Applying computational fluid dynamics to evaluate thermal building comfort in Douala, Cameroon

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ABSTRACT: Computational fluid dynamics (CFD) can simultaneously predict airflow, heat transfer and contaminant transportation in and around buildings. In addition, CFD can provide important information to help design energy-efficient, comfortable, and environmentally friendly buildings. This paper demonstrates the roles of CFD in building design for third world countries, showing its typical application in designing a thermally conformable, healthy, and energy-efficient building. Douala features a tropical climate with warm, humid conditions throughout the year. Due to these climate conditions, natural ventilation has been analysed since it can be considered the main way to achieve better thermal comfort and reduce energy usage in buildings. An accurate analysis of the site plan has been made in order to improve outdoor and indoor comfort and increase energy efficiency of the buildings by making use of passive strategies, such as natural ventilation in summer. It is well known that designers must consider the interrelationship between airflow patterns and building design in order to achieve thermal comfort and avoid extreme air movements. Therefore, indoor and outdoor airflows have been modelled simultaneously in order to achieve the best natural ventilation strategy. The use of such methodology does not necessarily mean additional costs in the building's realization and this can be considered an important aspect for developing countries. The purpose of this paper is to develop a building design methodology that supports the optimization of building design in the early stages in countries with severe climate conditions. The authors also discuss the typical areas where CFD can contribute to a successful building design, along with brief comments on the challenges of its application.
Keywords: Africa, developing countries, CFD, environmental comfort, energy balance

DEVELOPING COUNTRIES

The town of Buéa (150,000 inhabitants), the capital of the Southwest province of Cameroon, is a typical small African city. The fast, uncontrolled growth of the nearby city of Douala [1] contrasts with more gradual development in smaller cities, which is based on the progressive increase in the well-being of parts of the population due to the relative political stability and steady agricultural activity represented by endless plantations of banana, tea, and other products. The presence of schools, sports facilities, and a big university makes this town particularly interesting from a cultural point of view. Within this context it is possible to test a design approach that proposes technological and expressive innovations. On the one hand, it moves away from the simple reproduction of formal Western constructive models; on the other hand, it uses an approach that oversteps the size of vernacular typical local buildings, introducing a sustainable methodology not only from the environmental and economic points of view, but also from the language point of view. This approach places the climate and living comfort problems as central themes in defining the shapes and spaces of places and architectures. It brings the technological complexity of air's beneficial effects in the living space to the design simulation (more than one space in the same building), with the belief that this issue can be tackled in a systematic way to reduce energy consumption (and therefore costs) without having to resort to sophisticated technology that has already proved to be unsuccessful. For example, this may refer to the widespread repetition of architectural models typical around the world (buildings with large glass windows and thermally inefficient coatings), whose maintenance and air-conditioning costs become unsustainable, not to mention the difficulty in finding technical staff capable of managing all the life phases of such buildings. Design experiences developed in Africa by African and European architects [2, 3] aim to provide a contemporary architectural language, without losing the identity and traditions of the local construction.

The Buéa project aims to implement this approach, entrusting a significant part of the design process to climate control based on the principles of thermodynamics, with the goal of identifying new effective forms in order to determine greater comfort. The project is set at the entrance to the large town. Here the poverty and lack of services are evident, though signs of growth can be observed at street corners, where modern gas pumps, luxury hotels, and the gates of the university campus become meeting places in a city organized along a large paved axis road. Beyond this, masonry buildings rapidly give way to wood and sheet-metal huts. This mad rush in pursuit of a lifestyle based on duplicated stereotypical patterns of a wealthy appearance, however, leaves behind a large social gap and huge environmental problems. Here, more than elsewhere, the discussion regarding sustainable development is a current issue, with the only difference being that in this case there are no precedents to follow, and there is very poor awareness among the people about the disastrous effects caused by the rest of the world from the industrial age to the present day and of which we are only recently measuring the effects.

PLANNING AND URBAN DESIGN

In contrast to what happens in an urban area, for a case like the city of Buéa, urban design must provide an solution that fits within boundary conditions that are often not well defined or foreseen in an urban plan. Therefore, the first phase of this design process analysed existing elements in their current configuration—resulting from self-government and self-building practices—by selecting choices made by the people in recent years and following the criteria of common sense and suitability of some solutions, even on the small scale. In dealing with the urban theme, the aim was to overcome the traditional view that sees urban planning as a process separate from architectural design. The environmental project stands as a tangle of problems on which a single solution cannot be imposed from the top, but which rather requires different solutions whose equilibrium must be found by comparing the different needs that are revealed. Nevertheless, in a context devoid of any settlement rules, a frame of reference that lays the foundation for the subsequent development of settlements must be set.

Figure 1: Downtown Buéa masterplan.

The project therefore developed within a web of primary infrastructure that takes into account the existing roads and main unpaved streets that play a leading role in the local road network. The scenario that follows is summarised in a conceptual masterplan
(Fig. 1), which highlights the main actions, such as completion of the street paving, sewers, technological networks, the water supply, and public fountains. This kind of intervention is less expensive than private interventions and is more respectful of local traditions; it can be considered a social compromise, since it combines the convenience of having running water at home, with the corresponding loss of the opportunity to bring women together, as in the case of visiting the fountain. Squares and urban green spaces have also been identified, while leaving freedom in the design of building areas. As part of the plan, the Buéa Women Meeting Centre fits on the corner of the main street and the road leading to the university entrance, the heart of the lower town, and will establish the main face of the town entrance as a new architectural landmark.

SOCIAL ARCHITECTURE

The Buéa Women Meeting Centre (WMC) is a public space that includes a cultural centre and facilities designed to improve the status of women, helping them in their town duties as the heads of family management (Fig. 2). The space includes a nursery, toilets, a neighbourhood marketplace, a small parking lot, and a public fountain, where women can easily access a fundamental resource, water, in an orderly manner. Particular attention has been paid to social aspects analysed on-site, and how architecture can solve problems that result.

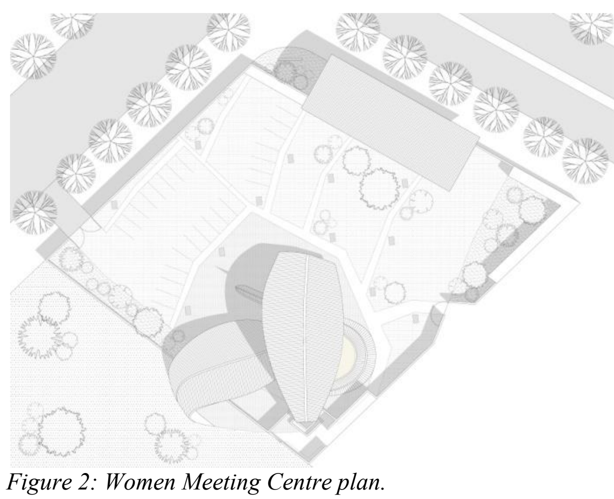

Figure 2: Women Meeting Centre plan.

The lifestyle is characterised by an innate sociability and spirit of sharing that is reflected in the time that people spend outside and on the streets, thus affecting work activities such as restaurant services, street vending, small businesses, and any other activity that mostly involves women. In this context, it is interesting to point out how a natural biological rhythm, which is now lost in countries where the availability of electricity allows people to enjoy the night, increasing safety on the streets, is maintained here (where the streets are in fact very precarious). Another element affecting daily life is the climate, important during the rainy season, when sudden strong storms flood the soil streets, blocking any type of activity.

Architectural design becomes a tool to effectively improve the living conditions and safety of the built environment, so perimeter walls play an important role in the study: the corners are dematerialised and visually open; the walled enclosure is still high but clear. Public facilities have been integrated in the structure, such as the nursery building, the market with fixed tables where girls can work more easily, sheltered from the sun and the harsh weather, the public fountain with seating where people can comfortably wait their turn. Moreover, both the drainage pavement throughout the square and the prevention of dust on pedestrian paths have been fundamental.

The concept of **comfort in the usability of spaces** has been introduced through small but important details. In addition, the WMC includes classrooms for adult vocational training, an auditorium, a hostel for guests at the cultural centre, offices, and a canteen. These other facilities have been specifically requested by the community, in an atmosphere of participative planning, considering the need to provide education to those who are no longer in school or who work during the day. Visiting Buéa, it is possible to understand how the auditorium is instead an urban object, visible at the edges of the main roads or in the public garden; it stands as a platform covered with a light shade structure, useful for recurring public events, religious celebrations, or graduation sessions. As such, its exclusive use, even in case of rain, its fixed seats, and the possibility of hosting personalities invited to conferences, becomes a source of pride for the cultural centre. Traditionally, any celebration or meeting ends with a small buffet so it is useful to have a café to accommodate guests.

BUÉA CLIMATE AND THERMAL COMFORT

Buéa is a town on the slopes of Mount Cameroon, an active volcano that rises 4000 m above sea level, 400 km north of the equator and 15 km from the Atlantic Ocean, which significantly affects the local climate, already perceived to be cooler and less humid at an altitude of 800 m. All of these aspects lead to an average rainfall typical of the tropical climate in the Gulf of Guinea, up to 5000 mm/m^2 per year, with the peculiarity of air flows from the SSW, thanks to protection by the mountain to the north. Therefore, the year consists of the rainy season, between April and September, and the dry season, from October to March, with a peak solar radiation of 6200 W/m^2. Therefore, the climate in Buéa tends to be humid and hot in the lower neighborhoods (Fig. 3, Fig. 4).

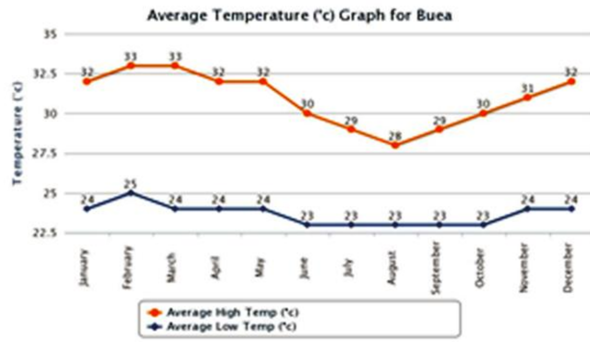

Figure 3: Plot of average temperature (°C) in Buéa.

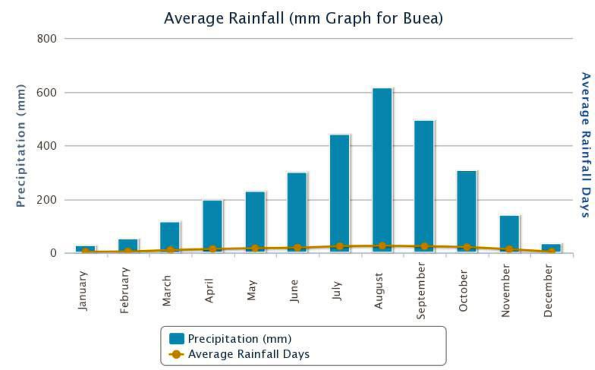

Figure 4: Graph of average rainfall (mm) in Buéa.

The specific objectives in the study are to evaluate and characterize the thermal perception of occupants in some areas, using the predicted mean vote and predicted percent of dissatisfied. The most widely used thermal comfort index is the predicted mean vote (PMV) index, which was developed by Fanger [4]. Fanger states that two conditions must be achieved to maintain thermal comfort. The first is the combination of skin temperature and the body's core temperature, which provides a sensation of thermal neutrality. The second is the realization of the body's energy balance, which is based on the conservation of energy.

The values of the PMV index range from -3 to +3, which corresponds to the occupant's feeling, from cold to hot, while the PMV null value represents a neutral sensation. The thermal stress established by the PMV is based on the steady state of heat transfer between the body and the environment. It is an empirical equation used to evaluate the mean vote on a rating scale of thermal comfort for a large population of people. To develop a curve and obtain average results, people were exposed to different environments over different timespans. The term PPD represents the predicted percentage of people dissatisfied at each PMV. Moving away from zero in either the positive or negative direction, the value of PPD increases. A curve has been developed to predict the percentage of people dissatisfied as a function of Predicted Mean Vote (Fig. 5).

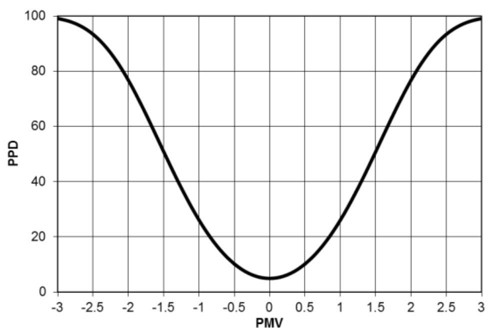

Figure 5: Predicted Percentage of Dissatisfied (PPD) as a function of Predicted Mean Vote (PMV).

ENVIRONMENT AND SHAPE

As mentioned above, the outdoor lifestyle, characterised by an original biorhythm and relationship with nature, is definitely the best assumption when designing a building according to the principles of meteorological architecture [5] and biomimicry. When studied closely, the large leaves of the banana tree, an abundant local crop, are seen to perform all of the functions required of a roof. Changing the scale of the natural element and working with its flexibility, it can be transformed into an architectural element, where the main rib becomes a central compluvium and the blade lends itself to protection, shade, and shelter from the rain. The combination of three 3D elements and a 2D element on the ground make up the typical tree trunk section, ideally recalling the function of a lifeblood highway, but in reverse, i.e., no longer from roots to leaves, but as a collector of water gathered from them. This function can easily be detected from the square as well, so the water tower also functions as a reference point for the public fountain.

The space below the three cover leaves, which hosts the classrooms, the auditorium, the canteen and the toilets, is a limited, but not closed, environment, in which the functions are organised in a systematic way, allowing air (Fig. 6) and light to permeate the space naturally. The dynamic shape outlined above not only performs formal tasks, but also follows a more careful design based on the study of climate aspects that characterise the place.

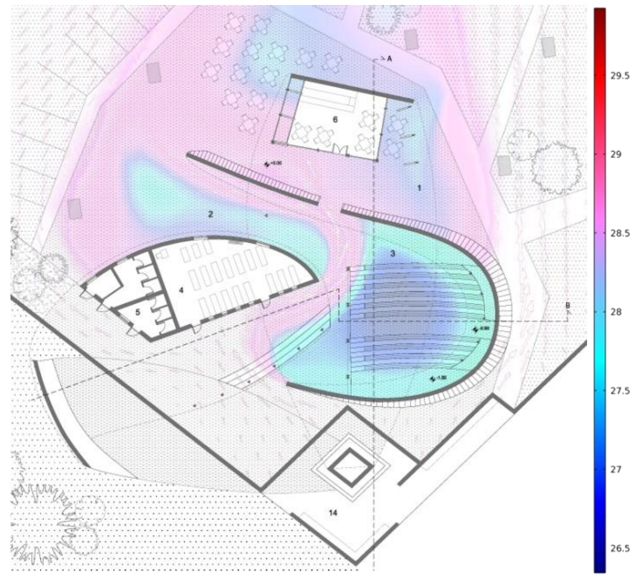

Figure 6: Pavilion tomography: temperature and velocity fields.

From the analysis of data collected during a three-month campaign in 2012 as well as time-series data from 1970 to 2000, it was possible to create a psychometric chart and a model of **adaptive design comfort** in relation to interviews conducted among inhabitants. It is important to stress that the model generated from purely environmental data is inconsistent with the adaptive model (Fig. 7), i.e., a project based solely on data analysis would lead to discomfort tending too much towards the cold side for a population accustomed to a tropical climate.

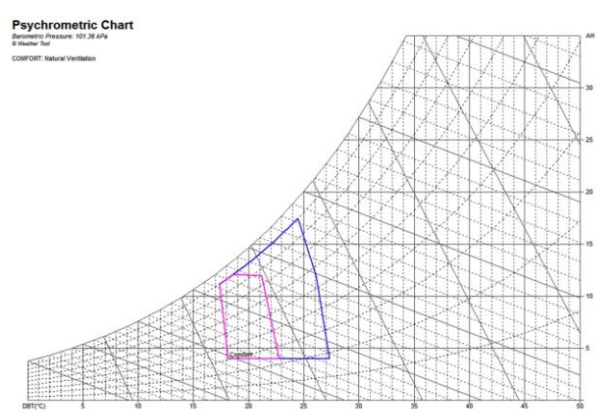

Figure 7: Data results and adaptive comfort.

Based on these observations, modelling of the pavilion was performed by applying the principles of computational fluid dynamics (CFD), which allowed for drafting and better orientation of the three elements making up the large roof: the main sail that hangs over the auditorium and canteen, the canopy that covers the multifunctional classroom and toilets, and the structure that surrounds and separates the auditorium from the entrance.

The resulting body, oriented towards the south and extending to the west, captures the prevailing winds above the fence and steers them towards the hypogeum hall where, due to the chimney effect, they are expelled through the opening on the roof between the two main leaves. This organic architecture is nothing more than a blower with extraction-flow systems based on passive technologies. During short, strong rainstorms, the opening that triggers the ventilation may be shielded with a waterproof fabric that decreases the ascending action without blocking it completely. The same happens for natural light percolating through the device. In the auditorium, where there is a greater concentration of people, cooling is implemented by a passive geothermal heat exchanger of 40 m^2, buried in the garden, which brings in cold air from the vents embedded on the floor. A system of buffer rooms on the perimeter of the central hall guarantees a temperature about 4 K lower than the external temperature

MATERIALS AND TECHNOLOGIES

The opportunity to travel to Cameroon was an important occasion to learn about traditional architecture and the Chefferie—still the centre of legislative and judicial power in small villages spread out in the rainforest—and to observe an ancient, original, and completely sustainable relationship between man and nature. Over the years, these powerful geometric constructions remained unchanged in form and technology, except for the replacement of straw roofs with metal sheets as a result of modern restoration work; the use of bamboo, a unique building material, is widespread and used in various forms, such as column, rods, and wires. Passive systems ensuring living comfort are part of the technical-cultural heritage of these populations. Over the centuries they have develpped "low-tech" solutions in order to fight the severe climate of these areas, but this has become drowned more recently in the concrete building traditions that would be considered "sustainable" today. For the design of the Women Meeting Centre, this consideration has proved to be an ~~design~~ inspiration and, at the same time, the recovery of traditional construction knowledge was desired. All of this resulted in a dry-assembled (Fig. 8) mesh made entirely of bamboo pipes, an economic, natural, local resource; metal sheets were chosen for roofing and cladding, which were thermally and acoustically insulated with coconut fiber (50-mm thickness, λ = 0.045 W/mK) in order to give a modern style and, in particular, to encourage one of the few thriving local

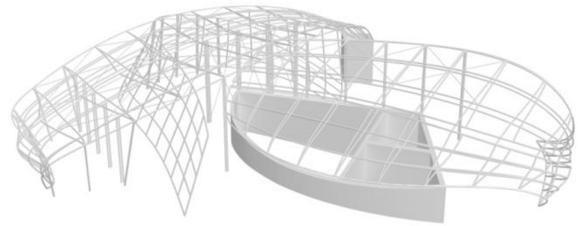

Figure 8: Bamboo structural shape.

industries. The demand for electricity was met with a photovoltaic plant of 3.5 kWp composed of modules placed on supports in the park; it includes protection from the sun. The overall energy balance is met by collecting rainwater in buried tanks with a capacity of 40,000 L, and cooling the pavilion with a geothermal heat exchanger in addition to the passive ventilation system described above. At the same time, **outdoor comfort** has also been satisfied by planting trees, mainly *Mangifera indica*, which can grow up to 20-35 metres in the tropical climate with a canopy that can reach up to 10 meters in diameter, providing good shade on pedestrian paths. Other widely used plants were *Cymbopogon citratus* and *C. nardus*, which produce a natural mosquito repellent, necessary in a place where malaria is still not controlled. A system of constructed wetlands for disposal of greywater was also planned for the garden.

RESULTS

The use of parametric CFD software allowed the modeling phases to be combined with the verification phases through a method of continuous computational analysis and adjustment of the solutions adopted. The effective validation of data extrapolated from the tomographies was instead undertaken with algorithms that follow Fanger's theory, i.e., calculating the PMV (Predicted Mean Vote) and the PPD (Predicted Percentage of Dissatisfied). Based on non-isothermal flow and heat transfer in solids and definite boundary conditions according to the representative day [6], defined as $U_0 = 3$ m/s $T_0 = 303$ K RH = 84%, it was possible to work on 3D models that reestablish the modification trends in real time. It is helpful, therefore, to size the three leaves that define the rainwater collector, (Fig. 6), correctly position the building apertures, verify the operation of the extraction chimney, and more generally, control air fluxes triggered by the building, generally being careful to avoid significant turbulence that could worsen living comfort. For this, a masimum limit of 3 m/s was set for internal fluxes, along with a minimum of 299 K for the auditorium temperature, as defined in the psychometric diagram of the project.

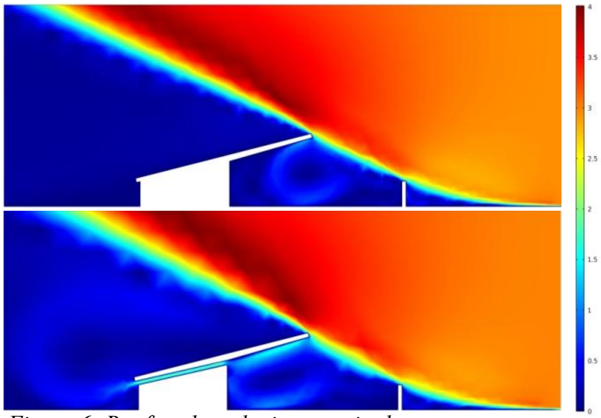

Figure 6: Roof study, velocity magnitude.

In addition, the success of such a bioclimate design was verified by calculating the PMV and PPD thermal comfort indices. The values calculated with Fanger's algorithm, as shown in Table 1, indicate the good thermohydrometric comfort conditions obtained from such a design, especially in the WMC.

Table 1: PMV Validation- Women Meeting Centre Buéa – (T: temperature, V: wind velocity, RH: relative humidity, PMV: Predicted Mean Vote, PPD: Predicted Percentage of Dissatisfied).

Place	T	V	RH	PMV	PPD
WMC/seats	26.3	0.12	84	0.00	5.00
WMC/steps	27.7	0.41	84	0.82	19.32
WMC/entrance	29.6	3.28	84	0.28	6.67
Bar/entrance	28.6	0.06	84	1.48	50.13
Bar/arcade	28.1	0.01	84	1.52	52.16
Aule/steps	29.8	0.44	84	1.58	55.78
Outdoor paths	29.8	1.83	84	1.03	27.81

CONCLUSIONS

This paper introduced the applications of CFD for building design in third world countries, e.g., Buéa, Cameroon. CFD can provide important information to assist in the design of energy-efficient, user-comfortable, and environmentally friendly buildings. It discussed the typical aspects that CFD can contribute to a successful building design, along with validation of thermal comfort reached using Fanger's indices (PPD and PMV).

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