Bioclimatic landscape design in extremely hot and arid climates

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ABSTRACT: In the desert the role of bioclimatic landscape design is to consider three major environmental factors, solar radiation, evaporation, wind and air flows. Therefore the landscape architect should be prepared with a group of design principals and design guidelines that can help him to improve the micro-climate and conserve energy. This paper presents a group of passive design strategies for bioclimatic landscape architecture in the desert. In this study, a bioclimatic landscape design strategy is proposed that consists of a three layers approach; (1) bioclimatic-zones concept, (2) thematic walled gardens concept, (3) extensive and intensive landscape concept. The passive design strategies should start at early design stage of the master plan creation. This study demonstrates that the three layers approach could be very efficient in order to enhance the microclimate passively with low energy and low water consumption rates. The three established strategies in the design stage have been tested and evaluated for a campus design in Egypt's hot arid desert. Some quantitative calculations and measurements together with shading analysis have been taken in order to verify these design strategies using the PET index. Finally, the three layers approach showed ability for improving the microclimate and cooling the outdoor environment. The paper set site planning and bioclimatic landscape design recommendations that can be applied in similar extremely hot and arid climates.

Keywords: outdoor, bioclimatic, thermal comfort, landscape, hot climate

1. INTRODUCTION

In extremely hot and arid climates, with high temperatures, humidity and dusty hot winds it is very important to consider the climatologically consequences of settlements and landscape design. In fact, the microclimate of urban settlements can be improved through bioclimatic landscape design and planning. The field of climatic outdoor design is relatively young and much of the research up to the work of Robinette during the 1980's could be classified as qualitative in nature [1-4]. However, the field has advanced considerably in the last two decades [5-6]. Various models are available to evaluate the human thermal comfort in hot climates. The model of Olgay is one of the earliest attempts to quantify thermal comfort in outdoor spaces. Others models include Steadman's sultriness model [7], the Index of Thermal Stress (ITS) by Givoni [8], Fanger's model that predict mean comfort response (Predicted Mean Vote - PMV) [9] and the Physically Equivalent Temperature (PET) index of Mayer and Hoppe [10].

Unfortunately, landscape architects and urban planners do not integrate the accumulated knowledge of climatology into applicable planning guidelines and tools as a way to improve the micro climate of the outdoor built environment [6, 11]. Most research is published in scientific literature and is not accessible to the majority of landscape designers and planners. Moreover, the design implications of the results are rarely extracted in a usable form.

1.1. Objective:

Therefore, main aim of this research is to develop a landscape design strategy for outdoor environment in hot climates based on bioclimatic principals. In order to provide landscape architects with design guidelines that can improve the microclimate and conserve energy in extremely hot climates. This work is drawn from a master thesis being prepared at Wageningen University as part of a design case study for the new American University Campus in Cairo [12]. The selection of the case was made based on the location aridity and harshness, which is located in Egypt's eastern desert. Numerical modelling was employed to test the proposed design strategy. Finally, the study identifies some key areas where research gaps remain.

2. BIOCLIMATIC LANDSCAPE DESIGN IN HOT CLIMATES

Landscape design in extremely hot and arid climates must necessarily consider microclimate of outdoor areas as spaces that can be environmentally controlled. There are many aspects that should be considered during the design of the outdoor environment including radiation, heat, emissivity, glare, and dust control. However, the most important considerations are listed below:

1. Solar Radiation Control
2. Wind Control
3. Evaporation Control

In order to address those climatic considerations landscape designers and planners use all available design elements and landscape treatments including vegetation, water and hardscape (see Figure 1). The use of every treatment for microclimate improvement is discussed in this chapter.

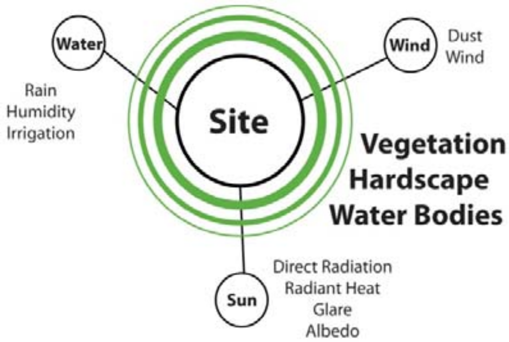

Figure 1, Landscape Design Elements

2.1. Vegetation

Vegetation is the most effective landscape element in surface and air temperature modification. Vegetation can be used very effectively as an intercepting device to control the sun's rays. The large variety of forms, textures, and colours of plant materials provides an endless palette to choose from, adding beauty as well as utility to the landscape. Climbing and clinging vines function as solar control devices on overhead trellises or provide protection for a hot wall. Groundcovers can reduce unwanted glare and prevent excessive heat gain near structures and outdoor areas. The right tree in the right location can shade the building during the hottest period of the year while letting the winter sun warm these same areas during the under heated period of the year [13]. Trees, shrubs, groundcovers, vines and turf provide solar control by effectively reducing direct and reflected radiation and absorbing heat.

The foliage and branches of plants selectively reflect, absorb, and transmit solar radiation and provides the cooling effect of evapotranspiration. Vegetation with a loose open foliage and branch structure will filter radiation, allowing a portion to pass through the canopy acting as a buffering agent to abrupt temperature changes. Dense foliage and multiple layers of canopy can almost totally obstruct incoming radiation. However, very little, actually penetrates the canopy, resulting in cooler temperatures at the shaded side of leaf surfaces. In addition, plants have rough textures compared to most manmade objects, and the leaf canopy presents a multi-faceted surface which is more efficient at diffusing incoming radiation. Needles and small-leafed plants commonly found in desert landscapes are very effective at reducing glare from reflective surfaces.

The ability of plants to buffer rapid temperature changes is an important attribute for solar control. The cool soil under shaded areas will absorb heat from the air faster than heat can be transmitted to it by conduction or convection, and the greater humidity associated with vegetation means more heat is required to raise ambient air temperatures significantly. Temperatures within planted areas, therefore, remain cooler through more of the day than that of surrounding areas. Plant cover will also reduce diurnal temperature fluctuations by trapping and reflecting outgoing thermal radiation at night. The capacity for vegetation to retain warm air at night is directly related to foliage density.

During the night the tree canopy blocks direct radiant heat loss from the ground to the sky, because radiation is emitted only from the upper layer of the leaves. However, whenever the air blow the canopy is warmer the air above, it rises, and the air that has been cooled by contact with the upper leaves can sink down to replace it, creating natural convective cooling [14].

Deciduous vegetation should be considered not only where shade is required to avoid excessive heat gain during the overheated times of the year but also when solar exposure is desired during the under heated periods. Because the leaf drop and re-foliation of most native plant material corresponds very closely to the times of year when solar exposure and shade, respectively, are needed, it is wise to take advantage of the natural rhythms of these plants.

The degree to which plants function as effective climate control devices depends on their size, shape, density, and location. The proper location for plant material is best determined using the sun path diagrams in conjunction with overheated period data. Plant material is multifunctional, however, providing more utility than just solar control, and care should be taken to consider all aspects of site design requirements before final placement of vegetation is decided [13].

2.2. Water

Water can improve the microclimate of outdoor environment. Many researchers propose to landscape designers' strategies to improve the microclimate: water surfaces, fountains, porous pots of water, reflecting pools, irrigation channels, moistened fabrics or sprinklers [13-14]. All strategies are favouring the cooling by evaporation. These strategies enables us to modify the climatic impact like the local heat, mass, and momentum balances influencing air quality and thermal comfort.

The surface temperature of the water surface is affected by the heat transfer caused by radiation, conduction, convection and the latent heat transfer due to water evaporation. Water is normally warmer in winter and cooler in summer, and usually cooler during the day and warmer at night, than the ground. Accordingly, the proximity of bodies of water moderates extreme temperature variations, and in summer lowers the heat peaks. Sites located leeward of large bodies of water or irrigated fields will benefit from evapotranspiration cooling and temperature modification.

Critical to this strategy is the ability to control the amount of water used. In hot arid regions water scarcity is limiting factor and must be considered [15].

2.3. Hardscape and Structures

Hardscape and structural elements can be used to enhance the microclimate or create protected outdoor spaces including trellis, pergolas, ramadas, tents, overhead canopies, car ports and low emissive pavements and paintings. In extremely hot climates, shade is the most passively effective landscape control strategy among the previously mentioned control concerns. Therefore, the use of hardscape and structure should aim protection from solar radiation in order to reduce thermal heat stress by providing shade and low emissive materials in outdoor spaces [13]. Materials such as reed, straw, bamboo should be considered in the design of hardscape and pavements. The utilization of natural paintings and sandy stones could be an example for good practice. The colour of the surface affects the degree to which solar radiation is absorbed. Light colours are more reflective and will be cooler than dark surfaces. If an outdoor dry surface is shaded effectively, its temperature would be somewhat elevated above the ambient air level. Cooling the pavement of a relatively wide shaded area can be lower the radiant temperature to which the people in the area are exposed [14]. The design of impervious surfaces can engage the scope of biotic ecosystem services, such as thermal tempering of the surfaces, production of biomass, storm water management, and nutrient cycling. It will also help in managing scarce resources and increasing biodiversity.

In short, the presented landscape design elements are the main tools that landscape designers and planners use for bioclimatic outdoor design. However, the challenging question is how to translate this knowledge into design strategies? The following chapter proposed an answer.

3. ESTABLISHING THE BIOCLIMATIC LANDSCAPE DESIGN STRATEGY

Based on the previously mentioned design guidelines and considerations, the proposed bioclimatic landscape design strategy integrates three basic design principles for microclimate improvement and thermal comfort in outdoor environment. These are the bioclimatic-zones concept, the thematic walled gardens concept and the extensive and Intensive landscape concept. The three concepts were developed and tested in the course of the master's study [12]. The main features of the constituent strategies are discussed below.

3.1. Bioclimatic-Zones Concept

The Bioclimatic-Zones Concept is a primary design principal for site planning in hot arid climates. As indicated by Attia [16], the Bioclimatic-Zones Concept is based on creating a set of zones, where each zone has a set of prescriptive landscape-design decisions that reflect a desired climatic comfort objective. As shown in Figure 2, the concept theoretically constitutes seven ring zones, where six protection zones protect the seventh core zone. The seventh zone, also referred to as the '*cool heart*', is meant to include thermally comfortable outdoor spaces for example inner gardens and courtyards. With the aid of prescriptive design guidelines and empirically verifiable measures for each zone the concept guides designer and planners to create bioclimatic site plans that can improve the microclimate and improve the pedestrian thermal comfort. Figure 2 illustrates the zones concept in which the desired comfort conditions for each zone is determined. In Table 1, the detailed design decisions in relation to the expected climatic impact are presented.

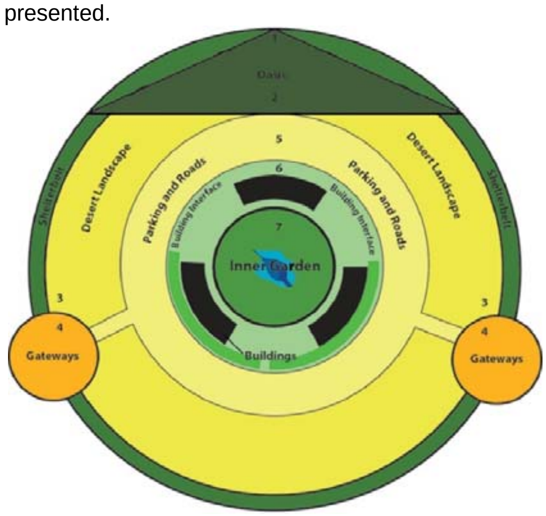

Figure 2, Bioclimatic-Zones Concept illustration for the Northern hemisphere deserts assuming N-S prevailing wind

Table 1: Bioclimatic-Zones Concept: Decisions and impacts matrix

Zone Name		Climatic Impact	Landscape Design	Verification
1.Shelterbelt		Wind, Sand Storm Protection	High Barrier Trees Mulching & Soil Stabilization	Less Wind Speed Cleaner Air (Dust)
2. Oasis		Air Filtering Lower Temp. Better Comfort	Palm Groves Shading Ground Cover	Higher Air Speed Lower Ambient Temp. Lower Dry Bulb Temp.
3. Desert landscape		Drought Tolerant Vegetation Soft Barrier	Boundary Layer Xeriscape Desert Conditions	Less Wind Speed Cleaner Air (Dust)
4. Gateways & Entries		Reduce Solar Radiation Better Comfort	Water Surfaces Vegetation	Lower Temp. Lower Relative Humidity
5.Parking and Roads		Minimize Solar Intensity	Shading	Less Direct Solar Radiation
6. Building / Landscape Interface		Reduce Direct Radiation Reduce Indirect Radiation	Deciduous Columnar trees Green Roof Green Ground Cover	Less Direct Solar Radiation Lower Ambient Temp. Lower Dry Bulb Temp.
7. Inner Garden		Cool Reservoir Promote North Wind Lower Temp. Reduce Solar Radiation Better Comfort	Green Ground Cover Shading, Canopy of trees Water Surfaces	Less Direct Solar Radiation Lower Ambient Temp. Lower Dry Bulb Temp. Higher Air Speed Cleaner Air

3.2. Walled gardens concept

The walled gardens concept is the second design principal that aims to assure a minimum climatic control. In the harsh desert climate, it is difficult to provide a green lush outdoor environment unless the open space is contained and protected from frequent desert storms. There are historical examples in ancient civilisation: the walled gardens of Egypt, the atrium of houses of the Roman and the Islamic gardens in Andalusia [17-18]. These all strongly recommend such strategic decision. The benefit of the wall relies in its ability to minimize the hot-dusty wind penetration in the open garden. In principal, walls in gardens allow the green shrubs, water elements and canopy trees to reduce the temperature and raise the wet bulb temperature. The wall concept might include physical walls or organic walls containing trees and plants or any other solution that achieves the desired climatic control.

3.3. Extensive/Intensive Landscape Concept

Due to the scarcity of water in hot arid climates the third design principal calls for water sensitive design. The Extensive and Intensive landscape concept divide the landscape design strategy into two types of landscape. The first is an extensive landscape that includes drought tolerant and indigenous species. The second is an intensive landscape that includes shade trees and ground covers for the '*cool heart*'. The implementation of Extensive/Intensive Landscape concept takes place at the end of the concept development and in parallel with the plant and irrigation schemes.

In short, the three discussed design concepts form the basis for the proposed bioclimatic landscape design strategy. The following chapter demonstrates the application of that strategy to a real case study.

4. CASE STUDY: AUC NEW CAIRO

4.1. Study Area

The new AUC campus is in the emerging settlement of New Cairo (latitude 30^{o} 01' N, longitude 31^{o} 5' E) of, approximately 35 kilometres east of AUC's present location. Within New Cairo, the new campus complex is located in the centre of the second phase of New Cairo. The site area is about 260 acres, with a mild slope from south to north. This natural topography is part of the larger system of land forms and wadis that fan out in an almost radial pattern at this location, constituting a "natural" terminus to the urban development of New Cairo. The site has a hot, dry desert climate with more than 330 days of sunshine per year. For this study, the existing urban planning and building arrangements shown in Figure 3 (in white) were kept and the new proposed strategy was applied to the campus outdoor environment. The site physical built environment was kept respected without any changes.

4.2. ENVI-MET simulation

The study verified the design strategy through numerical simulation. Simulations were made by ENVI-met. ENVI-Met is a three-dimensional non-hydrostatic urban climate model. It provides detailed environmental conditions, for instance, air temperature and humidity, for each landscape patch within each square within a grid system [19]. This information is especially valuable for the present study, in which one wants to evaluate the effects of vegetation on thermal environment of the various locations of the Campus.

The model input parameters used are shown in Table 2. Several simulations iterations took place for this case, including different types of vegetation covers and various atmospheric background conditions. The bare ground consists of exposed soil. The optimised scheme constitute of three types of trees are modelled namely date palm *(phoenix-dactylifera)*, carnaval tree *(cassia nodosa)* and mesquite tree *(prosopis-juliflora).* Both trees' types referred to as 20 m and 15 m dense parabolic crown trees in ENVI-met plants library. The carnaval is a large and ornamental shading tree with umbrella shape while the mesquite is medium size drought tolerant tree. Both species have a medium leaf density that allows ventilation and sufficient solar penetration for grass growth. The ground cover was made of *mesembryanthemum-edule* a succulent drought tolerant plant that grows rapidly. The climatic effect of the suggested design proposal is simulated and the findings are briefly summarized in the following chapter.

Table 2: ENVI-MET models' input

Location	Climatic Impact
Location	latitude 30^{o} 01' N, longitude 31^{o} 5' E
Date, time of simulation	16-20 July; 1400 hours (GMT +3)
Initial wind	3.0 m/s at 10m from 315 deg
Boundary	Temperature= 312K Specific humidity = 4.6g/Kg
Grid size	00x00x00 grid spacing, 10m; Z grid spacing, 10m
Plants	Trees in parking lots: 20m high, dense foliage, deciduous Street trees: 10m high, distinct crown, 9m wide
Surfaces/soil profiles	Asphalt road profile: asphalt to 60 cm, loam to 2m
Soil initial condition	Temperature = 309K
Weather File	Cairo Int. Airport

5. FINDINGS AND RESULTS

5.1. Final Design Proposal

Based on the site analysis and the design brief the *Bioclimatic-Zones Concept* was applied first to the whole site. The desired comfort condition for each place in the new AUC Campus was determined. For every colour, shown in Figure 3, a set of detailed design decision in relation to the expected climatic impact was made. For example, there was a need for a shelter belts and wind filtering zone on the north tip. Canopy trees were required around parking places and columnar trees were provided in places adjacent to south-west building facades. The '*cool heart*' was designed in the centre of the project in order to provide a large and comfortable outdoor-space or garden.

Figure 3, Final design proposal after implementing the bioclimatic landscape design strategy

Also the *Walled Gardens Concept* was applied to assure a minimum climatic control in this harsh desert climate. As shown in Figure 3, the urban buildings morphology was used as a wall from the west and a new 6 meter high wall, shown in red, was designed in the east side to guarantee a controlled '*cool heart*'. The '*cool heart'* works as a cool air reservoir that guarantees relatively cooler air in the campus centre. This has been done by distributing water fountains, cascades and surfaces all over the '*cool heart*'. During the summer semester temperature in the campus will mostly exceed $30^{o}C$,

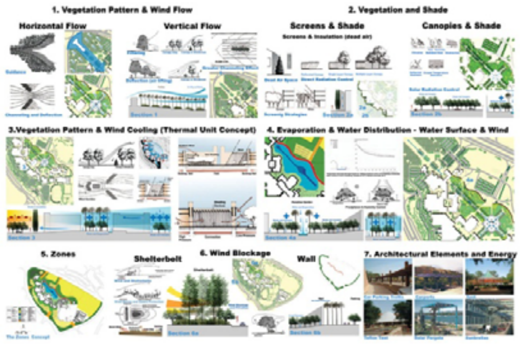

Figure 4, visualisation of the landscape strategies implemented in the design

therefore, the suggested walled garden will allow the green shrubs, water elements and canopy trees to reduce the temperature and raise the wet bulb temperature.

The *Extensive/Intensive Landscape Concept was* applied finally to address the scarcity of water. The intensive landscape strategy was restricted to the '*cool heart*' only and included fruit and shade trees and lush green ground cover. Any landscape treatment outside the '*cool heart*' was considered as an extensive landscape. The extensive landscape strategy included the placement of drought tolerant and indigenous species. The south-west side of the project is surrounded by a shelterbelt to prevent the undesired hot and sandy wind storms as shown in Figure 3. In the north tip of the project, a sort of wind catcher was created through palm grooves. The aim of the palm grooves was to guide and filter and deflect the air up prior reaching the '*cool heart*'. A group of vertical shade screens were located on the south-west facades of the Campus buildings to provide shades. Moreover, a loop road, surrounding the buildings and the parking areas was planted with canopy trees. All implemented design strategies are illustrated in Figure 4. Further details on the final design proposal are available in Annex A.

5.2. Quantitative Measures

Prior to the simulation work some quantitative shading analysis and measurements have been taken. The shading analysis was made in ECOTECT to guarantee that there was an oasis effects created in the '*cool heart*' based on the study findings of Potcher [20]. The analysis showed that more than 50 percent of the '*cool heart*' was shaded through vegetation and almost 80 percent of the ground was covered with vegetation. Obviously, the garden had to be shaded by deciduous trees or designed pergolas that allow winter sun and prevent summer sun. But this percentage of shade together with four water canals seems to lower the air temperature.

Another measure was made using the PET index to calibrate and validate the simulation model. The daily variation of the thermal index was taken during the last week of July 2006, including wet, dry bulb temperatures, wind and relative humidity. A hobo data logger and wind meters were fixed on 1.5 meter height in the '*core heart*' area. Figure 5 represents the measured data.

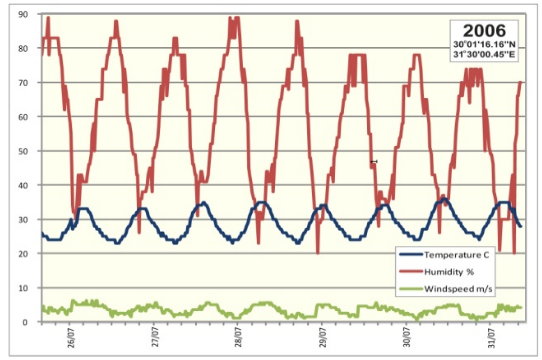

Figure 5, Site measurements for simulation calibration

5.3. Simulation Results

Simulations are reported here, and relevant results obtained from simulations. Figure 6 shows the detailed scheme of the new proposed design. Figure 7 below shows the simulation results. Down the colour scale means hot and up means cold, sowing the temperature value. As shown in Figure 7, the implementation of the bioclimatic landscape design strategy predicts potential temperatures improvements in the 'cool heart'.

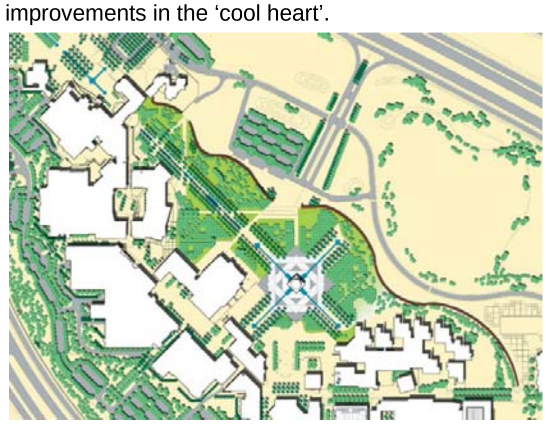

Figure 6, landscape design strategy after implementation

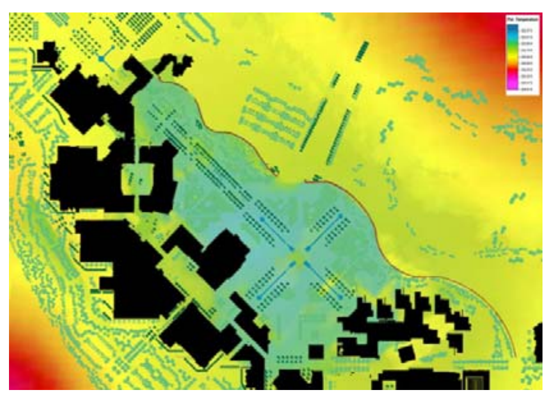

Figure 7, simulation results and temperature differences

Figure 7 shows the benefit of trees to moderate the outdoor environment in a hot and arid climate. The areas were trees were planted direct shade was provided and trees cooled the micro environment through shading of the underlying surface and evaporation.

6. DISCUSSION AND CONCLUSION

The value of much information gathered by this research was limited due to the individuality of the case study that represents the particular site microclimate. Also the suggested design strategy is suggestive and is not based on empirical post-design measurements that allow causative processes to be studied. However, in this study we approached the bioclimatic research agenda from a bioclimatic landscape design and planning approach rather than urban science approach.

From a planning and design viewpoint, we believe that the suggested bioclimatic landscape design strategy simplifies a great deal of non applied scientific data into a coherent design strategy of useful use in the design practice. Figure 7 can be well interpreted by designers and can inform and influence their design decision. This figure shows that complex scientific information can be translated into simple useful design strategy. However, in all cases, quantitative comparisons and measurements of the comfort conditions should be always done after the implementation by the use of the comfort indices.

Of all the design elements available to the designer, vegetation is found to be the most effective and plays a role in surface and air temperature modification. Trees and water elements have the potential to improve the outdoor thermal comfort due to shade and humidity. The combination of shade trees, ground cover and water elements was predictably found to be the most effective landscape strategy. Concerning the water consumption, trees and palms provide the most efficient means to reduce outdoor temperature, while the ground cover and water elements consume greater water quantities.

Finally this study demonstrated through design/planning and simulation the transformation of bioclimatic information into practical applied bioclimatic knowledge. The completed Master thesis should provide a coherent picture of the state of the field and identify where gaps remain.

7. ACKNOWLEDGEMENTS

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8. APPENDIX A:

Supplementary design data associated with this article can be found in the online: http://www.lar.wur.nl/NR/exeres/F9DFC895-9E36-48F2-9070-F1B582276B0D,frameless.htm?NRMODE=Published

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