Designing Health Structure in Emergency Contexts. Natural Ventilation as Response to COVID-19 Pandemic.

Natural Ventilation as Sustainable Response to Covid-19:
Designing an Airborne Disease Treatment Centre in Burkina Faso

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ABSTRACT: Climate, pandemic and energy have often shaped and characterised the transformations of our built environment. Today, under the current pandemic conditions, we are witnessing the ability (or not) of the built environment in responding to such emergency through changes and adaptation. Among many approaches to such changes and emergencies, we are presenting the idea of relying on passive design as a medium to manage and prevent pandemic events. In particular, this paper will focus on the tight relation between natural ventilation and architectural design as a sustainable response to Covid-19. To do so, the work focus on the design of a Severe Acute Respiratory Infection (SARI) Treatment Centre in Dori, Burkina Faso, in collaboration with an International humanitarian Institution. This experience shows the ability of passive design and natural ventilation to deliver a sustainable and resilient health facility able to engage the local community and optimise resources in a context of scarcity. The importance of this work is to inform design guidelines for further health facilities in the same climatic area, as well as to set the example of passive design support the prevention of the spread of air borne diseases.

KEYWORDS: Natural Ventilation, Thermal Comfort, Covid-19, Health Facilities Design, Passive Architecture, Pandemic

1. INTRODUCTION

This work presents a study conducted by a research team from Full: Future Urban Legacy Lab and Denerg - Energy Department from the Polytechnic of Turin in support of Techne Team, the Helpdesk of an International Humanitarian Institution. The relation between natural ventilation and architectural design as a sustainable response to Covid-19 is explored by presenting the work carried out on the design of a Severe Acute Respiratory Infection (SARI) Treatment Center in the city of Dori in Burkina Faso. The work carried out was aimed at providing compositional, technological and environmental solutions to respond to the need to adapt the ventilation health parameters required by World Health Organization (WHO) in a context of energy and material scarcity, by reviewing and modifying a preliminary existing building layout.

2. THE DESIGN CHALLENGES

The team at work was called to design a covid-19 hospital in a context of resource scarcity and hot climate. In Dori, Burkina Faso, the wet season is oppressive and mostly cloudy, the dry season is partly cloudy, and it is sweltering year round. Over the course of the year, the temperature typically varies from 60°F to 107°F and is rarely below 55°F or above 111°F, with a diurnal swing of about 50°F. Moreover, the months of December and January are characterized by important sandstorms.

The context of resource scarcity led the team to rely on the idea to apply passive design approach with a substantial focus on natural ventilation in order to limit, control, and prevent the covid-19 spread. Yet, the air flow rate parameters required for a covid-19 hospital was very demanding, setting the standard of air flow rate for critical patients at 160 l/s. Previous to covid-19, the parameter utilised for air flow rate in case of airborne disease was the of the guideline of tuberculosis transmission setting the ACH between 6 and 12 (Escombe, et.al. 2007).

Alongside this fundamental requirement, other design challenges were:

- To design the patients and medical staff flow layout organization, as it was important to ensure that infected patients, medical staff and untested patients had different and independent paths and circulation within the hospital.
- To review an existing layout design defined by the SARI Manual edited by World Health Organization. A pre-defined layout was

produced to ensure that all the medical operational needs were ensured, which set some design boundaries in terms of layout.

- To ensure the satisfaction of the need for a significant thermal control, as relying on natural ventilation called for the thermal control due to the hot temperature throughout the year.
- To embed in the design cultural aspects related to the local people belief, based on the idea that negative presence of bad spirits might enter through the open windows at night time, limiting the ability of ensuring the required air flow change from opening the windows.

3. METHODOLOGY AND DESIGN PROCESS

The methodological approach utilised was to verify the design layout through a number of simulations to ensure natural ventilation throughout the building, as well guarantee thermal comfort and that functional and social needs were met.

Overall Layout and ventilation strategy

The preliminary building layout set by the WHO SARI guidelines was organized in three identical blocks placed perpendicularly among them and containing ten patient rooms each. Each room was divided into three environments: a bedroom hosting the patient, a private bathroom and a small room filtering the access from/to the corridor.

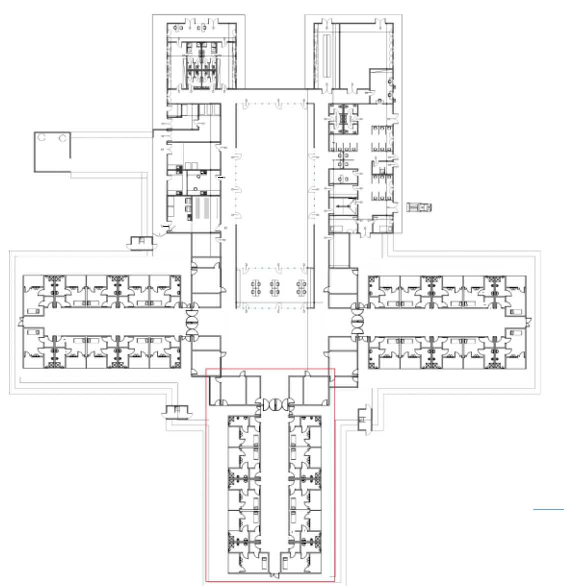

Figure 1: Overall layout for the SARI Treatment Centre of Dori, Burkina Faso (North as oriented)

In this context, natural ventilation approach was very critical in terms of resource management, costs savings, and reduction of both energy and maintenance costs. Nevertheless, the design of the natural ventilation strategy was challenging to fulfil the 160 l/s requirements. This fact was particularly valid as it was not possible to exploit the orientation of the building according to primary wind directions, as the predefined layout designed set the overall layout. Indeed, the three blocks were perpendicular to each other and optimizing one orientation would disadvantage another block.

To overcome these limitations, a building adopting a mixed-mode natural ventilation strategy was therefore designed. Some mechanical fans were have been envisioned to ensure the satisfaction of the strict performance limits and to reduce the risk of contaminants infection from the room to the corridor. M0oreover, each of the room environment was then designed with ad-hoc ventilation strategy:

The bedroom environment was envisioned as a cross-ventilation strategy with large openings oriented outdoor and a window over the upper part of the internal wall. The opening over the internal wall was not to communicate with the corridor but with the space under the roof. The different window heights allowed the stack effect to be exploited.

The bathroom was envisioned to be ventilated by a one-sided ventilation strategy, i.e. a unique window over the external wall. The ventilation of this environment was considered not crucial since the time spent by patients and operators within this environment is limited.

The room filtering the access from/to the corridor relied on mechanical ventilation. In detail, a fan was placed in the ceiling to extract exhaust air directly to the outdoor. This solution allowed the environment to have a negative pressure compared to the corridor and avoiding the dispersion of contaminants from the room to the corridor.

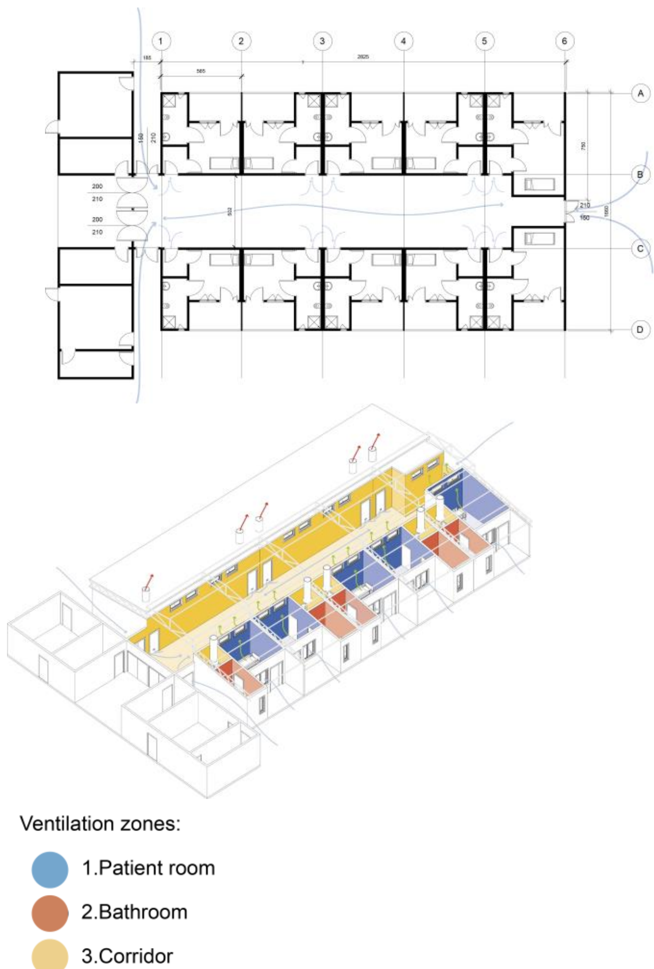

Figure 2: Overall dimensions and ventilation scheme for the SARI Treatment Centre of Dori, Burkina Faso

The patient waiting rooms at the treatment centre entrance was designed in order to decrease the risk of spreading the infection, by proposing a solution based on a punctual ventilation strategy that removes the exhaust air nearby the infection source. The proposed system consists of an air duct connected to the outdoors with air supply holes under the benches used by waiting patients. An exhaust fan is placed above the patient at the ceiling level. It extracts exhaust air directly to the outdoors, removing the infected air from the environment, and helping to decrease the risk of infection.

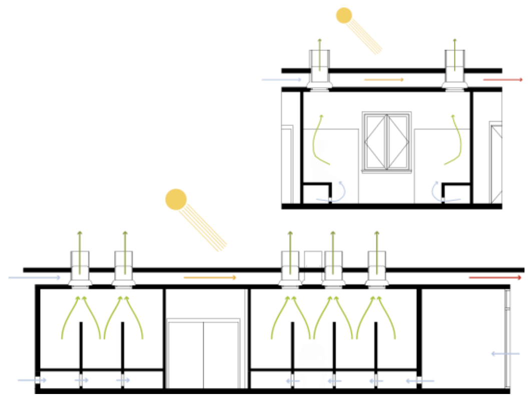

Figure 3 : Ventilation scheme for the patients waiting rooms

Thermal Comfort

The construction system was envisioned with the characteristics of ease construction, modular and easy to maintain. Regardless of the selection of the specific construction system, the proposed design was double roof system to prevent and decrease overheating, supported by a sequence of truss elements to improve the air collection and expulsion. This structural system envisioned, was not the only possible to be utilised, but it was essential to choose a system without structural elements, bearing walls, or other partitions that could block or alter the airflow intake or expulsion, as envisioned in this proposal.

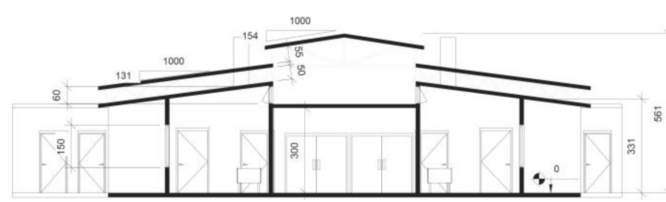

Figure 4: Double system roof and overall dimensions in section

In order to contribute to the thermal control of the building, the proposal suggested to rely on local natural materials such as adobe blocks isolated with natural fibres such as either kenaf (*Hibiscus altissima*), earth blocks and cow-dung, or fonio (*Digitaria exilis*) straw**.** These strategies were put in place during the preliminary design phase as suggestion to contribute to thermal control via passive design. Yet, further test and simulation need to be undertaken in the due course of the architectural and construction design phase.

Social Needs

In the area of Dori, Burkina Faso, there is the belief among the local people that negative spirits might enter into the house at night if windows are left opened. This belief added one more challenge to the ability of designing a space that can be naturally ventilated night and day, through window opening. To overcome this challenge, the team at work designed a system composed by a window and a ventilation vent that could be used at different time of day at night. During the day widows could be opened, while at night window were closed, but vent remained open. This strategy allowed to maintain a minimum airflow at night too, as well as respecting at the same time the social need of protection from bad spirits by having windows closed. The shape and dimensions of the vent have neem simulated and tested to find the optimal option, as it will be presented in the next section 4.

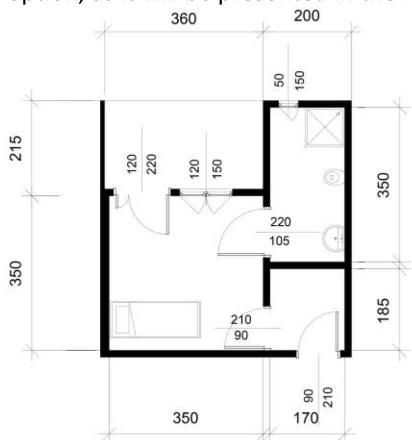

Figure 5: dimension of single room

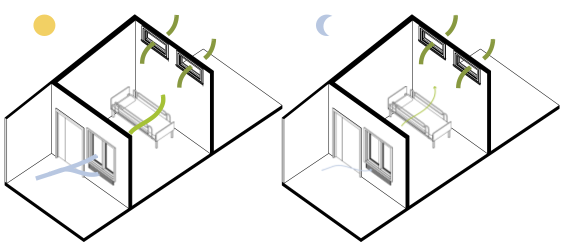

Figure 6: Ventilation system of single room

Natural Ventilation methodology

Natural ventilation is strongly influenced by stochastic processes that can modify the boundary conditions affecting the effective ventilation rate. In particular, two processes were individuated as much critical: the variation of wind intensity and direction and occupant behaviour. On the one hand, Weather conditions can be simulated using the Typical Meteorological Year (TMY) of the selected location, i.e. Dori in Burkina Faso. On the other hand, the occupant behaviour can be forecasted considering the worst condition that is represented by a manual closing of openings during night time (10:00pm to 7:00am) and during dust storm (occurring when wind velocity > 5 m/s) (Nigra, Simonetti, Galleano, Gentile 2022).

To assess the performance of the proposed building design, simulations were undertaken through Energy Plus - Design Builder. This software allowed the ACR of every single environment of the healthcare structure to be calculated on an hourly basis. The software was preferred over CFD due to the dimension of the single room and the time span of analysis. The TMY of Dori airport weather station were used as reference to simulate the climatic boundary conditions. Each room was listed as a single zone (e.g. room 1, room 2…), plus the corridor and the unconditioned environment under the roof were considered as standalone zones. Rooms were further segmented into bedroom, bathroom and divider filtering the access to/from the corridor. Each bedroom was considered occupied by a single patient 7/7 days and 24/24 hours (Nigra, Simonetti, Galleano, Gentile 2022).

Simulations were performed for the entire building. It was necessary to estimate the trend of airborne infection diffusion to further assess the effectiveness of the ventilation strategy. The formula used for calculate the concentration of virus quanta in the room is the following:

$$N_t = \frac{q \cdot I}{n} + \left(N_0 - \frac{q \cdot I}{n}\right) e^{-n \cdot t}$$

Where Nt is the quanta concentration at time t, q is the quanta/hour emitted by an infected person (for our simulations a value of 100 quanta/hour was considered), I is the number of infected people in the room (in this case 1 patient per bedroom), n is the ACR hourly profile resulting from the simulations of Design Builder, N0 is the initial concentration of airborne infection in the room and t is the time in hour. This formula is applied recursively updating the time-varying terms (Nigra, Simonetti, Galleano, Gentile 2022).

Once the quanta of infection in the room is known it was possible to estimate the risk of contagion of a person accessing the room. In this case the formula is:

$$Risk = 1 - e\left(-\frac{p \cdot q \cdot I}{V} \cdot \frac{N_t \cdot t + e^{-N_t \cdot t} - 1 - \left(\frac{N_t \cdot n}{q \cdot I}\right) e^{-N_t \cdot t} + \left(\frac{N_t \cdot n}{q \cdot I}\right)}{N^2}\right)$$

Where Risk is an indicator ranging between 0 (minimum risk) and 1 (maximum risk), p is the infected person respiration rate (0.6 m3/h is a typical value for sedentary activity), V is the volume in m3 and N is the concentration of airborne infection calculated with the formula above mentioned (Nigra, Simonetti, Galleano, Gentile 2022).

The risk increases according to the time spent with an infected subject. In the healthcare facility the major risk involves sanitary personnel taking care of the patient. It is reasonable that the time spent by the sanitary staff into the room is always less or equal than 1 hour. Thus, periods of 1 hour were considered as the most dangerous case. Therefore, the calculation is repeated recursively by varying the boundary condition and setting t = 1 hour (Nigra, Simonetti, Galleano, Gentile 2022).

4. RESULTS

The night time was outlined as the more critical moment for ensuring the required ventilation rate, withstanding, night time is also a moment when the room is occupied by the patient only, not representing a source of risk for the healthcare personnel. For this reason, the trend of contaminant in the environment was simulated to understand the variation of the airborne infection quanta in the room. The calculation was repeated on an hourly basis for the day of the year having the median value of ACR (in TMY occurred on 13-14 September) and the day of the year having the mini- mum value of ACR (in TMY occurred on 03-04 July). Since the night time is the most challenging period the simulation started at 10:00pm when the windows are closed.

After the simulation of the ventilation for the proposed the design, it was possible to see that at night window closure mode the limit of 160 l/s was not respected for the very majority of time, especially in the ward room, mostly due to the need of closing windows at night.

To overcome this limitation and improve the performance of the building, a ventilation vent was introduced, as mentioned in section 3 '*Social Need*'. This vent remains always open even during night time with the exception of the insect screen. Several dimensions of the vent were studied (minimum size with a circular 20 cm diameter and maximum dimension of rectangular 45*120 cm). The latter is a vent with the same width of the outdoor window and the height necessary to ensure minimum ventilation requirement for a significant majority of time. Specifically, even the minimum vent allowed the fresh air flow-rate to be in- creased in the more critical moments, i.e. nights with no wind and windows closed. However, the strict threshold of 160 l/s is overtaken very seldom during night time, especially in the leeward bedroom. This fact is a clear consequence of the stochastic variable affecting natural ventilation design (e.g. human behaviour closing windows and weather conditions causing low wind speed). On the contrary the wider vent solution ensures the respect of the threshold for the very majority of time. Nevertheless, a big opening vent on the outdoor wall may cause dissatisfaction of the patient's expectation (e.g. patient might not appreciate sleeping with low sense of security due to a large opening in the wall).

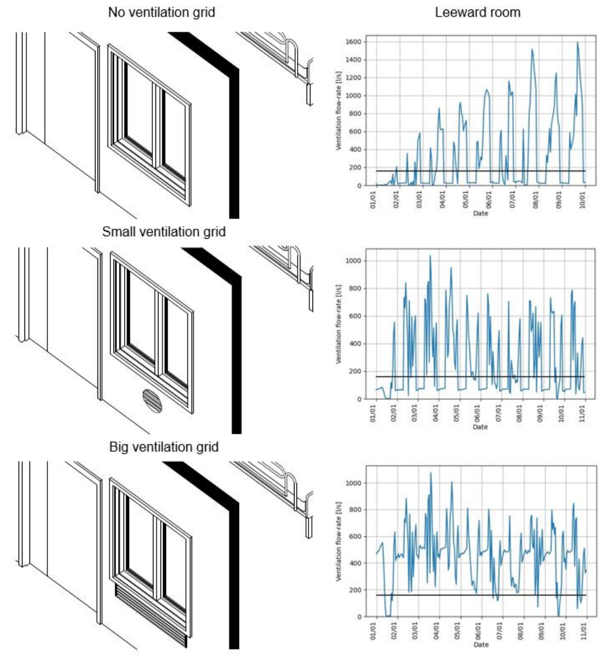

Figure 7: Airflow rate with different types and dimensions of ventilation vents

The different simulation studies prove that natural ventilation results to be efficient for SARI treatment centres in combination with mechanical systems, but design and operational precautions have to be taken.

As previously said, the ward presented in the preliminary project was based on a typical mechanical served facility, and modifications at the plan could be introduced to improve natural airflow by detaching the ward with a filter space. Furthermore, using a symmetric double-shell sloped roof enhances the thermal behaviour of the hospital by preventing excessive indoor heat gain and improving the collection of more fresh air for both the rooms and corridor thanks to the stack effect.

Using double top windows instead of a singular one can facilitate operations and leave a higher degree of airflow control while introducing a grid for night ventilation when the windows are closed can reduce the concentration of viruses in the air. In this case, operational precautions must be taken to prevent the risk of potential staff members infections. Indeed, we suggest that staff should enter the room in the morning for opening the windows only within a limited time span, and then exit before entering again 10 minutes later for visiting the patients.

The limitations of this work are that some of the design assumptions done during this preliminary study (i.e. stack height, materials, natural ventilation performance) will need to be confirmed during the design and construction phase.

5. THE RELEVANCE OF THIS WORK

The relevance of this work is multi-fold. This project has allowed to refine the ventilation and spatial scheme parameters for all SARI Treatment Centres in similar climatic zones and has stimulated interest in the relationship between engineering, architecture and health. Moreover, the designing process undertaken allowed to discuss the passive approach and the importance of natural ventilation in contrasting and managing the pandemic emergency of covid-19. Moreover, the work demonstrated the importance of include the participation of the users in the correct procedure of naturally ventilating the interior spaces, in order to avoid contamination. In this work the user participation was taken into consideration during the design phase in two ways: firstly, by collaorating with a local cultural mediator, and secondly by calculating during the simulation the optimal behaviour of the room occupants in terms of reducing time of exposure to contaminant in a non-ventilated room for a period of time.

The importance of natural ventilation demonstrated on this project allowed to set design and use guidelines also for other context such as school, public buildings, commercial premises, and housing.

6. CONCLUSION

Although the importance of natural ventilation for the health of buildings is not a new concept, the covid-19 pandemic has pushed many sectors – such as the architectural and the health one – to re-discover and re-apply principle of passive design in order to create resilient solutions to emergent problems. In doing so, guidelines for natural ventilation as a medium to manage and prevent airborne diseases have been presented and discussed in this work.

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