Assessment of the risk of tuberculosis transmission for five housing prototypes designed for a Haitian community

SUMMARY

The hospitalization of patients affected with tuberculosis (TB) can be particularly long and burdensome, especially in poor countries where the disease remains a major issue and beds in health care centres are a precious resource. Therefore a policy of decentralising TB treatment from hospitals to residential environments is starting to be considered worldwide, and new guidelines in support of such strategy are needed. This study illustrates a potential "risk assessment model" for TB transmission in dwellings that might help analysing both existing building stocks and new designs in order to apply the new policy, utilizing as a reference the general frame of risk assessment for buildings developed by civil engineering; the model was then tested on five housing prototypes proposed for the town of Saint Marc, Haiti, showing that environmental features of a building such as ventilation, crowding, temperature and relative humidity are among the most important parameters for the estimate of the risk. The final outcome of the analysis, however, highlighted how he most influential factor on the risk of spread of infectious diseases is the efficiency of the health care system operating in the building urban context.

KEYWORDS

Infectious disease, risk assessment, dwelling, Tuberculosis, HIV, Haiti

1 INTRODUCTION

Following the earthquake that devastated Haiti in 2010, Architecture for Health In Vulnerable Environments (ARCHIVE) launched a campaign to "raise awareness of how innovative housing designs can reduce the transmission of airborne diseases such as tuberculosis (TB)" (www.archiveglobal.org). The campaign included an international design competition to develop ideas for new housing prototypes, to be built in the town of Saint Marc, which would host families with at least one person living with HIV or AIDS, being at the same time affordable for a resource-limited setting and safe against the spread of airborne diseases.

Five winning designs were chosen according to their economic affordability, simplicity of assembly, bioclimatic design, ventilation strategies and low tech sustainable solutions, in this order of precedence: "Breathe House", "Maison Canopy", "Shutter Dwelling", "Bois l'Etat" and "Cycle House" (see appendix for details). By assessing each design, the aim of this paper is to illustrate a risk assessment model specifically designed to classify residential buildings according to the risk that at least one of their inhabitants may be infected with TB.

The objective of such a procedure, apart from evaluating the effectiveness of the five prototypes in lowering the danger of TB spread, was to highlight the key features that a house should possess in order to reduce the contagion risk for people already living in a high TB prevalence region such as Haiti.

2 MATERIALS/METHODS

The final outcome of the developed risk assessment method is a chart where each dwelling is plotted according to their risk scores that place them within one of five main risk categories or regions (from very low to very high). These regions are defined on the chart by two parameters: "impact of the risk" on the horizontal axis and "overall probability of the risk" on the vertical axis.

The two main parameters represent the combination of numerous factors, or sub-parameters found to greatly influence the possibility of TB spread in indoor environments (Valentini, 2010). The impact of the risk evaluates the extent of the danger represented by TB infection for humans, and summarises the following factors:

- **virulence of the disease**: how much damage TB can cause to a human body compared with how much effective and available the current forms of prevention and treatment are;
- **death rates**: statistical probability of fatal outcomes of the infection as a total number of deaths caused by the disease by the total number of individuals in the population.

The overall probability of the risk, instead, includes all the favourable and unfavourable features of a dwelling that may influence the probability of TB spread, such as:

- **infectivity and susceptibility of the dwelling occupants**: when TB cases are present in the building, their degree of infectivity can be measured through the sputum smear and culture tests, two of the most common procedures for the diagnosis of TB; with no infectious cases present, the parameter can be quantified utilising TB prevalence rates (statistical occurrence of cases in a population); as for susceptibility, some categories of individuals, among which children, elderly and especially immune-compromised subjects or people with a TB clinical history are particularly prone to TB infection, and their presence in the dwelling rises the overall probability of the risk;
- **urban and architectural features of the building**: these parameters quantify the degree of isolation of the community in which the dwelling is located, which may influence the availability of medicines and health care structures, and the levels of crowding of its neighbourhood, which acts on the probability that the dwelling occupants may get in contact with other infected individuals;
- **environmental features related to ventilation**: since TB is an airborne disease (CDC, 2005), ventilation rates and modes greatly influence the spread of the bacilli inside a dwelling; this sub-parameter takes into account the average ACH of the house, the position and area of the external openings, the average wind speed measured at such openings and the levels of crowding, quantified as number of individuals sleeping per room, which govern the amount of available fresh air per person;
- **environment features related to hygrothermal conditions**: TB bacilli travel from person to person through small droplets flowing in the air, expelled by infectious individuals when sneezing, coughing, talking or breathing (Spengler et al., 2001); the dimensions of these particles, the rate and distance at which they deposit and the viability of the pathogens contained in them are influenced by temperature and relative humidity, with a peak of risk at 25-40°C and RH<40% or >70%;
- **materials and cleanness of the surfaces that delimit the indoor space**: once deposited on a surface, the infectious particles could still be resuspended in the air, or they could otherwise be re-inhaled by indirect contact; therefore this parameters takes into account the likelihood that a surface hosts viable bacilli (rough, porous surfaces usually act as a more favourable culture medium for bacteria than smooth, water repellent materials) and the cleaning frequency and products utilised in the house.

The sub-parameters were then combined with the aid of an algorithm, based on the model of the ones used in civil engineering to calculate a building's risk of collapse (FEMA, 2005) which assigned to each factor a ranking scale – 1 to 3, 1 to 4 or 1 to 5 according to the different weight of each factor for the overall risk, with higher ranks corresponding to higher risk levels; the algorithm would then calculate the product of the rank values obtained by each analysed dwelling for all the sub-parameters belonging to the "impact" and "probability" of risk respectively. It must be noted that a multiplicative rather than additive method was used due to the presumed independence of each factor from the others, since no proof of possible correlations could be found in literature. The result would be two correspondent global absolute values, ranging from 1 to 20 for the impact and 1 to more than 1,000,000,000 for the probability score; these values would then be compared with two final impact and probability rank scale divided into 5 ranges, corresponding to the 5 degrees of risk represented in the chart, chosen according to the results of the analysis of some theoretical scenarios, where the different weights of each sub-parameter were calibrated.

In the present case, to assign a rank value to each of the listed sub-parameters for the five designs the data were either collected from the drawings and project briefs or inferred from general information about the town of Saint Marc and Haiti. Since none of the five designs had been realised at the time of the analysis, in fact, no real measure could be taken, and the prototypes were assessed according to two theoretical scenarios, as shown in table 1.

Table 1: Input data for the risk assessment evaluation

	BEST CASE SCENARIO	**WORST CASE SCENARIO**
virulence of the disease	risk group 3 (NIH classification)	
death rates	32 per 100,000 population, rank value 4 (WHO data, referred to 2009)	
prevalence rates	331 per 100,000 population, rank value 4 (WHO data, referred to 2009)	
infectivity	no infectious cases in the dwelling	one smear positive, culture positive test case not under treatment
susceptibility	presence of HIV positive cases	presence of HIV positive cases, of children/elderly and at least one person sleeping with the infectious case
urban features	semi-isolated community	
architectural features	low rise building in a non-crowded neighbourhood	low rise building in a crowded neighbourhood
ventilation rates	> 12ACH	2-4 or 4-6 ACH according to the openings design of each prototype
ventilation modes and openings area	wind dominant regime (stronger ventilation), openings area >10% or >20% floor area according to each design	temperature dominant regime (less effective ventilation), openings area >10% or >20% floor area according to each design
crowding	2 occupants per bedroom	3 occupants per bedroom
temperature	between 25-40°C, for both dry and rainy seasons	
relative humidity	between 40-70%,, for both dry and rainy seasons	
surface materials	according to the project briefs and drawings, mostly water absorptive surfaces in all cases	
frequency and modes of cleaning	use of water or detergents 3 or more times a week	use of water or detergents less than 3 times a week

3 RESULTS

With the data described, the model provided the results reported in fig. 1: clearly all the scenarios fall into the very high risk category, thus indicating a high probability of TB transmission in any case.

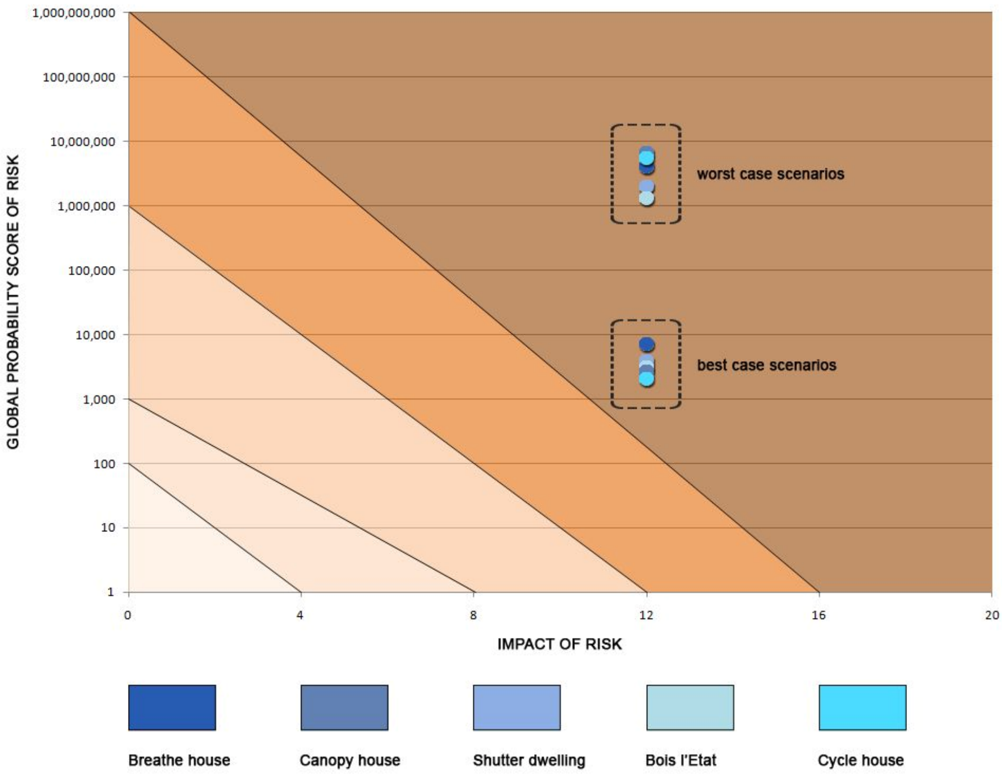

Fig. 1: The five designs risk assessment chart

Such result, however, is mainly due to the high TB death rates recorded in Haiti, which assign a rating of 12 to the risk impact for all the dwellings thus locating them at the right end part of the chart: there, even a low probability of the risk cannot lower the overall levels below “high risk”. However it must be reminded that the risk chart uses a logarithmic scale to visualize the risk probability score on the Y axis, and although the five designs appear clustered in both scenarios there are some essential differences among them.

Firstly “infectivity and susceptibility”, “urban and architectural features” and “hygrothermal conditions” were analysed, as these parameters are common to the five designs: as shown in table 2, “infectivity and susceptibility” is the most influential parameter, with a rank of 3 even in the best case, due to the presence of an HIV positive occupant and to the high prevalence rates; the other two parameters have a less pronounced effect, with none of them anyway ranked less than 2, thus contributing to the overall poor evaluation.

Table 2: Results for the shared parameters

PARAMETER	BEST CASE SCENARIO		WORST CASE SCENARIO	
	absolute value	rank	absolute value	rank
infectivity and susceptibility	24	3	540	5
urban and architectural features	3	2	6	3
hygrothermal conditions	4	3	4	3

“Ventilation, natural light and crowding” and “materials and cleanness”, instead, were consistently variable among the different designs, and have been analysed case by case: as shown in table 3, their ranking always ranges between 2 and 3, but with consistent differences in absolute values. The Cycle house, for example, was attributed the best score for ventilation, due to the spacious rooms and large openings; at the same time, it also gained the poorest evaluation in the worst case scenario, due to the absence of a valid backup ventilation strategy when the main openings are closed; instead the Breathe house, with its modular wooden panels and plywood or bamboo cladding, would be difficult to disinfect thoroughly and received the worst ranking for cleanness.

Table 3: Results for ventilation related parameters, materials and cleanness

	PARAMETER	BEST CASE		WORST CASE	
		absolute value	rank	absolute value	rank
Breathe house	ventilation parameters	4.6	1	50.0	2
	materials and cleanness	5.2	2	6.1	3
	probability score of the risk	6,814		3,927,269	
	worst to best case factor	x 576			
Maison Canopy	ventilation parameters	2.2	1	92.3	3
	materials and cleanness	4.7	2	5.5	2
	probability score of the risk	2,965		6,527,758	
	worst to best case factor	x 2,202			
Shutter dwelling	ventilation parameters	3.5	1	35.5	2
	materials and cleanness	3.6	2	4.2	2
	probability score of the risk	3,650		1,954,789	
	worst to best case factor	x 536			
Bois l'Etat	ventilation parameters	3	1	24	2
	materials and cleanness	3.6	2	4.2	2
	probability score of the risk	3,145		1,320,883	
	worst to best case factor	x 420			
Cycle house	ventilation parameters	2	1	100.8	3
	materials and cleanness	3.6	2	4.2	2
	probability score of the risk	2,097		5,547,709	
	worst to best case factor	x 2646			

Globally, in the best case scenario the Cycle house is the best performing design, thanks to its good ratings for both ventilation and materials, while the Breathe house is the poorest due to the choice of materials, the high levels of crowding and the small opening area. In the worst case scenario, instead, the best design is Bois l'Etat, thanks to its two backup ventilation strategies; unexpectedly, the worst performing design for the same scenario is not the Cycle house, despite its ventilation strategy, but the Maison Canopy, due to the fact that, when more than 2 people per bedroom are considered, while the Cycle house may still provide 10-15 m^3fresh air/person the Maison Canopy crowding levels fall below 10 m^3/person.

The worst to best case factor highlights the resilience of each design to the shift from best to worst case scenario: the Cycle house, for example, shows the highest increase in the probability of the risk, therefore changes in its parameters should be carefully studied as its overall performance dramatically changes with them. Bois l'Etat, instead, shows a small difference between the best and worst case: the design, therefore allowing for minor changes in its ventilation modes or materials with little differences in its levels of safety.

4 DISCUSSION

The application of the risk assessment model to the five designs showed that, when the local virulence of the disease is high, immediate diagnosis and treatment cannot be guaranteed and the cohabitation of infectious and susceptible individuals cannot be avoided, there is little that buildings can do to lower the overall risk.

Further empirical research is needed to quantify the risk posed by factors affecting disease transmission in dwellings. If findings were then incorporated into an assessment model such as has been presented here could be used to support a new housing policy for Haiti and other developing nations. This could promote the construction of buildings with features similar to those that received a positive evaluation in the risk assessment. However it should be emphasised that the model presented here is intended as an illustration of an approach based on current knowledge and needs to further validation.

5 CONCLUSIONS

The present study represents an attempt to evaluate the risk of spread of infectious diseases such as TB in a residential environment in Haiti. According to its results risks due to the specific health care system of the country and overall levels of sanitation tend to dominate and leave little room for a consistent decrease of the overall risk due to the mere design of the dwellings. However buildings last for a considerable time and as health systems and conditions improve it is important that buildings do not then present unnecessary increased risk of disease transmission.

It is true that particular methods of environmental controls applicable indoor such as air cleaning with HEPA filters and ultraviolet germicidal irradiation (UVGI) lamps, or even personal protections such as powered air-purifying respirators (PAPR), were not taken into account; however, although surely effective, these devices are expensive and require accurate maintenance, which makes them hardly feasible for an economically depressed region.

Therefore it would be easy to conclude that developing countries in need of lowering the burden of airborne infectious diseases should focus their efforts on improving their network of health care services first; however this study also suggests that a carefully designed house could also serve as a similarly suitable environment to a hospital caring for TB patients in poor countries. This would alleviate the burden on health care systems to redistribute their limited resources in order to improve overall efficiency.

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APPENDIX

Table A: The five winning prototypes for Haiti (source: www.bustler.net)

PLACEMENT	PROJECT DESCRIPTION
1st place 	**Breathe House** ▪ different natural ventilation strategies (main cross ventilation for air cleaning, induced stack effect for air exhaust), ▪ elements of sustainability (rainwater harvesting and composting toilets), ▪ choice of locally available building materials and of a prefabricated wooden structure, easy to mount on site even for less skilled workers.
2nd place 	**Maison Canopy** ▪ a wooden roof structure covers both the open and private spaces, separating air polluting activities as cooking from the sleeping areas, ▪ all the main openings are provided with screens, to avoid insects and allow the operation of the windows even during bad weather, ▪ rainwater catchment system, compost toilets and roof solar panels for sustainability.
3rd place 	**Shutter Dwelling** ▪ typical Haitian building techniques (concrete block walling and timber framing or cladding), ▪ separation between the sleeping areas, where HIV/AIDS patients live, and the other spaces, ▪ open areas are shielded with pivoting screens and louvers against bad weather conditions, ▪ thermal solar panels and rainwater collection for sustainability.
Honorable Mention 	**Bois l'Etat** ▪ cross ventilation through the main openings, roof buffer and stack ventilation from floor to ceiling through dedicated openings, ▪ specific indications of urban and landscape design, prefiguring interactions based on the common management of the gardens, ▪ PV panels and rainwater harvesting for sustainability.
Merit Award 	**Cycle house** ▪ independent energy supply consisting of a stationary bicycle working as an electricity generator when in situ, but also movable and available as a normal mean of transport, ▪ core sleeping and health care areas separated from the open kitchen, patios and gardens.

The third scenario
A last scenario was hypothesised, and reported in fig. A: if TB control in Haiti was improved as much as to lower the death rates to less than 10/100,000 cases, the same analysed designs, with no mechanical ventilation systems, minimum energy consumption and cheap building materials could be assessed as just moderately hazardous, even when highly susceptible individuals, as HIV positive patients, are hosted inside. The model confirms that, when attempting to prevent TB outbreaks, a good network of health services is in the end the most valuable weapon.

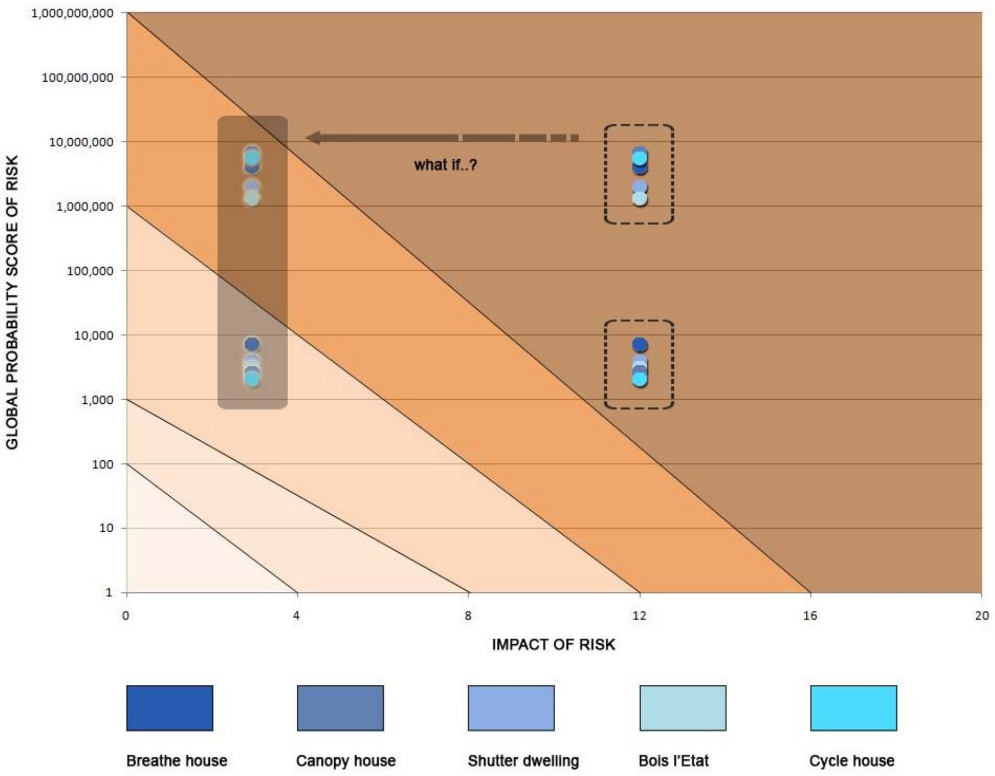

Fig. A: Assessment of the effect of the risk impact