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Fabio Fantozzi, Pietro Galbiati, Francesco Leccese, Giacomo Salvadori, Michele Rocca

Dept. of Energy Engineering, Systems, Territory and Constructions
University of Pisa, School of Engineering, Largo Lucio Lazzarino, Pisa, IT.

E-mail: f.leccese@ing.unipi.it

Abstract. In the last few years, to meet the need of build efficient homes in a short time and with maximum constructive simplification, lightweight prefabricated building systems have proved to be particularly suitable, especially in geographical areas which must deal with emergency situations (i.e., temporary housing). In this paper the winter and summer thermal performance of a building prototype, realised with modular steel framed elements, have been studied, in both winter and summer conditions. Special attention has been paid to the optimisation of the dynamic thermal performance of the multi-layered envelope structures. The dynamic thermal behaviour of the outer wall, analysed and discussed in details in the paper, shows that it is possible to improve the performance of lightweight walls by using an optimised stratigraphy characterised by an opportune sequence of resistive and capacitive layers. The influence of inner structures (partitions, floor and roof) on the building thermal behaviour has also analyzed trough the introduction of room performance indices appropriately defined. The results of the study have been discussed with special reference to the requirements fixed by the Energy Performance Buildings European Directive (EPBDs) and the resulting implementation in Italian Legislation.

1. Introduction

In the last few years, lightweight prefabricated building systems have proved to be particularly suitable in geographical areas which must deal with emergency situations such as earthquakes, weather-climate events, situations of conflict, and others (see Figure 1).

In the past a considerable part of post-disaster temporary housing programs have been unsustainable and culturally inadequate as a result of unsuccessful strategies, misunderstandings about users' real needs and misconceptions in dealing with local conditions and resources [1].

Disaster-affected families who have lost their homes need a private and secure place to restart their daily activities as soon as possible after the disaster, yet temporary housing programmes tend to be overly expensive, too late and responsible for undesirable impacts on the urban environment [2].

Housing reconstruction programmes play a decisive role on the disaster recovery and providing temporary housing is a crucial step of these programmes. During the reconstruction of permanent housing, it allows victims to have a private and secure place to return to their normal life. It has been widely used after the largest scale disasters but it has also been greatly criticized, mainly for being unsustainable and culturally inadequate [1].

The selection of temporary housing to ensure sufficient levels of comfort is very important also for the psychological effects on the earthquake survivor. A research on a comparison of people assigned to

containers, converted into mobile homes, vs. wooden dachas vs. a control group, that had not lost their homes in the earthquake, have shown that container inhabitants reported greater discomfort, felt more dominated by the situation and, importantly, reported more psychological stress symptoms than those living in dachas or in regular homes. Again, it may surprise that the well-being of people living in dachas was closer to that of control participants than to fellow earthquake victims living in containers. In particular, people in dachas did not reliably differ from control participants in terms of feeling dominated or in terms of psychological stress symptoms, but they did express greater general discomfort [3].
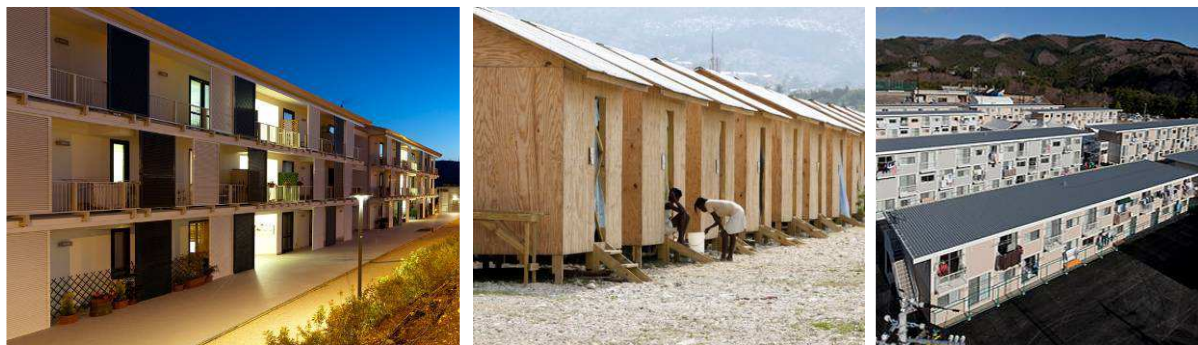
Figure 1. Examples of temporary housing units in earthquake areas: (left) L'Aquila, 2009; Haiti, 2010; Japan, 2012 (right).

It may be stated that these buildings require shorter construction times and simple construction steps, and they should not be mistakenly considered as "temporary housing." On the contrary, they must ensure high safety standards (against fires, earthquakes, etc.) as well as high levels of living comfort (thermal, acoustic, etc.), even in remote areas lacking services and utilities, such as electricity or gas supply.

This study is focused on the analysis of the dynamic thermal behaviour of a new prefabricated building system; the EN ISO 13786 method has been followed, implementing a spreadsheet calculation file [4]. In particular, the parameters: periodic thermal transmittance Y_{ie} (Wm^{-2}K^{-1}), decrement factor f_a and time shift φ (h) have been analyzed. The aim of the research was to study the dynamic thermal characteristics of the building envelope in order to enhance its performance by optimizing the stratigraphy of the outer multi-layered walls. The choice of the stratigraphy which optimizes the dynamic thermal characteristics has been performed using the method of lumped parameters [5].

It also aims to explain that the inner structures (partitions, floor and roof) play a role in the summer thermal performance considering the passive behaviour of the building. The analysis of the influence of inner structures on the energy performance of the room was established through the introduction of performance indices, similar to those above, but appropriately redefined [6].

2. Description of the new building system

The study has been carried out (with both computational simulations and on-site measurements) on a building prototype [6]. The new building system consists of modular steel framed elements (pre-assembled at the factory), which are shipped to the construction site including fixtures and equipment (see Figure 2).

The main features that characterize the new building system can be summarized in the following aspects: shorter construction times, construction flexibility, good seismic performance, energy saving, acoustic insulation, workplace safety, installation without scaffolding, easy maintenance and low costs.

The system involves the construction of a foundation slab designed according to the building loads and to the ground properties, taking into account of seismic aspects. The outer wall are anchored on the edge of the foundation. The modular elements of walls and floors (which constitute the supporting structure) are joint whit bolts. The new building system allows to create different solutions of ventilated facade covering whit stone, ceramic, aluminium, plastic materials with various surface finishes. The building typologies that the systems includes are multi-storey residential buildings, emergency housing units, commercial/office and industrial building.

Figure 2. Images of the new lightweight prefabricated building system (courtesy of HOMLEG, www.homleg.it).

In Table 1 are shown the stratigraphies of the outer walls, horizontal structures (floor) and inner partitions used in the standard solution [6], currently under production in Italy (Tuscany Region). In particular in Table 1, for each layers, are shown: thickness (d), thermal conductivity (λ), density (ρ) and thermal capacity (c).

3. Winter and summer thermal performance of the building envelope

The evaluation of the winter and summer thermal performance was initially carried out on the outer wall (W0) without the external coating layer (Ref.: Outer wall, layers 1 and 2, Table 1).

The winter behaviour of the outer wall has been evaluated by calculating the overall thermal tramittance U, amounting to 0.29 $Wm^{-2}K^{-1}$ ($R_{Tot}=1/U=3.45$ m^2KW^{-1}). In Italy, as European Directive EPBD implementation [7-9], limit values (U_{lim}) of the overall thermal transmittance for the outer wall of buildings have been fixed for each of the six climates zone (A÷F) in which the Italian territory is slip up. In particular, the more stringent limit values (Italian colder climate, zone F) are: $U_{lim}=0.33$ $Wm^{-2}K^{-1}$ (for vertical walls). It can be observed that the overall thermal trasmittance of the W0 wall is always less than the limit values set for each climate zone [7].

As regards the summer thermal behaviour, has been calculated the periodic thermal transmittance Y_{ie} ($Wm^{-2}K^{-1}$), the decrement factor f_a. and the time shift φ (h). In Italy, for the municipalities in which the maximum intensity of the solar radiation on a horizontal plane is higher than 290 Wm^{-2}, the following requisite have been imposed [8]: for the vertical opaque walls (facing South, South-West and South East), the value of the surface mass M_s should be higher than $(M_s)_{lim}=230$ kgm^{-2}, otherwise the value of the periodic thermal trasmittance Y_{ie} should be lower than $(Y_{ie})_{lim}=0.12$ $Wm^{-2}K^{-1}$.
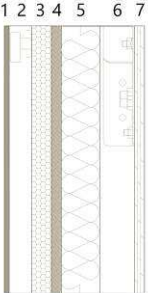
On the national guidelines for energy certification of buildings [9], in order to rate the "summer performance level" of the opaque outer walls the following parameters are used: decrement factor f_a and time shift φ (see Table 2). In [9] it is also specified that, in cases of values of f_a and φ do not belong to the same performance level, the assignation of the building summer performance level is based on the value of the time shift.

The W0 wall exhibits: $Y_{ie}=0.121$ $Wm^{-2}K^{-1}$, $f_a=0.41$ and $\varphi=6h49'$ (see Table 3). The W0 wall does not fulfil the limits imposed on the summer thermal behaviour and results in performance level IV (see Table 2).

In order to achieve better summer performance, it was decided to gradually fill (in step of 1cm) the air cavity (Ref.: Outer wall, layer 5, Table 1) with insulating material (i.e. rock wool). Consequently 15 different wall stratigraphies (from W1 to W15, see Table 3) has been examined.

In Table 3 the calculation results, for W0 (outer wall in the standard solution) and for the subsequent 15 stratigraphies (from W1 to W15), are shown. All the dynamic thermal characteristics has been calculated with respect to a reference period (24h) of the oscillation of the thermal field. It can be observed that it is sufficient the addition of a centimeter of insulating material to fulfil the limit imposed on periodic thermal trasmittance, however the W1 wall remain in performance level IV (φ=7h23', W1, see Table 3).

Table 1. Stratigraphy of the main components of the new lightweight prefabricated building.

		d (cm)	λ (Wm^{-1}K^{-1})	ρ (kgm^{-3})	c (JK^{-1}kg^{-1})
Outer wall	*Ext*				
	1- Outer coating	-	-	-	-
	2- Air cavity	4.5	0	1	1004
	3- Expanded polystyrene	8	0.033	20	1450
	4- OSB panels	1.8	0.13	650	1700
	5- Air cavity	15	0	1	1004
	6- OSB panels	5.4	0.13	650	1700
	7- Plasterboard sheet	1.2	0.21	900	837
	Int				
Floor	*Top*				
	1- Tile, cork	0.8	0.045	130	1764
	2- Silicone-mastic	0.5	-	-	-
	3- Plywood	3	0.13	500	2092
	4- Neoprene	0.3	-	-	-
	5- Plywood	3	0.13	500	2092
	6- Steel	0.5	52	7800	460
	7- Air cavity	19.5	0	1	1004
	8- Plywood	1.4	0.13	500	2092
	Down				
Partition	1- Plasterboard sheet	1.3	0.21	900	2300
	2- Rock wool	8	0.041	70	1030
	3- Plasterboard sheet	1.3	0.21	900	2300

Table 2. "Summer performance level" for the opaque building envelope.

Level	I	II	III	IV	V
Description	Excellent	Good	Medium	Sufficient	Poor
Time Shift φ (h)	$\varphi > 12$	$10 < \varphi \leq 12$	$8 < \varphi \leq 10$	$6 < \varphi \leq 8$	$\varphi \leq 6$
Decrement Factor f_a (-)	$f_a < 0.15$	$0.15 \leq f_a < 0.3$	$0.3 \leq f_a < 0.4$	$0.4 \leq f_a < 0.6$	$f_a \geq 0.6$

From Table 3 it can be observed that 3 cm of insulating material are necessary to achieve the performance level III (φ = 8h21', W3) and 9 cm of insulating material are necessary to achieve the performance level II (φ =10h10', W9). The most insulated solution (W15) exhibits the following thermal properties (see Table 3): U=0.146 Wm^{-2}K^{-1} (R_{Tot}=1/U=6.85 m^{2}KW^{-1}), Y_{ie}=0.026 Wm^{-2}K^{-1},

f_a=0.175 and φ=11h38'. Despite of the excellent thermal behaviour, U<<U_{lim}, Y_{ie}<<$(Y_{ie})_{lim}$, the W15 wall achieves a summer performance level rated as good (level II), being: 10<φ≤12h.

To further improve the dynamic thermal behaviour of the outer walls the Authors have proceeded with an optimization of the stratigraphy of the W15 wall [10-12].

Table 3. Thermal characteristics of the 16 stratigraphies analyzed: thermal trasmittance U, periodic thermal trasmittance Y_{ie}, time shift φ and decrement factor f_a.

Stratigraphy	Thickness insulating material (cm)	U (Wm^{-2}K^{-1})	Y_{ie} (Wm^{-2}K^{-1})	φ	f_a
W0	0	0.295	0.121	6h49'	0.410
W1	1	0.276	0.111	7h23'	0.403
W2	2	0.258	0.095	7h55'	0.370
W3	3	0.243	0.083	8h21'	0.340
W4	4	0.229	0.072	8h43'	0.314
W5	5	0.217	0.063	9h03'	0.292
W6	6	0.206	0.056	9h21'	0.273
W7	7	0.196	0.050	9h38'	0.256
W8	8	0.187	0.045	9h54'	0.242
W9	9	0.179	0.041	10h10'	0.228
W10	10	0.172	0.037	10h26'	0.217
W11	11	0.165	0.034	10h42'	0.207
W12	12	0.158	0.031	10h58'	0.197
W13	13	0.153	0.029	11h14'	0.188
W14	14	0.147	0.026	11h29'	0.180
W15	15	0.146	0.026	11h38'	0.175

4. Optimization of outer multi-layered walls

The problem of how to define the stratigraphic pattern of a wall provided with a thermal resistance R_{Tot} (including surface thermal resistances) and a thermal capacity C_{Tot} fitting for minimizing the periodic thermal transmittance Y_{ie} (i.e. the decrement factor f_a) has been solved by using the method of lumped parameters [10-12].

This method will be solved by considering that the definition "wall stratigraphy" refers to how many purely resistive layers provided with a thermal resistance r_s and how many purely capacitive layers provided with a thermal capacity c_s constitute that specific wall on the basis of a given layer sequence order. A *2n+1* layered wall, consisting of *n* capacitive layers and *n+1* resistive layers, can be outlined as follows (with $R=\Sigma r_s$ and $C=\Sigma c_s$):

$$[INT] \ [r_n] \ [c_n] \ [r_{n-1}].......[r_1] \ [c_1] \ [r_0] \ [EXT]$$

Given that the different resistive and capacitive layers are respectively represented by triangular matrices of the following type ($j=\sqrt{-1}$ and ω angular frequency of oscillation of external field):

$$\begin{pmatrix} 1 & r_s \\ 0 & 1 \end{pmatrix} \quad , \quad \begin{pmatrix} 1 & 0 \\ j\omega c_s & 1 \end{pmatrix}$$

For $n=\infty$, we obtain a typical homogeneous wall (i.e. a wall with uniformly distributed capacity C and thermal resistance R).

The problem of defining the wall stratigraphic pattern fitting for minimizing Y_{ie} is characterised by the following non-dimensional parameter:

$$\gamma = \omega R C$$

which corresponds to the product of an outer thermal field angular frequency ω and the wall's time constant RC. The obtained results can be summarized as follows.

For $\gamma < 18$, the optimal symmetry configuration is that obtained with $n=1$, corresponding to a three-layered wall, whose capacitive layer (C) is placed between two identical resistive layers ($R/2$), of the following type:

$$[INT] \; [R/2] \; [c] \; [R/2] \; [EXT] \qquad\qquad (\overline{T}_1)$$

Such a configuration is characterized by:

$$Y_{ie} = 1 / R \sqrt{1 + \gamma^2 / 16} \quad , \qquad \varphi = (P / 2\pi) \arctan(\gamma / 4)$$

For $18 < \gamma < 42$, the optimal symmetry structure is that obtained with $n=2$ (five-layered wall), of the following type:

$$[INT] \; [r_0] \; [c_1] \; [r_1] \; [c_1] \; [r_0] \; [EXT] \qquad\qquad (T_2)$$

For $42 < \gamma < 76$ the optimal solution is a T_3 symmetry structure obtained with $n=3$ (seven-layered wall), for $76 < \gamma < 100$ the optimal solution is a T_4 symmetry structure obtained with $n=4$ (nine-layered wall), and so on.

For each case with $n>1$, the optimal resistance and capacity values corresponding to the different layers are dependent on the γ value. It has been proved that entirely symmetric walls $\overline{T}_n$, consisting of n capacities and $n+1$ resistances whose values are all identical, with $c_n = C/n$ and $r_n = R/(n+1)$, approximate with a very good accuracy the behaviour of the above defined optimal configurations T_n, within the respective γ intervals.

It must be observed that whatever real wall can be outlined as a lumped-parameter wall provided with a sufficiently high number of layers. The above presented analysis shows that, for a given γ, the optimal stratigraphy is characterized by a low n value, which excludes the possibility of it being other than a lumped-parameter stratigraphy. The lumped parameter model is therefore not limitative.

Even the problem of defining the wall stratigraphic pattern fitting for maximizing the time shift φ is characterized by a non-dimensional parameter γ, the solution to this problem is very similar to the solution previously obtained with regard to minimizing Y_{ie}, if we except that the transition from one optimal stratigraphic pattern to another takes place for considerably lower γ values. The analysis turns out to be very simple when its spectrum is limited to entirely symmetric type $\overline{T}_n$ walls.

If such is the case: for $\gamma < 3.5$, a type $\overline{T}_1$ wall gives an advantageous solution, with $n=1$ (three-layered wall), for $3.5 < \gamma < 6.7$, a type $\overline{T}_2$ wall gives an advantageous solution, with $n=2$ (five-layered wall), for $6.7 < \gamma < 10.1$, a type $\overline{T}_3$ wall gives an advantageous solution, with $n=3$ (seven-layered wall) and so on.

In the case of high γ values, the number of layers which are needed to maximize the time shift φ is found to be in its turn very high, whereas the relevant structure approximates a homogeneous wall's structure, with an uniform distribution of R (including surface thermal resistances) and C.

5. Stratigraphic pattern optimization of the outer wall

In this analysis has been performed for the W15 wall without the innermost coating layer (Ref.: Outer wall, layer 7, Table 1), hereinafter named W15* (see Table 5). In Table 4, the thermal properties of the W15* wall, in particular the thermal resistance R (m^2KW^{-1}), the thermal capacity C ($Jkg^{-1}K^{-1}$) and the thermal diffusivity α ($m^2\mu s^{-1}$) of the different layers, have been reported. In Table 4 the parameters p_1 and p_2 have been also reported. The parameters p_1 and p_2 are defined as: $p_1 = C/C_{Tot}$, $p_2 = R/R_{Tot}$, where

C_{Tot} (kJm^{-2}K^{-1}) is the overall thermal capacity of the wall and R_{Tot} (m^{2}KW^{-1}) is the overall thermal resistance of the wall. In the analysed case (W15*) C_{Tot} and R_{Tot} are respectively: 92.7 kJm^{-2}K^{-1} and 6.81 m^{2}KW^{-1}.

Table 4. Thermal properties of the W15* wall (see also Table 1).

		EXT	Expanded polystyrene	OSB panel	Insulating material (Table 3, W15)	OSB panel	INT
R	m^{2}KW^{-1}	0.04	2.424	0.138	3.659	0.415	0.13
C	kJm^{-2}K^{-1}		2.3	19.9	10.8	59.7	
α	m^{2}μs^{-1}		1.14	0.12	0.57	0.12	
p_1			0.025	0.215	0.117	0.644	
p_2			0.365	0.021	0.551	0.063	

In order to understand the behaviour of the resistive layers (for example, a layer of insulating material), the value assumed by p_1 must be sufficiently low; similarly the capacitive layers should be evaluated considering the value assumed by p_2 [13-14].

In view of these aspects a new stratigraphy (Type 1) has been analysed. The Type 1 wall, keeping the same alternation of materials capacitive-resistive-capacitive-resistive of W15* and the same thicknesses of the different layers, is composed only of OSB panel (capacitive layers) and expanded polystyrene (resistive layers). The optimization of the dynamic thermal behaviour of the Type 1 is then processed by changing the sequence of layers from the inside outwards, see Figure 3.

Starting from the Type 1, three other stratigraphy have been designed in order to show the variation of the dynamic thermal characteristics of the opaque envelope of the new building system examined (see Figure 3 and Table 5). The Type 2 has been obtained without vary the thicknesses of the individual layers and by shifting toward the centre the capacitive layers (OSB panel) and outwards the resistive layers (expanded polystyrene). The Type 3 has been obtained by keeping the order of the layers of the Type 2 but making it symmetrical (the two layers of expanded polystyrene have the same thickness equal to 11.5 cm). The Type 4 has been obtained by searching the configuration that minimize the periodic thermal transmittance Y_{ie} through the use of the method of lumped parameters applied to the Type 3. The results of the optimization is a seven layers stratigraphy with alternated resistive and capacitive layers that shown the following thermal properties: ω=7.27·10^{-5}, γ =48.24 (42<γ<76), C_{Tot}= 86.23 kJm^{-2}K^{-1} and R_{Tot}=7.69 m^{2}KW^{-1}. The resistive layers (expanded polystyrene) are 4 of thickness 5.8 cm and the capacitive layers (OSB panel) are 3 of thickness 2.4 cm. A further fractionation of the stratigraphy does not allow appreciable improvements of the dynamic thermal performance of the wall.
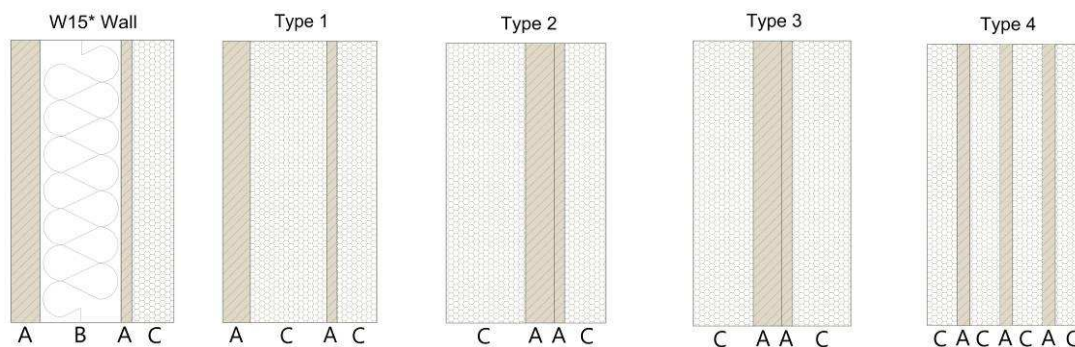
Figure 3. Different type of walls studied (A: OSB Panels, B: insulating material, C: expanded polystyrene).

From the results shown in Table 5, it can be observed that the different analysed solutions obviously have the same overall thickness (30.2 cm) and a surface mass M_s (kgm^{-2}) very low (always less than 60 kgm^{-2}). Of course the Type 1, 2, 3 and 4 walls, that are designed with the same materials and the same overall thickness, have the same thermal transmittance (U=0.130 Wm^{-2}K^{-1}) that is considerably lower than the limit value fixed for the climate zone more burdensome by the Italy legislation.

From the results reported in Table 5, it can be also observed that the Type 4 wall, optimized with the method of lumped parameters, shows a significant improvement of the time shift with respect to all the other proposed solutions. In particular the Type 4 wall, with φ=13h55', is characterised by a summer thermal performance level rated as excellent (level I).

Table 5. Thermal characteristics of W15* wall and the new Type 1..4 walls.

	d (cm)	M_s (kgm^{-2})	U (Wm^{-2}K^{-1})	R_{Tot} (m^{2}KW^{-1})	C_{Tot} (kJm^{-2}K^{-1})	Y_{ie} (Wm^{-2}K^{-1})	fa	φ
*W15**	30.2	59	0.147	6.81	92.69	0.029	0.20	11h02'
Type 1	30.2	51	0.130	7.69	86.23	0.028	0.22	10h07'
Type 2	30.2	51	0.130	7.69	86.23	0.012	0.09	8h51'
Type 3	30.2	51	0.130	7.69	86.23	0.011	0.08	8h47'
Type 4	30.2	51	0.130	7.69	86.23	0.006	0.05	13h55'

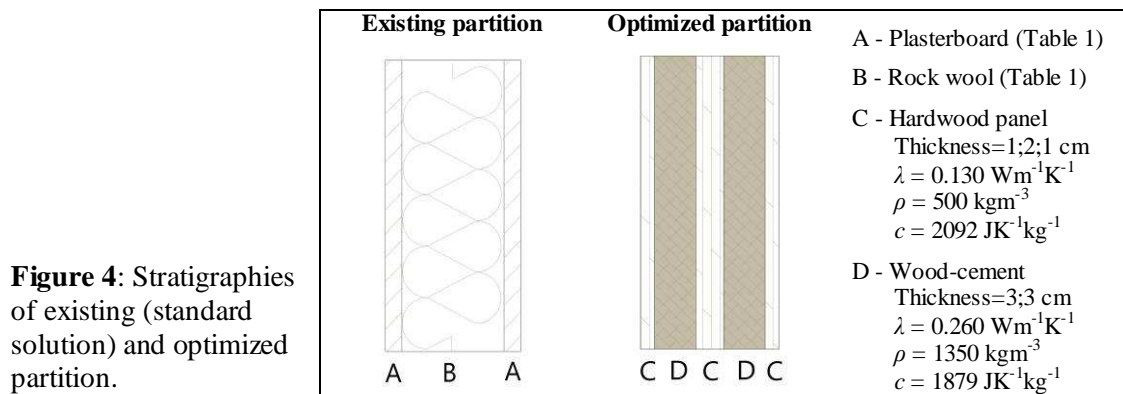## 6. Thermal influence of the inner structures

The thermal comfort of a building depends not only on the outer structures (roof and façades) but also on the inner structures, this is especially evident when the passive behaviour of the building is studied, that is when the response of the building to variations of the external temperature is analysed in the absence of an air conditioning system. The question involved is one of great relevance. It must be noted that a building which has been the object of an effective thermal planning so as to show an excellent passive behaviour, can provide, in the summer time, a satisfactory comfort level even when no air-conditioning system is installed or, at the most, when the role of that system is limited, with clear savings in energy consumption. For an overview on how far inner structures contribute to buildings' thermal comfort, readers are referred to [10-12].

In order to perform this analysis the performance indices, decrement factor η and time shift ψ as defined in [5-6], can be used. The dynamic thermal insulation of the building is much higher (and therefore the internal conditions are much less bound to the external ones) the smaller is η and ψ. In the present paper a type room, with square plane (side length of 5m) and a useful height of 3 m, has been studied. We have assumed thermal transmission as uni-dimensional and any effects brought about by thermal bridges will be neglected. Under such conditions the surface passing, at a given temperature, through the wall's midspan, can be outlined as being adiabatic. As a consequence, the only sector being affected by thermal problems within the room is half of the wall giving onto the room itself.

To study the influence of the inner structures (partitions, floor and roof) and of the outer wall on the performance indices (η and ψ), four different configurations of the type room (see Table 8) have been considered. The configuration R0 is composed by the inner structures described in Table 1 (floors and partitions) and the outer wall W15*; the configuration R1 is the same that R0 except for the inner structures that are optimized (see description below and see Table 6); the configuration R2 is the same that R0 except for the outer wall that is Type 4, and finally the configuration R3 that is composed by optimised inner structures and the outer wall Type 4.

The optimized partitions is defined as a type of partition with a thermal capacity greater than the existing one. The optimised partition walls have been obtained using also the method of lumped parameters and alternating layers of hardwood panels and wood-cement panels (see Figure 4) with thermal properties shown in Table 6. In Table 6 are also shown the values of the coefficients κ_1 and κ_2, which represent the thermal capacity on both sides of the partitions.

From the results shown in Table 7, it is observed that the attenuation factor η is progressively reduced from $2,81 \cdot 10^{-3}$ to $0,33 \cdot 10^{-3}$ passing from the configuration R0 to configuration R3, with an overall reduction of 88%. The behaviour of the time shift ψ is, on the contrary, more complex. The transition from configuration R0 to configuration R1 (optimized inner structures) produces a reduction in the time shift from 14h36' to 13h32'. The configurations R2 (optimized outer wall) and R3 (optimized partitions and optimized outer wall) exhibits higher values of time shift; being the R2 configuration the best, with an increase of ψ (compared to the R0 configuration) equal to 20%.

Figure 4: Stratigraphies of existing (standard solution) and optimized partition.

A - Plasterboard (Table 1)

B - Rock wool (Table 1)

C - Hardwood panel
  Thickness=1;2;1 cm
  $\lambda = 0.130$ Wm^{-1}K^{-1}
  $\rho = 500$ kgm^{-3}
  $c = 2092$ JK^{-1}kg^{-1}

D - Wood-cement
  Thickness=3;3 cm
  $\lambda = 0.260$ Wm^{-1}K^{-1}
  $\rho = 1350$ kgm^{-3}
  $c = 1879$ JK^{-1}kg^{-1}

Table 6. Thermal properties of existing partition (standard solution) and optimized partition.

Partition	Thickness (cm)	U (Wm^{-2}K^{-1})	M_s (kgm^{-2})	κ_1 (kJm^{-2}K^{-1})	κ_2 (kJm^{-2}K^{-1})
Exsisting	10.46	0.43	29	12.5	12.5
Optimized	10	1.25	101	50.5	50.5

Table 7. Summary of the four configuration of the type room analyzed.

R0 "Standard solution"	R 1	R 2	R 3
Existing partition Outer wall **W15***	Optimized partition Outer wall **W15***	Existing partition Outer wall **Type 4**	Optimized partition Outer wall **Type 4**
$\eta = 2.81 \cdot 10^{-3}$ $\psi = 14h36'$	$\eta = 1.5 \cdot 10^{-3}$ $\psi = 13h32'$	$\eta = 0.6 \cdot 10^{-3}$ $\psi = 17h28'$	$\eta = 0.33 \cdot 10^{-3}$ $\psi = 16h57'$

7. Conclusive remarks

The study presented in this paper has been designed in order to combine the well-know benefit of the prefabricated buildings with the energy high standard required by the market and the current construction sensivity.

The results show that it is possible to improve the dynamic thermal performance of the outer walls (lightweight prefabricated walls), by using an optimised stratigraphy characterised by an opportune sequence of resistive and capacitive layers.

The method of lumped parameters proves to be useful in deriving the stratigraphy which optimizes the dynamic thermal behaviour of the wall, minimizing the periodic thermal transmittance Y_{ie} and maximizing the time shift φ. The method also highlights how the inner partitions (optimized by

increasing the thermal capacity) help to keep the indoor air temperature constant against external temperature variations.

The calculation results make explicit the "weight" that the effects of thermal properties of each component on the determination of overall values of decrement factor and time shift for the type room. It is also clear that, with keeping attention on the simplification of the present case, the partitions play a significant role in the overall energy balance.

References

[1]   Felix D., Branco J.M., Feio A., 2013. Temporary housing after disaster: A state of the art survey. *Habitat International*, **40**, pp. 136-141.

[2]   Johnson C., 2007. Impacts of prefabricated temporary housing after disasters: 1999 earthquake on Turkey. *Habitat International*, **31**, pp. 36-52.

[3]   Caia G., Ventimiglia F., Maass A., 2010. Container vs. dacha: The psychological effects of temporary housing characteristics on earthquake survivors. *Journal of Environmental Psychology*, **30**, pp. 60-66.

[4]   EN ISO 13786, 2007, Thermal performance of building components – Dynamic thermal characteristics – Calculation methods.

[5]   Leccese F, Fantozzi F, Salvadori G, Rocca M, 2014, Thermal performance of outer and inner multi-layered walls in buildings, *32rd UIT Heat Transfer Conference*, Pisa (I), 23-25 June 2014, ETS (Pisa), ISBN: 978-8846739971, pp.1-8.

[6]   Fantozzi F., Galbiati P., Leccese F., Salvadori G., Rocca M., Maragno F., 2014. Dynamic thermal analysis of new lightweight prefabricated building system, *32rd UIT Heat Transfer Conference*, Pisa (I), 23-25 June 2014, ETS (Pisa), ISBN: 978-8846739971, pp.1-9.

[7]   D.Lgs.vo n.192 del 19 agosto 2005, Attuazione della direttiva 2002/91/CE relativa al rendimento energetico nell'edilizia (modificato dal D.Lgs.vo n.311 del 29 dicembre 2006).

[8]   D.P.R. n.59 del 2 aprile 2009, Regolamento di attuazione dell'articolo 4, comma 1, lettere a) e b) del D.Lgs.vo n.192 del 19 agosto 2005, concernente attuazione della direttiva 2002/91/CE sul rendimento energetico in edilizia.

[9]   D.M. Sviluppo Economico del 26 giugno 2009, Linee guida nazionali per la certificazione energetica degli edifici.

[10] Ciampi M, Fantozzi F, Leccese F, Tuoni G, 2003, On the optimization of building envelope thermal performance – Multi-layered walls design to minimize heating and cooling plant intervention in the case of time varying external temperature fields, *Civil Engineering and Environmental Systems*, Taylor & Francis, Vol. **20 (4)**, pp.231-254.

[11] Ciampi M, Leccese F, Tuoni G, 2004, Multi-layered walls design to optimize building-plant interaction, *Int. J. of Thermal Science*, Elsevier, Vol. **43 (4)**, pp.417-429.

[12] Ciampi M, Leccese F, Tuoni G, 2005, On the thermal design of the external walls in buildings. *8th REHVA World Congress*, Lausanne (CH),9-12 October 2005, ISBN: 978-3-033-00585-3, CD-Rom, pp.1-8.

[13] Ciampi M, Fantozzi F, Leccese F, Tuoni G, 2001, A Criterion for the Optimization of Multi-layered Walls, *7th RHEVA World Congress*, Napoli (I), 15-18 September 2001, AICARR Milano (I), CD-Rom, pp.1-15.

[14] Ciampi M, Leccese F, Tuoni G, 1999, Optimization of multi-layered wall and building-systems interaction (in italian), *17th UIT Heat Transfer Conference*, Ferrara (I), 30 June-2 July 1999, ETS (Pisa), Vol. II, pp.503-514.