RESEARCH PAPER

TU DELFT // ARCHITECTURAL ENGINEERING

BACK TO THE ROOTS

Passive design strategies for climate specific architecture on the Island of Aruba

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Introduction

In light of the current climate crisis, sustainability and circularity are indispensable parts of the creation of architecture. The building sector alone generates over a third of annual global CO2 emissions of which most are not caused by the construction, but the building operations (Global Alliance for Buildings and Construction, 2018). Electrification and the transition to renewable energy are the most important solutions to reduce the carbon footprint. However, although it is technically possible to use a huge PV system to supply an overly large energy load of a poorly designed building, DeKay & Brown (2014) argue that it is neither prudent nor rationally elegant. Instead, it is suggested that the reduction of CO2 emissions not only be due to the transition to green energy, but also by optimising a buildings efficiency and accordingly minimizing the energy consumption of the built environment as a whole.

In the context of building operations, the most energy goes into regulating desirable (indoor) living conditions. By considering the given climatic conditions and resources of a site in the early stages of the design path, the architecture itself can both reduce environmental stresses on the building but also use favorable resources to its advantage and therefore passively drive performance. There is extensive knowledge on such passive design strategies, however, every specific geography asks for their own unique set of design tools in response to the site's climatic conditions and resources.

Aruba is an interesting country to introduce passive design strategies to. Current building standards show almost no consideration into sustainability with designs that offer little to no thermal comfort without the use of mechanical appliances. The local environment on the other hand offers an abundance of usable resources such as constant cooling trade winds that can be used to a buildings advantage. Therefore, there is a lot of potential to provoke a sustainable shift in the built environment.

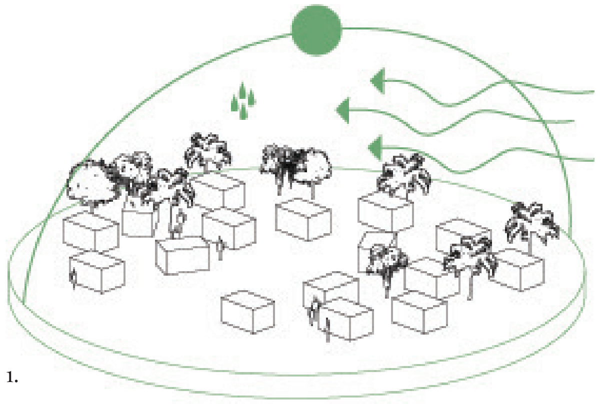
This paper sets out to define the appropriate set of passive design strategies for architecture on the island which in turn could lead to more holistic and energy efficient design solutions. It is part of a larger framework of research on architectural sustainability for the island in the Caribbean and forms the technical foundation on which a design proposal for a nature inclusive neighborhood will be based.

To define the essence of this paper, the following research question is introduced:

How can passive design strategies be integrated in the built environment of Aruba to contribute to comfortable living conditions and minimize the reliance on mechanical appliances?

The conclusion of this paper will be an overview of applicable passive design strategies, appropriated to the specific climatic conditions and resources of Aruba. Therefore, the first chapter will provide a thorough analysis of Aruba's climate as well as the desirable living conditions that architecture must aim to provide. This will serve as a guideline as to what should be focused on in the search for appropriate passive design strategies.

The structure of the rest of the paper is a direct result of the different scales following an architectural design process, from urban, to building, to material and vegetation. The foundation of this research is based on extensive literature research on passive design strategies, selected within the guidelines of the given context and its climate.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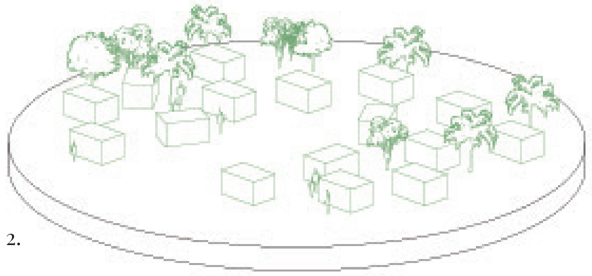
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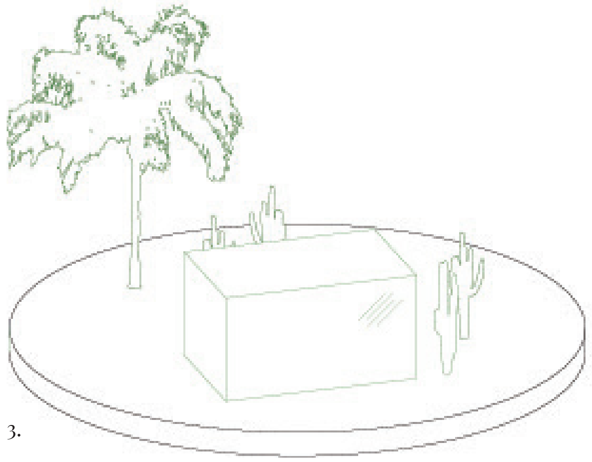

3.

1. Climate

2. Urban scale

3. Building scale

Climate of Aruba

A thorough understanding of Aruba's climatic conditions is necessary to serve as a guideline to know what environmental influences a building has to protect against and/or use to its advantage. There are many aspects to a climate but for the purpose of this paper climatic analysis remains limited to those which influence a building's thermal conditions. The information is mostly sourced by the weather station at the local airport and read using the software Climate Consultant. The data has then been interpreted and presented in a way that contributes to the purpose of this research. For example, describing monthly averages throughout the course of a day and consequently highlighting the extremes.

Aruba's climate is classified as hot semi-arid which is the second driest after desert conditions (Beck et al., 2006). The average yearly precipitation is around 700mm of which about 40% occurs during the relatively rainy period from October to December. Table 4 shows the average hourly temperature throughout the different months. Dry-bulb temperatures are measured by a freely exposed thermometer to air, but protected from solar radiation and moisture. Daily temperature variations are about 4-5 ° celsius from day and night. Table 5 shows the amount of solar radiation on a horizontal surface per m2. During the day, the sun is averagely the strongest from 11am to 4pm. The period with the lightest amounts of solar radiation throughout the day is November to January. This is directly related to the lowest stance of the sun during the year (fig. 6).

Although Aruba is considered to have a dry climate due to little rainfall, the above average humidity throughout the year (fig. 7) causes the overall thermal experience to be similar to the summer seasons of hot humid climates. Therefore, research on passive design strategies for hot humid climates could also be considered appropriate for Aruba.

What makes Aruba's climate particularly interesting is the abundant presence of constant cooling tradewinds. Table x shows that throughout the entire year, there is a strong wind and most importantly, a consistent wind direction (fig. 8). About 90% of the time, wind directions are within 12.5 degrees from the east (fig. 9).

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
25.8	25.4	25.7	26.4	27.2	27.2	26.7	28.0	27.9	27.8	27.3	26.0	1 Hour
25.5	25.2	25.5	26.2	27.2	27.0	26.6	27.8	27.7	27.5	27.1	26.0	2
25.5	25.1	25.5	26.1	27.1	27.0	26.6	27.8	27.6	27.3	27.1	25.9	3
25.4	25.0	25.3	26.1	26.9	27.0	26.5	27.7	27.4	27.2	27.0	25.8	4
25.3	24.9	25.3	26.0	26.8	27.1	26.7	27.5	27.4	27.1	26.9	25.7	5
25.3	25.0	25.3	26.0	26.8	27.1	26.7	27.5	27.4	26.9	26.8	25.7	6
25.1	25.0	25.2	26.3	27.1	27.3	26.9	27.8	27.4	27.3	26.8	25.6	7
25.9	25.8	26.1	27.4	27.9	28.2	27.9	28.9	28.3	28.6	27.6	26.2	8
27.2	27.3	27.5	28.8	28.6	29.2	28.7	30.0	29.3	29.9	28.5	27.3	9
28.0	28.2	28.4	29.8	29.5	30.1	29.8	31.0	30.1	30.6	28.9	28.2	10
28.5	29.1	29.5	30.3	30.0	30.8	30.6	31.6	30.8	31.1	29.4	28.9	11
29.1	29.6	29.9	30.7	30.3	31.3	30.9	32.0	31.0	31.5	29.7	29.3	12
29.2	29.8	30.4	30.9	30.9	31.4	31.0	32.5	31.4	31.4	29.9	29.3	13
29.1	29.8	30.1	31.1	31.2	31.3	31.1	32.3	31.7	31.3	29.6	29.4	14
28.9	29.5	29.9	30.5	31.1	31.2	31.1	32.3	31.5	31.3	29.7	29.3	15
28.5	29.3	29.3	30.0	30.6	30.9	30.7	31.8	31.1	31.0	29.4	28.7	16
28.0	28.4	28.6	29.2	29.6	30.2	30.0	30.9	30.5	30.4	28.9	28.2	17
27.0	27.4	27.8	28.1	28.8	29.2	28.9	30.0	29.6	29.6	28.2	27.5	18
26.4	26.3	26.5	27.2	28.0	28.3	28.0	29.0	28.9	28.9	27.7	26.8	19
26.1	26.0	26.0	27.0	27.6	27.8	27.6	28.5	28.5	28.7	27.8	26.5	20
26.1	25.9	25.9	27.0	27.5	27.7	27.4	28.4	28.3	28.6	27.7	26.4	21
25.9	25.7	25.9	26.9	27.4	27.5	27.2	28.3	28.2	28.4	27.6	26.3	22
25.8	25.7	25.9	26.7	27.3	27.5	27.0	28.2	28.2	28.2	27.6	26.2	23
25.9	25.5	25.8	26.7	27.1	27.4	26.6	28.1	28.0	28.0	27.4	26.1	24

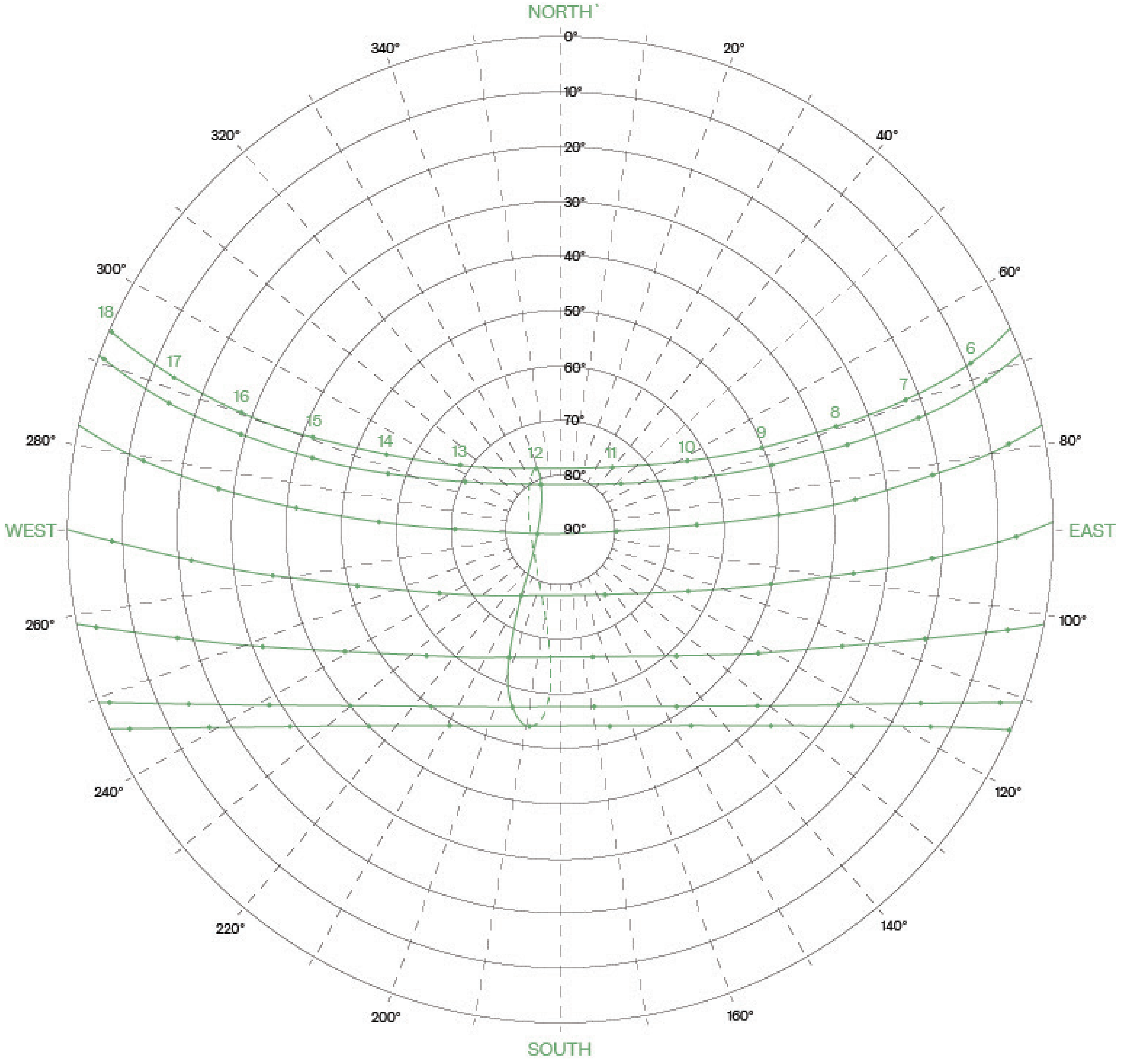
░ < 27°C ▒ > 27°C < 30°C ▓ > 30°C

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
0	0	0	0	0	0	0	0	0	0	0	0	1 Hour
0	0	0	0	0	0	0	0	0	0	0	0	2
0	0	0	0	0	0	0	0	0	0	0	0	3
0	0	0	0	0	0	0	0	0	0	0	0	4
0	0	0	0	0	0	0	0	0	0	0	0	5
0	0	0	0	0	0	0	0	0	0	0	0	6
0	0	0	1	9	10	4	0	0	0	0	0	7
24	39	77	76	127	132	109	89	120	83	94	38	8
143	252	311	242	317	357	324	264	342	244	300	174	9
339	484	525	453	511	567	543	473	564	426	496	370	10
515	660	724	643	688	684	671	668	700	595	623	555	11
679	812	885	779	776	835	856	787	857	732	763	665	12
750	888	960	857	859	871	865	880	913	789	801	718	13
771	844	889	888	818	797	794	891	864	774	719	724	14
733	815	822	810	761	740	777	864	758	710	638	662	15
652	642	669	693	595	608	634	762	592	577	466	560	16
483	428	449	531	396	410	410	595	383	419	253	399	17
279	203	221	331	185	206	221	379	154	227	71	209	18
52	18	23	128	21	36	40	161	9	0	0	0	19
0	0	0	0	0	0	0	0	0	0	0	0	20
0	0	0	0	0	0	0	0	0	0	0	0	21
0	0	0	0	0	0	0	0	0	0	0	0	22
0	0	0	0	0	0	0	0	0	0	0	0	23
0	0	0	0	0	0	0	0	0	0	0	0	24

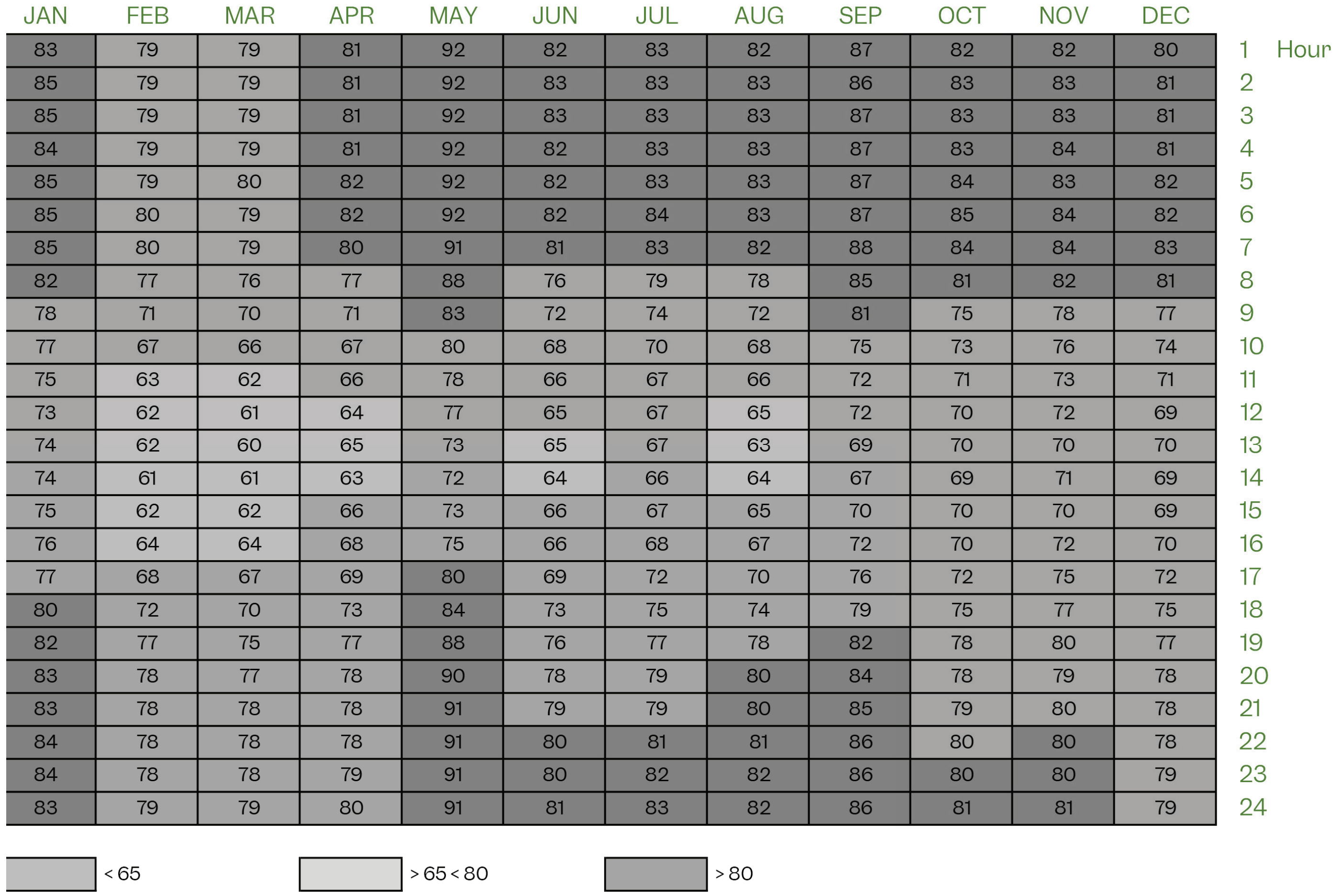
□ 0 ░ > 0 W/m2 < 600 W/m2 ▒ > 600 W/m^2

4. Average hourly dry bulb temperature per month

5. Average hourly solar radiation on horizontal surface per month



6. Sun path of Aruba



JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Hour
83	79	79	81	92	82	83	82	87	82	82	80	1
85	79	79	81	92	83	83	83	86	83	83	81	2
85	79	79	81	92	83	83	83	87	83	83	81	3
84	79	79	81	92	82	83	83	87	83	84	81	4
85	79	80	82	92	82	83	83	87	84	83	82	5
85	80	79	82	92	82	84	83	87	85	84	82	6
85	80	79	80	91	81	83	82	88	84	84	83	7
82	77	76	77	88	76	79	78	85	81	82	81	8
78	71	70	71	83	72	74	72	81	75	78	77	9
77	67	66	67	80	68	70	68	75	73	76	74	10
75	63	62	66	78	66	67	66	72	71	73	71	11
73	62	61	64	77	65	67	65	72	70	72	69	12
74	62	60	65	73	65	67	63	69	70	70	70	13
74	61	61	63	72	64	66	64	67	69	71	69	14
75	62	62	66	73	66	67	65	70	70	70	69	15
76	64	64	68	75	66	68	67	72	70	72	70	16
77	68	67	69	80	69	72	70	76	72	75	72	17
80	72	70	73	84	73	75	74	79	75	77	75	18
82	77	75	77	88	76	77	78	82	78	80	77	19
83	78	77	78	90	78	79	80	84	78	79	78	20
83	78	78	78	91	79	79	80	85	79	80	78	21
84	78	78	78	91	80	81	81	86	80	80	78	22
84	78	78	79	91	80	82	82	86	80	80	79	23
83	79	79	80	91	81	83	82	86	81	81	79	24

▨ < 65

□ > 65 < 80

▨ > 80

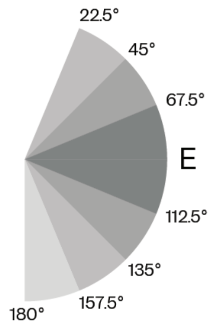
7. Average hourly relative humidity per month

Hour	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	6.4	6.5	7.8	5.7	5.8	8.1	7.2	6.9	7.0	3.6	5.7	6.1
2	5.8	6.6	7.3	5.5	6.0	7.6	7.0	6.7	6.6	3.5	5.6	6.0
3	5.8	6.6	7.2	5.3	6.4	7.5	6.9	6.5	6.2	3.4	5.5	5.9
4	5.8	6.5	7.2	5.1	6.6	7.5	6.9	6.1	5.9	3.3	5.6	5.8
5	5.8	6.4	7.3	4.8	7.0	7.4	6.5	6.1	5.6	3.2	5.5	5.8
6	5.9	6.4	7.2	5.1	7.2	7.6	6.7	5.9	5.5	2.9	5.4	5.7
7	5.8	6.5	6.8	5.1	5.8	7.8	7.2	6.1	5.4	3.1	5.2	5.8
8	5.7	6.6	7.5	6.7	6.8	9.0	8.0	7.5	6.8	3.6	6.0	6.6
9	7.1	8.0	8.4	7.3	7.5	9.7	8.9	8.6	7.7	4.7	7.3	7.5
10	8.6	8.8	9.0	7.8	8.1	10.1	9.4	9.0	8.2	5.2	7.8	8.5
11	8.8	9.2	9.3	8.1	8.3	10.3	9.5	9.0	8.2	5.4	8.0	8.8
12	9.0	9.1	9.4	8.0	8.0	10.1	9.4	9.2	7.9	5.5	8.0	8.8
13	9.1	9.1	9.2	7.9	7.7	10.0	9.2	9.2	7.9	5.6	8.3	8.4
14	8.7	8.8	9.3	7.7	7.8	10.3	8.7	9.3	8.0	5.3	8.2	8.7
15	8.7	8.7	9.1	7.6	7.4	9.7	9.1	9.6	8.0	5.3	8.1	8.7
16	8.8	8.2	9.0	7.3	7.7	9.6	9.0	10.1	8.2	5.2	8.2	8.5
17	8.3	8.7	8.9	7.5	8.0	10.0	8.7	10.5	8.4	5.1	7.9	8.0
18	7.5	8.3	8.8	7.3	7.3	9.7	8.6	9.8	8.3	5.1	7.3	7.4
19	6.6	7.8	8.3	6.7	6.8	9.0	8.3	8.8	7.8	4.5	6.7	7.0
20	6.3	7.5	8.3	6.5	6.2	8.9	7.9	8.4	7.3	4.3	6.7	6.8
21	6.6	7.4	8.0	6.4	6.0	8.7	7.7	8.3	7.1	4.2	6.5	6.5
22	6.4	7.2	7.9	6.1	5.8	8.5	7.4	8.0	7.1	4.0	6.4	6.5
23	6.4	7.0	7.9	5.9	5.9	8.3	7.4	7.8	6.7	3.9	6.4	6.5
24	6.4	6.9	7.6	5.8	5.5	8.1	7.0	7.5	6.9	3.8	6.0	6.3

░ < 6 m/s ▒ > 6 m/s < 9 m/s ▓ > 9 m/s

8. Average hourly wind speed per month

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Hour
77	117	100	73	134	147	109	85	127	115	136	87	1
76	99	115	73	119	117	124	88	105	116	142	87	2
77	112	97	75	182	159	135	88	137	124	125	89	3
77	123	108	76	191	167	136	89	175	123	148	90	4
79	108	97	76	114	118	140	87	149	124	154	90	5
78	132	112	77	120	154	121	88	125	125	135	91	6
80	111	113	74	107	114	130	89	111	118	121	93	7
83	100	108	75	123	99	117	90	105	114	115	91	8
83	97	102	74	123	126	107	91	123	122	126	95	9
83	111	96	72	135	128	127	93	121	120	125	94	10
84	125	115	74	129	117	119	92	115	124	114	96	11
81	114	109	73	127	117	117	91	125	122	125	96	12
83	120	117	73	128	134	126	88	125	120	132	99	13
81	104	100	73	106	103	105	83	96	114	102	94	14
81	103	98	70	97	114	93	80	113	124	113	93	15
78	106	106	66	83	121	140	74	110	126	102	93	16
78	104	108	65	89	114	100	69	84	111	92	95	17
78	104	90	64	98	104	92	69	89	96	113	90	18
76	105	91	62	99	113	102	68	108	98	101	88	19
78	83	105	65	92	112	111	71	87	98	91	85	20
74	106	86	64	96	94	147	74	104	95	119	86	21
74	100	115	70	95	113	113	76	100	114	103	86	22
78	100	86	74	103	116	111	79	103	116	110	86	23
79	102	103	76	134	127	120	84	124	113	142	89	24



9. Average hourly wind direction per month

Desirable living conditions

According to the ASHRAE standard 55 comfort model, the living conditions on Aruba are generally considered to be uncomfortable throughout the entire year, with exceptions mostly being nocturnal. However, several factors could result in one's thermal comfort zone to expand over higher temperatures and humidities such as personal acclimatization, appropriate clothing and air movement (Mishra, 2013).

To give a more detailed and substantiated explanation of desirable living conditions in relation to Aruba's natural thermal environment (non-air conditioned), a log has been kept over the course of 4 weeks throughout the months of November and December 2021. Data of both comfortable and uncomfortable temperature/humidity circumstances were collected as well as notable external factors such as wind or precipitation. Based on these findings, the following results can be drawn.

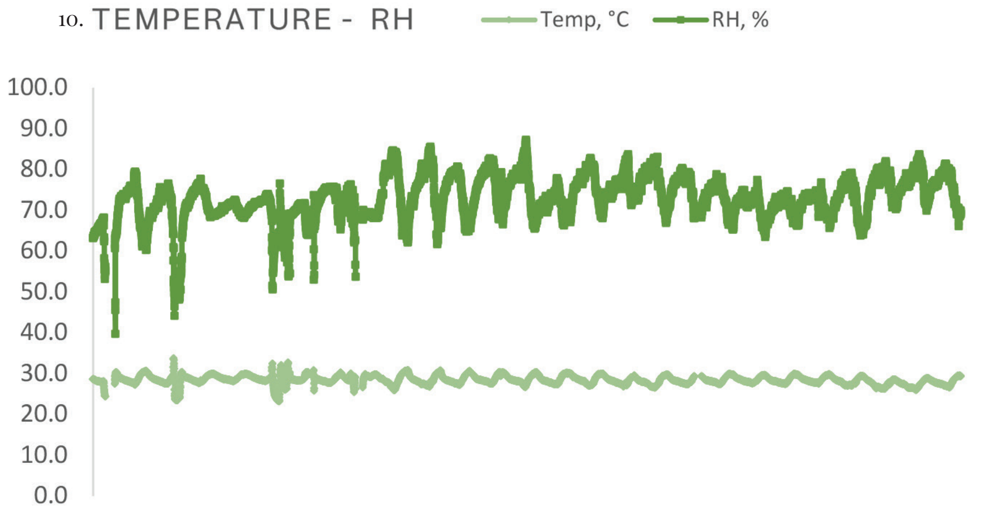
- Generally, conditions are bearable/comfortable before 10am and after 5pm, when solar radiation is at its lowest or absent.

- Humidity is directly related to the path of the sun as it fluctuates according to the amount of solar radiation and thus rate of evaporation (fig. 10).

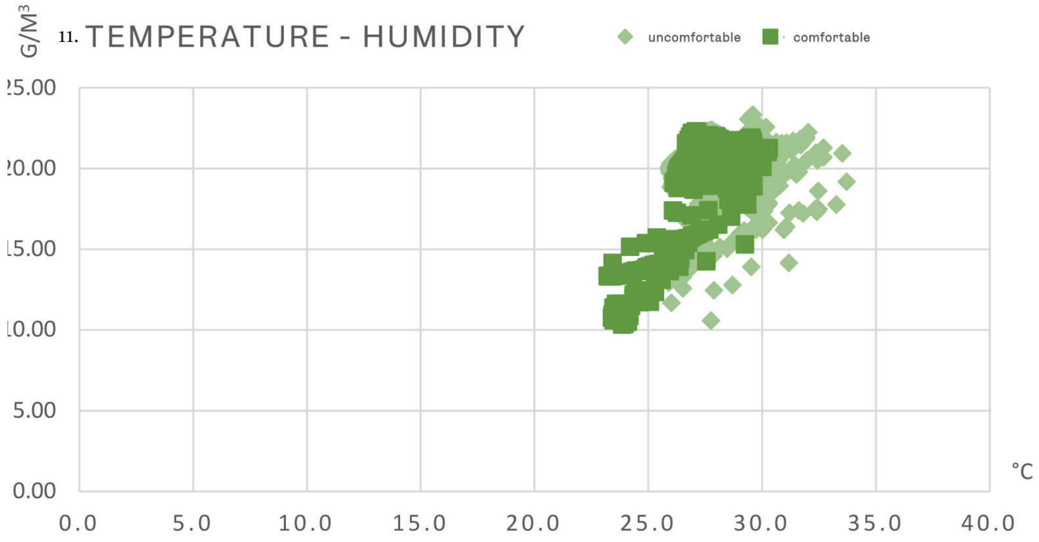
- Lower temperatures are more important than lower humidity when it comes to thermal comfort (fig. 11).

- Warmer temperatures may be experienced as more comfortable when average wind speeds are higher.

- After some rainfall, thermal conditions are significantly more comfortable, despite a higher overall humidity.



10. Temperature and relative humidity from November 17th to December 13th 2021

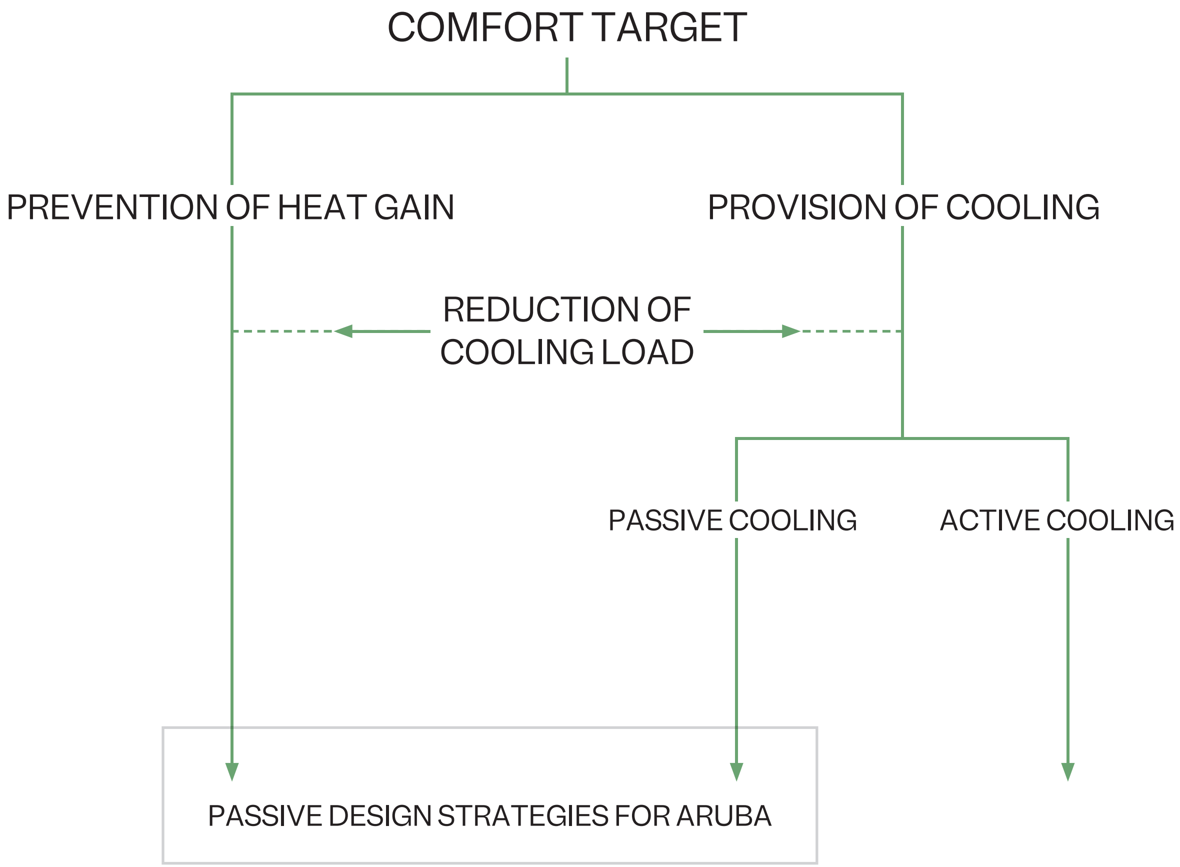


11. Point graph of experienced comfort - temperature in relation to absolute humidity

Ultimately, the aim of passive architecture is to contribute to a pleasant indoor climate with the lowest possible running energy load. Within the context of Aruba, there is a need for general cooling throughout most part of the day. This may be approached by prevention of heat gain on one hand and provision of cooling on the other. Both share the goal of passively reducing total cooling requirements. However, preventing heat gain is subject to minimizing the amount of heat entering a building whereas cooling relies on removing it, usually through natural ventilation. Therefore, the main objective is to architecturally design in such a way that least influences the external thermal environment, especially the wind, except in the protection against solar radiation (Baker, 1987).

Passive Design Strategies

This chapter is divided according to the different scales of a design process. Starting with the site, then the urban plan, architectural design, material selection and vegetation use. To structure it even better, a distinction is made between the two previously mentioned approaches to reduce the cooling load: prevention of heat gain and provision of cooling. Figure x shows this schematically.

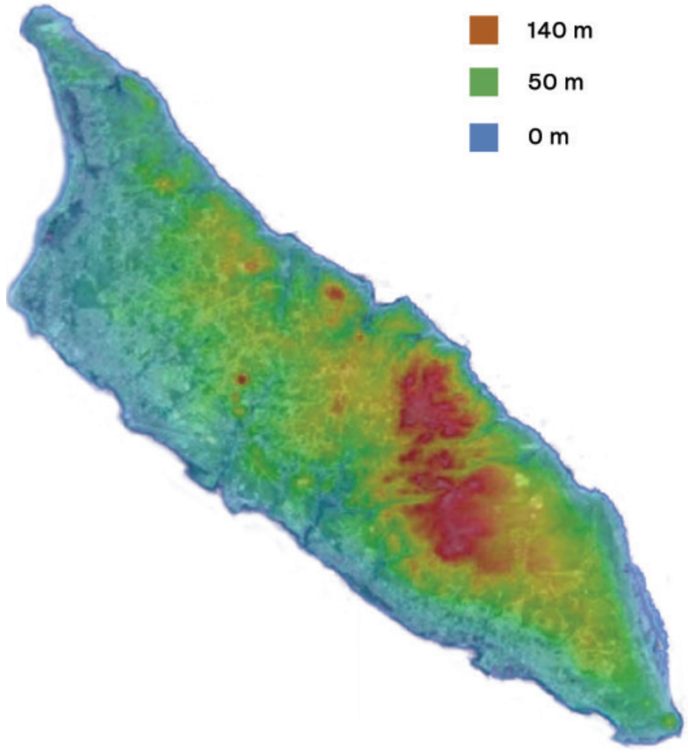


Urban scale

Topographic microclimates

On a large scale, topography together with solar radiation and wind can combine to produce microclimates that accentuate certain characteristics of an area's macroclimate. Some sites within the topography can therefore be more favorable than others as they could potentially enhance the access to desirable climatic resources or mitigate unwanted ones. Considering the location of a building group can thus enhance comfort and productivity, change the length of heating or cooling seasons and thereby reduce future related energy consumption beforehand (Dekay & Brown, 2014). Certain principles can be considered when predicting slight differences in the microclimate of a specific topographic site.

Aruba's topography does not offer extreme differences in height, where cooler microclimates can be taken advantage of at higher elevations. However, there is a principle related to slopes independent from altitude that could be taken into account. The amount of solar radiation captured by different types of terrain depends on the slope and orientation towards the sun. For example, south oriented slopes capture the most, north the least, and the east and west sides capture more morning and respectively evening sun (DeKay & Bron, 2014). There are a couple of hills and mountains in Aruba where this principle can be considered. Thus, in climates with cooling requirements, it is best to build on north oriented slopes. Next, east facing slopes are most beneficial because this is where the prevailing wind comes from. When oriented to the west, the hill itself could be a disturbing factor with respect to the wind strength on site.

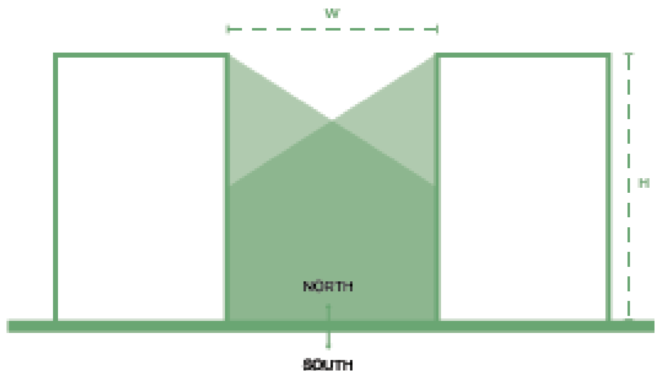


12. Elevation map of Aruba

Urban microclimates

Urbanization creates an urban heat island due to excessive heat accumulation resulting in higher temperatures in cities than in surrounding rural environments. The intensity of the effect can be reduced by various strategies. Studies on UHI in tropical environments remain numerically inferior to that of temperate climates (Giridharan & Emmanuel, 2018). However, because the known causes are largely unrelated to the prevailing climate ((Kleerekoper et al., 2012), mitigation strategies are likely to be helpful on Aruba as well. Mainly when they fall within the previously mentioned strategic approaches of prevention of heat gain and provision of cooling. Carrión et al. (2020) have set out the most typical UHI mitigation strategies appropriate for tropical climates: shading, ventilation, green infrastructure and albedo enhancement of building materials and pavements.

Shading is a highly effective means to reduce the daytime heat stress in complex urban environments, especially in high rise high density environments. The importance of shade provision is more pronounced in the tropics with the source of shading essentially being less important than the shade provided (Emmanuel et al., 2007). Maximum daily temperatures within street canyons decrease with increasing H/W ratio (FOOTNOTE: H= building height, W= street width) due to mutual shading provided by the buildings. Shade enhancement through increased H/W ratio of street canyons has the highest mitigation effect on the temperature when oriented parallel to the North-South axis (fig. 13). On the other hand, air-flow at street level is negatively affected by this same increase. Urban ventilation enhancement has received considerably more attention in the tropics than any other mitigation option. Therefore, shading by means of vegetation could be considered to be more appropriate on Aruba.



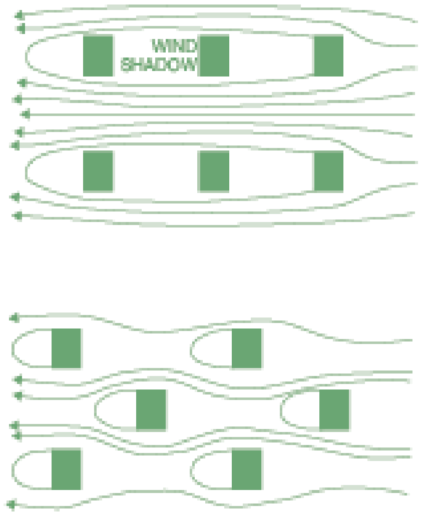
13. Mutual shading over N-S axis

Urban patterns - Maximizing ventilation

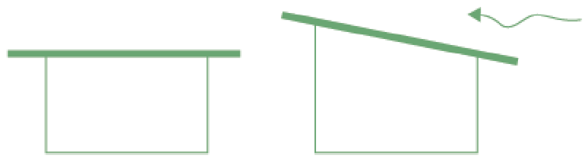
Urban ventilation is not only an effective means to mitigate UHI effects but also allows air to consequently enter buildings on an individual level which in turn is beneficial for indoor thermal conditions. The provision of good airflow and ventilation by wind begins with a careful consideration of the urban plan. In addition, several environmental factors of a site may either enhance or diminish wind speeds such as land relief or obstructions in the form of buildings as well as dense vegetation. Most problems however, will only be encountered when a combination of negative factors are present (Baker, 1987).

In dense urban environments, ventilation corridors oriented along the prevailing winds can contribute to the overall air movement. In turn this may contribute to better cross ventilation in the individual buildings. Therefore, it is desirable to design urban plans in such a way that main streets are oriented preferably along but at least within 30 degrees of the prevailing wind direction (DeKay & Brown, 2014). The percentage of the general present wind velocity let through a street can be predicted by determining the blockage ratio of a certain building group composition. This is a rather complex calculation as there are a lot of contributing parameters. Most significant is the relation between the heights of the buildings and the width of the street. Buildings should not be closer than at least six times their height and obviously taller buildings should preferably be to leeward of lower rise buildings (Baker, 1987). Additionally, it is better if the buildings can be staggered in their placement relative to each other in order to minimise the mutual disturbance of wind shadows on the leeward sides(fig. 14).

Furthermore, the volume of the building also affects the size of the wind shadow. Evans (1980 in Baker, 1987) concluded that the shadow gets longer as the building gets higher, but also wider (perpendicular to the wind direction). The shape of the roof also affects this,



14. Influence of building placement on wind shadow



14b. Roof sloped according to prevailing winds

e.g. pitched roofs (<45 degrees) are generally in favor of a narrower wind shadow, especially when they are only sloped facing the wind direction (fig. 14b: compared to equally sized buildings with flat roofs which height is equal to the lowest point of the pitched roof).

Vegetation patterns

The presence of green within the built environment can reduce UHI effects. Many studies have shown that vegetation, in the form of green corridors, parks, courtyards but also, green roofs and facades, have a cooling effect on its surroundings. (Wilmers, 1990, Jáuregui, 1990, Honjo & Takakura, 1990 & Abu et al, 1998). Vegetation helps mitigate the urban heat island by evapotranspiration, which is the combined process of evaporation from the soil and transpiration from a plant (Waller & Yitayew, 2016). In addition, tree canopies contribute to the cooling effect by providing direct shading on surfaces and thereby blocking about 90% of the sun's radiation. The latter usually has a larger impact on the air temperature, especially in smaller green areas (Oke, 1989).

The overall cooling effects of different green arrangements depend mostly on its size, selection of species and the interval of the patterns. It is suggested that smaller green areas scattered throughout the city with sufficient intervals are more efficient in equally cooling the surroundings than fewer larger green areas (Shashua-Bar & Hoffman, 2000).

On Aruba, trees will have the greatest mitigating effect by providing shade to buildings and open spaces such as streets and public squares. Incidentally, when trees are used to provide shade to buildings, it is necessary to place them intelligently to avoid breakup of the wind. In that particular case, it is questionable whether vegetation is the appropriate choice of shading as ventilation is the main way of passive cooling on the island.

Building scale

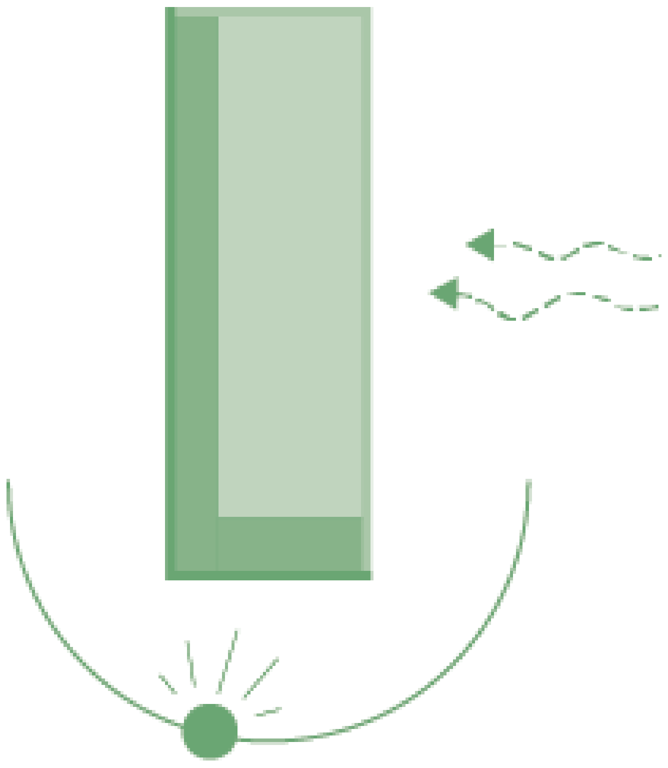
Prevention of heat gain

Orientation and spatial organisation

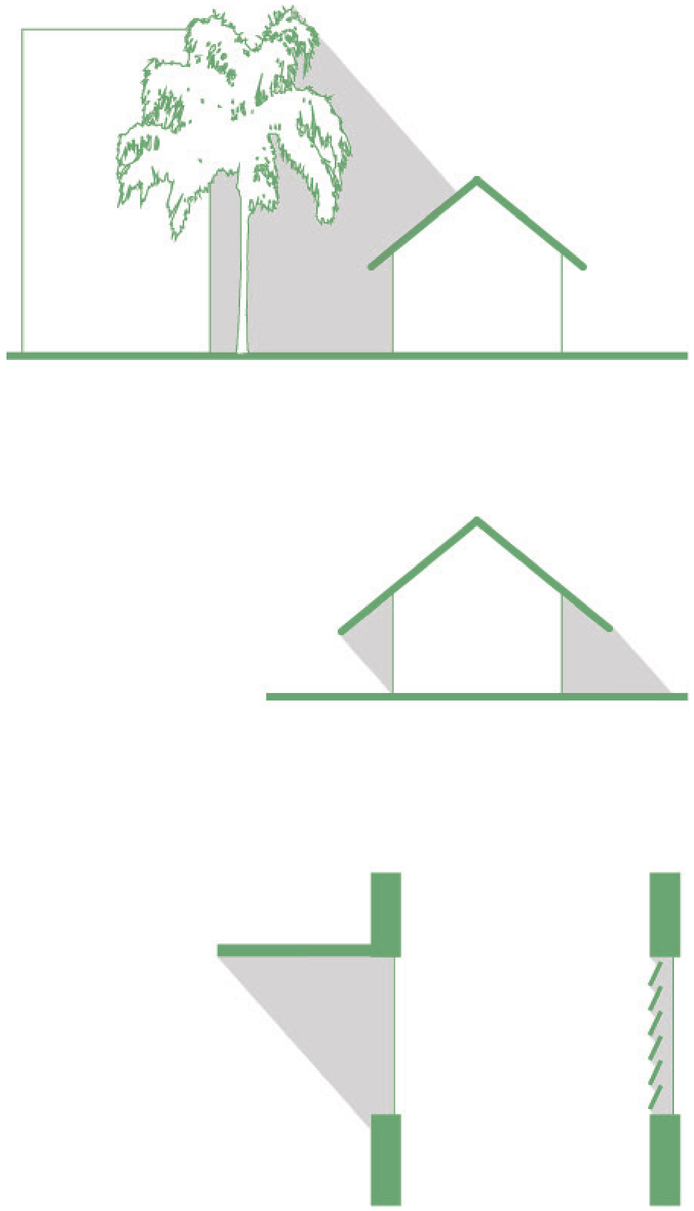
The main cause of internal heat gain in tropical climates is the excessive amount of solar radiation (direct, diffused and reflected) that heats up exterior surfaces and consequently enters through conduction, but also directly through facade openings. Therefore, intelligently orienting a building as well as its interior spaces and architectural features is crucial in order to optimize its overall passive performance (Abdul Wahab et al, 2014). What needs to be considered when orienting a building and its interior is the availability of daylight, protection from solar radiation and the amount of prevailing wind on the facades.

Not all spaces in a building share the same thermal requirements. Spaces that have less strict temperature demands can therefore be used as buffer zones between the outdoor environment and rooms where thermal comfort is most important. Based on the type, duration and time of use of certain spaces, for example, storage, bathrooms, circulation and bedrooms can be cleverly oriented. In addition, transitional outdoor spaces such as covered balconies, terraces or atriums can mediate between the ex- and interior of a building by providing shade and thereby cooling the air before it enters the building.

Kitio et al. (2014) concluded in a study for passive design strategies in West Africa that spaces where thermal comfort is most important are best oriented on the sides where the wind is strongest, because here the effects of solar radiation are less present. Furthermore, it is recommended that most windows, as well as the longest facades should be out of and/or protected from direct sunlight. By placing the longest sides of the building to intercept the prevailing wind (East) and the shortest towards the orientation where solar radiation is at its highest (South), ventilation of the facades is most



15. Warmer and cooler areas of a building relative to the sun and prevailing winds



16. Possibilities of shading from most to less beneficial

effective and thus thermal impact of the sun minimised (Insisiengmay, 2005). The same is true for the roof which by far catches the most solar radiation. When the roof is inclined towards the prevailing wind, the heat gain will be minimized by natural ventilation. This strategy also minimizes the wind shadow behind the building as previously discussed.

Shading

As a continuation of thoughtful orientations towards the sun and wind, it is then important to further protect glass areas, but also opaque surfaces such as façades and the roof to further protect against heat gain from solar radiation (Chenvidyakarn, 2007). In addition to dedicated shading devices, there are other different ways to effectively shade the building and its openings, such as overhangs, louvers, neighbouring structures or vegetation. However, in general, the most effective way is through external shading objects as they interrupt the solar radiation even before it hits the building envelope.

For hot humid climates such as Aruba's it is important that the means of external shading do not significantly affect the wind as this in turn will weaken the efficiency of possible natural ventilation. To estimate if proposed shading objects within a design will offer enough shade throughout the entire year, the lowest and in the case of Aruba, also the highest stance of the sun should be considered, respectively the path of the 21st of December and the 21st of June (Baker, 1987). This makes it clear that it is also necessary to protect the north side of a building from the sun.

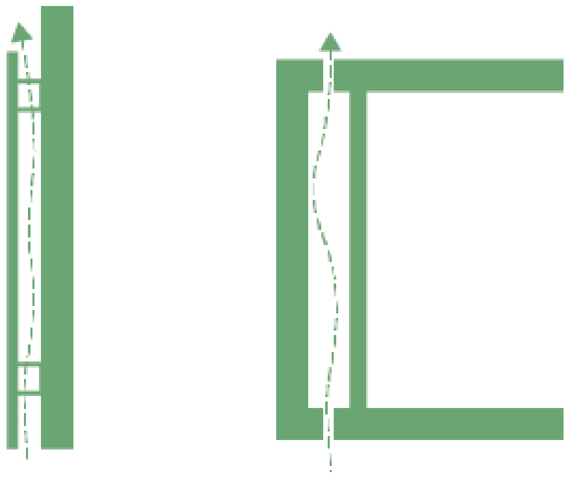
Roof / ventilation

Usually, the roof captures most of the solar radiation. In Aruba, where roofs are mostly concrete/cement-based, this can account for 50-70% of the total incoming heat (Chang et al., 2014). Besides external shading, there are several strategies to mitigate internal heat gain through the roof. Besides the already mentioned strategy of sloping the roof towards the prevailing winds and thus minimizing the effects of solar radiation, ventilating between the roof and the ceiling (attic) is another option to reduce heat transmission to the underlying interior spaces. Adding insulation above the ceiling will contribute even more, especially above air-conditioned rooms (Bade et al., 2005, Ong, 2011). Ventilation of the roof can be provided, for example, by eaves-vents as inlet and rooftop ridge-vents as outlet. The airflow will be driven by means of rising warmer buoyant air.

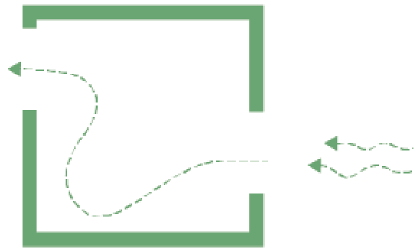
Furthermore, two other techniques can be applied: a cool roof, which includes using a reflective surface to reflect sunlight and therefore absorbs less heat, and a double skinned-roof, based on both shading and ventilation strategies. The latter has been researched to be more effective in tropical climates and does not bring about the issue of glare (Lee, 2015). A double skinned roof is essentially a second roof that provides shade to the entire building and also mitigates heat transfer by ventilating in between. Using insulation can be even more effective against heat gain and also prevents condensation when applied to an air-conditioned building. However, this may block heat loss during night time and is thus overall less profitable for non air-conditioned spaces.

False walls / partial lining

The same principle of preventing heat transmission through the roof by ventilation could also be applied to walls in the form of a lightweight lining through which air can flow. It is a relatively costly solution, however, where shading is not possible or favorable for a particular wall, partial lining or fake walls (double skin) can be taken into consideration (Baker, 1987) (fig. 17). On Aruba, where the wind predominantly comes from the east, this strategy would be most efficient on south-west facing walls, especially when the inlet vents can be positioned towards prevailing winds to stimulate the air flow.

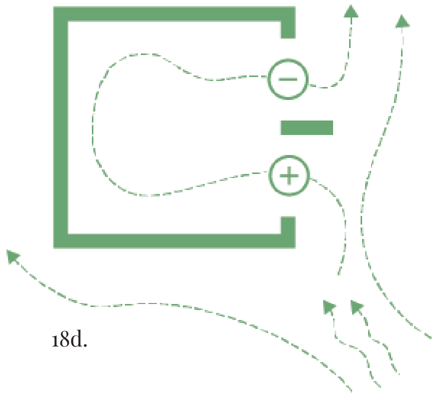


17. False wall and Partial lining

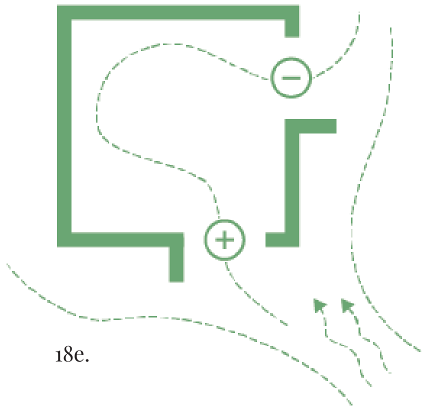


20a.

18b.



18d.



18e.

Provision of cooling

Even with the best efforts to prevent excessive heat gain, in a tropical climate like Aruba's where temperatures usually exceed the interval of thermal comfort, the provision of cooling remains significant. Where the previous chapter focussed on preventing heat to enter, this one will discuss ways of removing heat from a building. The key means to provide passive cooling in hot humid climates are natural ventilation and heat dissipation led by (indirect) evaporation. Considering the relatively high tradewind velocities as well as the prevalence of it's direction, Aruba offers the perfect conditions to optimally integrate natural ventilation in architectural design.

Ventilation

Ventilation offers cooling within a building based on the concept of convection, moving warmed up air to the exterior and replacing it with cooler fresh air. In addition, it can also provide users with physiological cooling when the air velocity is sufficiently high. The latter is especially desirable in this specific climate as it increases a human's rate of evaporation and results in a direct cooling sensation of the body. Looking at the comfort zone chart for thermal environmental conditions, this direct cooling effect may be experienced with an air movement velocity from as little as 0.1 m/s (Olgyay, 1967). On Aruba, where relative humidity is usually around 70%, temperatures up to 32 degrees celsius could be tolerable when exposed to a breeze of at least 1 m/s, preferably between 1.5 - 2.0 m/s (Givonni, 1991). However, this depends on one's personal acclimatization to the climate.

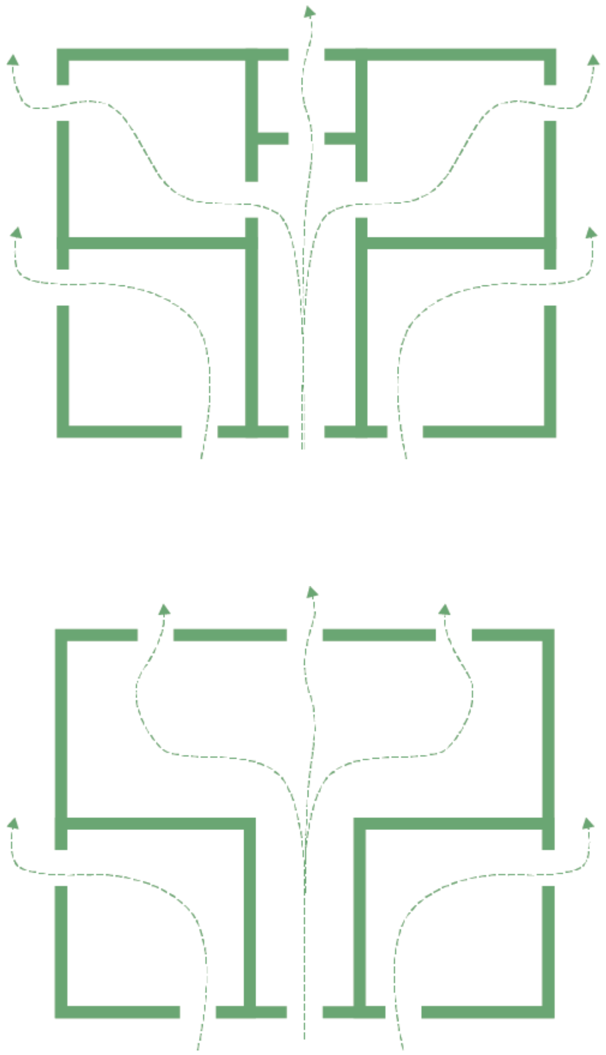
Passively stimulated, ventilation can be achieved by means of either wind, buoyancy or when executed properly, an equally stimulating combination of the two.

Cross ventilation

This technique is based on pressure differences between the in- and exterior of a building and therefore relies on the force of the wind for its efficiency. The provision of two large openings in different, preferably opposite walls are the first step to achieve effective ventilation in hot humid climates (Chen, 2001).

Several studies agree that in general, the following qualitative guidelines can be used to enhance efficiency of cross ventilation (Chenvidyakarn, 2007): (a) One of the openings intercepts the prevailing wind, (b) Windows at body level increase the potential of physiological cooling, (c) Blockage of the air path is minimised, (d) Wing walls next to the openings provide smoother and stronger entry of air into the building. The latter is based on the idea of creating both positive and negative wind pressures around respectively the windward and leeward side of a wing wall and with this enhancing either the in- and outlet of wind through the windows. Figure 18 d and e show on what side of the opening the wing wall should be placed depending on the wind direction and whether it is an in- or outlet.

Ideally, cross ventilated buildings are elongated perpendicular to the prevailing winds in order to maximise exposure. On Aruba this means facing the longest facades towards the east, which corresponds to the optimal orientation to prevent excessive heat gain from solar radiation, as previously discussed. However, it is not always possible to have windward facing openings for every room, in which case an intelligently designed sequence of spaces and/or the use of ventilation corridors can increase air flow efficiency throughout the building (fig. 19).



18a. one of the openings intercepts the prevailing wind

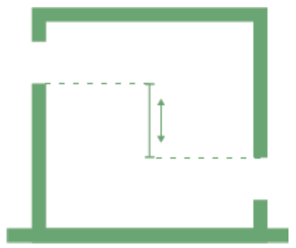
18b. openings at body level

18d. wing walls with openings in same wall

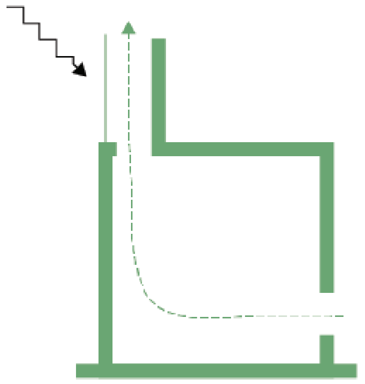
18e. wing walls with openings in adjacent wall

19. Possibilities of sequence of spaces / ventilation corridor for the purpose of cross ventilation

20a.



20b.



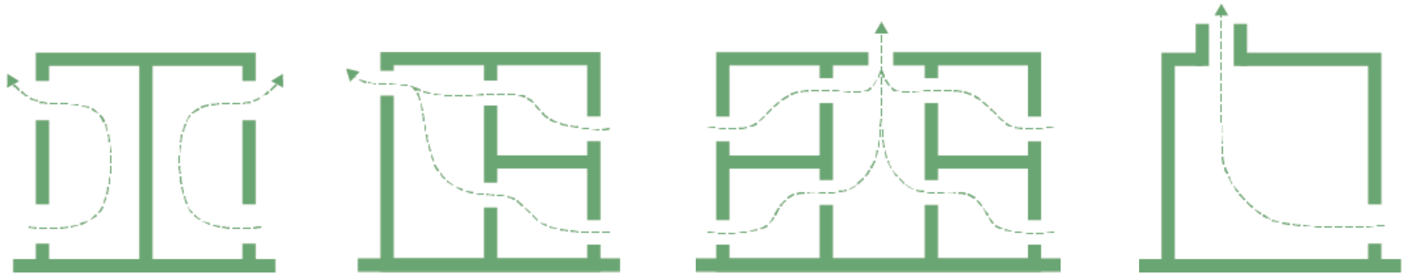
20c.

Stack ventilation

Where cross ventilation relies on pressure differences between the interior and exterior of a building, stack ventilation depends on the contrast in temperature to create a pressure gradient through a vent to drive air movement by buoyancy. For both techniques counts, the bigger the difference the stronger the air flow (DeKay & Brown, 2014).

However, while stack ventilation may supply a building with sufficient fresh air and prevent the interior temperature from rising high above the exterior, the amount of air movement caused through this technique is generally not strong enough to contribute to physiological cooling (Nugroho, 2009). Therefore, it should not be considered as a replacement of cross ventilation but rather an alternative for when wind velocities are low for example.

The stack effect essentially induces warm air removal through openings higher in the building, leading cool, fresh air to infiltrate through openings situated lower. The temperature differences that stimulate this buoyancy driven ventilation are usually a result of internal heat sources such as lighting or the users themselves. In addition, there are several strategies that may maximise the heat discharge potential of buoyancy driven ventilation (Chenvidyakarn, 2007): (a) enlarging the vent areas. (b) maximizing the vertical distance between the in- and outlet. (c) heating up the last part of the ventilation path. The last approach asks for careful implementation in the form of a so-called solar chimney which is sufficiently separated from the used spaces to avoid heat gain (fig. 20c). These structures appear to have potential in hot humid climates with strong solar radiation such as on Aruba (Asano, 2001). Figure 21 shows different strategies in elevations to stimulate stack ventilation.



21.

20a. enlargement of vent areas

20b. maximizing vertical distance between in- and outlet

20c. heating of last ventilation path

21. tall rooms, tall room on the side, tall room in the middle, stack vents in every room

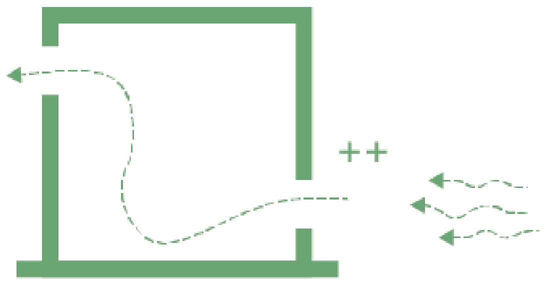
Combined natural ventilation

Stack ventilation originally does not rely on the force of the wind, hence it is consequently independent from orientation. However, both cross- and stack ventilation can mutually enhance or reduce the airflow of the other, depending on the relation between in-, outlets and the prevailing winds. On Aruba, where the wind direction is relatively constant, it is fairly simple to design based on both principles. Locating inlets on the windward (east) side and outlets on leeward side of a building, can mutually enhance cross- and stack ventilation and thus optimize the cooling potential through natural ventilation (fig. 21). Consequently, plan and section strategies for both cross- and stack ventilation can be combined, oriented along the prevailing winds (fig. 22).

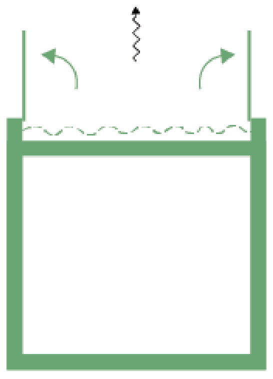
Indirect evaporative cooling

When water in liquid state evaporates into gas, every gram extracts about 2550 J of heat from its surroundings (Amer, 2015). Evaporative cooling uses this concept as a means of passive heat dissipation. In hot humid climates however, to avoid indoor humidity levels to rise, the evaporation processes are desired to be kept outside of the building by cooling an exterior surface such as the facades or the roof. In turn, these elements may serve as heat sinks, absorbing warmth through its interior surface by day and providing cooling at night. Consequently, several systems are appropriate to achieve indirect evaporative cooling, particularly a roof- pond or spray.

There are numerous roof pond systems that each differ in terms of structural and/or operational characteristics. Kolokotsa et al. (2011) have set out a summary of these variants, discussing overall implications, design considerations and the state of the art. Examples of the diversity include roof ponds with or without covers, sprays, ventilation and so on. Nonetheless, research on the application and effectiveness of the different variations within hot humid climates remains limited to a selection.



22. Combined cross- and stack ventilation with inlets on windward side

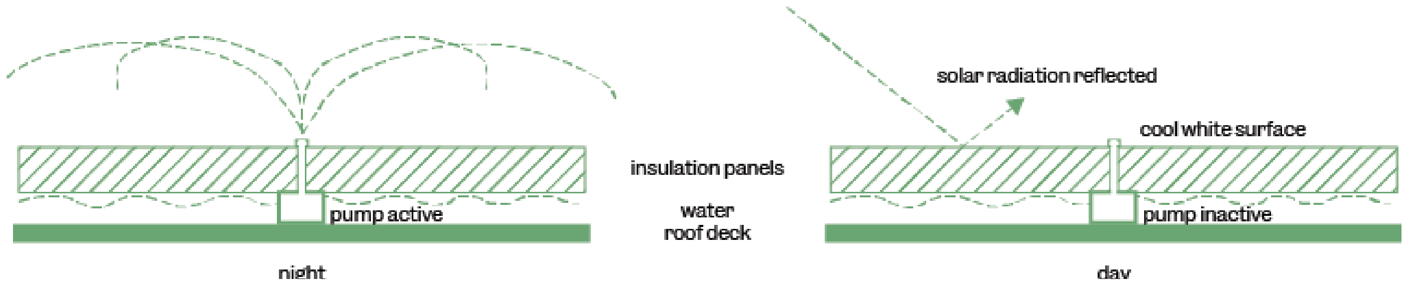


23.

Theoretically, roof ponds that are protected against solar radiation during the day and exposed to the sky in order to remove the absorbed heat by convection, radiation and evaporation at night, would seem most appropriate for a climate such as on Aruba (Givoni, 2011).

An example of a so-called “coolroof” that has been tested in Mexico has shown that it is capable of cooling the interior air significantly below exterior temperatures (Chavez, 2007). The particular system in question uses floating panels of insulation to provide protection against solar radiation during the day and a pump to circulate the water over the panels at night to remove absorbed heat (fig. 24). Other studies executed in Mexico include using operable foldable panels to cover the roof pond during the day, also show desirable results (Givoni, 2004) (fig. 23).

Roof ponds are a relatively costly strategy to acquire passive cooling, both in construction and maintenance. In addition, they require a thorough substantiated understanding of their applicability within Aruba as for example the stagnation of water carries the risk of hosting insect larvae. A less structural and low maintenance means of cooling the roof by indirect evaporation is spraying its surface with water. A case study using this technique has shown potential in a hot humid climate (Asano, 2001). This strategy may be effective for implementation on Aruba in combination with wind intercepting sloped roofs. Water could be collected throughout the year, especially during the rainy season and consequently be used for the purpose of indirect evaporative cooling during the warmer months.



Materials

In hot humid climates, preventing heat gain as much as possible is most significant to passively reduce the cooling load of a building. Therefore, all facets of an architectural project must contribute to this cause in order to gain optimal efficiency. In addition to previously discussed architectural strategies, materials of the building envelope as well as of surrounding surfaces should help minimize heat gains and consequently prevent excessive rises in temperature. Consequently, materials with high thermal mass are less desirable to be used in this climate.

Although shading may directly protect against the sun, in reality, a continuity of heat gain remains from diffuse and reflected solar radiation. Therefore, it may still be valuable to construct a building envelope in multiple layers.

- Insulation from the outside, to lessen conductive heat transfer through opaque surfaces that receive solar radiation.

- Ventilation to remove excessive heat that has been accumulated between different layers of the envelope. The cavity could be internally coated with a reflective foil to block radiative heat transfer.

- Additionally, for the windows where heat ingress from the sun is most obvious, a single low emissivity coating facing outwards can reduce incoming solar radiation as well as heat that has been built up on the exterior glass surface.

Besides the materials of the building envelope and surrounding surfaces, also their colour and texture are important in terms of thermal properties. Generally, materials with high albedo absorb less heat and accordingly have lower surface temperatures which in terms of thermal comfort is more desirable on Aruba.

23. roof pond with openable covers

24. roof pond with nocturnal spray

Physical characteristics that affect albedo are color, surface texture and construction material properties. Objects with a light colored as well as smooth, flat surface tend to be less prone to heat gain and are therefore favorable in the built environment to passively mitigate the urban heat island effect (Doulos et al., 2004).

Research has shown that white colored roofs averagely have a lower diurnal temperature than that of the surrounding air (Ahmed & Mohamed, 2012 in Affandi et al., 2016). This result is due to the roof in this case, having a greater long wave radiation during the day time than the net solar radiation it absorbs. Moreover, special coatings which stimulate radiative cooling to clear night skies could increase benefits for the roof even further.

Vegetation

Vegetation can be used in a variety of ways to moderate temperatures of urban environments throughout different scales and hence reduce overall cooling requirements. The key means appropriate vegetation design offers within the framework of maintaining thermal comfort in hot climates are (a) the provision of shade, (b) reduction of reflected solar radiation (c) evapotranspiration processes and (d) thermal insulation of building surfaces (fig. 24).

Studies in hot humid climates have shown that plants, particularly in the form of urban parks hold the ability to noticeably lower the ambient temperature by a few degrees below surrounding built areas (Yu & Hien, 2006). Also, (climbing) plants grown either directly against or on integrated support structures can lower the temperature of external building walls significantly by most of all providing direct shade (Cuce, 2017). Furthermore, similar results have been reported when comparing temperatures of a green roof to that of an exposed roof surface. Roof gardens both prevent heat gain and provide cooling through shading, thermal insulation and respectively evapotranspiration processes. However, moisture levels of the substrate must be kept above a certain level as dry soil may reverse desirable effects (Hien et al., 2007).

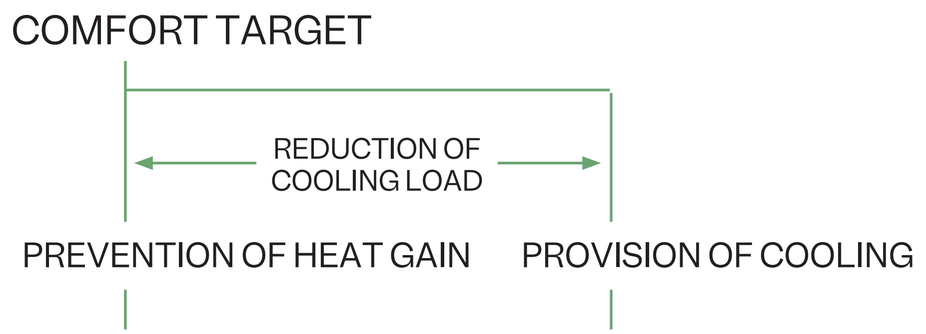
When applying vegetation as a passive design strategy, it is important to consider the specific purpose when choosing certain species. Based on the physiology and leaf area/morphology of a plant, some may be more effective in promoting evapotranspiration cooling whereas others may be better at providing shade (Cameron et al., 2014). For example, a comparative study on the thermal effects on the surroundings of twelve different tree species in the tropics of Brasil shows that the size and shape of the trunk, leaves and crown as well as the permeability of the canopy influence their efficiency both individually and in clusters (Abreu-Harbich et al., 2015). The Caesalpinia pluviosa F. presented the best results both single and in cluster. On Aruba, the Caesalpinia coriaria, a tree from the same family with similar characteristics grows naturally. However, further research is needed to be able to say anything about the quantitative effects of certain species and thereby identify the most suitable local plants of Aruba for specific passive design purposes.

24. Benefits of vegetation: shade, reduction of reflected solar radiation and evapotranspiration processes

Conclusion

This paper was focused on finding the appropriate set of passive design strategies for Aruba's climate. Although it is barely possible to gain optimal living conditions without the use of active mechanical appliances, it is still significant to passively contribute to thermal comfort and thereby minimize the active energy load. It was found that the prevention of heat gain as well as the provision of cooling is necessary throughout the entire year to help achieve desirable living conditions. There is an extensive amount of passive design principles that can be integrated in the built environment on Aruba to achieve this within the architectural design itself.

The scheme on the opposite page summarizes the strategies according to the different scales of the design path as well as the specific approach towards reducing the energy load.



	PREVENTION OF HEAT GAIN	PROVISION OF COOLING
URBAN	- Mutual shading of buildings - Shading by vegetation	- Ventilation corridors - Vegetation patterns
BUILDING	- Building orientation elongated to intercept prevailing winds - Spatial organisation according to cooler areas on windward side - Buffer zones - Roof sloped towards the wind - Shading (preferably outside the building envelope) - Roof ventilation - False walls / Partial lining	- Cross ventilation (wind driven) - Stack ventilation (inlets on windward side) - Indirect evaporative cooling: Roof pond / spray
MATERIAL	- Lightweight materials - Insulation with ventilated cavity - High albedo materials for external building- and surrounding surfaces	- Radiative cooling coating
VEGETATION	- Shading by vegetation: Roof garden Green walls - Surrounding plants and trees	- Evapotranspiration: Roof garden Green walls - Surrounding plants and trees

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