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Sustainable and low-cost solutions for thermal and acoustic refurbishment of old buildings

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Abstract. This paper investigates the possibility to realize solutions for buildings thermal and acoustic refurbishment by using end-of-life household materials, such as cardboard, clothes, and egg-boxes. These solutions can be installed to improve the indoor quality in neighborhoods populated by people below the poverty threshold. The considered end-of-life household materials and their combination have been analyzed from the acoustic and thermal points of view. First of all, the sound insulation and the sound absorption properties have been determined by means of an impedance tube. Then, the summer and the winter thermal performances, when coupled to different wall systems, have been investigated analytically. The results suggest that good thermal and acoustic characteristics can be achieved in a contained thickness by coupling end-of-life household materials.

1. Introduction

Good structural performance but weak thermal and acoustic insulation performances characterize the most widespread building technologies in Europe. Despite in recent years many buildings have been refurbished from an energetic point of view, this kind of interventions is not reasonably priced for low-income people. Consequently, in these realities, tenants are often forced to live in unhealthy conditions because the heating system is missing, or ventilation is not adequate. This phenomenon of social urban vulnerability is common in many developed countries. In the orbit of urban vulnerability are found concepts such as exclusion, marginality, and poverty which, though not synonymous, may be mutually reinforcing. The correlation between poverty and low indoor air quality (IAQ) has been highlighted in several studies [1,2]. This problem mainly affects elderly people and people forced to stay home for many hours, like long-term unemployed or disabled. The city of Barcelona, like many other cities in the world, suffers strong internal vulnerabilities and inequalities because of differences in the social composition of the population through spatial distribution. The Raval area is the one with the highest concentration of poverty in the whole urban area of Barcelona, and it is characterized by two population groups, that are elderly people and immigrants, both with low incomes. Nowadays, building design embraces many aspects such as environmental, social and sustainability issues [3]. For example, local sustainable construction materials should be chosen, and local workers should be involved as already done in several projects [4]. For this reason, building systems must be cheap, made of materials easy-to-be-found in the vicinity of the building site, safe and easy to be installed during the construction phase also by non-skilled workers. From this point of view, end-of-life household materials are cheap (or even free), easy-to-be-found, safe and, when discharged, they have properties that can still be exploited. The possibility to reuse these materials was investigated by several authors: properties of clothes [5], cardboards [6], and plastic containers [7] were analyzed in several works. The reuse of these materials reduces the amount of produced waste and, consequently, of material discharged in the environment; indeed, only a small percentage of household waste materials is recycled. For example, in 2017, only the 14% of the textile waste was recycled and the rest was addressed to incineration [8].



This article is part of a project that aims to develop the knowledge towards possible low-cost improvements in thermal and acoustic comfort conditions for people living under the poverty threshold, providing also simple and fast application solutions. However, these solutions not only aim to solve the thermal and acoustic vulnerability, but also to become an instrument for social change and the realization of individuals. In particular, in this paper, the acoustic and thermal performance of a group of end-of-life household materials are investigated with the aim to identify a solution to be installed indoor on vertical walls to guarantee an improvement of the acoustic and thermal conditions. About acoustic comfort, the two main properties to be considered are the attitude of the material to dissipate acoustic energy, expressed through the sound absorption coefficient α , and the sound insulation capability, represented by the sound transmission loss TL . In this work, to determine these parameters a four-microphone transmission tube has been used in this work. This apparatus is a double standing wave tube equipped with four microphones. By means of this device it is possible to determine the transfer matrix of a material. For this reason, this device is particularly suitable for the acoustic characterization and optimization of complex layered structures [9]. Another advantage is that it requires smaller samples if compared to the 10 m² necessary to perform measurements in a transmission suite. The only drawback using a transmission tube is that only the “normal incidence” characteristics of the materials can be evaluated, while in real life applications diffuse incidence is the actual condition. Nonetheless, with the experimental tests it has been possible to compare the acoustic performances of several samples when subject to normal incidence. These first results will be refined in future studies. Then, some of the tested configurations have been analyzed also from the thermal point of view. Since the systems are designed for Italy and the Raval neighborhood, that are situated in the Mediterranean area, both the summer and the winter conditions have been considered. Indeed, since in these locations, summer is characterized by a wide daily temperature variation, it is necessary to consider not only the thermal conductivity and thickness of the layers, but also their heat capacity and their position in the wall.

2. Methods

In this paper, a group of end-of-life household materials has been analyzed from the acoustic and the thermal points of view. Firstly, end-of-life household materials have been tested acoustically and, then, some of them have been analyzed thermally.

2.1. Acoustic performances

The acoustic characterization has been carried out according to the procedure described in the ASTM E2611 standard [9]. The procedure requires the measurements to be performed using a four-microphone impedance tube. Such device has a loudspeaker, generating a wide-band white noise, mounted at one end and an anechoic termination at the other end. The sample is placed in the central section, between two microphone pairs. A multichannel analyzer measures the microphones signals and computes the transfer functions. Such functions are then post-processed by a MATLAB script based on the ASTM E2611 [10] standard to obtain the acoustic parameters of the sample and its transfer matrix. The single materials and the combinations reported in Table 1 have been tested. For each sample type, three tests have been performed and the results have been averaged. The tests have been organized as follows: the first two sets are made of egg-boxes samples featuring single/double layers (test 02-03-22) and egg-boxes coupled with polyester fiber (test 04-05). In some cases, a steel sphere was embedded inside the polyester fiber and the structure closed using a cardboard layer (test 07-08-17). In order to accommodate the steel element inside the structure, a cylindrical hole was made at the center of the cardboard disks. A third set of samples includes samples mainly made of cardboard (test 13-14). Samples made of clothes of different fabric types represent the fourth experimental set. Several repetitions have been performed for each measurement to assess how the ability of the person assembling the samples can affect its performances. This aspect will be further investigated in future analysis. The fifth (and final) set of measurements has been made on samples obtained by combining egg boxes, clothes and metal elements. In general, to improve the acoustical behavior, disks and egg-

boxes exposed to the sound source were perforated to allow the sound to pass through the first layer. The sequences reported in Table 1 start with the material closest to the sound source. The frequency range investigated goes from 100 Hz to 3150 Hz.

Table 1. Specimens tested in the impedance tube. The diameter of the samples is 46 mm.

TEST NUMBER	SPECIMEN DESCRIPTION	SPECIMEN THICKNESS [mm]	SPECIMEN MASS [g]	MAT 1	MAT 2	MAT 3	MAT 4	MAT 5	MAT 6	SECTION
2	Single pyramid of egg box (direct)	50	2.78							
3	Perforated single pyramid filled with loose polyester (direct)	50	3.6							
4	Perforated single pyramid filled with loose polyester and metal ball (reverse)	50	12.63							
5	Perforated single pyramid filled with loose polyester and metal ball (direct)	50	12.63							
7	Perforated single pyramid filled with loose polyester and metal ball, closed by cardboard disk (direct)	50	13.33							
8	Perforated cardboard disk + perforated single pyramid filled with loose polyester and metal ball, closed by cardboard disk (direct)	50	13.33							
13	9 cardboard disks: 2 perforated + 5 with central large hole + 2 whole	24.21	6.47							
14	9 cardboard disks: 2 perforated + 5 with central large hole filled with metal ball + 2 whole	24.21	15.4							
17	Perforated cardboard disk + perforated single pyramid filled with loose polyester, closed by cardboard disk (direct)	50	4.36							
22	2 pyramids of egg box (reverse)	50	4.19							
26	Piece of fabric: cotton	100	19.31							
27	Piece of fabric: cotton	50	12.53							
28	Piece of fabric: polyester	50	13.81							
29	Piece of fabric: plush cotton	50	8.45							
30	Piece of fabric: viscose	50	17.41							
32	Perforated single pyramid filled with plush cotton (direct)	50	8.91							
33	Perforated single pyramid filled with viscose (direct)	50	20.07							
34	Perforated single pyramid filled with viscose and metal ball (direct)	50	29.03							
35	Perforated single pyramid filled with viscose and metal bottle cap close to the pyramid (direct)	50	21.83							
36	Perforated single pyramid filled with viscose and metal bottle cap far from the pyramid (direct)	50	21.83							

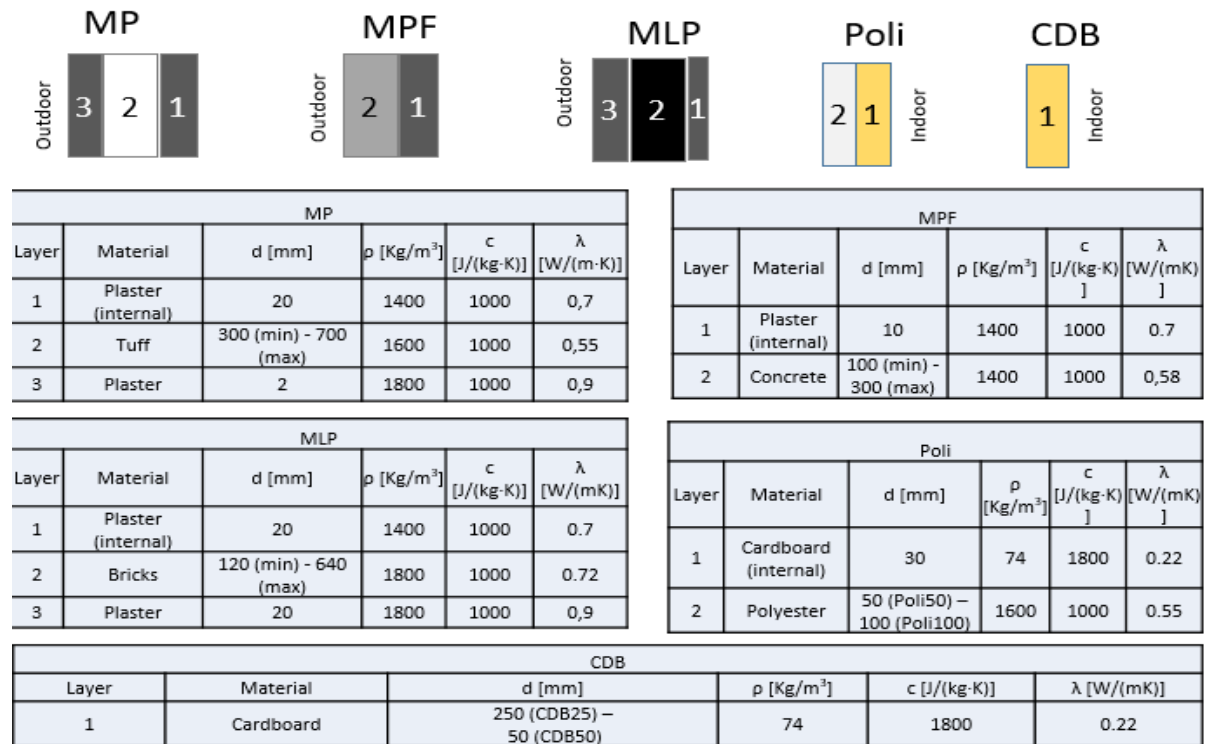


Figure 1. Walls configurations (*MP*, *MPF*, *MLP*) and the additional panels (*Poli*, *CDB*) considered in the analysis. The additional panels are installed internally.

2.2. Thermal investigation

The thermal effect of an insulating panel made of end-of-life household materials applied to different walls has been investigated. The aim of the analysis is to understand if the materials at hand exhibit promising characteristics that can justify further investigations. Three basic wall configurations called *MP103*, *MLP01*, and *MPF01* have been considered. Such configurations have been renamed *MP*, *MLP* and *MPF* in the following part (Section 3.2). These basic types of walls have been extrapolated from the UNI/TR 11552 [11] standard and represent the typical building solutions used for Italian council estate. Since, as stated in [11], the wall thickness is variable, the largest and the smallest thicknesses have been considered. The thermal performances of the walls have been compared with those of the walls equipped with one of the additional insulating panels shown in Figure 1 (*Poli* or *CDB*), these latter installed on the internal side of the wall. Indeed, the solutions considered in this paper are designed for historical urban contexts in which the external appearance of the buildings must be preserved and external intervention are not allowed. In the following sections, type and thickness of each configuration are declared in the name. For example, *MPmin-Poli50* represents the thinner wall configuration *MP* coupled to the *Poli* panel. The variable layer of the *Poli* panel is 50 mm thick. In particular, the periodic thermal transmittance Y_{12} , the delay, the thermal transmittance U and the decrement factor f have been calculated according to the UNI EN ISO 13786:1999 [12]. The periodic thermal transmittance Y_{12} , an important parameter for the evaluation of the summer comfort conditions, represents the amplitude of the density of heat flow rate on one side when the temperature amplitude on that side is zero and there is unit temperature amplitude on the other side. The decrement factor f describes how well the wall reduces the internal temperature peak. The thermal transmittance, instead, describes the insulating performance in stationary conditions like the ones found during the wintertime.

3. Results and discussion

3.1. Acoustic performances

The absorption coefficient α and the sound transmission loss TL of the samples reported in Table 1 have been determined by means of a 4-microphone impedance tube. When dealing with the acoustic comfort both sound absorption and sound insulation performances are influential. Yet, since the reference walls have good sound insulation basic performances, sound absorption can be considered more interesting. In Figure 2, for the first set of samples the most interesting sound insulation performance is the one given by specimen 22 (reverse double pyramid) with a TL following the mass law up to 800 Hz and then a behavior typical of double walls, with a mass-spring-mass resonance frequency around 1800 Hz. Also the specimen 02 (single egg box) showed an acceptable performance, with a rather flat TL of 12 dB from 100 Hz up to 2000 Hz, while specimen 03 (perforate egg box with polyester) is not able to reach the performances of the other samples. For the same samples, with the exception of sample 02 which is not permeable to air, α is characterized by wide peaks at given frequencies due to holes obtained in the egg cardboard behaving like Helmholtz resonators (sample 03) or quarter wavelengths resonators (sample 22). In the case of sample 03 the peak around 700 Hz is very wide due to the presence of sound absorbing polyester fiber inside the main volume. As concerns the second set of samples, TL curves are all very similar as can be seen in Figure 3. This behavior can be explained by the nature of the samples which are built with the same elements: the egg cardboard, the polyester foam and the steel sphere. The only variables are the orientation of the samples and the presence of a cardboard disk. The TL of samples 04 and 05 are characterized by the typical mass law behavior due to the single egg cardboard, except a dip around 1200 Hz. The samples 07 and 08 have higher values of TL due to the double or triple layer structure which causes an increase of the mass and an increase of the curve slope due to multiple resonances of the layers. In particular, sample 08 exhibits very interesting performances at low frequencies and the higher TL of the group also at high frequencies. For these samples α is characterized by multiple peaks typical of the resonators featured in the cardboard parts. The breadth of the peaks depends again on the presence of polyester fibers. The best sample is *Test 08*, having a rather high α also at high frequency, with a maximum of 0.95 at 2 kHz. The third set of samples shown in Figure 4 presents very similar TL curves for all the samples. The performances are very similar and TL at low frequency is the highest among the entire group of tested materials. Such behaviour is due to the density of the stacking, which makes the samples similar to sandwich materials featuring non compressible cores. For this reason the trend is characterised by a linear behaviour followed by the typical coincidence dip. For samples 13 and 14, α is marked out by a maximum around 600 Hz due to the resonance of the Helmholtz resonators featured in the cardboard. For sample 17, α is very similar to the one of sample 08 (having a very similar structure), with three peaks reaching a value of 0.8. The fourth set considers tissues and results are shown in Figure 5. Comparing the different samples, the TL curves are all very similar and are typical for porous materials. The better performances are reached by the thicker samples (sample 26 – 100 mm) and by the sample having the higher density (sample 30 – high density viscose). Also, α curves have a shape typical for porous materials, with an S shape, low values at low frequencies and values approaching 1 at high frequencies. The fifth and last set is a combination of tissues, egg boxes and metal parts. As can be seen in Figure 6, the TL curves have very similar trends. If compared to the TL curves of the fourth set, the values are generally higher at low frequency due to the higher mass per unit area of the samples. Sample 36 has the best performances for this group. As concerns α , the behavior is dominated by the Helmholtz resonator characteristic shape featuring a peak around 400 Hz followed by an increase of the coefficient due to the presence of the tissues. As a general remark, the higher the flow resistivity of the tissue, the lower α in the high frequency region.

3.2. Thermal performances

Since clothes and cardboard have shown good acoustic performances, they have been evaluated also from the thermal point of view. Given their limited thickness, egg-boxes have not been considered in this section.

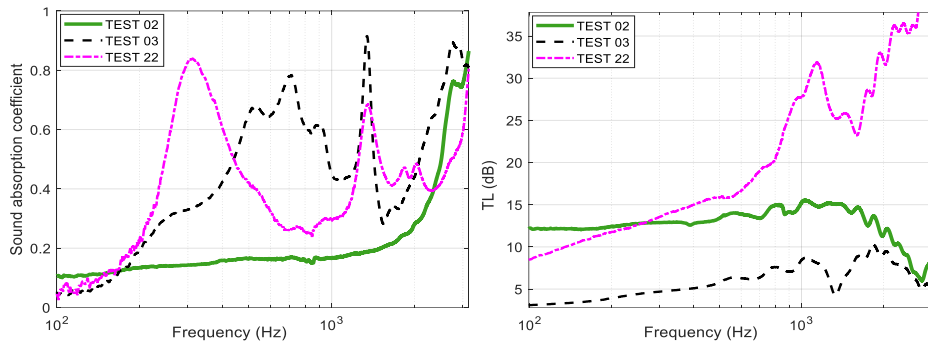


Figure 2. Acoustic properties of samples made of clothes (one fabric at a time).

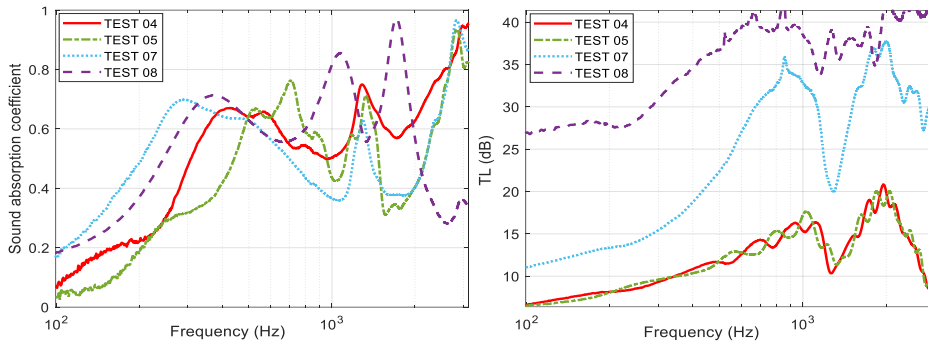


Figure 3. Acoustic properties of samples made of at least one egg-box.

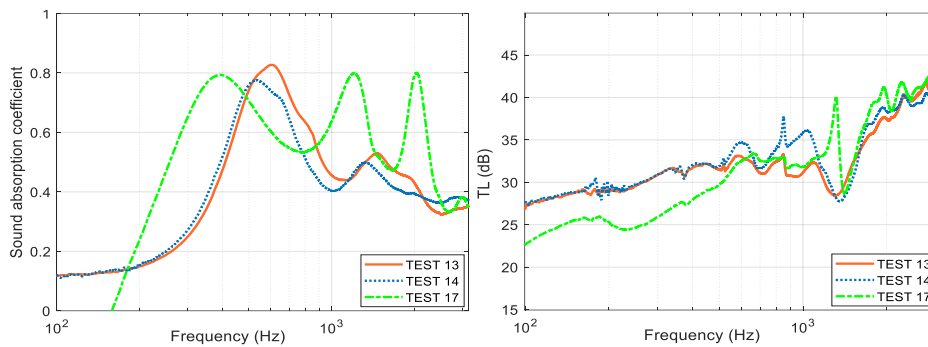


Figure 4. Acoustic properties of samples made of egg-box coupled with other household waste

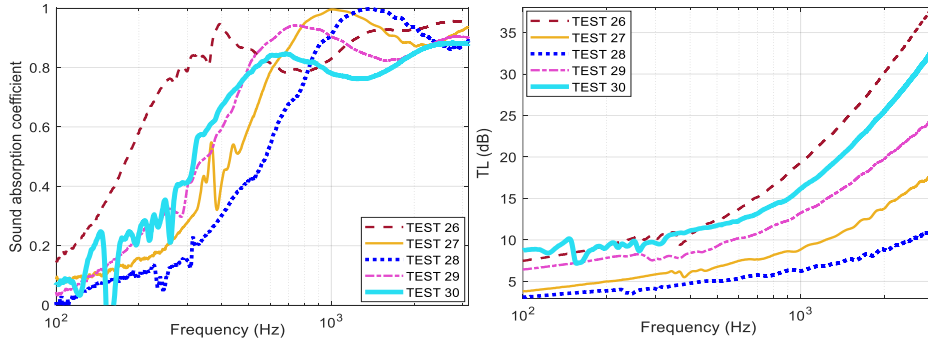


Figure 5. Acoustic properties of samples made of clothes combined with other household waste

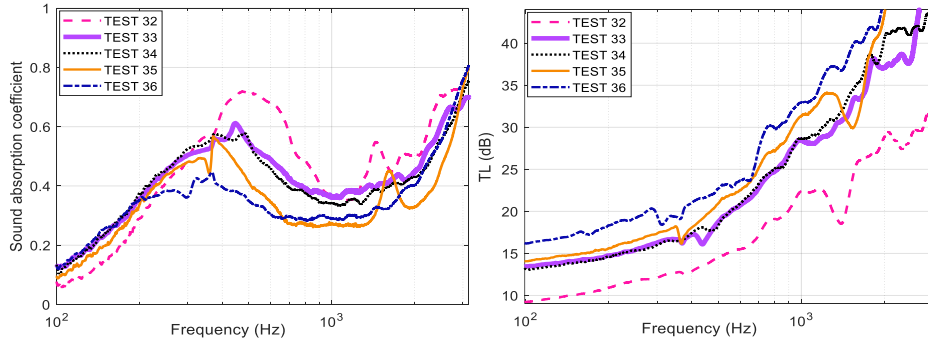


Figure 6. Acoustic properties of samples made of cardboard.

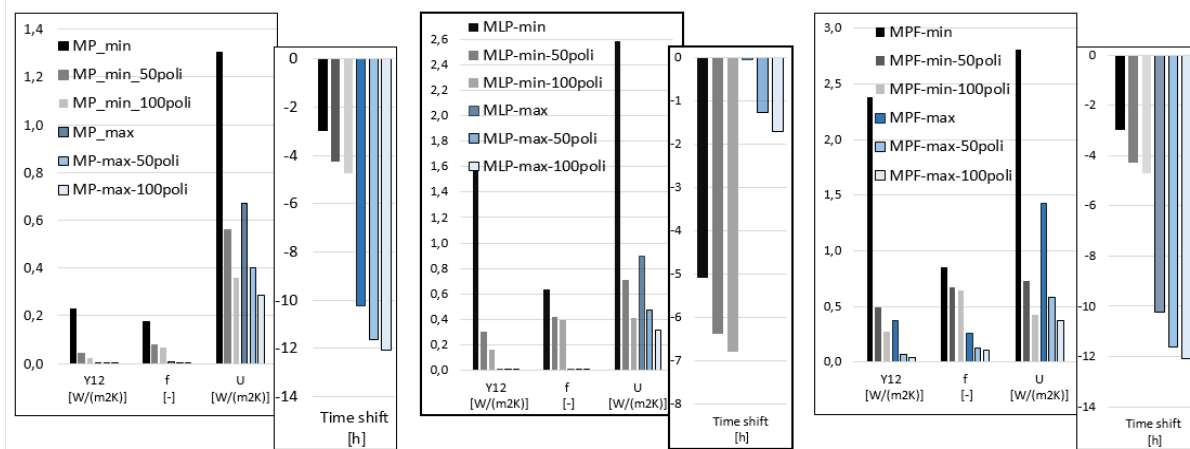


Figure 7. Dynamic thermal characteristics of *MP*, *MLP*, *MPF* wall configurations coupled with the *POLI* additional panels.

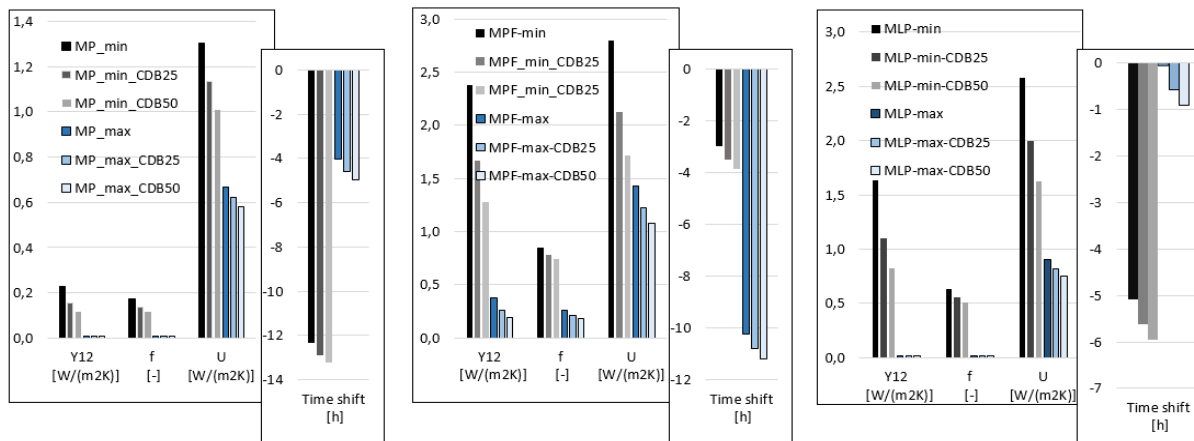


Figure 8. Dynamic thermal characteristics of *MP*, *MLP*, *MPF* wall configurations coupled with the *CDB* additional panels.

The thermal characteristics of *MP*, *MLP* and *MPF* wall configurations with and without the additional insulating panels are shown in Figures 7 and 8. In Figure 7 it can be noted that the addition of the panel *Poli* (made of clothes and cardboard), determines a reduction of Y_{12} , f , and U , whereas the delay of the dynamic thermal transmittance slightly increases in modulus. In particular, a significant reduction of Y_{12} has been obtained with the thicker *100POLI* panel. A significant reduction of U has been obtained for *MPF* and *MLP* wall configurations. For the thicker version of the panel (*100POLI*), the decrement factor f increases of about 2 hours, and for *MP-max* and *MPF-max* the addition of the panel corresponds to a time shift of about 12 hours. Even if the increment of f is limited, the time shift represents a good improvement because the indoor temperature peak takes place when it is possible to cool the indoor ambient naturally, simply opening the windows. In Figure 8 it is shown how the addition of a cardboard layer determines a decrease of Y_{12} , f and U . As regards the time shift f of the dynamic thermal transmittance, the variation is lower than one hour. However, with the same thickness, better performances belong to the panel made of polyester and this is probably due to the fact that this latter has greater density.

4. Conclusions

In this paper the acoustic and thermal performances of several end-of-life household materials have been investigated. From the acoustic point of view, the best compromise between sound absorption

and transmission loss has been obtained for samples made of cardboard, but interesting results have been obtained also for samples made with two egg-boxes, especially in terms of transmission loss. Moreover, it has been shown that higher density clothes ensure a better acoustic performance. Due to the practical difficulties met when manufacturing the samples, which are often non planar, further analysis will be required to investigate how the operators manual skills affect the acoustic performances of the specimens. From the thermal point of view, the installation of panels made of clothes and cardboard respectively determines a reduction of the periodic thermal transmittance and the thermal transmittance. However, due its greater density, panels made of clothes are more effective. This paper shows that end-of-life household materials have a potential for the refurbishment of old buildings from both the acoustic and the thermal points of view. Future works will investigate how the application of these panels can affect the hygrometric behavior of the walls. Moreover, other configurations will be tested acoustically.

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