Analysis of Energy Consumption of a Building Placed in Milan by Adopting Common Building Insulation Materials and Recycled Surgical Masks

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Abstract

The paper analyses using recycled materials for insulation panels, focusing on repurposing surgical masks for building insulation in a circular economy. Since insulation panels made from recycled materials are suitable for use in disadvantaged contexts, dynamic simulations are performed before and after applying the panels in an apartment of approximately 80 m² of floor area, part of a social housing complex in Milan (Italy). The TRNSYS software analysis focuses on the heating season, assessing the impact before and after energy retrofit interventions with an inside application of insulation panels. Additionally, further analyses compare energy savings using commercial insulants like mineral wool and polystyrene. Results show that the reduction in thermal energy demand for heating employing commercial insulants is comparable to the obtained from employing non-commercial insulants. Moreover, the comfort analysis also displays similar results after the employment of commercial and non-commercial insulants.

1. Introduction

The building energy demand share was 30 % of the final energy consumption in Europe in 2021, as stated by the United Nations Environment Program report of 2022 (United Nations Environment Programme, 2022). In the Italian scenario, according to the IEA report about Italian energy policy (IEA, 2024), the energy used in buildings started to decrease in 2017 due to efficiency measures. However, the demand for thermal energy in residential buildings is still high, and the majority of energy consumption is for space heating. A strategy for Energy Retrofitting of the National Building Stock has been issued by the Italian government in March 2021 (MiTE, 2021). It foresees that buildings are expected to contribute 60 % of the annual final energy savings target by 2030. Possible strategies to contain consumption aim to make generation systems more efficient, preferring systems with a low environmental impact, implementing adequate energy management systems, and improving the performance of the building envelope to reduce buildings' dispersion through the external envelope. Alongside the topic of energy efficiency, sustainability has become a key factor in building design, and in general, there is a search for the possible reuse of end-of-life household materials (EoLHM). In particular, after the COVID pandemic, surgical masks have resulted in an environmental pollution issue (Badillo-Goicoechea et al., 2021; Wang et al., 2022; Chowdhury et al., 2021). One innovative approach to enhance building envelope efficiency within a circular

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economy is repurposing waste materials to create insulation panels for construction. This method supports sustainability by reusing materials and can empower individuals in underserved communities to self-produce and install these panels in their homes. A previous work by Rossi di Schio et al., 2024, analysed the thermal conductivity of insulation panels made from surgical masks following ISO standards (ISO 8301, 1991). The results, Table 1, indicate that surgical mask insulation panels have thermal conductivity similar to commercial insulators, especially for sample densities greater than 60 kg/m³ (conductivity values of 0.039-0.052 W/(m K) in the density range between 60 and 90 kg/m³).

Table 1 – Results from experimental tests performed on insulating panels made of surgical face masks (Rossi di Schio et al., 2024)

Test ID	Sample characteristics	Specimen density, ϱ (kg/m³)	Conductivity, λ (W/(m K))
T1*	Masks in an ordered arrangement	90	0.039
T2	Masks in disordered arrangement	90	0.042
T3	Crumpled masks	76	0.052
T4*	Crumpled masks sanitized	60	0.066
T5	Crumpled masks sanitized	70	0.060
T6*	Crumpled masks sanitized	75	0.059
T7	Crumpled masks sanitized	80	0.054
T8	Crumpled masks sanitized	90	0.050
T9	Crumpled masks sanitized treated with flame retardant	60	0.053
T10	Crumpled masks sanitized treated with flame retardant	70	0.050
T11	Crumpled masks sanitized treated with flame retardant	75	0.059
T12	Crumpled masks sanitized treated with flame retardant	80	0.044
T13	Crumpled masks sanitized treated with flame retardant	90	0.052

*Panel characteristics considered in dynamic analysis.

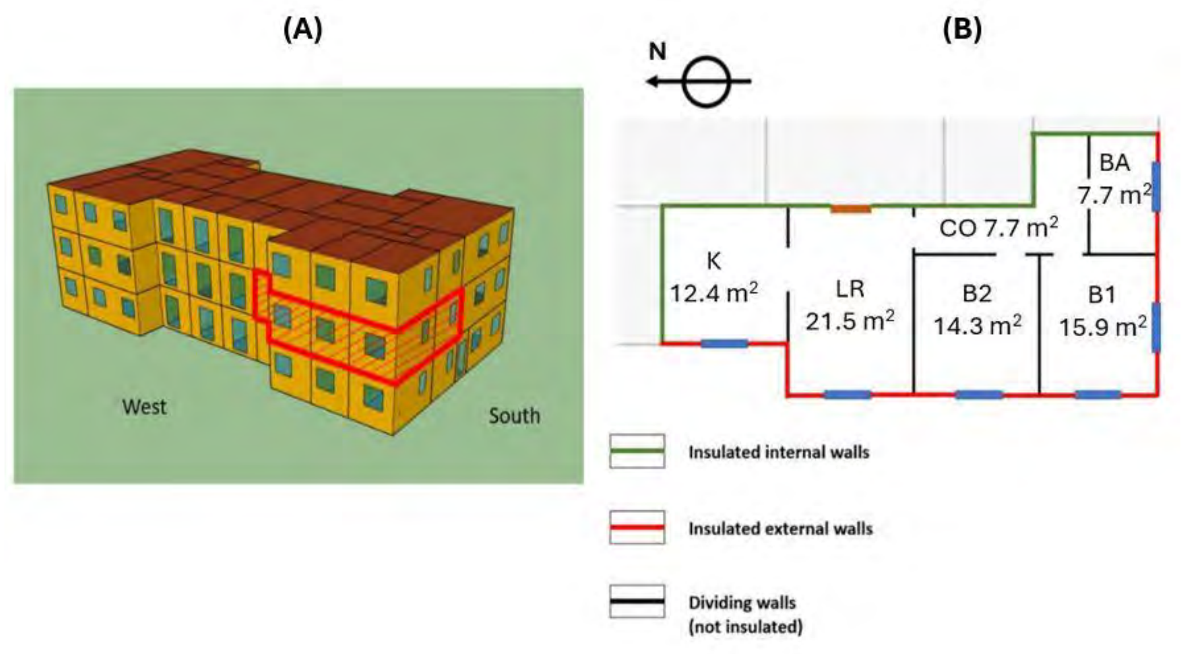

Fig. 1 – Layout of the apartment block analyzed in the dynamic numerical study A) and dimensions of the dwelling B). The apartment consists of six thermal zones, which are bathroom (BA), room 1 (B1), room 2 (B2), living room (LR), kitchen (K) and corridor (CO)

The present work aims to determine the reduction of thermal energy achievable using insulating panels made from reused materials and compare it with commercial insulation panels. Through TRNSYS simulation, the reduction of thermal energy achievable in a residential apartment as a part of a social house in Milan is calculated. Moreover, a comfort analysis is also conducted, determining the value of the comfort indices PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied people) (Fanger, 1970), within the thermal zones of the considered apartment.

Table 2 – Layer characteristics. The elements in yellow concern the post-intervention. Superscripts a, b and c, refer to the experimental results of tests T1, T6 and T4 respectively. s represents the layer thickness, λ is the thermal conductivity, c_t the thermal capacity, ρ represents the layer density, and U is the transmittance of the envelope component

Pre-intervention	Element	s (m)	λ (W/ (m K))	c_t (kJ/ (kg K))	ρ (kg/m³)	Post-intervention
External wall U=1.302 W/(m²K)	Plasterboard	0.015	0.20	1.45	660	U = 0.376[a]/ 0.495[b]/0.533[c] W/(m²K)
	Insulant	0.08	0.039[a]/ 0.059[b]/0.066[c]	0.87	90[a]/75[b]/ 60[c]	
	Internal plaster	0.01	0.70	1	1400	
	Hollow bricks	0.08	0.36	0.8	1000	
	Air gap	0.16	-	-	-	
	Hollow bricks	0.08	0.47	0.8	1000	
	External plaster	0.01	0.90	0.8	1800	
Internal wall U = 1.364 W/(m²K)	Plasterboard	0.015	0.20	1.45	660	U = 0.372[a]/ 0.489[b]/0.525[c] W/(m²K)
	Insulant	0.08	0.039[a]/ 0.059[b]/0.066[c]	0.87	90[a]/75[b]/ 60[c]	
	Internal plaster	0.01	0.70	1	1400	
	Hallow bricks	0.16	0.36	0.8	1000	
	Internal plaster	0.01	0.70	1	1400	
Floor/ceiling U = 0.626 W/(m²K)	Slabs	0.01	1.00	1	2000	U = 0.626 W/(m²K)
	Light concrete	0.15	0.21	0.8	800	
	Concrete	0.05	1.14	1	2400	
	Hollow bricks	0.20	0.36	0.8	1000	
	Internal plaster	0.01	0.70	1	1400	
Partition wall U = 1.958 W/(m²K)	Internal plaster	0.01	0.70	1	1400	U = 1.958 W/(m²K)
	Hollow bricks	0.08	0.36	0.8	1000	
	Internal plaster	0.01	0.70	1	1400	

2. Materials and Methods

The building is analyzed through dynamic simulations performed with the commercial software TRNSYS 18 (Klein et al., 2017), and it is located in Milan (lat. 45°28′01″ N, long. 9°11′24″ E). Weather data are provided by the Meteonorm database (Meteonorm, 2024).

The dynamic analyses aim to determine the thermal demand of the building during the heating season in the presence of various types of commercial and non-commercial insulators applied to the external walls and adjoining unheated spaces. The non-commercial insulators are made from reused materials. Specifically, in previous work, the authors analyzed the possibility of employing reuse materials (specifically surgical face masks) to create insulating panels that can be employed in construction. As reported by (Rossi di Schio et al., 2024), the thermal conductivity of cardboard panels filled with surgical masks in different configurations was determined: the thermal properties were analyzed considering different panel densities, in the range of 60-90 kg/m³, changing the arrangement of the masks in the cardboard box (ordered and disordered, crumpled masks), and finally, the thermal conductivity obtained following sanitation performed by high-temperature washing in a dishwasher and after the application of a commercial flame retardant (FEUERFEST® Fire protection impregnation for textiles, DIN 4102) was analyzed. The results obtained are reported in Table 1. It is observed that, in general, for the same treatment or type of sample, there is a decrease in conductivity as density increases. Moreover, the thermal conductivity tends to increase for the same density, following sanitation and the application of the flame retardant. This aspect is due to the residual moisture in the material that increases following the treatments (Wang et al., 2023).

3. Setting of the Analysis

A dynamic numerical analysis was performed using TRNSYS software to assess the possible energy saving achievable when panels made of surgical face masks for building insulation are used. According to Fig. 1, the analyzed apartment is on the first floor of a building block in Milan (Italy). It is approximately 80 m^2 and consists of six thermal zones. The building characteristics are summarized in Table 2, and they are typical of the Italian building's heritage, which was realized between 1970 and 1990 (Ballerini et al., 2022). The standard heating season goes from the 15th of October to the 14th of April, with 2404 heating degree days and a winter design temperature of -5 °C, while the hourly and mean monthly outdoor temperature refers to the Meteonorm database (Meteonorm, 2024). The Energy Performance Index for Heating (EPH), the predicted mean vote, and the predicted percentage of dissatisfaction (ISO 7730, 2006) estimated in the different scenarios have been compared.

Six scenarios have been analysed in which different panels have been installed indoors, as reported in Table 3. Scenario S1 is the pre-refurbishment reference case, and scenarios S2-S4 refer to insulating panels made of surgical face masks. In contrast, the last two scenarios consider commercial insulating materials made of mineral wool (scenario S5) and polystyrene (scenario S6). The insulating panel thickness s was set at 0.08 m, while density ϱ and thermal conductivity λ varied according to Table 3. The position of the insulating panels is shown with a red (insulated external walls) or green line (insulated internal walls) in Fig. 1B): the panels have been installed indoors on the vertical walls, and they are coupled with a plasterboard layer 0.01 m thick. All the external and internal walls that separate the apartment from the stairwell and other properties have been insulated.

The heating system consists of a boiler (with an output power of 20 kW) connected to a storage tank 0.1 m^3 and five radiators installed in the different thermal zones (except for the corridor). The radiators, whose characteristics are listed in Table 4, are three-column cast iron terminals whose flow rate is controlled by thermostatic valves.

Table 3 – Characteristic of the panels for the intervention. For the panels made of surgical face masks, the specific heat value has been determined by comparing values in the literature and related to fibrous materials (FLUM ROCK, 2024)

Case	Type of panel	U external wall (W/m²K)	U internal wall (W/m²K)	Insulating panels		
				ρ (kg/m³)	c_t (kJ/(kg K))	λ (W/(m K))
S1	Reference case	1.302	1.364	-	-	-
S2	Masks panels	0.376	0.372	90	0.87	0.039
S3	Masks panels	0.495	0.489	75	0.87	0.059
S4	Masks panels	0.533	0.525	60	0.87	0.066
S5	Mineral wool	0.339	0.336	90	1.03	0.035
S6	Polystyrene	0.347	0.343	20	1.45	0.036

Table 4 – Radiator surface area and thermal power output, considering an input/output temperature difference of 60 K

Thermal zone	Power output (kW)	Radiator surface area (m^2)
B1 - Room 1	3.70	1.19
B2 - Room 2	1.90	0.63
LR - Living room	3.15	1.00
K - Kitchen	2.45	0.81
BA - Bathroom	2.45	0.81

The radiators and the thermostatic valves are modelized employing 320 e 362 (Holst, 1996); in particular, type 362 allows modelling the radiator with a first-order model, and in this way, it also takes into account the transient and dynamic effects that occur when the radiator is turned on and off.

The water temperature setpoint is 70 °C for the boiler outlet, 20 °C for the thermal zones from 6:00 a.m. to 11:00 p.m., and 18 °C at night. The bathroom temperature setpoint is 24 °C during the day and 18 °C at night. The temperature of adjacent apartments is 20 °C, while that of the building block entrance, stairwells, and hallways is determined by the software. The windows mean transmittance (considering both glass and frame) is 2.83 W/(m^2K). The internal gains refer to four occupants, and electrical equipment is selected by the IEA SFH Task 44 (Dott et al., 2013). For all the thermal zones, the air change rate is 0.5 h^{-1}. The building was simulated using type 56 (Klein et al., 2017), and the simulation time step was set to 10 s.

4. Result and Discussion

The estimated EPH values obtained from dynamic simulations are compared in Table 5 along with the annual thermal energy demand reduction (in comparison to case S1 without additional insulation): the presence of insulating panels made of masks (scenarios S2-S4) leads to an energy demand reduction between 39 % and 48 %. The energy consumption is reduced by 3586 kWh in scenario S2, comparable to the values determined for scenarios S5 and S6 with commercial materials due to the insulating panels' comparable thermal conductivity.

Table 5 – Annual results obtained by the simulations: thermal energy demand of the apartment ET, annual apartment energy demand related to the floor area (79.86 m2) EHH, and energy demand reduction of cases S2-S6 with respect to case S1

Scenario	ET (kWh)	EPH (kWh/m^2y)	ET reduction (kWh)
S1	7756	97.1	-
S2	4170	52.2	3586 (46.2 %)
S3	4586	57.4	3170 (40.9 %)
S4	4712	59.0	3044 (39.2 %)
S5	4070	51.0	3686 (47.5 %)
S6	4095	51.2	3661 (47.2 %)

The mean radiant temperature and the internal and external surface temperature for thermal zone K (kitchen), referred to as the coldest day of the heating season, are shown in Fig. 2. According to Fig. 2, the presence of the insulating panels yields an increase in the surface temperature: the temperature in the kitchen is very similar for cases S2 and S5, while, for case S1, it remains below 20 °C till 8:00 am.

The predicted mean vote (PMV) and predicted percentage of dissatisfaction (PDD) indexes have been determined and represented in Fig. 3. The PMV is calculated using the empirical model proposed by Fanger (1970): it represents the average vote expressed by the occupants based on their thermo-hygrometric comfort perception.

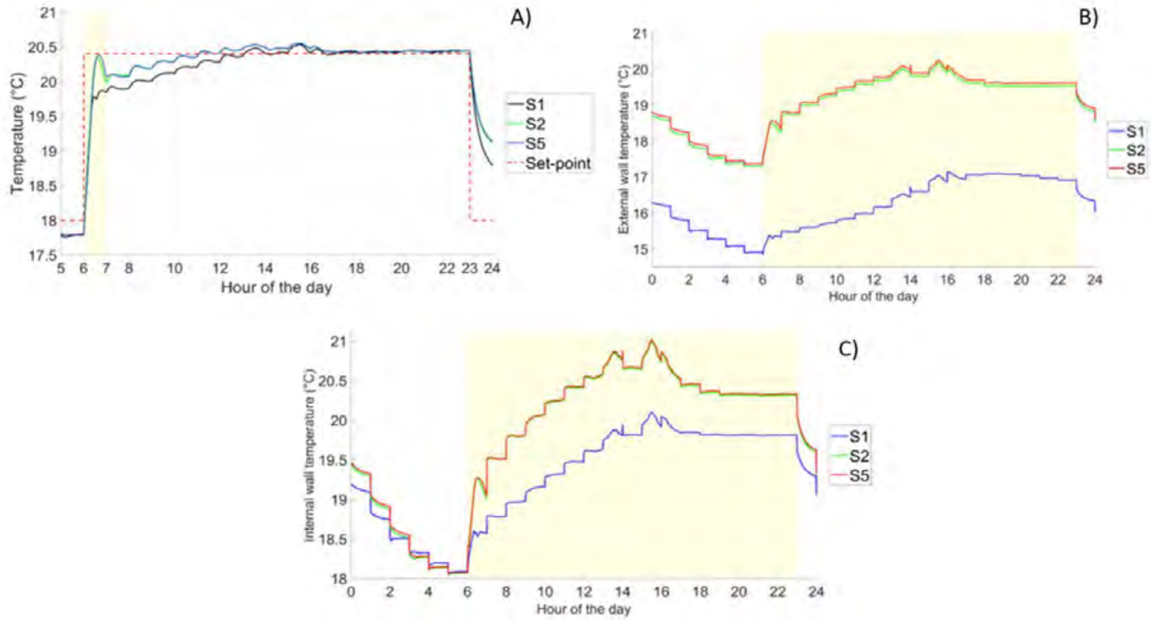

Fig. 2 – Air temperature estimated for thermal zone K (kitchen) in scenarios S1, S2 and S5 on the 15th of January A), and temperature of the external B) and internal C) walls. The set point temperature is 20 °C in the period detected in yellow. The internal wall considered divides the kitchen from a stairwell of the apartment block, which is an area of the building that has no heating system, while the external wall faces West

Feeling very cold is rated -3, while feeling extremely hot is rated +3; 0 indicates a neutral condition. The PPD index indicates the percentage of people who would express dissatisfaction. Hourly data has been calculated by averaging daily data along the heating season for three thermal zones: the bathroom (BA) and the two rooms (B1 and B2). Air velocity is set at 0.1 m/s, clotting factor at 1 Clo (representative of complete wintertime clothing) and metabolic rate at 1.1 Met. In contrast, the air temperature, the mean radiant temperature and the humidity ratio for the calculation of the PMV are determined hourly by the dynamic simulation. Fig. 3 shows that the PDD increase is higher in room B1 than in room B2 because the two zones have different exposition to the external ambient since B1 presents two vertical walls exposed to the outside air, while room B2 only has one. Therefore, insulating panels of surgical face masks (scenario S2) or rock wool (scenario S5) lead to greater thermal comfort, as expected. Moreover, for all the considered cases, the PDD is higher during the first hours of the day due to the heating system set-point change from 18 °C to 20 °C: the set-point temperature is reached in one hour in almost all the thermal zones.

Considering PMV values averaged only during the heating season when the system is operational (6:00 a.m. - 11:00 p.m.), values in room B1 were -0.63 for the uninsulated case, while results were -0.53 for scenario S2 and -0.50 for scenario S5. Similar values were obtained for the other room (B2), which were -0.61, -0.54, and -0.53, respectively. In the bathroom, the values were all close to thermal neutrality, with 0.00 for S1, 0.09 for S2, and 0.12 for S5.

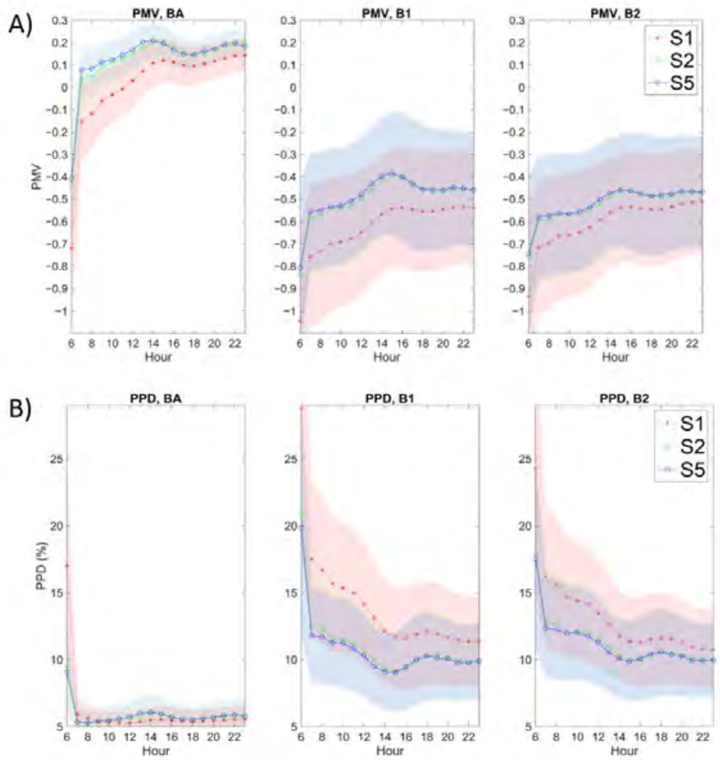

Fig. 3 – The PMV A) and PPD B) indexes estimated for the bathroom (BA), room 1 (B1) and room 2 (B2). The values are the mean of the daily hour data determined along the heating season. The colored area represents the standard deviation

5. Conclusion

This dynamic analysis presents the energy savings achievable following insulating panels made from reused materials in a residential building located in Milan, Northern Italy; specifically, the analysis concerns the use of insulating panels for building insulation composed of surgical face masks.

The dynamic analysis concerns 6 different scenarios: the same apartment (part of a condominium) designated as a social house was analysed using the TRNSYS package before the installation of insulating panels and then, after the application of both commercial and non-commercial insulating panels (panels made of surgical face masks). The main findings are:

- The dynamic analyses conducted using panels with face masks reduced the energy required to heat the building, ranging from 39.2 % to 46.2 % compared to the apartment without insulation.
- The dynamic analyses ran considering instead commercial insulating materials applied to the same building led to a reduction in the thermal energy required for heating equal to 47.5 % and 47.2 % in the case of rock wool and polystyrene, respectively.
- The comfort achievable inside the rooms following commercial insulators is similar to that obtained using panels formed from surgical face masks.

The dynamic analyses show that the annual reduction in energy required for heating the considered apartment in the case of commercial insulators is similar to that achievable using insulated panels formed with reused materials if these have a density equal to or greater than 90 kg/m^3. Future developments will include the analysis of the thermal demand for cooling pre- and post-intervention and the analysis of further reusable materials that are employable in construction.

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