REGIONAL HOSPITALS IN HUMID TROPICAL CLIMATE - GUIDELINES FOR SUSTAINABLE DESIGN

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Abstract: Developing countries are facing numerous challenges in the process of providing adequate health care to often deprived and diminished social groups. Being a country made up of a mainland territory and five islands in Gulf of Guinea, almost entirely covered by tropical rainforest, with poor road infrastructure, Equatorial Guinea is a showcase of various obstructions in developing effective health care system.

The paper explores guidelines for creation of model regional hospital, commissioned by Ministry of Health and Social Welfare, with the aim of achieving high level of replicability through minor program and site-specific adjustments. The demonstrated strategies are applied on a local hospital designed to provide all basic types of health services while retaining a high level of technical independence. The architectural concept was formulated aiming to maximize the use of natural ventilation, daylight and rainwater management, leaving the operation block, laboratory and intensive care unit practically the only parts of the structure that would need mechanical air conditioning. The potential and effectiveness of use of photovoltaic units in enhancing hospital's resilience through on-site energy production was explored. The structure was designed having in mind local climate, culture and customs, thus offering a possibility of strong integration with local community. The building technology was thought over to enable efficient and cost-effective construction and proper resilience for tropical rainforest environment. The result is a structure providing for contemporary, high quality medical service, interpreting local climatic and cultural contextual premises through modern architectural expression.

Key words*: sustainable architecture; climate; health care; resilient hospitals; efficiency; photovoltaic application*

1. Introduction

Developing countries are facing numerous challenges related to providing adequate health care to all social groups. World Health Organization (WHO) data for Equatorial Guinea show that on average 53% of population has access to sanitation and 43% to potable water and electricity [1] with life expectancy of only 46 years [2]. Insufficient personal, professional, financial and pharmaceutical support constitutes some of the key healthcare issues. With only 0.25 physicians per 1000 population [3], Equatorial Guinea belongs to the most stressed countries globally.

Health care system has been organized at four levels: health posts (basic service, usually just one person), local health centres (small institutions with several staff performing counselling, checkups, emergency treatments and simple analysis), district level hospitals (various in size and composition: policlinic and stationary parts providing wider scope of checkups, laboratory, surgical block, maternity etc.) and two main health centres (large scale with all services). According to the WHO, currently there are 18 public hospitals (2 regional), 42 centers for public health and 161 medical posts, but they are not all functional [1], [4]. Scientific interest related to the healthcare system in Equatorial Guinea has been focused mainly on the investigation of most common diseases, mortality causes, life expectancy etc. but there are no studies that are examining the qualitative aspects of the system [5].

Basic postulates for the development of the concept were derived from the experience of visiting a local hospital near Lambarene in Gabon (Established in 1913 by Albert Schweitzer, the Nobel Prize laureate, and in operation ever since). It successfully integrates local building tradition with western medical approaches and proves the principle of cross-cultural partnership to be a valid one. Developing social dimension has proven to be very important factor in improving healthcare services [6], and it is even more so in sensitive and underdeveloped communities [7]. The main goal of the research was to establish design guidelines and applicable proposals that would result in a modern, self-sustained structure that can adapt to different program, various location specificities and that could be easily managed by the local workforce.

2. Methodology

Issues of sustainability and resilience were considered as the starting point in the process of formulation of design guidelines. Starting from high level of technical independency, environmental and societal components, as well as affordability and longevity of proposed solutions were also targeted throughout the process. Design approach was based on bioclimatic architecture [8], integration of passive measures and the use of renewable energy sources. Furthermore, the spatial modifications of typical hospital layout elements were considered, in order to make them more acceptable for patients and their accompanying persons. Finally, in addition to choosing building materials and technologies already available at the local market, more durable and less demanding in terms of operation and maintenance products were favored in order to provide longer life-span, reduced running costs and minimized demand for specialized work force throughout building's life cycle.

The method was developed following the research process that included several steps:

- Identification and analysis of local conditions – establishing the design context,
- Identification and analysis of relevant passive and active measures and exploring adjustments and upgrades of general principles – establishing design strategies,
- Application of design strategies on a specific program of a typical mid-size healthcare facility,
- Discussion of resulting design in context of sustainability, resilience and WHO's Hospital Safety Index parameter.

2.1. Design context

The design context was established taking into consideration local climate, socio-cultural context, available infrastructure, institutional healthcare organization and capacity as well as locally available resources.

The climate in Equatorial Guinea is predominantly tropical-monsoon (*Am* by Köppen Climate Classification System) and tropical-wet (*Af* by Köppen Climate Classification System) [9]. This means that the temperatures and the relative humidity are rather constant throughout the year: averaging around 25°C, with min. temperature never below 19-20°C (annual: 21°C) and maximum temperature never above 31-32°C (annual: 30°C). The precipitation level is high with some minor seasonal variations. Being close to the Equator, the number of daylight hours is approximately 12 throughout the year, but regular clouds reduce the number of sunlight hours to 3-5 per day. Low wind speeds with the daily mean 2-3m/s [10] are also typical for this area.

Good bioclimatic design should, therefore, provide adequate thermal comfort relying on basic passive design strategies [8], [11], [12], answering the main challenge of protecting buildings from overheating and enabling easy cooling when needed [12], [13]. Minimization of HVAC systems through introduction of natural ventilation has been proved to be a valid strategy [14], [15] especially in the developing countries where people are used to slightly higher temperature levels.

Very high precipitation rates have strong influence on architectural design in terms of form, materials and rainwater management. Since the infrastructure is poor, rainwater collection would provide for higher level of independence.

Specific parameter of design context has been represented through the local customs and culture where it is quite common for family members to accompany patient for consultations, check-ups, and stay with them even while hospitalized. For this reason, special attention has to be dedicated to accommodating different functional parts, especially waiting rooms and common areas where visitors can stay with the patient.

2.2. Design strategies

Design strategies are derived mainly from the bioclimatic principles, emphasizing no-cost or low-cost design features. Technical systems were proposed having in mind limitations of infrastructure and available maintenance options.

2.2.1 Site plan

In the given climate conditions characterized by extensive sun exposure and precipitation in particular, the main design strategies for site planning should minimize paved surfaces in order to prevent overheating and rainwater runoff while maximizing rainwater infiltrations through green areas. Applicable design guidelines and quantification methods can be found in following LEED credits:

- Rainwater management (Intent: “To reduce runoff volume and improve water quality by replicating the natural hydrology and water balance of the site, based on historical conditions and undeveloped ecosystems in the region”) [16], [17].
- Heat island reduction (Intent: “To minimize effects on microclimates and human and wildlife habitats by reducing heat islands”) [16], [17].

In addition to improving social dimension of healthcare, as recognized in [6], [7] some guidelines from LEED certification system for healthcare can also be useful:

- Places of respite (Intent: “To provide patients, staff, and visitors with the health benefits of the natural environment by creating outdoor places of respite on the healthcare campus” [16]
- Direct exterior access (Intent: “To provide patients and staff with the health benefits associated with direct access to the natural environment”) [16].

Landscaping design could also help enhancement of the effects of passive measures; vegetation could provide additional shading of paved areas, or vegetated screens adjunct to building’s volume to generate cross-ventilation [11], [13].

All proposed design strategies could be treated as no-cost or low-cost design solutions since they do not impose additional financial burden.

2.2.2 Massing

Proper building massing is a prerequisite design measure for achieving adequate natural ventilation in hot humid climates [11], [13], [18], [19]. Structure has to be designed as a non-compact one, with minimal exposed thermal envelope area, and at the same time it has to be very “porous” enabling “comfort ventilation” [19]. Fig. 1 shows the development of the scheme illustrating the relation between massing and basic functional groups of a mid-size hospital. Typical compact form (Fig. 1a) composed of the functional spaces (white) and corridors (yellow) can be “interrupted” with open spaces -marked grey (Fig. 1b). By division and separation of primary volume (Fig. 1b,c) a surface to volume area as well as cross ventilation potential is increased. In this way, functional groups of a hospital which are commonly organized within the compact building volume and distributed vertically (at different floors) are “broken” into separate wings either inter-connected by open-covered corridors or free standing, depending on functional and organizational structure of the healthcare institution. Each wing is functionally independent, visually recognizable and, at the same time, easier for the direct patient access and control. Structure becomes, in a way, a complex whose layout can be easily adopted to any site.

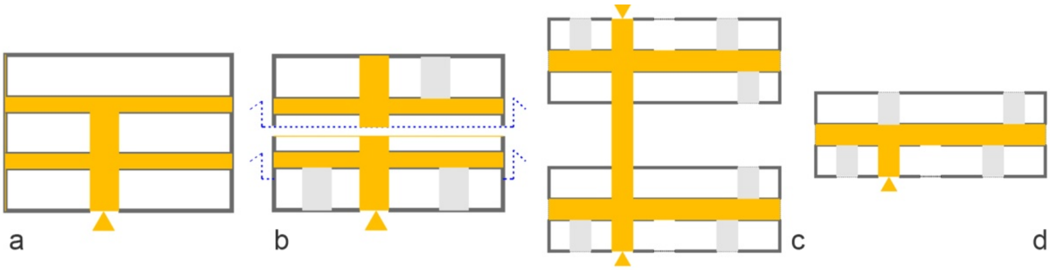

Figure 1. Massing options: a) conventional layout, compact building form; b) inserted “open” spaces (marked grey, adjunct to the main corridor) – separation of the primary mass; c), d) separated wings, enabling cross-ventilation - c) connected wings, d) single free-standing structure

Due to the hospitals’ specific sanitary and healthcare procedures, requirements regarding comfort and its controllability vary and the the proposed massing principle is not of the same relevance for all functional groups. For public areas and waiting rooms in general admissions and regular check-ups, lower level of technical controllability is allowed, passive measures are prevailing for conditioning and massing should be designed following the principles stated above. For the most demanding spaces such as surgery unit, special care unit, laboratories etc. retaining high level of technical controllability is imperative. For such program groups, the massing should prioritize energy efficiency to ensure secure functioning in all conditions, thus contributing to the resilience of the hospital.

2.2.3 Ventilation and moisture control

Basic modification of the building form starts with detaching the building from the ground. This common design strategy [13] is providing the needed airflow preventing excess moisture; detaching the roof further enhances the airflow around the main volume (Fig. 2a-b). Proper sizing and placement of windows [20], [21] fosters effective ventilation (Fig. 2c), covering all aspects of Givoni's "comfort ventilation" [19]. Finally, more elaborated design includes introduction of exhausts into intermediate spaces (detached roof voids etc.) and addition of external permeable envelope. These "intermediate" spaces are not conditioned as internal (enclosed) spaces but have more favorable comfort conditions compared to those on the outside (Fig. 2d).

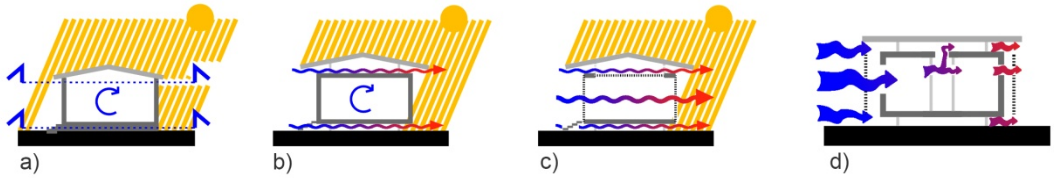

Figure 2. Natural ventilation - generative process of design strategies: a) conventional layout; b) structure detached from the ground and detached roof, overhangs providing solar protection and reducing surface temperature of thermal envelope; c) openings and voids for cross-ventilation; d) additional exhaust and external shading, further protecting enclosing walls from overheating.

2.2.4 Thermal comfort

In hot humid climate passive strategies for thermal comfort mainly rely on ventilation and moisture control as well as to proper massing [11], [12], [13], [18]. Prevention of overheating of the façade and ventilation of the sub-roof spaces are preconditions for minimizing the need for mechanical systems. As the sensitivity of different functional groups may vary, ventilation and moisture control have to be supported by proper technical systems, but prevention of overheating retains the same importance for all functional groups - either as a contribution to integrative passive measures or to mitigate energy needed for conditioning [15].

2.2.5 Daylighting and Sun control

Daylighting and Sun control do not contribute exclusively to energy efficiency through reduced operating hours of electrical systems, but they also contribute to improved conditions for patients fostering the recovery process [22]. Simple measures such as proper placement and sizing of windows, coupled with adequate shading, contribute to both aspects.

Dominant strategy was to use the building form as the controlling mechanism and to avoid any sophisticated technical solutions that are in need of expert maintenance (Fig. 2).

2.2.6 Rainwater management

Design features and technical equipment for rainwater collection and purification are in most cases crucial for provision of proper sanitary conditions. Proposed design allows for proper water collection and storage as well as implementation of available systems [23], [24] but further research regarding the technology and needed capacity is required.

2.2.7 Materials and building technology

Rainforests offer some of the most noble and durable construction wood. Yet, in countries like Equatorial Guinea, wood is not appreciated as a contemporary building material, especially for public buildings [25]. Despite the abundance of this resource, there are only a few processing facilities - tropical wood is exported as timber or applied in simple way in the form of sidings. Clay is scarce, leaving concrete and concrete hollow blocks as the main construction material. Construction steel can be used as well, but one should keep in mind the necessity of skilled workforces and engineering needed for steel construction. For these reasons, the structure for the proposed hospital is designed as a combination of massive bearing walls and low-tech steel roof construction.

Finishings need to be chosen having in mind extremely high relative humidity and heavy rain falls, coupled with often-troublesome maintenance. Therefore, durable, low-maintenance finishings should be considered: ceramic tiles, composite aluminium panels, sheet metal etc. Previous experiences on other projects developed in the same climate have proven this kind of finishings to be adequate for these specific conditions.

2.2.8 Renewable energy

In context of climate, infrastructure and available technologies, integration of renewable energy sources (RES) is practically inevitable if sustainability and resilience are recognized as design prerequisites. Connection of consumers to the electricity power system is often not possible and the construction of photovoltaic (PV) system is the most economical solution for the electrification of the consumers [26], [27]. Equatorial Guinea has an excellent geographical position considering the potential of solar irradiation, partially reduced due to the climatic conditions.

The latitude of all possible locations for local hospitals in the country is between 0.9° and 2.3°N so, the theoretical optimal angle for the application of PV in term of direct irradiation would be around 1.6°. On the other hand, diffuse radiation is maximal for the horizontal PV system. So, unlike in other latitudes, the tilt angle of 0° maximizes both direct and diffuse radiation regardless the orientation. [28].

3. Results

3.1. Proposed design for typical hospital

Program for the project consists of primary health care unit (consultations and basic checkups) with examination rooms (Wing A, Fig. 3), laboratory (Wing B, Fig.3), maternity and surgery wards (Wing C, Fig. 3), and stationary patient and staff rooms located on the first floor.

All functional parts have been designed as separate elements, grouped in several cubic buildings, connected together by the elliptic based volume serving as a centre of the architectural composition.

Form of the complex, as illustrated on Fig. 3, allows for independent usage and access (segregation of the patients), as well as multi-phased construction process.

Subdivision of program through construction of separate buildings (wings) formulated by identical design principle allows for accommodation of different size units, ranging from local healthcare units to larger hospitals, keeping the recognizable architectural language that can be symbolically identified with the primary function. In this way, the proposed design can be considered as a model, setting the ground for different developments.

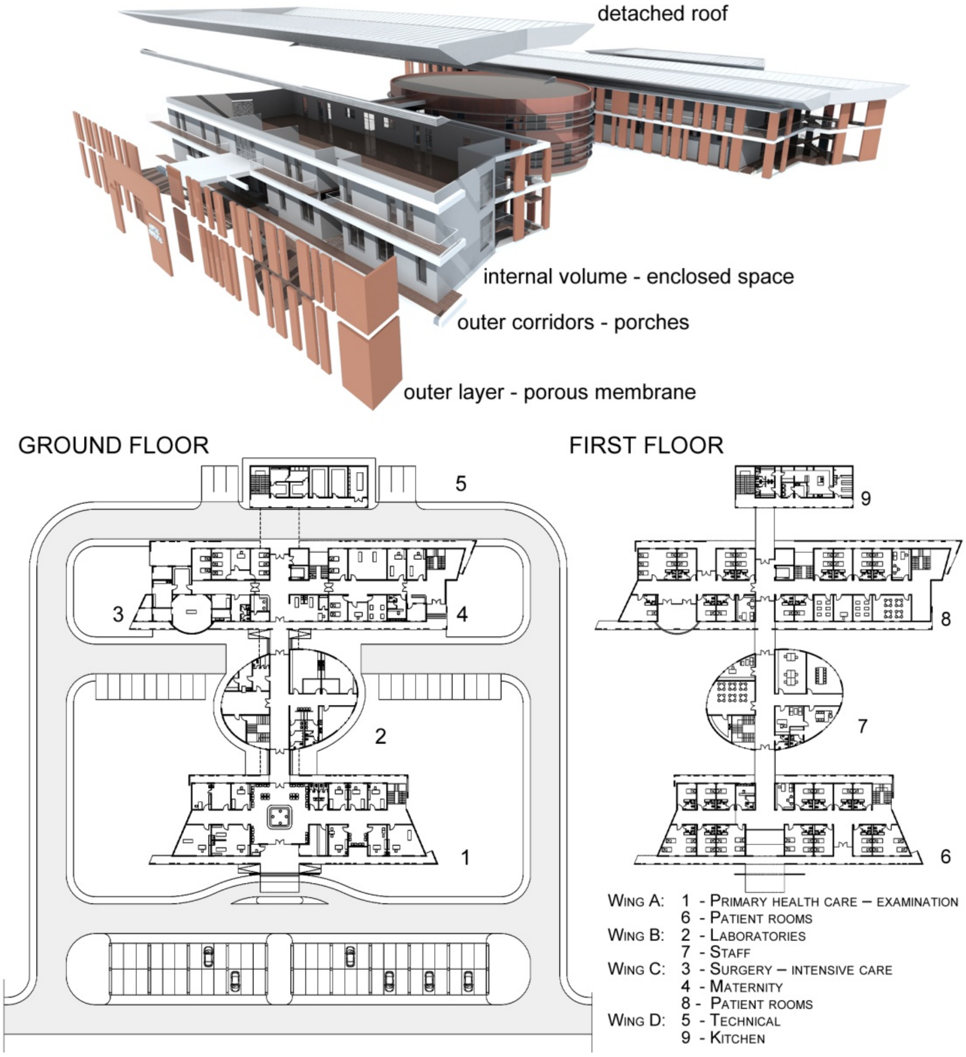

Figure 3 "Exploded perspective" of the Hospital building (top) and floor plans (bottom)

3.2. Passive measures: ventilation, moisture control, thermal comfort, daylighting and sun control, rain water management, materials and building technology

In order to provide for natural ventilation, the building was composed of several volumes arranged in parallel manner, with enclosed intermediate green areas. Layout and placement of primary composition (wings A, B, C) allows for creative application of vegetation in the form of screens or barriers in order to enhance difference in pressure and maximize cross ventilation [13]. External corridors are practically open, enclosed only by mosquito nets in the form of sliding panels. They are, through the voids in internal volume - waiting rooms, connected to the internal corridors, enabling the cross ventilation. For this reason, doors and windows are equipped with the “grille” systems that can be, if needed, efficiently closed.

Building is composed of three major condition areas:

- Spaces with no mechanical systems for air conditioning (public areas, waiting rooms, corridors and porches) - entirely naturally ventilated
- Spaces with basic air conditioning (examination rooms and patient rooms) - designed to function relying on passive design measures, and equipped with basic air conditioning systems.
- Spaces with permanent air conditioning systems (surgery unit, intensive care unit, laboratories) - require steady conditions (temperature, humidity, airflow etc.) and adequate air sanitary levels, so all necessary mechanical systems have to be permanently available

The large roof has been designed detached from the mass of the buildings and has been separated from the main volume by cross-ventilated area.

Building concept is based on segregation of thermal mass by creation of porous external envelope composed of the alternating wall parts and voids and massive internal sections. By applying the concept of two outer layers, it was possible to create different thermal building zones: internal enclosed zone (which can be, if necessary, easily conditioned) and outer, semi-enclosed zone, that reinterprets the traditional porch covered by the roof with large overhangs preventing from overheating. Use of light-coloured, cool pavement materials with higher solar reflectance index (SRI), as suggested in the design proposal (recommended SRI of minimum 30), further mitigates the heat loads [29].

Double-layered outer facade with external corridors and large roof overhang were designed to provide sufficient shading, while retaining large glazed surfaces on inner envelope. Fixed horizontal Sun louvers systems were only applied in central oval area that has standard flat roof without overhangs.

One of the main components of the design - the large roof - has been used for protection from heavy rainfall as well as for rainwater collection. Storage has been placed in the technical area between the roof and upper level, making the use of the collected water possible just by gravitational flow. By implementation of adequate filtering and surplus water evacuation, design has incorporated rainwater management, in the form of technical water for flushing and cleaning purposes, as one of the main strategies.

Building size, form and construction technology have been adjusted to the local potential, which is rather modest, so planned construction process does not require sophisticated machinery or skills and can be executed with available workforce after basic onsite training.

Use of wood was, for the sake of easy maintenance, restricted only to the elements that are intended for internal use and that could be produced locally.

4. Discussion

Developed architectural concept serves as the ground for implementation of various RES principles and technologies. In the process of development of the model it has been estimated that many of the available technological solutions are not applicable in this phase mainly due to the need for engagement of highly qualified personnel or intensive maintenance. Therefore, focus has been on the implementation of the PV system as one of the widely used technologies with proven performance. At the same time, validity of the model has been tested using Infrastructure, resilience and hospital safety index (HSI).

4.1. Calculations of estimated energy production using PV systems

The solar potential calculation, as well as the possible energy production for the target location, was calculated using PVGIS (Photovoltaic Geographical Information System) software developed by European Commission and Institute for Energy and Transport [30]. The results are shown as monthly or annual solar potential for specific PV system, orientation and mounting angle.

The hospital complex consists of 4 Wings, with total (usable) roof area of 2100 m^2 potentially available for application of PV systems having in mind building's specific geometry. It was assumed that 85% of the stated area is covered with PV system, and that the efficiency of the conversion of solar energy into electricity is 18%, which is the common value for the modern monocrystalline silicon solar cells. Designed installed capacity on the building is approx. 321 kWp. Equipping of the parking shading structures with the same PV system could significantly contribute to on-site energy production with additional 142 kWp, increasing the installed capacity of the whole PV system to 463 kWp. Monthly production from all PV systems (Wing A, Wing B, Wing C, Wing D and parking places) is shown in Fig.4.

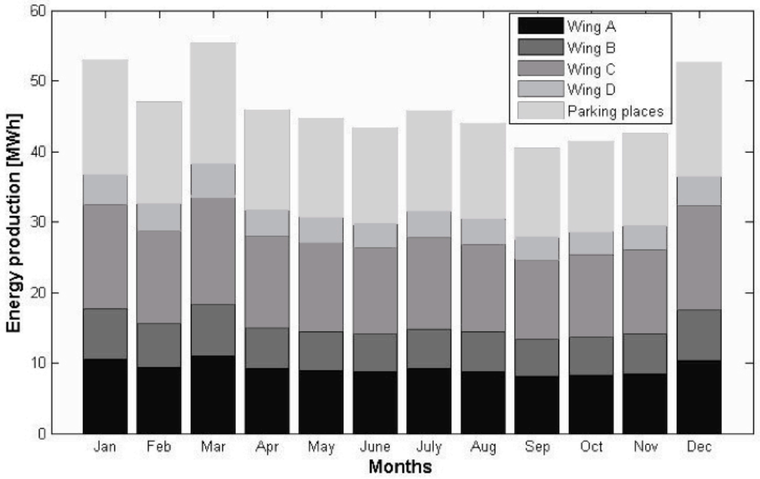

Figure 4 Production of the PV system for proposed regional hospital; location data for Malabo, Equatorial Guinea

Total production of the proposed PV system is 555 MWh, which means that capacity factor of the system is CF = 13.69%. This is the average capacity factor globally, so it can be concluded that the cloudy sky significantly reduces expected production from PV system. On the other hand, the production from PV system is almost constant throughout the year, so it can be considered as the stable source of the electricity.

4.2. Infrastructure, resilience and hospital safety index (HSI)

The development has been planned as a self-sufficient complex, so all needed infrastructure should be provided on site. For this reason, a separate technical building designated to electrical generation (batteries and additional generator) and water supply (water tanks) has been designed in order to provide stable support for all hospital's facilities.

Designed as a local healthcare centre, often in remote areas, the analyzed hospital stresses the importance of resilience of such facilities, not only in extreme situations, but in day-to-day operation. Emphasizing the climate-responsive design may be crucial, but is not the sole component of the hospital's resilience. Other sustainability-related issues addressed through this design also contribute to hospital's capability to cope with potential upsets:

- Involving the local community into construction process shifts the perception of the institution and its services, while implementation of simple building techniques enables quicker recovery of the facility. During the design stage contacts with several local healthcare officers were established and their opinion has been categorized and used as the weighing factor in the evaluation process.
- Diversification of spatial and operational regimes allows for securing high level of sanitary conditions even in extreme situations, since less demanding units can function with minimal energy consumption, while the on-site produced energy can be used efficiently for surgery and intensive care units, enhancing functional capabilities in the state of emergency.

Hospital Safety Index (HSI) is a tool aimed to help health authorities to gauge the overall level of safety of a hospital or heath facility in emergency situations [31]. It addresses the hazards related to geographical position and geotechnical properties of the soil, structural and non-structural aspects, as well as various functional aspects.

Regarding the Structural aspects of HSI, the applied hospital design (materials and building technology would contribute positively to the evaluation of "*Degree of safety related to structural system and type of materials*", where structural systems and materials and corresponding building technology were stated as a favorable solution [31].

Regarding the Non-structural aspects of HSI, the proposed design addresses the following categories [32], [33]:

- "Lifelines" - Electrical system, Telecommunications systems, Water supply system and Storm drainage system
- Heating, ventilation, air conditioning (HVAC) and/or hot water
- Architectural components

From the group of functional aspects, the proposed design approach contributes to the category "Plans for preventive maintenance and repair of critical services" [32].

While the scope of issues addressed through HSI is universal and endorsed by World Health Organization, the evaluation tool is "calibrated" primarily for Central America and cannot be directly applied to other regions, but stated observations, recommendations and design guidelines are enhancing the level of sustainability. In the design process, HSI was used as the verification tool for developed solutions.

5. Conclusions

Quest for sustainable design of a local hospital in challenging environment, requires "reading" and learning from local customs, building principles and construction logic but, at the same time, implementation of contemporary architectural language, technology and materials.

Model hospital building has been developed having in mind specific design context and defined design strategies, which fostered combination of low-tech bioclimatic strategies with latest high-tech solutions thus enabling sufficient resilience of the structure. Hierarchy of hospital functional groups regarding desired level of controllability of comfort parameters and respective technical independency was established enabling the implementation of passive strategies in environmentally less demanding areas and high efficient building and equipment solutions in technologically and sanitary demanding zones. Longevity of the applied materials, simplicity of construction solutions combined with low maintenance characteristics have also been evaluated and included in the design. Finally, the effects of use of PV systems on reference design have shown that significant amount of energy can be generated this way. Some roof area may also be allocated to solar thermal collectors for sanitary hot water preparation.

Developed model has been tested on real site location, in design phase, incorporating all functional programme elements and fulfilling the desired technological needs and standards. Development of the hospital model has also been envisioned as the learning ground (showcase) for the construction as well as management and maintenance activities that will educate future staff providing sustainability and replicability of the procedure.

The synergy of tradition and modernity under the carefully defined process can provide an adequate answer to many of the challenges that are arising from the complex relationship between demanding hospital standards and local environment, resulting in recognizable and tailorable model building that can adapt to various programs and locations.

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