and ventilation exchange between the outdoor and indoor environment as seen in **Figure 1**.

Lechner [1] presented many simple passive devices used for cooling in hot climates like simple courtyard, wind tower, thermal massing, windows, arcade, shading devices, and solar chimney. In addition the book discussed the ventilation principles and pattern. Many studies investigated in different approaches and methods the potential of passive cooling techniques in saving energy and cooling the indoor space in different climates. Nunes and Oliveira Panão [2] suggested a method to calculate the monthly cooling energy needs in zones where passive cooling systems are installed and applied on an office ventilated by passive devices like earth cooling and solar chimney. Kachkouch et al. [3] investigated three passive techniques in the real conditions in hot semiarid climate. The study tested the effect of three main techniques are, shading ceiling color and insulation on heat flux. The study concluded that these techniques helped to reduce heat flux with best results of white painted. Prieto et al. [4] showed how important it is to apply the passive strategies in early design stages and use active equipment after that if necessary. They studied, using simulation software, the effectiveness of selected passive cooling strategies like glazing, shading, color, and heat sink in commercial

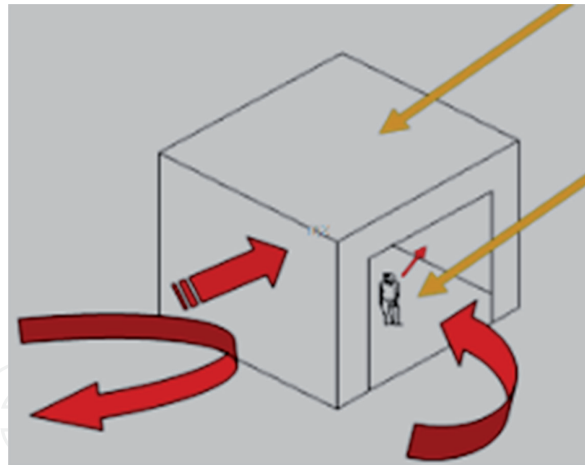


Figure 1.
The interaction of the building with the environmental elements (author).

buildings in warm climates. The study concluded that the efficiency of the passive strategies conditioned to both the harshness of a given climate and design of different building parameters. Tejero-González et al. [5] reviewed many passive design techniques and parameters affecting applicability of such techniques. The study investigated how the climatic parameters are needed to be studied thoroughly to design and select passive cooling/heating techniques. Panchabikesan et al. [6] studied many passive design techniques like evaporative cooling, nocturnal radiative cooling, and phase change material (PCM) in different climatic conditions in India to reduce energy consumption. The study showed that these techniques best result in hot climates. Oropeza-Perez and Østergaard [7] review many passive and active cooling methods that could be used in residential buildings. They studied firstly many technologies in term of heat balance, secondly they scientifically analyzed the results, and finally they focused on feasibility and economic value of the findings. The study developed a decision-making program to find out the most suitable cooling method in dwelling design. Passive cooling focuses on controlling heat gain or heat loss in a building in order to reduce energy consumption and in order to create the indoor thermal comfort [8].

3. Passive cooling actions

Understanding the sources of heat gains that affect thermal comfort in the building is essential for deciding the type of actions to be taken to avoid as much heat gains as possible, to slow the heating process to remove the uncontrolled gained heat, or to store cold air or elements. The four passive cooling actions include the following:

1. *Storing* of cold mass or air within building envelope. This action is defined by keeping cold air or mass away from direct heat gains to provide spaces with cold air or cool down the air before entering the interior spaces like courtyards, basements, earth spaces, and thermal masses.
2. *Avoidance* of direct external solar radiation heat gain. This action is conducted by applying design considerations and devices in the building. Avoidance could be applied by using shading windows and glazed areas, using landscape, designing of self-shading forms, and considering colors and reflectivity of external surfaces.

3. *Removal* of gained heat from the interior or exterior sources. This action is required to remove portion of undesirable heat that could not be avoided or slowed. The action can be performed through controlled ventilation, by using wind towers, earth tunnels, and windows to support ventilation requirements.
4. *Slowing* heat transfer from the external climate through the building envelope. This action is conducted by using techniques like efficient insulation and double glazing window units.

The four actions of passive cooling, *storing*, *avoidance*, *slowing*, and *removal*, are discussed in this section in detail with regard to the cooling principles and the designing process, focusing on the variables affecting their performances. Each device or principal will be discussed based on the following categories:

- The required actions of implementation from designers in each design process, in stages of early stage (analysis), middle stage (design), and final stage (performance)
- The building variables related to the devices and principles
- The required conditions of using the device
- Using case studies and examples of integration of devices and actions in the buildings' design

Some passive systems have direct impact on the architecture design, like the design of an opened atrium or a courtyard, and some have less direct influence, like the type of material and use of louvers or shading systems. Therefore, the level of integration between these systems and the architectural elements varies among the different types of systems and actions. However, it is important to understand the requirements of the chosen passive systems and to make the right decisions of when and where to integrate them within the designing process.

3.1 Storing devices

Storing refers to keep cold air or low temperature object away from direct heat sources to be used to cool down interior spaces. Throughout architectural history, and particularly in hot climate regions, devices were developed for this purpose as storage design elements, like courtyards, earth spaces, basements combined with wind towers, thermal masses, and sunken courtyards. For the purpose of this research, courtyards are discussed as one of the most efficient devices in storing cold objects or air.

3.1.1 Courtyard

Courtyard is an opened space surrounded by rooms with openings on the conjoint wall between the rooms and the courtyard space, to allow air exchange daylight, and view. The courtyard as passive design device works as a modifier of the microclimate and acts as a heat sink and cold air storage. Buildings with internal courtyards are characterized as a suitable solution for cooling in hot climate regions to provide inner spaces with cold air and daylight.

The working mechanism of the courtyard depends on the cycle of day and night, which results on a continuous change of air temperature and the difference in air temperature between the inside and outside of the courtyard (**Figure 2**). Therefore the

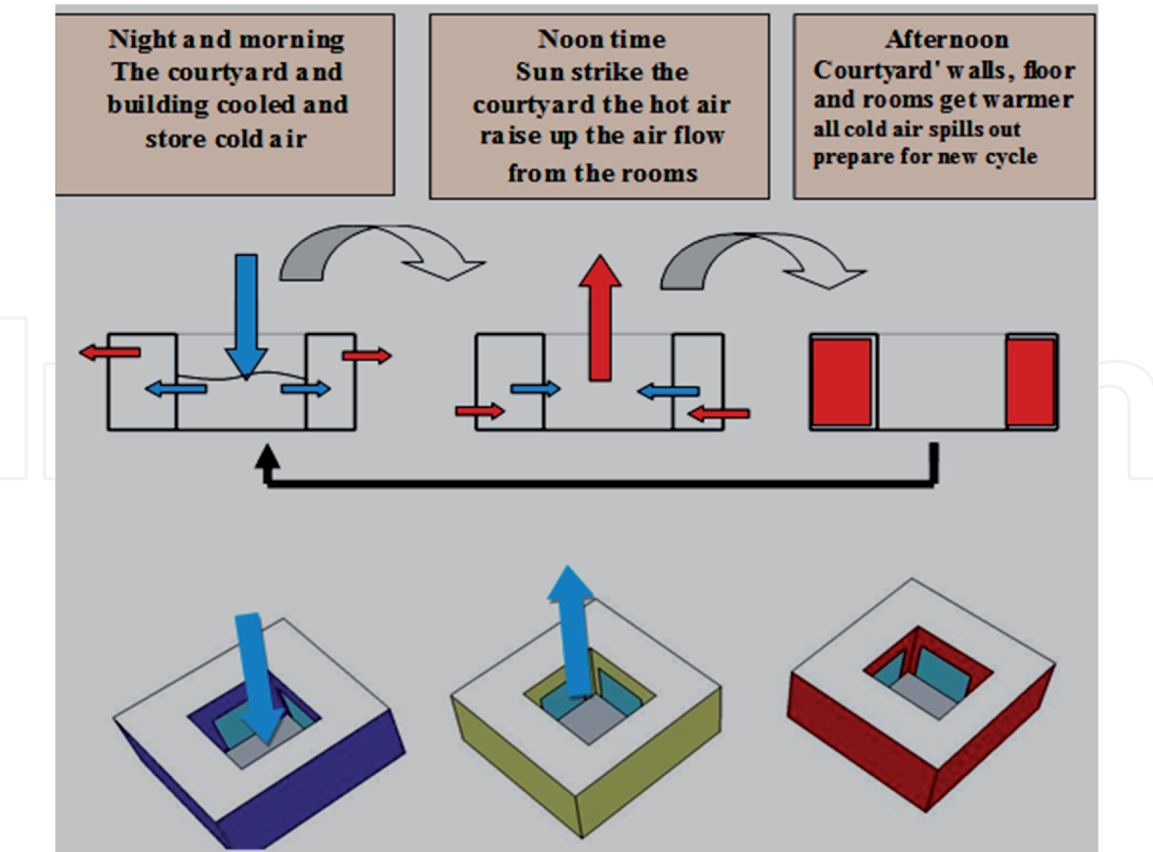


Figure 2.
The three periods in the working mechanism of a courtyard (author).

performance quality of the courtyard house depends on the heat exchange processes between the indoor spaces and the courtyard and then between the courtyard space and the external open spaces. It consists of three main periods; during the first one, the cool night air sinks into the courtyard and flows to the surrounding rooms, and therefore the spaces and surfaces are cooled until noon time. During this period, the courtyard works as storage of cold air and cold air exchange with surrounding rooms. The second period starts at noon, when the sun strikes the floor of the courtyard directly and the temperature of air inside the court's space starts increasing gradually, causing the hot air to move up, and consequently, air is drawn from surrounding rooms to the courtyard space through the openings, resulting in cooling the surrounding rooms. The last period starts when the courtyard and the surrounding rooms get warmer, and all cool air leaks out, which prepares the system for a new cycle in the next day.

3.1.1.1 Courtyard design variables to maximize storing effect

The passive cooling performance of courtyards depends on three types of elements: the courtyard elements like walls, floor, and landscape greeneries; building elements like windows and built space characteristics; and finally site elements like location, climate, and orientation as summarized in **Table 1**. The cooling performance of courtyards depends on providing the enclosed spaces protection from direct solar radiation and controlled airflow by studying the orientation of the courtyard with regard to the solar path and providing trees for shades and designing with consideration of prevailing winds. **Table 1** summarizes the different variables affecting the cooling performance of a courtyard that designers need to take in consideration in the designing process:

Optimizing the passive cooling performance of courtyards in hot regions depends mainly on how to design an efficient storage space by studying shading patterns, geometrical shape, and thermal mass material.

Elements	Variables	How to maximize storing action in hot climate
Walls, floor	Height-to-width or to area ratio	High H/W ratio [11]
	Material, thickness, color	High thermal mass stores low temperature, heat absorbance, and reflection
Geometrical shape	Inside stepped or tilted walls [27]	Increases the shaded areas and improves courtyard's thermal performance and storing action in hot regions
	Outside stepped or tilted [27]	Increases surface exposure to sun and therefore reduces the shaded areas
Landscape	Greenery type, height	Define the patterns of shade or expose shaded area on floor and walls
Windows	Location, window/ wall ratio	As the openings allow air to be drawn from the rooms to the courtyard
Orientation	North-south or west-east	A balance based on prevailing winds and solar angles, to optimize shading and ventilation

Table 1.
Courtyard design variables (author).

Zamani et al. [9] studied how to improve the thermal performance of the courtyard by studying various design factors such as proportion, orientation, geometry, opening characteristics, and material. In addition they studied more variables like shading devices, vegetation, and water pools and their impact on heat mitigation.

Sadafi et al. [10] explained how using internal courtyards in terraced houses in tropical regions improves the natural ventilation and thermal comfort. Meir et al. [11] investigated how two semi-enclosed attached courtyards will affect the microclimate in the enclosed courtyards and the attached built volume. Muhaisen [12] showed that courtyards' shading performance depends on the form's properties, location, latitude, and available climatic conditions. Berkovic et al. [13] studied the effect of courtyard design variables, like orientation, horizontal shadings, galleries, and trees, on the thermal comfort of the courtyard's surrounding functions. Muhaisen and Gadi [14] investigated how courtyards' proportions and surface colors considerably influence thermal comfort of the surrounding spaces. Al-dawoud and Clark [15] investigated how different design parameters of the courtyard affect the thermal comfort in spaces surrounding the courtyard. They approved that courtyards are more energy efficient in hot-dry and hot-humid climates in comparison to cold climates.

The design of courtyard with other devices and elements should be made to enhance storing effect and ventilation process, which include the opening, thermal mass, landscape, and building form. Elements that could be integrated should enhance storing action of the courtyard like thermal mass, wall geometry, and landscape. Moreover, to enhance heat exchange between the courtyard and surrounding spaces, other devices could be integrated with the courtyards like wind tower, solar chimney, basement, and opening design and bearing in mind the design requirements in early stages of design process. Therefore, design decisions will have direct impacts on the building's form, orientation, area, zoning, function distribution, and relations with the outdoor and site design.

3.2 Avoidance

Avoidance, as a passive cooling action, refers to all the methods used to prevent and reduce the amounts of heat gains from direct solar radiation or wind. The key methods of avoidance include different shading devices, building's form, and

landscape. Additional factors, including building’s orientations and surfaces’ colors and textures, can help to prevent gained heat from reaching inner spaces.

3.2.1 Shading devices

Cho et al. [16] presented an integrated approach for exterior shading device design analysis that included cooling energy performance and economic feasibility in high-rise residential buildings. The research investigated the effect of 48 exterior shading devices on the sunshading/daylighting performance. Palmero-Marrero and OLiveira [17] studied the effect of static louver shading devices on east, west, and south facades for various locations on the energy demands during cooling and heating seasons. The research concluded that the shading device reduced the total annual energy demands in buildings of countries with long dominant cooling seasons and high ambient temperatures and solar radiation.

Datta [18] studied the effect of external fixed horizontal louvers on the thermal performance in the buildings. The study was aimed for reducing the overall energy requirements for the entire year by maximizing the shading device system to reduce solar gains during summer and allow them during winter. The study used TRNSYS as a simulation to maximize the efficiency of the device, and different slat lengths and tilt angles were tested in four Italian cities. Yao [19] evaluated the effect of shading control strategies on the daylighting, visual comfort, and energy performance in buildings.

Designing buildings with the passive approach requires integration of many factors together in the process, such as orientation, shading devices, and building form in order to reduce energy consumption in the building as a whole as seen in **Table 2**. Largely glazed facades and large windows have been increasingly used in new buildings, allowing access to daylight, solar heat gains, and external views. The increase in glazed surfaces requires significant attention in building design, regarding the impact they have on cooling, heating, and lighting loads demands. Therefore, it is important to provide these buildings with a proper shading design that would provide interior spaces with thermal comfort by controlling solar heat gains and reducing glare while maintaining the initial purpose of large glazed surfaces to provide external views and sufficient daylighting.

Many researches were conducted to study the performance of shading devices in order to optimize their performance, save energy, and achieve the maximum thermal comfort. Datta [18] used computer simulation to study variables related to horizontal shading devices and their effect on the thermal performance in buildings in Italy. The study showed that shading devices could help save energy and

Elements	Variables	How to maximize avoidance actions
Types by	Horizontal louvers	Southern windows block high solar angles
	Vertical louvers	East and west windows block low solar angels
	Diagonal or eggrate	Block low and high angles on east, south, and west directions
	Overhangs, canopy	The depth and height, considering solar noon in summer and winter
Device’s variables	Space to depth	Depth-to-spacing ratio to balance between sunrays block and view out
	Material	To reflect or to absorb sunrays

Table 2.
Shading device variables (author).

improve the thermal performance of the buildings. Palmero-Marrero and OLiveira [17] proved that shading devices could improve thermal performance of buildings and save energy in many cities in different latitudes and climatic conditions.

3.2.1.1 Shading in existing buildings and new buildings

A study that has been conducted at Jordan University of Science and Technology to design shading devices showed that the process of designing shading devices for an existing building required reflections of various parameters besides thermal comfort. Many tools were used to monitor the performance of shading devices like patterns of use and users' behavior in the new setting. The study used real measurements, computer simulation, user's survey, and observation usage. The study showed that user's preferences like view out, natural lighting, illuminance levels, and thermal comfort were the most influential indicators in designing shading devices. Moreover, user's behavior and patterns of use in the office in question were monitored and proved that a well-designed shading device can improve thermal comfort, user satisfaction, and user behavior from energy consumption point of view. The study was conducted in two stages: in the first stage, temporary materials were used to study the integration

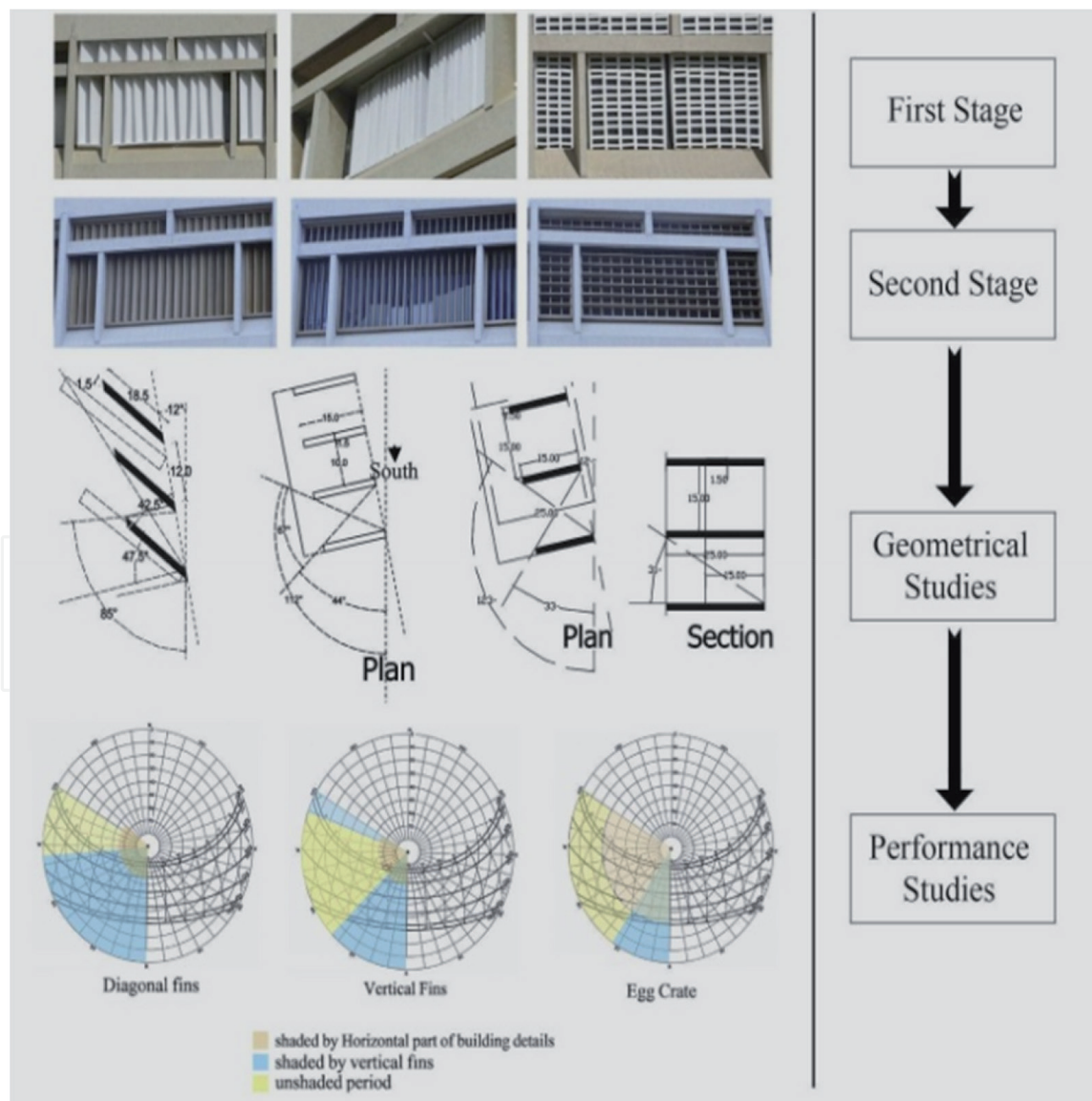


Figure 3. *Stages of designing shading devices in the existing building and their performance with reference to users' preferences [20].*

of all variables as seen in **Figure 3**. In the second stage, permanent materials were used, and long-term monitoring was conducted in order to generalize the best design for shading devices in offices with large windows at the university campus [20].

3.2.1.2 Self-shading and building form

Hemsath and Alagheband Bandhosseini [21] stated that building form and orientation as early decisions in the design process could have a great impact on energy consumption, lighting, cooling, and heating load. Authors emphasized on the relation between the building’s forms, shapes, daylight, and energy consumption in the early design phase, instead of using mechanical and artificial light. Many non-rectangular shapes had been evaluated in terms of self-shading and energy consumption like an L or U shape that can offer solar advantages. Zhou et al. [22] studied how optimal building design could enable harvesting of the maximal micro-wind power around low-rise residential buildings.

Zerefos et al. [23] compared polygonal and prismatic building envelopes to orthogonal building envelopes based on energy behavior and energy consumption in Mediterranean climates. The study showed that prismatic formed buildings gain lower solar than orthogonal forms and so consume less energy by an average of 7.88%. Moreover, Caruso et al. [24] used the mathematical theory of calculus of variation to find the best geometric form to minimize direct solar irradiation incident on the envelope. The paper also aimed at finding useful guidelines and rules for designers to follow during early decision-making stages to reduce the total amount of direct solar irradiation [24].

Azari et al. [25] showed that there are various architectural features of a building that could influence its indoor thermal comfort, daylight, and energy consumption, such as building shape, orientation, wall forms, window-to-wall area ratio, window size, glazing material, wall structure, and shading. They may increase solar gain and daylight duration during winter, which would be beneficial and could lead to overheating during summer. Yasa [26] studied the comfort conditions of different configurations of buildings like open courtyard configurations, closed courtyard configurations, and configurations of courtyards with apertures on the wall.

Designers can use building’s forms as self-shading approach that shades the outside surface materials, windows, and glazed areas (**Table 3**). An example of a self-shading building is the library of the University of Nottingham, UK, which was designed with large glazing surfaces to utilize daylighting without causing glare as seen in **Figure 4**. The design was based on using self-shading form to protect inner spaces from direct sunrays.

Element’s construct	Concepts	Variables	Notes
Building’s elements	Exterior wall tilt angle	Winter and summer solar angle	Studying the maximum and minimum solar angles to determine the optimum tilt angle of the external walls for the building to act as self-shading form
Site’s elements	Climate	Hot climates	Self-shading forms for buildings with large glazed surfaces and high requirements of daylighting
		Cold climates	Requires less self-shading forms and increase of the direct heat gains

Table 3.
Self-shading and building form variables.



Figure 4.
Library building at University of Nottingham, UK (author).

3.2.1.3 Landscape

Trees and landscape can improve the thermal environment and reduce the temperatures of interior spaces and surfaces in buildings. Monitoring tree effects on buildings showed that trees and landscapes do not only provide shade and reduce air temperature but also prevent buildings’ materials from gaining and storing heat and radiating it back later as seen in **Table 4**. A study conducted in Jordan University of Science and Technology compared two identical glazed corridors of orientation and materials, but one of them with trees and landscape providing shade, and one without trees. The study showed that shaded building’s surfaces with high trees recoded a lower temperature of 34°C than identical spaces with temperature of 41°C in summer day as seen in **Figure 5**.

Designing with avoidance systems requires analysis of the solar angles laterally with the dimensions and orientation of the building’s site to identify the type of shading devices with integration and function and daylight strategies. Designer’s decision of the building’s form should consider self-shading building, orientation, elevation design, and relation to landscape to enhance avoidance actions. Performance evaluation of avoidance actions required integration of cooling decisions with all building elements, such as glazing area, orientation form and mass design, facade design, and opening.

3.3 Removal

Removing, as a passive cooling action, refers to the removal of undesirable gained heat in interior or exterior spaces in a building. Natural ventilation normally is the main strategy used to take unwanted heat out of the buildings. It depends mostly on pressure differences to circulate air between inner and outer spaces, allowing air to enter or escape from buildings. Devices like windows, openings,

Variables	Notes
Tree type	Evergreen or deciduous trees affect the periods and area of shading on buildings, walls, courtyards, and outdoor spaces in summer and winter
Height and horizontal spread	The pattern of shade provided by different types of trees
Distance from building	Location of shade on building, walls, walking area, and courtyards

Table 4.
Landscape variables (author).

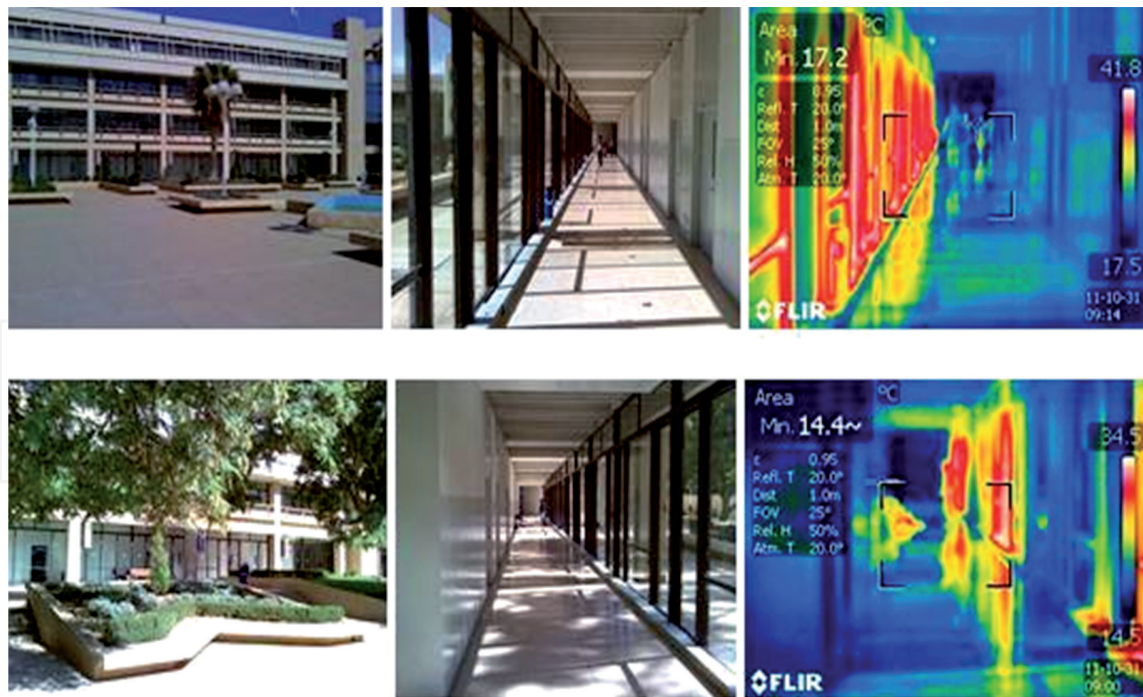


Figure 5.
 The effects of trees on surface and air temperatures in identical spaces (author).

wind towers, sunspaces, earth tunnels, and roof openings are used to move air through a building.

Natural ventilation follows three main principles that designers should understand well in order to induce passive ventilation into any building's design, which includes stack ventilation, Bernoulli's effect, and the Venturi effect. These three principles use air pressure differences due to height, air temperature, or wind speed, to pull air to or from buildings. Therefore, the main concept of passive ventilation design is achieved by maximizing the use of one or more of the three principles in order to induce natural ventilation.

3.3.1 Stack effect

Stack effect depends on temperature differences to circulate air, as hot air rises up and cool air sinks down (**Figure 6**). The design for ventilation that depends on stack principles is achieved by letting hot air rise up within spaces or specific devices and exhausting it from upper openings, which allows it to be replaced by cooler air from lower openings. The designer's role in the process is represented in designing air movement and its exhaustion and penetration, which includes the following methods:

1. Accelerating the rising of hot air by designing a long vertical space that crosses through the building section, like atriums, double-skin facades, solar chimneys, or wind towers
2. Designing inlet openings for cold air to enter the building from a well-planned and controlled cold space like shaded courtyards or urban spaces, basements, etc.
3. Increasing warm air to activate the stack effect and accelerate the ventilation process using devices like sunspaces, solar chimneys, and skylights in the building's design

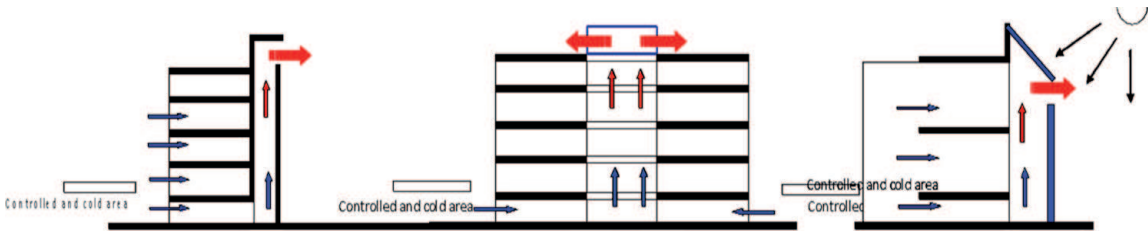


Figure 6.
Stack effect (author).

3.3.2 Bernoulli’s effect

Bernoulli’s effect depends on the reduction of air pressure associated with the wind speed. In buildings, designers use wind speed differences to circulate air inside or around the building **Figure 7**. Air movement around and above buildings creates positive and negative pressures, causing fresh air to be sucked through specific openings into the buildings at the same time allowing hot air to escape through designate openings and locations. The designer’s role in the process is represented in planning and designing air movements with regard to the negative and positive air pressures zones, and it includes the following methods:

1. Designing the building’s surroundings with the least possible obstructions to allow air flow around, creating the necessary positive and negative pressure zones.
2. Designing the building’s form to go with the direction of the wind rather than obstructing it; this is to increase wind speed around the building and create positive and negative pressures.
3. Designing openings in the areas of positive and negative pressures with integration with the interior space distributions to maximize ventilation process.

3.3.3 Venturi effect

Venturi effect causes acceleration in air speed when it passes from a wide section area to a thinner section area, developing a negative pressure zone at the thinning points, which help suck the air from near spaces as seen in **Figure 8**. Designers can make use of this effect in building’s designs by:

1. Designing urban settings, landscape, and group buildings with regard to the large scale to allow them to capture wind and increase its speed

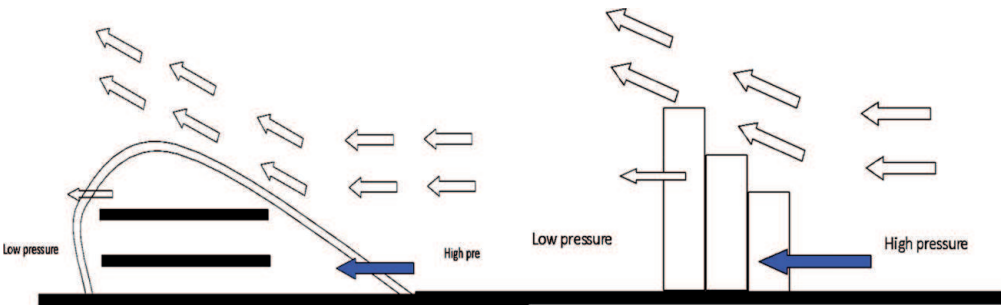


Figure 7.
Bernoulli’s effect (author).

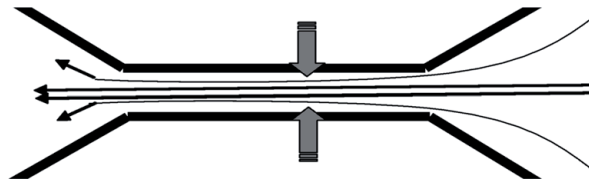


Figure 8.
 Venturi effect (author).

2. Using upper openings in atriums and skylights to improve the performance of the effect
3. Using elements like ventilation ducts and pipes to improve the performance of the effect

3.3.4 Wind tower (wind catchers) and solar chimney

Wind towers are used to catch air from higher levels and push it into the interior spaces of a building. A cooling process takes place by heat exchange between the walls of the tower and the hot collected air or by using evaporative cooling at the bottom of the wind tower. Fresh cold air flows to the inner spaces through an opening at the end of the wind tower. At night, wind tower works as a chimney to suck the hot and exhausted air from the room to the outside environment, causing cooler air to replace hot air from other openings. The performance of wind towers can be improved by implementing a water source, like a fountain, at the bottom of the wind tower, which helps cool the gathered air. Additionally, the wind tower can be combined with courtyards and underground tunnels to increase the cooling process of the collected air. A wind tower operates in various ways depending on different factors like the time of day, the presence or absence of wind, and the difference of air temperature inside and outside the building (Table 5). The fundamental principle of wind tower operation system lies in changing the temperature of the air inside the tower, therefore changing the density, which is a key factor in circulating air and improving the device's performance.

Solar chimney helps to increase the airflow from interior to upper level and to be replaced by cold air from outdoor shaded area like courtyards or basements.

3.4 Slowing

Slowing, as a passive cooling action, refers to the reduction of heat transfer through the building's surfaces by conduction. It depends on the interaction of the building's envelope with the outdoor environment by receiving and absorbing heat and then transferring it to the inner spaces. The performance of slowing as a cooling action depends on many key factors in the building's envelope, such as thermal insulation, thermal masses, building's volume-to-surface area ratio, building materials, and double glazing. These variables control the amount of heat transfer from outdoor environment to inner spaces and therefore reduce the need for heat removal and the associated cooling loads.

3.4.1 Thermal mass

The two main factors designers should take into consideration when choosing a thermal mass material and surface are *thermal time constant (TTC)* and *diurnal heat capacity (DHC)*. These two factors describe the behavior of an area of material when subjected to heat and the time needed to store and release heat. The relative values of TTC are particularly important when the building is affected by a heat flow, while the

Element's construct	Variables	Notes
Device's elements	Orientation	The openings to be orientated toward the wind
	Height	Affects the wind speed entering the tower and building and heat absorption by menials
	Material	Thermal mass material cooled hot air
	Inlet opening	The size of inlet and outlet openings affects the amount of collected winds, its speed in the tower itself, and its speed as it enters spaces
	Outlet openings	
	Integration with inner spaces	Affects the patterns of air distribution inside the building

Table 5.
Wind tower variables (author).

DHC values are important when the solar gain affecting the building is considerable. Both measures indicate the amount of interior temperature swings that are expected from a material based on outdoor temperature. The *thermal time constant* is used to describe the behavior of thermal masses in building envelopes, and it depends on the heat capacity (Q) and the heat transmission resistance (R). In short it represents the effectiveness of the thermal capacity in a building. TTC is calculated for an area by multiplying heat capacity per unit (QA) by the resistance of heat flow of that area (R):

$$TTC = QA \times R \tag{1}$$

where QA = thickness × density × specific heat and R = thickness/conductivity.

In calculating the TTC per area, (TTCA) for a composite wall, the QA × R of each layer, including the outside and inside air film layers, is calculated in sequence, and they are calculated for each layer from the external wall to the center of the section in question. A high value of TTC means a high thermal inertia of the building, and it results in a low interior temperature swings. The *diurnal heat capacity* is used to describe the building's capacity to absorb the solar energy and to release the stored heat. DHC measure is particularly important when designing a thermal mass that is subjected to direct solar heat gain. It is considered a function of density and thicknesses of material layers, specific heat, and conductivity. The total DHC of a building is calculated by adding the DHC values of each surface. The DHC is a measure of how much cold the building can store during the night in a ventilated building. Design with thermal mass should consider distributing mass to absorb heat near the sources and thereafter to release the heat to start new cycle the next day.

4. Combining of devices and integration with design process

Optimizing the performance of passive cooling devices and techniques can be achieved by identifying their relation to building design process, where these devices can be implemented and integrated with other architectural and cooling elements to accomplish more than one function. This integration encourages designers to take into consideration the implementation of passive cooling devices and techniques as an integrated stage within the designing process, like analysis, planning, and evaluation stages.

and strategies in the early stage (analysis) of the design process give the passive cooling an essential part in the design performance values. Considering such strategies

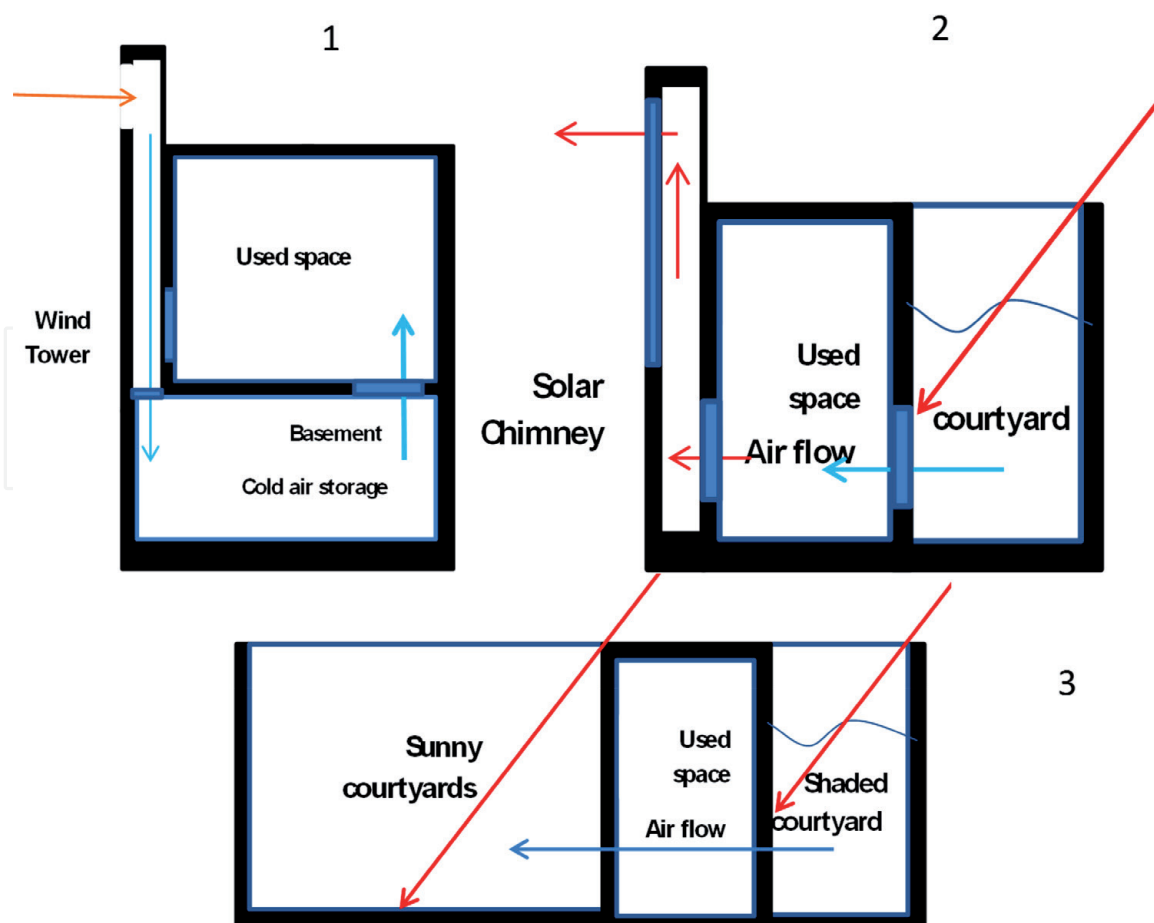


Figure 9.
 Example of integration of storage devices and removal devices: (1) combining wind tower with base ment, (2) combining solar chimney with courtyards, and (3) combining two courtyard sunny with shaded one (author).

as design variables will develop building design and create integrated relations between architectural elements and passive cooling devices. Therefore, find creative solutions for passive cooling, and improve the performance of traditional techniques to be easily practiced in modern designs. In addition, considering cooling performance of a building under the designing process as performance criteria in building design process will help designers reevaluate their decisions on passive cooling performance. To do so, computer simulation software can be used to identify which decisions, devices, and variables need to be reviewed during the evaluation stage.

Combining more than one device or principle of passive cooling in building design requires designers to consider passive cooling strategies in all designing processes. The integrated design will create cooling strategies that have a significant and direct impact on building form, plans, sections, and functional distribution, and user's interaction and behavior in the building as seen in (Figure 9). Therefore, an integrated building design approach is needed to make the architectural systems, passive cooling systems, and active systems work together within a complete integrated framework to improve performance and save energy, as cooling loads can be minimized through environmental designs that involve judicious use and implementation of shading devices, vegetation, colors, materials, and insulation.

4.1 Design matrix

This paper presents a guideline for implementing passive cooling systems and devices by discussing the four passive cooling actions, which designers should take into consideration in the process of creating a building. It discusses the various

Sources of heat	Actions required	Design solution	Design stage
Direct heat gain from solar radiation on building envelope materials	Avoidance	<ul style="list-style-type: none">• Shading devices• Self-shading building form• Landscape design• Urban design	<ul style="list-style-type: none">• Early stage (analysis): analyze the relation with local climate, solar angles, and prevailing winds, to prevent heat gain• Middle stage (design): design these variables to protect the inner space from direct gain• Last stage (performance): evaluate the performance of each element in terms of avoidance of heat gain
	Slowing	<ul style="list-style-type: none">• Thermal mass• Insulation material• Color	<ul style="list-style-type: none">• Early stage (analysis): analyze the relation with local climate, solar angles, and prevailing winds, to slow heat gain• Last stage (performance): evaluate the performance of each element in terms of slowing of heat gain
Direct heat gain from solar radiation on windows and glazed surfaces	Avoidance	<ul style="list-style-type: none">• Shading devices• Reflective materials and glass• Orientation design	<ul style="list-style-type: none">• Early stage (analysis): analyze the relation with local climate, solar angles, and prevailing winds, to prevent heat gain• Middle stage (design): design these variables to protect the inner space from direct gain• Last stage (performance): evaluate the performance of each element in terms of avoidance of heat gain
	Slowing	<ul style="list-style-type: none">• Double glazing	<ul style="list-style-type: none">• Early stage (analysis): analyze the relation with local climate, solar angles, and prevailing winds, to slow heat gain• Last stage (performance): evaluate the performance of each element in terms of slowing of heat gain
Indirect heat gain by conduction with outdoor environment through building envelope	Avoidance	<ul style="list-style-type: none">• Landscape• Orientation	<ul style="list-style-type: none">• Early stage (analysis): analyze the relation with local climate, solar angles, and prevailing winds, to prevent heat gain• Middle stage (design): design these variables to protect the inner space from direct gain• Last stage (performance): evaluate the performance of each element in terms of avoidance of heat gain
	Slowing	<ul style="list-style-type: none">• Insulation	<ul style="list-style-type: none">• Early stage (analysis): analyze the relation with local climate, solar angles, and prevailing winds, to slow heat gain• Last stage (performance): evaluate the performance of each element in terms of slowing of heat gain
	Removal	<ul style="list-style-type: none">• Orientation• Implement removal devices	<ul style="list-style-type: none">• Early stage (analysis): analyze the relation with local climate, solar angles, and prevailing winds, to help remove or convey the heat outside inner spaces• Middle stage (design): design these variables to remove hot air from the inner space• Last stage (performance): evaluate the performance of each element in terms of removing gained heat

Sources of heat	Actions required	Design solution	Design stage
Indirect heat gain by convection through the ventilation and infiltration currents	Avoidance	<ul style="list-style-type: none">Controlled ventilationVentilation from shaded area	<ul style="list-style-type: none">Early stage (analysis): analyze the relation with local climate, solar angles, and prevailing winds, to prevent heat gainMiddle stage (design): design these variables to protect the inner space from direct gainLast stage (performance): evaluate the performance of each element in terms of avoidance of heat gain
	Slowing	<ul style="list-style-type: none">Thermal mass	<ul style="list-style-type: none">Early stage (analysis): analyze the relation with local climate, solar angles, and prevailing winds, to slow heat gainLast stage (performance): evaluate the performance of each element in terms of slowing of heat gain
Internal heat gains by human activities, equipment, machines, and lighting	Removal	<ul style="list-style-type: none">Ventilation	<ul style="list-style-type: none">Early stage (analysis): analyze the relation with local climate, solar angles, and prevailing winds, to help remove or convey the heat outside inner spacesMiddle stage (design): design these variables to remove hot air from the inner spaceLast stage (performance): evaluate the performance of each element in terms of removing gained heat
	Avoidance	<ul style="list-style-type: none">Design with daylight	<ul style="list-style-type: none">Early stage (analysis): analyze the relation with local climate, solar angles, and prevailing winds, to prevent heat gainMiddle stage (design): design these variables to protect the inner space from direct gainLast stage (performance): evaluate the performance of each element in terms of avoidance of heat gain

Table 6.
Design matrix in relation to cooling actions (author).

variables affecting each device within each action, and it explains in details the major issues that need to be considered for each device and action in the three design stages of any building. This integration of passive cooling principles in the design stages represents a new invention in architectural technology and a guideline of passive cooling design for designers and architects. **Table 6** summarizes the required passive cooling actions and design solution that are used to minimize the effects of various heat sources and their implementation considerations in each of the three design stages.

4.2 Integration design: devices and principles for maximum performance

The combination of two principles or devices will be discussed in a way to improve performance, increase efficiency, and integrate devices with building design. Many devices can be combined together to perform more than one function and shift cooling and passive design to be as a comprehensive and integrated design approach.





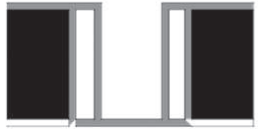
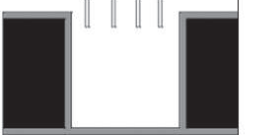
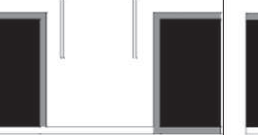
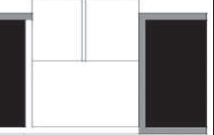




N	1	2	3	4
A				
B				
C				

Table 7.
Courtyard configurations [27].

The momentum of passive and green architecture helps to develop new devices that perform more functions and help other devices to perform better.

The design process of such composite design required multi-dimensional analysis of each device and how it could be integrated with other devices.

1. Analysis stage: for each device the working mechanism and condition required to perform well should be thoroughly analyzed.
2. Design stages: design the devices to perform more than one function. In addition design the device to improve the function of other devices
3. Performance stage: reevaluate the integration between devices and architectural systems and how they performed together using experiments or computer simulations.

The following discussion will show how some devices have been integrated and designed with other devices to improve their performance and to become as innovative passive design approaches.

The design of wall geometries of the courtyard could help to improve its cooling performance. Freewan [27] showed that the design of wall geometries helps to control direct incident of sunrays on the courtyard's floor, reduce glare, and improve both daylight quality and quantity. It helped to reduce heat gain from artificial light as it introduces daylight from shaded area. The study showed how wall geometries increase the shading area and time and therefore help to store cold air for long time to ventilate inner spaces with fresh cold air. These configurations as seen in **Table 7** improved courtyard design especially in regions with hot and clear sky [27].

Advanced and modern wind towers were used in university building at the University of Nottingham to be cooling and daylighting devices. They were

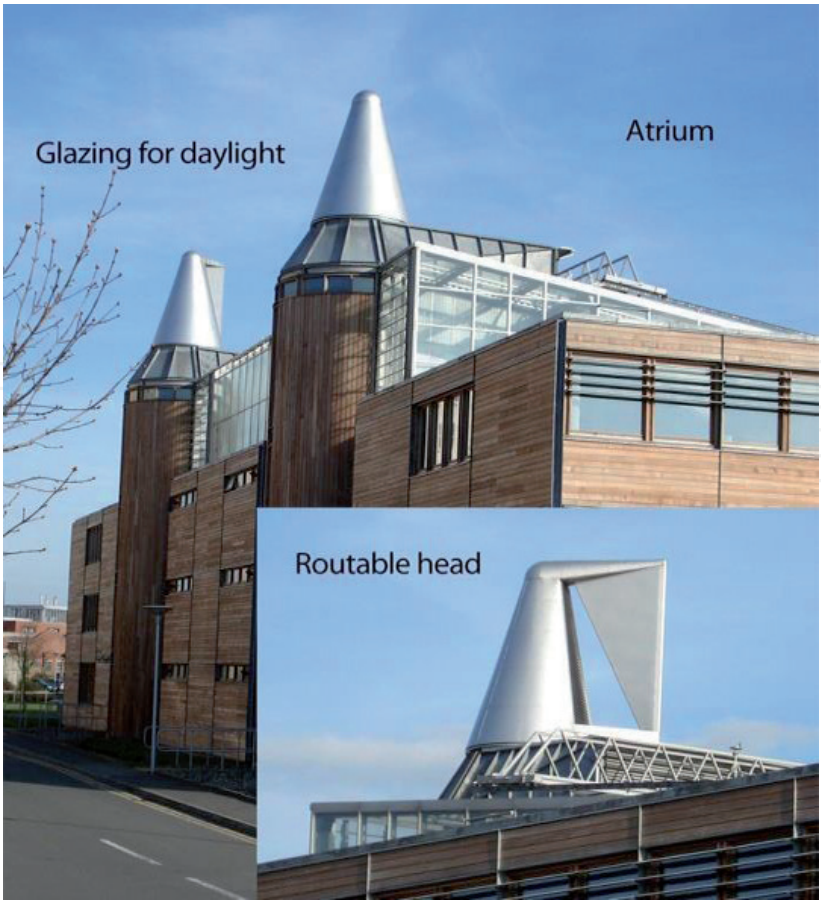


Figure 10.
Combining wind catcher with atrium and daylight elements (author).

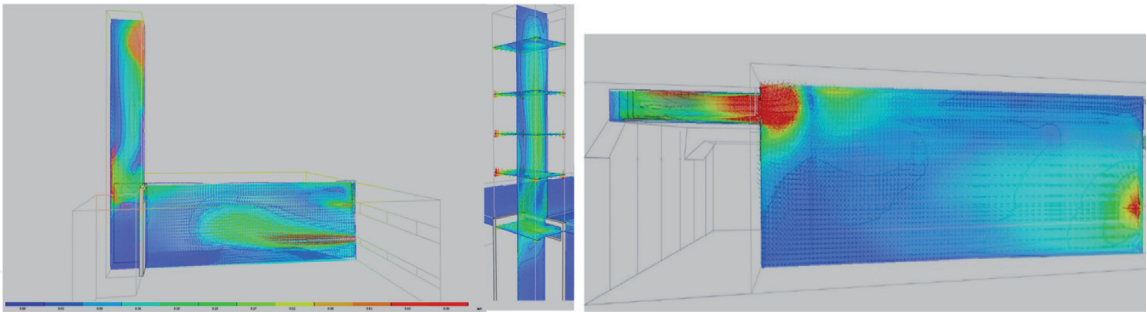


Figure 11.
Integration of windows with wind tower and horizontal duct.

developed to have rotatable head to maximize the efficiency. The new wind towers were designed in integration with atrium and opening figure. The towers were used as wind tower, stairs, daylight devices with large glazed area at top part. They were designed with integration with atrium for maximum performance **Figure 10**.

A study [28] has been conducted at Jordan University of Science and Technology to design adjustable shading devices for existing and new buildings in mild climate with hot summer and cold winter. The research aimed at designing optimized double-positioned external shading device systems that help to reduce energy consumption in buildings and provide thermal and visual comfort during both hot and cold seasons. The design was based on comparison of performance of many variables to determine the best fit characteristics for two positions of adjustable horizontal louvers on south facade or vertical fins on east and west facades for summer and winter conditions. The adjustable shading systems can be applied for new or retrofitted office or housing buildings. The

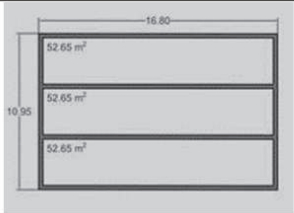
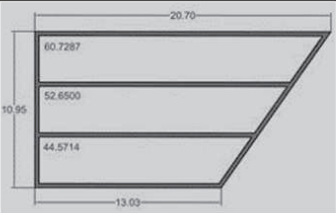
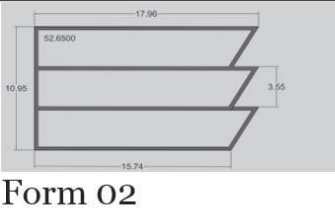
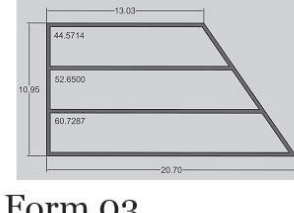
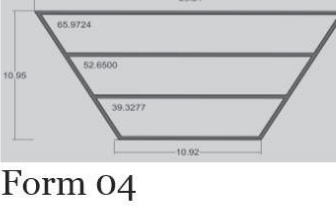
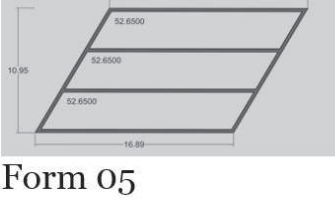
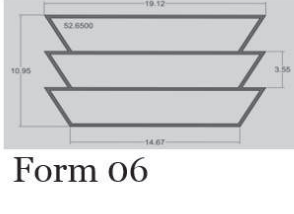
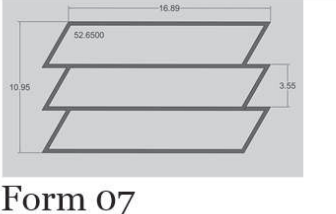
Form configurations		
 <p>Form 00</p>	 <p>Form 01</p>	 <p>Form 02</p>
 <p>Form 03</p>	 <p>Form 04</p>	 <p>Form 05</p>
 <p>Form 06</p>	 <p>Form 07</p>	

Table 8.
Form configurations [30].

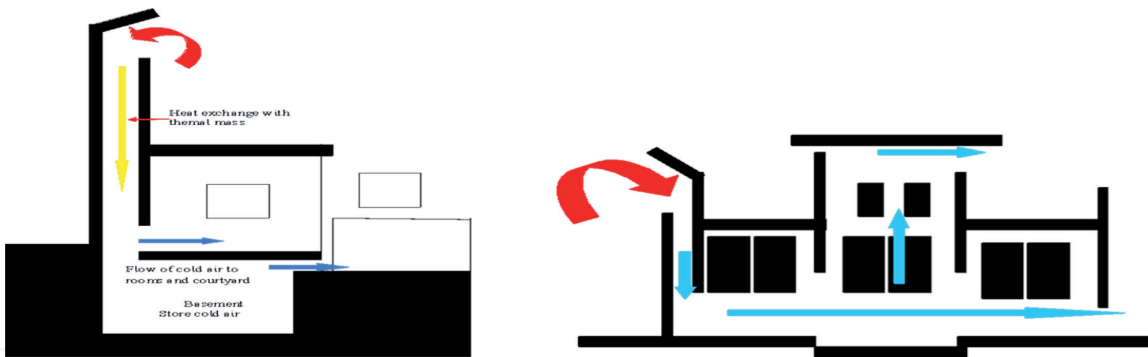


Figure 12.
Combining wind towers with courtyards and basements (author).

optimized shading devices for summer and winter positions helped to reduce the net annual energy consumption compared to a base case space with no shading device or with curtains and compared to fix shading devices.

Freewan and Abdallah [29] studied integration of many devices to improve ventilation process in university classrooms. The study showed that integration of wind tower with side windows or side horizontal ventilation duct with side windows helped to improve the natural ventilation in classrooms, activate stack effect, and increase the air velocity (**Figure 11**).

Freewan [30] studied how the building's form and wall geometries could help to reduce energy consumption and improve thermal and visual comfort. Inward and outward tilted south and north facing facades were studied in the study. Thermal energy performance and daylighting were investigated for many inward and outward angles for both south and north directions. The tilted configurations were achieved as an acceptable balance between cooling, heating energy consumption, and daylighting performance and compared to vertical facades

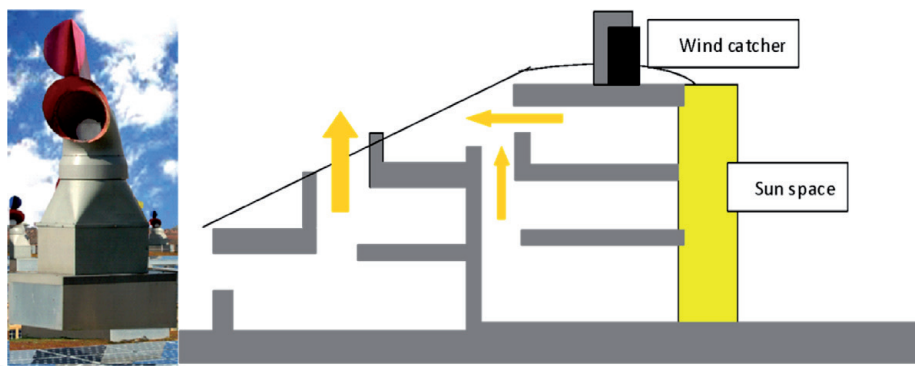


Figure 13.
BedZED design and wind catcher (author).

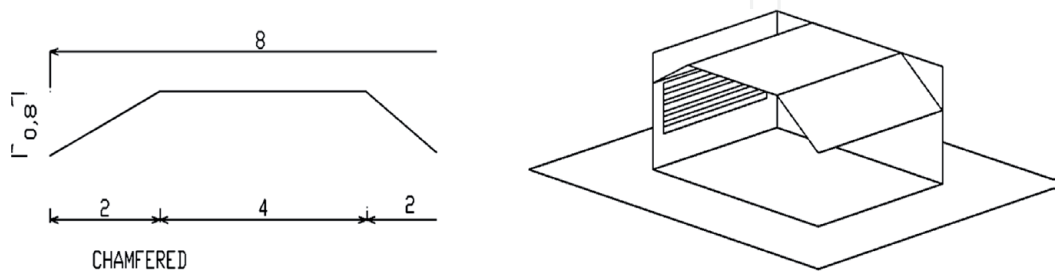


Figure 14.
Combining shading devices with ceiling geometries [31, 32].

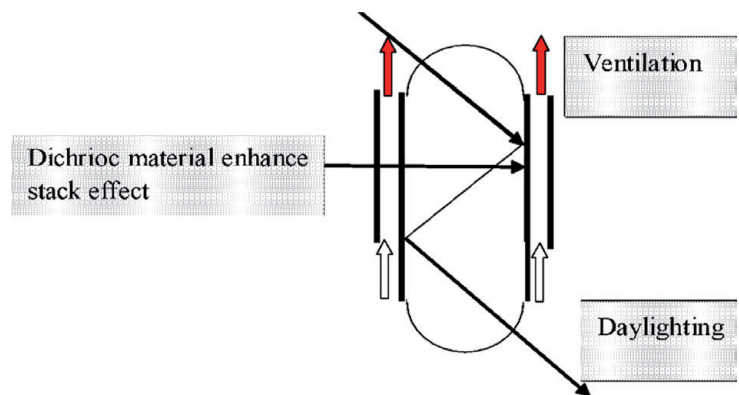


Figure 15.
Working mechanism of light pipe as daylighting devices and ventilation devices (author).

to provide best solar shading, energy consumption, and daylight performance. Many variables were monitored and studied like self-shading, time and period of exposure to sun rays, and how the tilted facade performed. The results showed outward tilted facades for the south orientation performed well as they reduced cooling load and improve both daylight quality and quantity. On the other hand, inward facades for north orientation performed well in terms of daylight compared to vertical facade (**Table 8**).

Wind tower as ventilation and heat removing tools was integrated with courtyard or basement to increase airflow rate and bring cold air to be stored. Configurations like these can be found in Iraq and Egypt, which help activate the stack effect to circulate the cold air to the occupied spaces (**Figure 12**). In modern design wind tower can be integrated with wind tunnel as the wind tower is used to circulate the air, while the tunnel is used to cool the air.

In Beddington Zero Energy Development (BedZED) in the UK, wind catchers with routable head were designed in integration with the buildings' form, sun

space, space articulation, and functional zoning (**Figure 13**). The BedZED climatic design was based on more than ventilation principles.

Shading devices and light shelf were studied to be integrated with ceiling geometries in order to maximize shading and daylight performance in hot climate to save energy (**Figure 14**). Many ceiling geometries were investigated to find maximum daylight performance while keeping the optimum shading effects [31, 32].

Light pipe is an advanced daylighting technology used to bring light to a space with no direct contact to outside. It is a cylindrical tube connected to a collecting unit and a diffusing unit. The literature review shows that many researchers have studied the light pipe. Elmualim et al. [33] used dichroic material to develop the light pipe's performance as an integrated system for daylighting and ventilation. The integration is based on using two concentric channels for both daylighting and natural ventilation; the inner one will guide sunlight and daylight into occupied spaces, while the outer one enables passive stack ventilation (**Figure 15**).

5. Conclusions

Implementing passive cooling systems in building design has many advantages over using the fossil fuel-based cooling systems, as they produce no environmental impacts and GHG emissions. The implementation of passive cooling devices in any building design requires many considerations and analyzation of the various variables affecting the cooling performance, and these considerations need to be taken from the earliest design stages and not only at the end of the architectural project, to allow these systems to reach the fullest possible potentials and to be integrated within the design itself, rather than being an additional solution that is forced into a building.

This chapter represented a guideline and innovations in building design process on a comprehensive level that take into consideration the four passive cooling actions, *store*, *avoid*, *remove* and *slow* of heat, and the different devices used for implementing each of the four actions and the variables affecting their cooling performance. All the actions, devices, and variables then were discussed within the three design stages: analysis, designing, and performance stages. The research then concluded with a summary of the required passive cooling actions and the design solutions that need to be used to minimize the effects of the various heat sources and the implemented considerations in each of the three design stages. This chapter encourages designers to integrate passive cooling solutions, actions, and devices in the designing process from early stages of the design while taking into consideration the different variables and requirements concerning the passive devices and their implementation in all design stages.


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