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Prefabricated and low impact residential modules: comparative analysis between ventilation systems

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Abstract. The recent natural and anthropic disasters have led some of today's experimental researches to be oriented towards the study of residences for temporary living. During an emergency, the lack of primary resources and services often forces part of the affected population to live in inadequate health and environmental conditions. These problems are aggravated by the psychological damage to which the displaced people are subjected, as well as by the temporary nature of the residence. The temporary residence project should respect different requirements, e.g. construction speed, the ease of transport and the flexibility of the interior spaces. The aim of the present research is to improve the internal comfort of modular and prefabricated living areas designed for emergencies, through the application of a controlled mechanical ventilation system. The study aims to develop combinable and transportable modules that allow to obtain multiple spatial and planimetric combinations of accommodation thanks to an easy and quick junction system, the same for almost all panels. The easy assembly and disassembly as well as the ease of transport make these modules reusable and easy to install, fundamental characteristics as different emergency situations can occur in places very distant from each other. To achieve the required performance, a controlled mechanical ventilation system has been designed to make the modules adaptable to any environmental and climate context. A comparative analysis was carried out between a mechanical ventilation system and natural ventilation. For the mechanical ventilation an autonomous system for each module was chosen compared to a centralized system with ducts distributed in the house. The proposed solution allows to guarantee an adequate level of air health, without a significant increase of the associated costs.

1. Introduction

It is possible to define an emergency as a state of alteration of a balance. Actions that break the balance are attributable to unpredictable and uncontrollable events such as: meteorological, hydrogeological, telluric or biological calamities. A natural disaster causes a morphological and social upheaval of a territory, which often impose the abandonment by the residents of the affected areas, for more or less long periods, or definitively. In this sense, architecture is of great importance in emergency management; there is a particular attention to the prevention of damage caused by disasters, but there is also the shrewdness of preparing adequate measures to face their consequences. For the temporary accommodations, the government should dispose them as soon as possible; a solution could be the prefabricated housing modules. Depending on the construction processes, two possible design responses can be distinguished. The first, called *low tech*, uses materials extracted in situ and local construction techniques. It allows to preserve the environmental identity and, in many cases, the labour is represented by the same population involved. The second, *high tech*, released from the reference context, is based on the application of modern systems and materials. [1]

Unfortunately, today the chronicles tell of displaced people living for years in containers, or others transferred to hastily built homes. In Italy for example, after the disastrous earthquake that struck L'Aquila in 2009, innovative solutions for emergency housing settlements were adopted, such as the



transformation of the tent concept into a permanent home¹. These temporary housing agglomerations allow to understand the gradual evolution of technological systems during an emergency. The housing emergency, in the period of energy and economic crisis, can develop lightweight prefabrication solutions for low-cost quality residential homes [2]. To this end, housing modules that are easily achievable and with good environmental comfort performance should be designed. Therefore, the theme of environmental comfort in the residences should also be investigated in emergency residences for a double reason: the longer time spent in these homes and their energy containment.

Recently, several studies have been conducted with the aim of reducing the concentration of pollutants and harmful particles. An important parameter, depending on the behaviour of the occupants, is the window opening rate [3]. Some researchers have developed models to correlate the frequency of opening windows to parameters such as external conditions, the position of the house and the concentration of pollutants [4]. Natural ventilation strategies, through an open window, can maintain an acceptable IAQ (Indoor Air Quality), but involve excessive energy consumption. In this context, the adoption of a controlled mechanical ventilation system seems to be an adequate solution to balance these two needs, namely to guarantee air quality and reduce energy waste. These studies confirm that additional ventilation is usually needed in air-conditioned residential buildings [5]. The role of the occupants becomes particularly relevant: when pushed by the perception of an unsatisfactory air quality, they can open windows and induce an excessive ventilation speed, with negative consequences from the energy point of view. The aim of this research is to design prefabricated housing modules for emergency which can be easily transported, assembled and with high energy performance. The houses can accommodate a number of inhabitants proportional to their inner surface, and can be placed in different climate zones depending on the request. With reference to a residential unit module, a mechanical ventilation system is initially conceived based on different possible configurations (single or double flow). The proposed configurations are suitable for supplying fresh outside air and diluting indoor pollutants. The type of system was evaluated considering the best performance associated with the easiest installation system in the modules.

2. Materials and methods

The object of the current analyses are flexible accommodations where each module has its own specific function. The seven designed modules allow different combinations thanks to the easy jointing system. Each module has an identification code which characterizes it during the construction of the house (Figure 1). This system allows to create single buildings with a net internal height of 2.7 m. Moreover, these houses guarantee high technological content, rapidity of construction and low cost, typical characteristics of buildings in emergency. The modules can be reused because, thanks to the reversible joints used, they are easy to assemble, disassemble and transport. The dimensions of the module (10x2.5x3.3 mc) allow, in fact, transport on articulated lorries, on a ship or on train to be able to travel long distances in a short time. Although the buildings are designed to make the modules adaptable to any environmental and climatic context, this research aims to evaluate the thermal comfort performance of the residential modules installed in a hypothetical emergency settlement in Catania. This choice allows to set the necessary boundary conditions that characterize the environment where it is installed. The meteorological data therefore refer to the Catania Fontanarossa station (Latitude 37.47°, Long. 15.05°). The dynamic simulation was carried out through Design Builder, a dynamic energy simulation tool based on the Energy Plus[®] engine. Design Builder[®] allows to draw the building 3D model, to assign its physical and thermal characteristic and to contextualize the building in the real climatic conditions of the place where it stands (Figure 2). It allows to analyse the building's energy consumptions and the parameters of living comfort.

The emergency settlement is hypothesized by arranging different combinations of modules, to create housing solutions for different family groups (from 2 to 6 people for family). The house model used for the simulation is the one for 5 inhabitants because it is the most widespread housing solution

¹ CASE project and MAP (Prefabricated Housing Modules), created for the post-earthquake in Abruzzo, 2009.

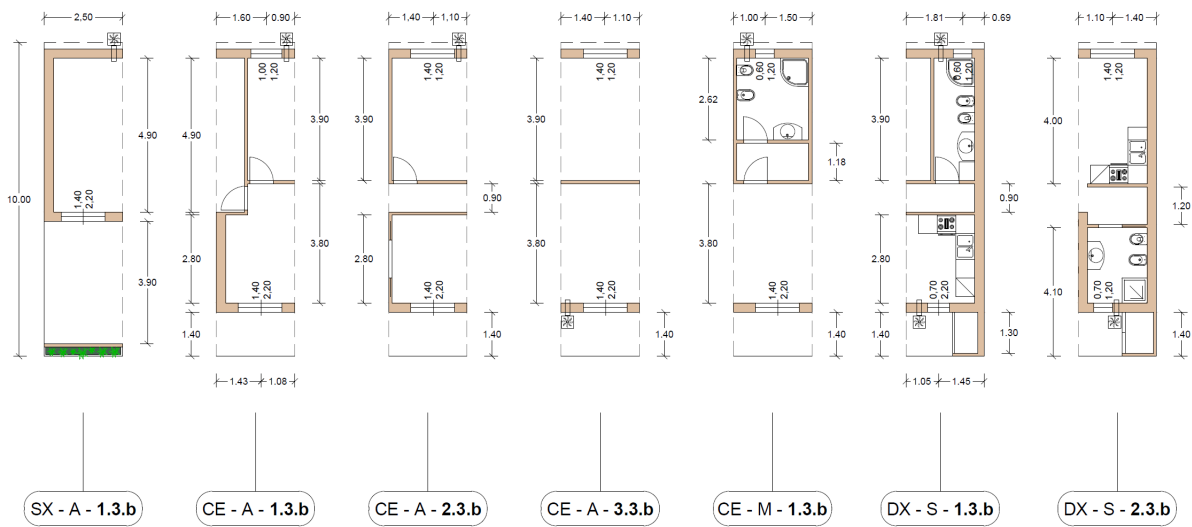


Figure 1. Classification of modules and position of air diffuser.

in the settlement. For positioning in the ground, it is considered that the main facades, containing the glass surfaces, are oriented towards south and north, while the east and west facades are blind. The overall net horizontal apartment surface is $A_{net}=82.7 \text{ m}^2$, with the corresponding volume $V=223.3 \text{ m}^3$ (Table 1).

The design of the modules also considers the internal quality of the air; establishing the level of air acceptability within living spaces is not easy because it varies for each person. To this end, two different types of ventilation systems (single-flow and double-flow systems) have been identified [6]. Single-flow systems perform air extraction through a series of terminals located in humid rooms (kitchen and bathrooms) and connected to a fan through ducts on the walls. Fresh air is introduced through special

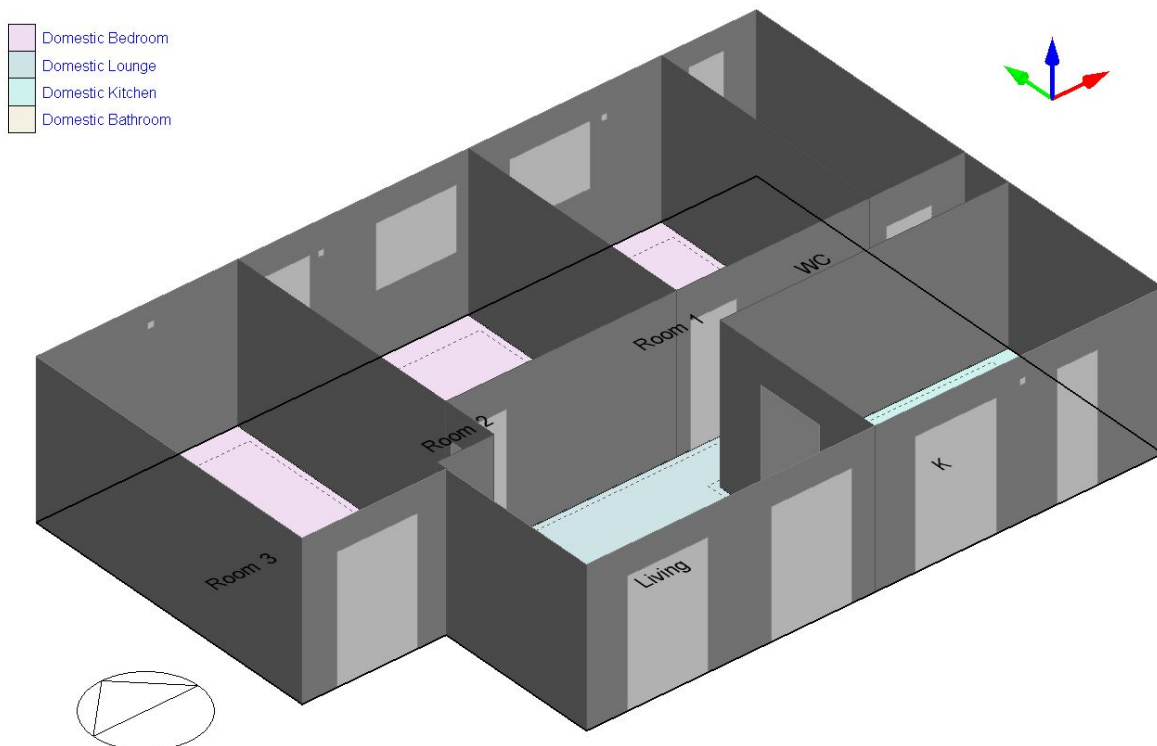


Figure 2. Classification of modules and position of air diffuser.

air vents placed in the living rooms, exploiting the difference in pressure between the internal and external environment. This pressure difference causes the transfer of a set air flow, with consequent dilution and removal of pollutants. On the other hand, dual-flow CMV systems extract air from wet rooms and supply it cleaned up to living rooms. The system has two fans and a heat recovery unit of the expelled air, which can be used to preheat the supply air [7]. The occurring air flow rate in mechanical ventilation simulations has been calculated with reference to the Italian standard UNI 10339:1995. The standard reassumes the environmental wellbeing conditions for N_p occupants by quantifying the outdoor air flow rates in buildings used for civil use in:

$$q = 11 \times N_p \times 3,6 \text{ m}^3/\text{h} \quad (1)$$

Considering that the housing module is intended to accommodate five people the rate of ventilation assumed is of $200 \text{ m}^3/\text{h}$.

Finally, these results are compared with the energy needs of a housing module without mechanical ventilation systems, where the renewal of the air is left to the occupants, who open and close windows. The natural ventilation parameter was set considering that windows and glass doors are open from 20:00 to 21:00 in the kitchen and from 07:00 to 08:00 in all other rooms [8]. Pressure coefficient values should be derived from pressure measurements in wind tunnels using small scale models of the actual building. However, in the literature, sufficiently reliable values are available for buildings of regular shape.

Table 1. Geometric features of the dwelling made of 5 modules.

Room	Net surface [m^2]	Volume [m^3]	Window size [m]	Window area [m^2]	Orientation
Living room	21.4	57.8	1.4 x 2.2; 1.4 x 2.2	6.16	S
Kitchen	12.9	34.8	1.4 x 2.2; 0.7 x 2.2	4.62	S
Bedroom 1	12.5	33.8	1.4 x 1.1	1.54	N
Bedroom 2	15.6	42.1	1.4 x 1.1; 1.0 x 1.1	2.64	N
Bedroom 3	15.2	41.0	1.4 x 2.2	3.08	N
Bathroom	5.1	13.7	0.6 x 1.1	0.66	N
	82.7	223.3			

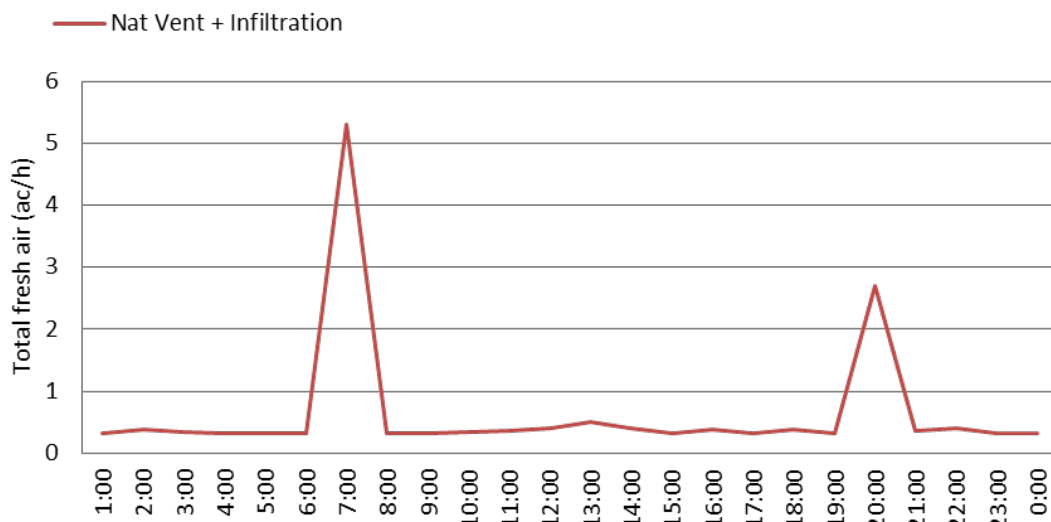
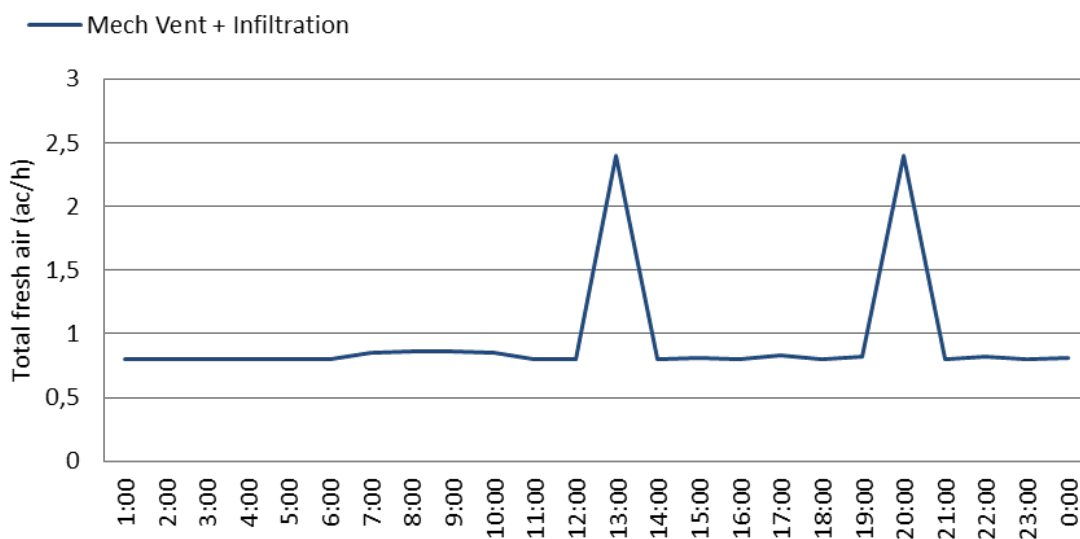
3. Result and discussion

The analysis of the thermo-hygrometric comfort of the emergency housing modules is part of a larger project of prototyping prefabricated modules. Other researches have been conducted by Cascone et al. to analyse their transportability and flexibility [9]. The design of the housing modules considers the correct arrangement of the openings in order to allow adequate natural ventilation of the rooms. However, when is not possible to use this type of ventilation, due to cold climates and strong winds, mechanical ventilation can be used. Table 2 shows the energy consumption for the different solutions. Comparing the thermal and energy demands of the analysed systems, natural ventilation requires the most energy to compound the energy losses resulting from the opening of the windows. The single-flow ventilation, limiting the air flow rate during the day, allows to reduce the energy consumption of the building. On the other side, double-flow ventilation, having a more efficient heat recovery unit, allows to reduce energy consumption compared to single flow. However, the greater energy consumption of the single-flow system is mitigated by considering the difficulty of installation. The most appropriate type of mechanical ventilation should consider several factors; in addition to the correct sizing of the system rate flow, the easiest laying and installation of the modular system should be considered. The choice to use a dual-flow ventilation system with heat recovery would require installation of internal ducts that would be difficult to integrate with the modularity of the construction system. The installation system that best integrates with the principle of modularity is the single-flow ventilation because each unit could be integrated into the modules during prefabrication and would not require further work on the site. Moreover, this solution allows to improve the cleanliness of the air thanks to the air extraction in the most humid areas of the house, such as the kitchen and bathrooms.

Table 2. Thermal and energetic needs for the ventilation models.

	E_{th} [kWh/year]	E_{el} [kWh/year]
Natural ventilation	1100.25	1881.46
Single flow ventilation	454.34	497.56
Double flow ventilation	58.24	83.21

As for natural ventilation, a significant result of the simulations is the amount of outdoor air introduced into the house. The daily profiles for a typical day in winter (February 1) are shown in Figure 4. The maximum inlet air flow occurs between 07:00 and 08:00, when the proposed scenarios provide for the opening of all windows of the house. This scenario allows effective cross ventilation of the whole house but at the same time a high energy expenditure. In the time slot included between h. 19:00 and the h. 20:00 only the kitchen windows remain open; in this case the ventilation speed is lower than the previous scenario. In the remaining hours of the day, when all the windows of the house are closed, only the air intake for infiltration is evaluated. In this case the software counts a lower air flow in the house depending on the parameter that has been assigned.

**Figure 3.** Natural ventilation.**Figure 4.** Mechanical ventilation – single flow.

By comparing the natural ventilation system with the single-flow system it is possible to note that in both cases the expulsion of air at room temperature leads to energy consumption due to a subsequent heating of the supply air. In the single-flow ventilation system the flow rate is kept constant throughout the day, the only flow variations occur in the time bands h. 12:00 - 13:00 and h. 19:00 - 20:00 as an extra extraction was set up in the kitchen in the software (Figure 4). This allows energy to be contained, guaranteeing always fresh and clean air.

4. Conclusion

Until a few decades ago, the only way to ventilate buildings in the residential sector was to periodically open the windows. However, in recent decades all the energy saving regulations in buildings have led to a gradual increase in the thermal insulation of the building envelope. This choice has generated several disadvantages such as: the stagnation of odours, the increase of relative humidity in closed rooms and the accumulation of polluting products generated inside the home. New constructions show moderate heat losses through the enclosure and, as a consequence, natural ventilation has become a significant element in the energy balance of a building. Due to the sudden events that are affecting our planet more and more frequently, emergency architecture today represents an increasingly widespread construction type. The aim of the research is to design adaptable and reusable spaces, able to react to changes in society. In particular, the comparative analysis between the mechanical and natural ventilation show that the common practice in which the renewal of the air is entrusted to the occupants of the house, without any control, can induce excessive natural ventilation and a consequent waste of energy. The adoption of controlled mechanical ventilation systems in housing units is a convenient to guarantee an adequate air flow rate and energy saving. The choice of the most appropriate type of mechanical ventilation must take into account the modulation of the residences and therefore the air flow needs to be modifiable for each residence. Despite, from an energy point of view, the double-flow system is more convenient, it could be better to install a single-flow system, integrated into a single module to increase air intake depending on the size of the house. These systems, without requiring an excessive installation time, can guarantee indoor air quality, bringing significant savings in primary energy. To progress this research, other studies could be conducting to improve the installation system and compare, as well as energy costs, also the economic savings deriving from these systems.

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