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Waste Recovery and Thermal Analysis of Refurbished Buildings' Walls: The Sustainable Big Bag

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Abstract: The construction sector has a high environmental impact, especially due to C&D waste. At the same time, the increase in the temperature of the Earth's surface due to pollution requires interventions on the built environment, aimed at improving the performance of the envelope in hot climates. In the literature, there are studies on components to increase thermal efficiency, but they are limited by long or expensive production processes or high environmental impact. This research considers Italy as a reference area. The aim of this research is to design, prototype, and verify a sustainable component to be included in the stratigraphy of light mass vertical closures to increase their heat capacity that allows for the reuse of C&D waste and the optimization of site operations both in the selective demolition phase and in the redevelopment phase of the building. The method follows the following phases: analysis of the type of waste from C&D, analysis of international best practices, analysis of the possibilities of intervention on vertical closures according to the pre-existing structure and choice of cases of greatest scientific interest, design of the sustainable big bag by reusing inert materials from selective demolition and recycled polypropylene fabrics, prototyping and verification by laboratory tests, and software analysis to verify the thermal advantage. The use of the sustainable big bag allows for construction advantages, facilitating site operations both in the construction and waste disposal phases, energy advantages by improving the heat capacity of the envelope, and increases in the sustainability of the intervention through the reuse of waste materials.

Keywords: solid wall; heat capacity; brick; selective demolition; circular chain

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1. Introduction

More than 30% of the EU's environmental footprint comes from buildings, and C&D (construction and demolition) waste is the largest waste stream, excluding extractive waste [1]. Waste from the construction sector can be caused by anthropogenic interventions such as the redevelopment of heritage or armed conflicts or by natural causes such as earthquakes and floods. In the latter case, the increase in intense atmospheric events is also linked to increased temperatures due to environmental pollution, thus generating a vicious circle [2]. Confirming the importance of the topic and the speed with which the scientific debate is evolving, the European Union in August 2024 republished the protocol for the management of C&D waste, introducing new guidelines for "pre-demolition and pre-renovation audits", i.e., investigations before demolition or renovation [3]. Strategies aimed at reducing C&D waste are debated in the literature; among all, the selective demolition and circularity of materials/components of the supply chain prevail. In this regard, some studies deal with deconstruction in the various phases of the building life cycle: the design phase ("Architectural Design for Deconstruction (DfD)" and "Structural DfD"), the end-of-life (EoL) phase ("Planning for Deconstruction (PfD)" and "Post-deconstruction"), and the second-life phase ("Second-life Performance") [4]. Some studies analyze and compare, also using LCA, the impact of the various possible scenarios for the ecological treatment of C&D waste, emphasizing the impact of the transport sector [5–7]. Other studies analyze the performance of materials obtained through the reuse/recycling of C&D waste, focusing on sustainable concretes [8,9]. Some studies highlight the convenience of reusing building elements from post-earthquake selective demolition operations as a secondary raw material in post-disaster areas, also with the help of cloud databases, such as Digital Material Bank (DMB) [10–12]. Due to environmental pollution, in particular greenhouse gas emissions, the average temperature of the planet has already increased by 1.5 °C compared to the temperature of the pre-industrial period, and an increase of about 2–3 °C is expected by 2100 [13]. According to the UCCRN report, currently, in 350 cities around the world, for at least three months of the year, there are maximum temperatures that do not fall below 35 °C. By 2050, the number of cities will become 970 [13]. This analysis is also confirmed by a study by ETH Zurich [14], which indicated that in 2050, cities will have the climates that cities located about 1000 km further south currently have. If the current pollution trend remains unchanged compared to the pre-industrial situation 300 years ago, the average temperature experienced by humans in 2070 will increase by about 7.5 °C, about 2.3 times the average increase in global temperature, and in 19% of the Earth's surface, an average annual temperature of more than 29 °C will be experienced (a situation currently present in only 0.8% of the Earth's surface and mainly in the Sahara) [15].

However, some studies show that it is difficult to predict the impact of pollution on human well-being [16,17] and that there are possibilities for local adaptation, which, if sufficient resources are present, could enhance the effects [18].

It is therefore essential to act in parallel. On the one hand, it is necessary to limit the environmental impacts due to the construction sector and in particular to the waste supply chain, with strategies and actions aimed at increasing the sustainability of the construction site. At the same time, it is necessary to redevelop the built heritage by making their envelopes energy-efficient, in particular in response to the exacerbation of extreme hot climates. In this way, it will also be possible to create "thermally safe" buildings.

In the literature, there are studies on components to increase thermal efficiency, but they are limited by long or expensive production processes or high environmental impact. In fact, the heat capacity of the current building envelope is increased through massive systems or PCM (phase change material). Among the massive systems, studies concerning the use of raw Earth-based materials [19–21] recur, such as the case of compressed Earth blocks (CEB) [22], which, while emphasizing the excellent thermal performance, impose a wet construction technique with an impact on the timing and phases of the construction site. There are also studies concerning the thermal masonry blocks that show that it is possible to decrease the temperature of the internal air by 3.8 °C and 4.4 °C, respectively, in spring and in summer compared to the lightweight one, but at the same time, these systems require processes that are often energy-intensive both in the production phase and at the end of life [23]. On the other hand, PCMs, even if they have a high capacity for the accumulation of latent thermal energy and temperature stabilization, present problems such as fire risk, potential toxicity, pollution, reduced mechanical performance, and higher initial costs [24–26].

The research goes beyond existing studies by defining a component to increase the thermal inertia of the vertical envelope with a dry, fast, and low-cost construction process that reuses demolition waste without the need for reprocessing. The use of this component integrated in the vertical wall improves thermal inertia while generating economic and logistical advantages and increasing the sustainability of the building and site.

2. Method

This study is focused on Italy, both because it has a building stock with about 50.2% [27] made up of non-valuable buildings built between the years 1960 and 1990 that, due to obsolescence, need redevelopment interventions and because, in the last 10 years, it has been subject to about 950 calamitous events [28], which, by damaging the assets, have generated large quantities of waste from C&D. It is, therefore, an area that allows us to experiment with the applicability of research when C&D waste is generated both anthropologically and by natural disasters, giving rise to different characteristics of the waste, which amply cover the field of applicability of the research. The proposed method can also be replicated in places that have typological and quantitative affinities with the type of waste and climatic analogies with Italy.

The aim of the research is, therefore, to design, prototype, and verify a sustainable component to be included in the stratigraphy of light mass vertical closures to increase their heat capacity and overcome the current state of the art via quick and easy to build, environmentally friendly, and low cost options. The reuse of C&D waste without further reprocessing operations and through a dry system provides economic gain, sustainability, and the optimization of site operations both in the selective demolition phase and in the redevelopment phase of the building.

This research was carried out following a method in phases, as identified below (Figure 1):

- Qualitative and quantitative analysis of C&D waste in Italy, using officially recognized Italian national databases. The analysis is necessary to identify which product fraction is prevalent and what its material and dimensional characteristics are.
- Analysis of international best practices. Best practices are identified both for the reuse of waste derived from C&D and for the reuse of components with characteristics similar to those of the product fraction identified as prevalent.
- Analysis and typing of case studies of interventions on vertical closures according to the pre-existence and definition of the cases of greatest scientific interest.
- Definition of the minimum performance above the minimum values required by the legislation.
- Component design and small-scale prototyping.
- Laboratory checks using a climatic chamber to verify the non-impact of grain size variation on thermal results and a software analysis, which allows for quantitatively verifying the thermal advantage that can be obtained. If sufficient performance is not obtained, the design and prototype are varied, and the relevant checks are carried out again until satisfactory values are reached.

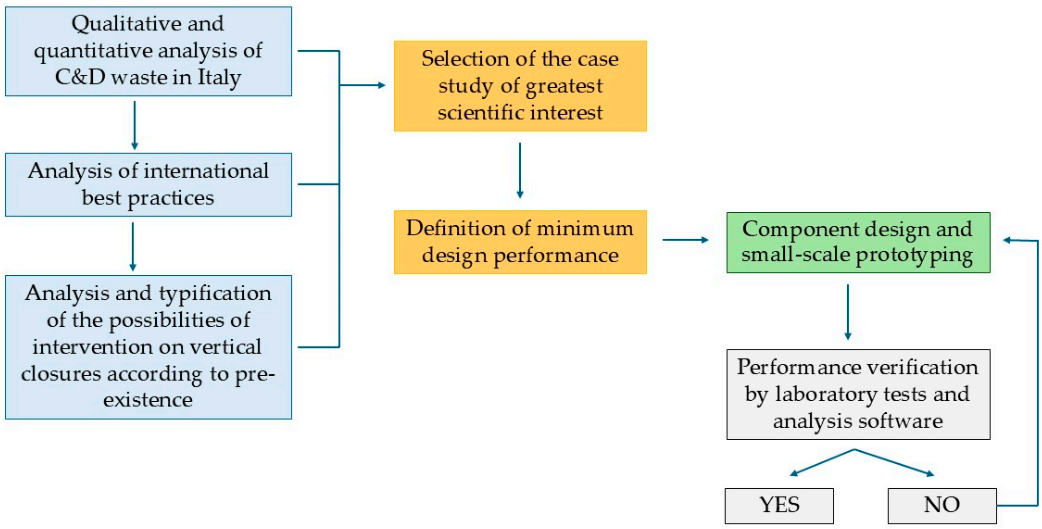


Figure 1. Phases of the research method.

3. Preliminary Analysis

3.1. Typological and Quantitative Analysis of C&D Waste in Italy

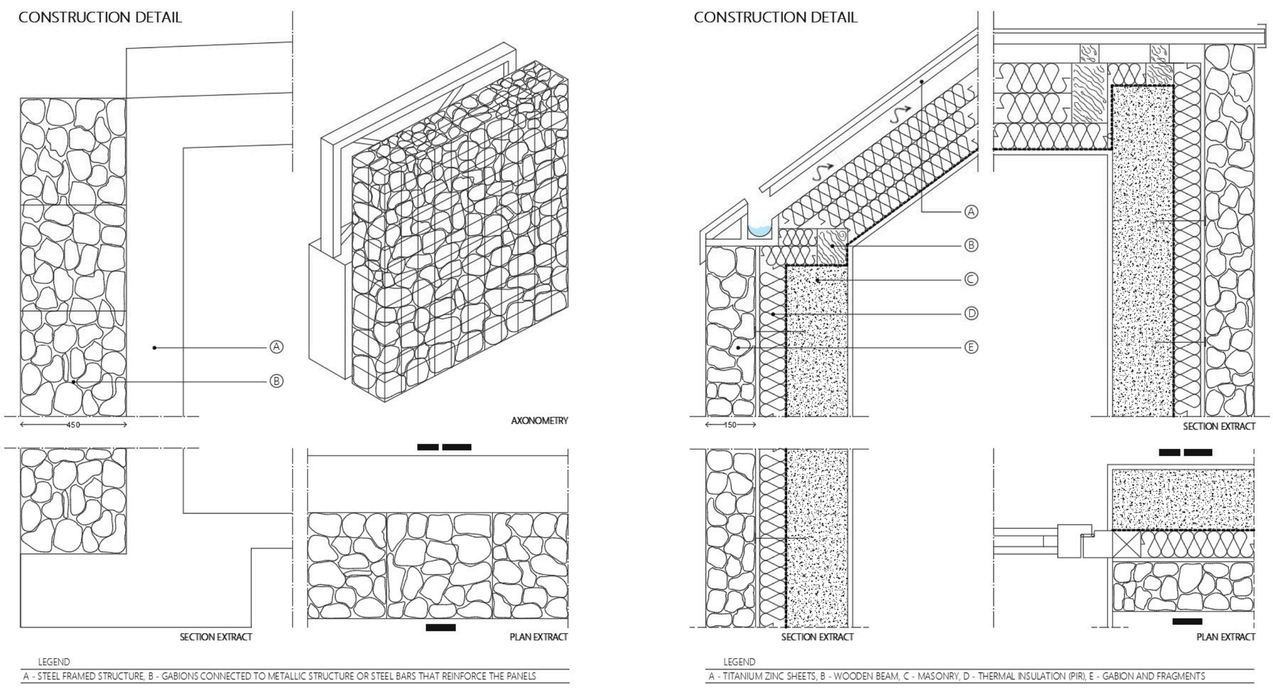
The analysis of the data shows a growing trend in the construction sector starting from 2021, also in consideration of the government incentives provided for the sector in recent years, aimed at the energy requalification of the buildings in question. These construction/renovation activities, as well as the continuation and start-up of public works, have led to significant environmental impacts in terms of greater quantities of waste produced. The total production of waste from construction and demolition operations, excluding earth, rocks, and dredging materials, amounted to almost 59.4 million tonnes (+18.4% compared to 2020, corresponding to 9.2 million tonnes). Material recovery, totaling almost 47.6 million tonnes, recorded an increase of 21.7%, corresponding to almost 8.5 million tonnes. Mineral waste therefore represents a percentage equal to about 88.8% of all waste produced. Their main form of recovery is their transformation into fine or coarse aggregates that can be used in the production of concrete or asphalt or in the construction of roads. Table 1 below shows the percentage of waste from construction and demolition operations, consulting the ISPRA Database [29].

Table 1. Percentage of waste from construction and demolition operations.

Aggregation of the Waste Categories Referred to in Annex 1, Point 2 of Regulation (EC) No. 2150/2002 (Codes EER 17)	**Aggregation of Economic Activities According to the NACE Rev. 2 Classification Under Regulation (EC) No. 1893/2006 F: Construction**	
	Production	**Preparing for Reuse/Recycling**
Voice Description	**Tons**	**Tons**
6.1 Ferrous metal waste	4,952,316	4,411,731
6.2 Non-ferrous metallic waste	423,660	314,966
6.3 Mixed metallic waste, ferrous and non-ferrous	228,023	179,798
7.1 Glass waste	104,216	91,430
7.4 Plastic waste	53,985	38,392
7.5 Wood waste	293,117	264,428
12.1 Mineral waste from C&D	53,340,326	42,270,588
National total	**59,395,643**	**47,571,333**

3.2. Analysis of Best Practices

From waste to resource, from resource to reuse in new contexts: The recycling of inert material, whether stone or brick, is gaining more and more space in the different architectural types that characterize our living environment. Reuse takes place mainly through metal gabions, inside which aggregates with different degrees of integrity are inserted. These elements are used as retaining or retaining walls or as finishing elements of the building envelope. There are international best practices that highlight the use of gabions filled with aggregates mainly as an external finishing layer (Figure 2). One of the best practice examples is the Moueix family's winery in Napa Valley, designed by Studio Herzog & De Meuron, in which metal gabions filled with stone material (although not reused) are used for thermal control and natural lighting of the space [30], or the "House in the Land scape" located in Za Wierce and designed by Studio Kropka, in which metal gabions with lithic filling are used with an aesthetic function as a layer finishing of the envelope to recall the construction culture of the place [31]. The use of aggregate-filled metal gabions on the casing allows for mass change, air tightness, and light permeability to be managed.



(**a**) (**b**)

Figure 2. Construction details: (**a**) Moueix family's winery; (**b**) "House in the Land scape".

3.3. Analysis of the Intervention Cases

The Italian and global heritage built heritage are mainly characterized by reinforced concrete framed buildings and brick load-bearing masonry buildings. Consequently, the reuse of the commodity fraction depends on the type of building. Therefore, three design possibilities were analyzed, considering the increase in mass, air tightness, and light permeability (Figure 3):

- Case A. Positioning of the new envelope outside the load-bearing structure of the existing building. Regardless of the load-bearing structure (whether it is framed in reinforced concrete or load-bearing brick masonry), the new envelope can be positioned outside the pre-existing structure. This design hypothesis has several disadvantages:

low lightness, low stability, difficulty in assembly and management, and lack of intrinsic and environmental requirements.

- Case B. Positioning of the new envelope within the load-bearing structure of the existing building. Although this type offers advantages such as ease of assembly and excellent environmental requirements, the disadvantages are numerous: loss of internal cubic meters, lack of stability, difficulty of management, and lack of environmental requirements.
- Case C. Positioning of the new envelope equal to the pre-existing one. The advantages are numerous: greater stability, ease of assembly and handling, and optimal intrinsic and environmental requirements.

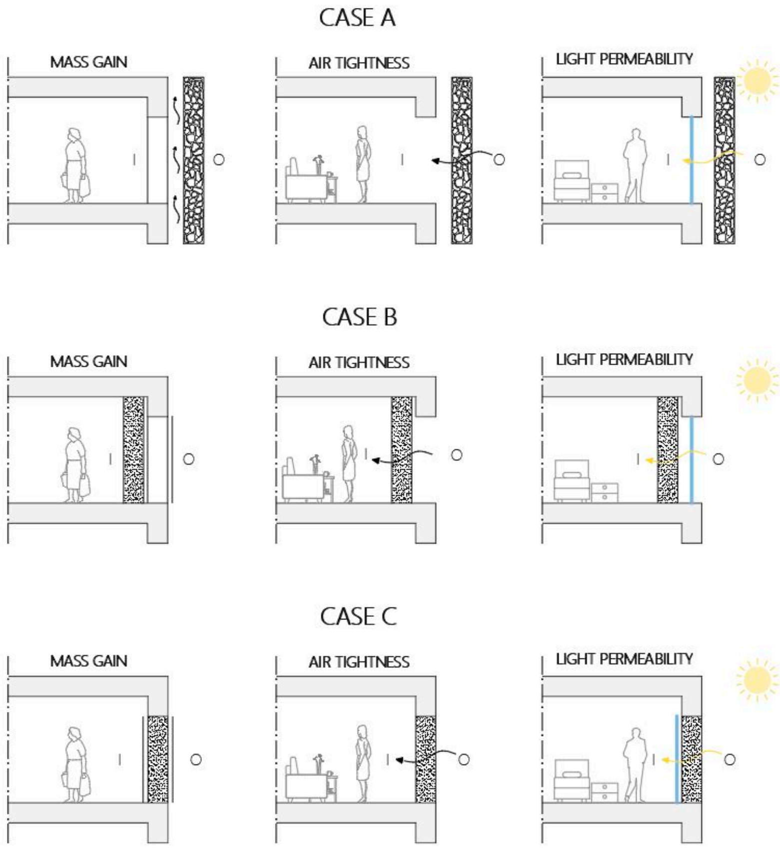


Figure 3. Cases A, B, and C analyzed with respect to mass gain, air tightness, and light permeability.

Case C is the one that has the greatest advantages from a construction point of view and allows for any constraints due to the maintenance of the shape of the pre-existing building to be overcome. Therefore, the field of investigation of this research is limited to the design of a sustainable component that can be inserted into the envelope in a position similar to the pre-existing envelope and thus optimizes the mass.

4. Results

The analysis of international best practices (Section 3.2) has highlighted the reuse of inert material inside gabions mainly as an external finishing layer of the envelope in new buildings. On the other hand, the analysis of the design possibilities of intervention has shown that when it comes to the redevelopment of the built environment, the positioning of thick elements (such as gabions filled with aggregates) outside or inside the pre-existing load-bearing structure has numerous disadvantages. Therefore, the present research's aim is the design and prototyping of a component to be inserted into the stratigraphy of the recovered envelope in a position similar to that of the pre-existing one and increases the mass of the vertical closure in the case of buildings with a reinforced concrete framed structure. This component is therefore one of the layers of the vertical closure that serves the purpose of managing the mass of the envelope and must be integrated with other functional layers to achieve the other performances (thermal, water and air tightness, etc.).

4.1. The Sustainable Big Bag Project

The Sustainable Big Bag consists of a polypropylene bag anchored to the pre-existing reinforced concrete beam and filled with aggregates derived from selective demolition carried out on the same site or on neighboring sites (Figure 4). To facilitate assembly operations, the bag has a height of 2.4 m (equal to the Italian standard distance between the lower and upper slabs) and a width and length of 18 cm. These dimensions allow for adaptability to the pre-existing structure and, at the same time, allow for easy handling of the component but can be customized according to the building on which work is being carried out. Each bag is equipped with eight ring straps, four of which are lower and four higher for anchoring to the pre-existing structure and, among them, four are functional straps for filling and positioning the big bag. The bags are positioned vertically to one another in order to minimize thermal discontinuities in the wall. The structural stability of the bag is guaranteed by the tensile strength of the polypropylene and by the filling with compact aggregates, which ensure uniform weight distribution and solid anchoring to the pre-existing structure. Polypropylene bags are used on site for the storage of rubble but have small dimensions which allows for their handling; therefore, the companies in the area are already equipped with a know-how that allows their production. Polypolypropylene is also a material resistant to tearing by cutting that is well suited for containing rubble, which has an irregular and often sharp profile. In fact, polypropylene is a sustainable choice for the production of bags thanks to its mechanical resistance, lightness (density 0.9 g/cm^3), and recyclability (code 5). PP woven fibers are breathable, waterproof, and durable, ideal for repeated use. Although they are not biodegradable, responsible management can optimize its environmental impact. Therefore, the choice of the polypropylene bag represents a compromise between technical performance and environmental sustainability.

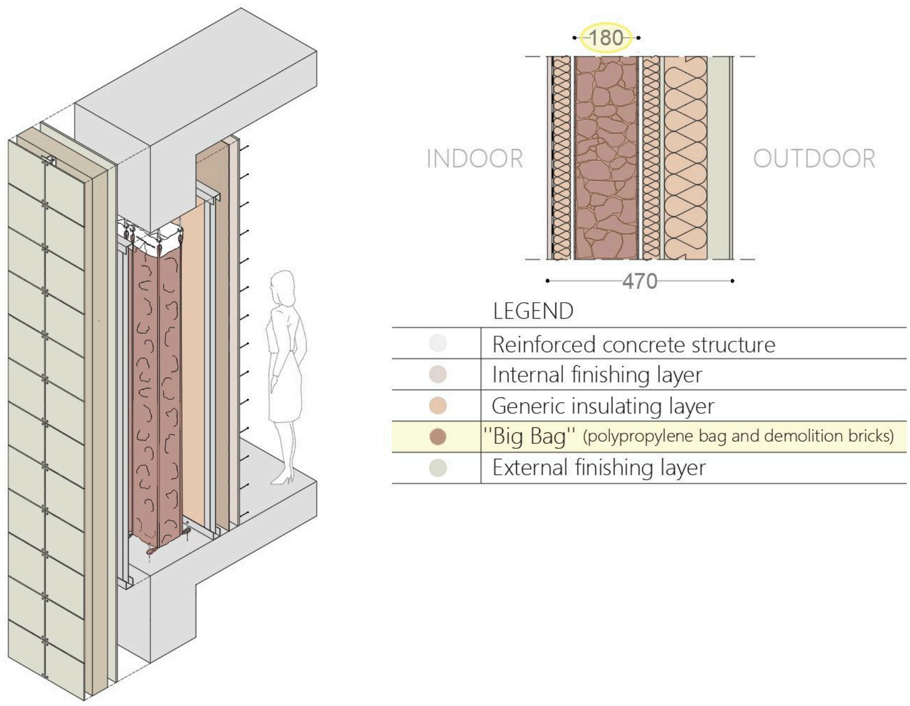


Figure 4. Sustainable big bag and its technical details in a standard vertical closure.

The durability of the polypropylene "big bag" can vary depending on several emblematic factors such as environmental conditions (exposure of the bag to high and low temperatures, humidity, freeze–thaw cycles, or direct sunlight), or storage and transport conditions. Whereas during production, the "polypropylene bag big" is placed in a controlled environment and is not exposed to atmospheric agents, during real use, storage will take place inside the construction site, on the floor or at the foot of the building; depending on whichever is the more suitable and optimal procedure for that specific intervention, its durability will be suitable for its specific use. Furthermore, these fundamental and essential aspects can be addressed by adding special stabilizers (additives added preliminarily during the process of polymer production) to help prevent degradation of the fabric.

4.2. Construction Phases and Sustainable Construction Site

The sustainability of an intervention depends on many factors: the first is a correct and shared planning that provides the design of a procedural process that guarantees compliance with contractual times. Through the application of the EU regulatory framework and in compliance with DNSH ("Do No Significant Harm") [32], it is possible to achieve sustainability. These European objectives can only be achieved when the project and the construction site have a close interaction, as the foundations of the elements of sustainability concerning the three dimensions—environmental, economic, and social—are already laid out in the design phase. The construction site is a work area where the construction, renovation, and demolition of buildings with different uses take place. The set-up phase is the main phase, which distinguishes it and determines the final success of the work. Security and organization are some of the main objectives to take into account. Depending on the pre-existing structure and the type and quantity of inert waste derived from the demolition operations, it is possible to make sustainable big bags at the foot of the building and then move them to the floor or make them directly on the floor where they will be mounted.

In the case of the construction of sustainable big bags at the foot of a building, after demolition and material selection operations, the aggregates are placed inside the polypropylene bags, through two different processes. In the first procedure (Figure 5), the rubble conveyor already present on the construction site is used directly, while in the second (Figure 6), the wheel loader is used. The latter, thanks to its conformation, throws the material into the bags positioned vertically and supported by a special steel frame that prevents overturning and facilitates the filling operation.

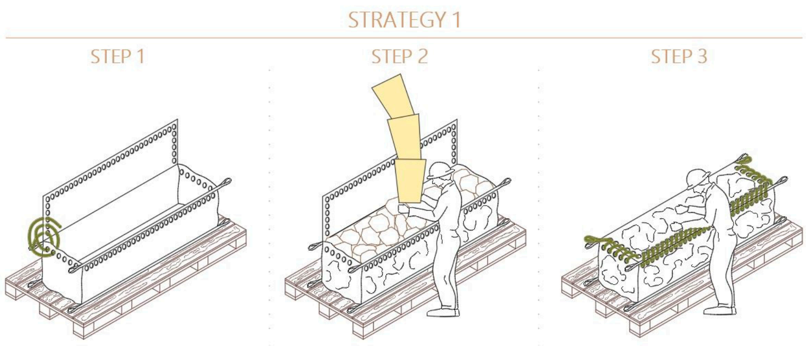


Figure 5. Strategy 1 for the construction site at the foot of the building.

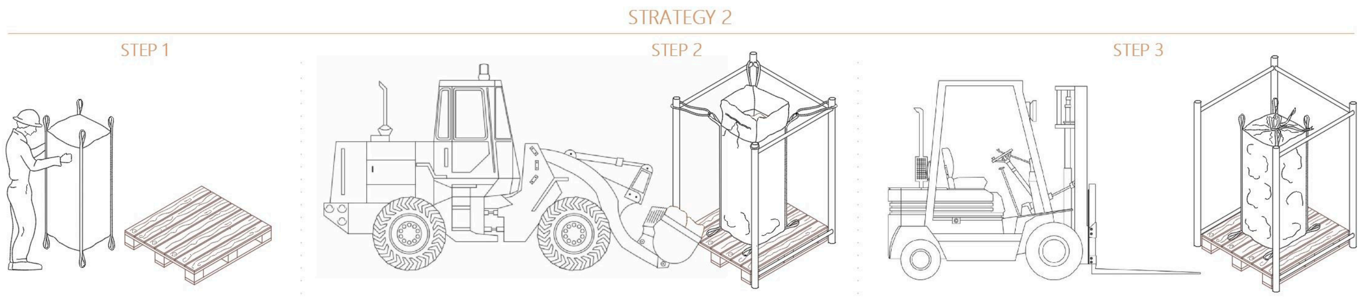


Figure 6. Strategy 2 for the construction site at the foot of the building.

Subsequently, the filled bags will be transported by a forklift to the point of interest and then lifted by a crane to the floor, subject to intervention (Figure 7). The case of the construction site at the foot of the building is less sustainable than that on the floor, as it uses a mechanical means of transport for filling the bags with demolition bricks, as well as for moving and lifting them to their designated height. Therefore, although the handling of demolition material takes place within the construction site, the time and costs related to each operation increase.

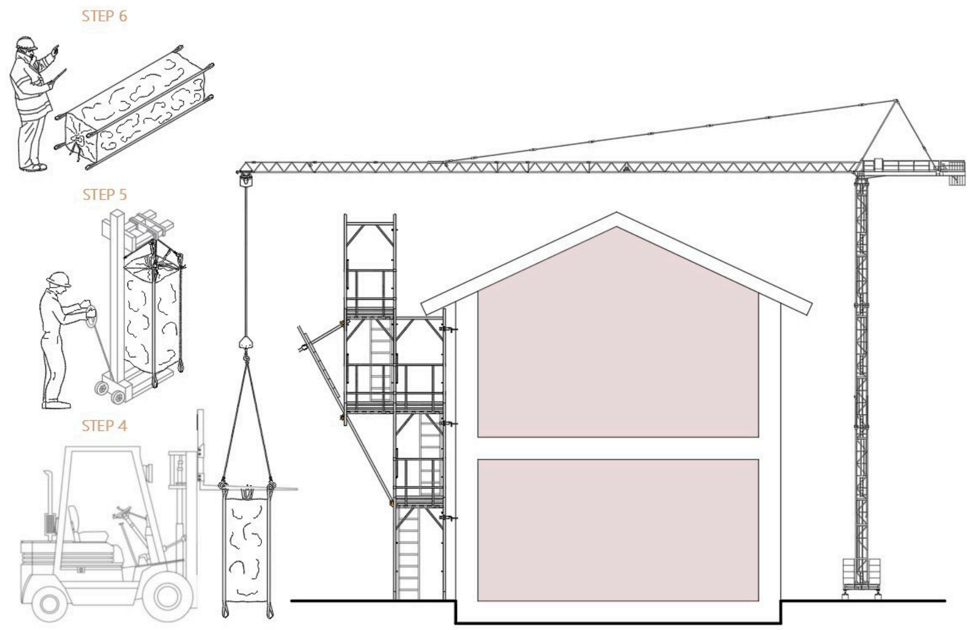


Figure 7. Handling and lifting of the bags to the floor.

In the case of the construction of sustainable big bags on the building floor, the aggregates resulting from selective demolition are temporarily stacked directly on the floor of the reference floor. After the demolition operation, the recovered material is collected inside the "big bags" through the selection and classification of materials and a gradual pouring in layers. The first procedure (Figure 8) involves the use of a scaffolding that helps the operator in filling the bag, the latter positioned vertically and anchored to a reinforced concrete beam by means of special hook hooks.

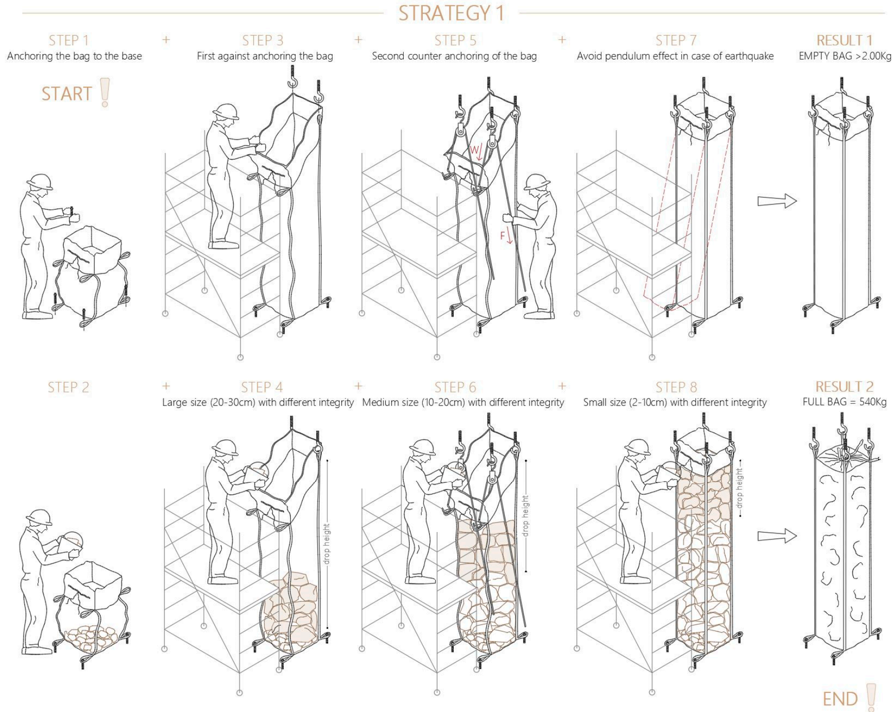


Figure 8. Strategy 1 construction site on the floor of the building.

The second procedure (Figure 9) uses a winch, which, thanks to its morphology, supports the bags' belts positioned horizontally on the plane, greatly facilitating the operation and reducing the number of operators required. Subsequently, in the first case, the bag does not need to be moved since its initial position corresponds to the final one. In the second case, the bag must be overturned with a special winch and then anchored with hooks in the reinforced concrete beam.

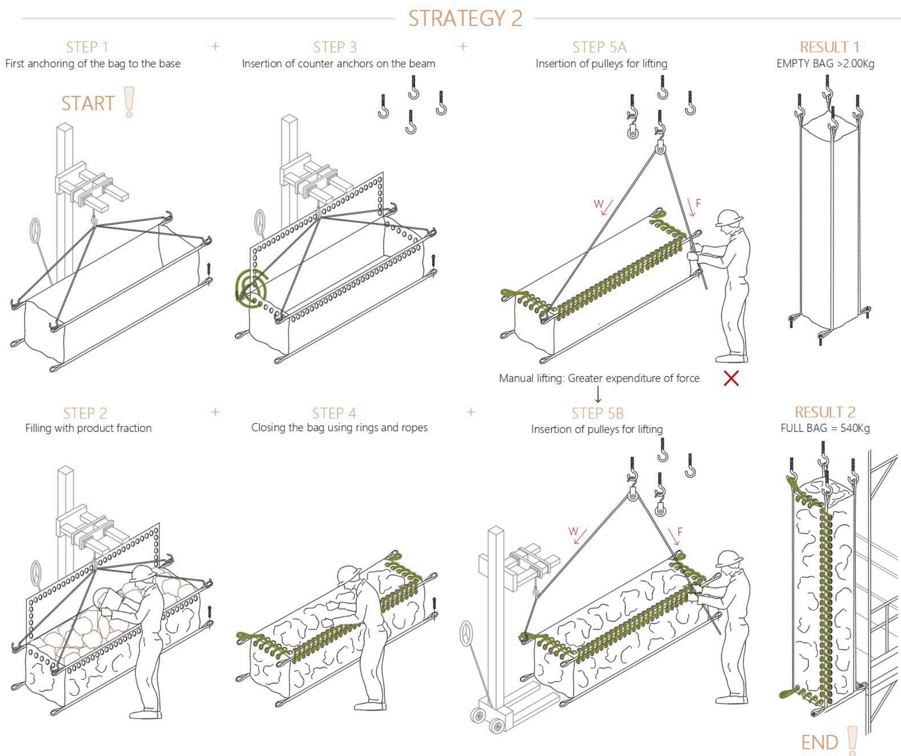


Figure 9. Strategy 2 construction site on the floor of the building.

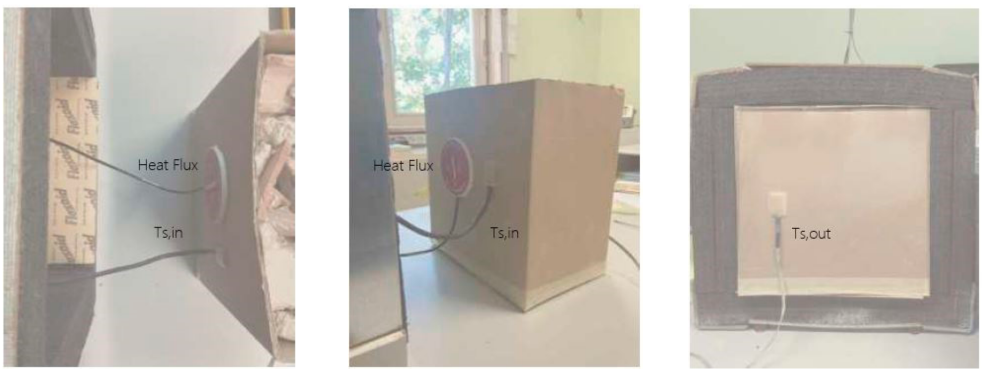
The construction site at the floor is more sustainable than that at the foot, as it does not require mechanical means of transport for filling the bags with the demolition bricks, nor for moving and lifting the bags to the floor subject to intervention. Therefore, this strategy is considered more suitable and sustainable in order to reduce the time and costs related to each operation significantly.

4.3. Experimental Tests and Software Simulations

The experimental tests aimed to calculate the conductance and transmittance of the sustainable big bag to verify that the insertion of this component in the wall did not give rise to thermal discontinuities such as to negatively affect the thermal performance of the envelope, also in consideration of the variability of the inert size following the demolition operations. On the other hand, the software analysis aimed to verify compliance and improvement in the minimum values required by the Italian regulations for heat capacity [33]. The aim was to experimentally derive the conductance (Λ) and transmittance (U) values of three samples consisting of "waste" materials derived from demolition, using the Hot Box (or climatic chamber), with the Heat Flow Meter (HFM) method. The three samples are rigid cardboard containers measuring 25 cm in length, 25 cm in height, and 15 cm in thickness. Although the approach and theoretical simulation aims to use the flexible polypropylene bag system as a casing, it was decided not to place the latter inside the hot box, as it would not have allowed for an experiment compatible with the dimensions of the Hot Box. This choice was deemed viable because the material and thickness of the bag contribute negligibly to the thermal resistance of the analyzed sample. As far as filling is concerned, each sample has a different grain size, in order to reflect the actual variability of the inert fraction that can result from demolition operations either when performed manually, or when performed by mechanical means, or both. Specifically, we have analyzed the following:

- Sample 1: rubble fraction with dimensions from 2 cm to 30 cm and sand;
- Sample 2: rubble fraction with dimensions from 2 cm to 30 cm;
- Sample 3: rubble fraction with dimensions from 10 cm to 30 cm.

The heat flux measurements were carried out with the help of the Hot Box of the "G. Parolini Lab" of the University of L'Aquila, whose dimensions are 640 mm long, 340 mm high, and 360 mm wide. A detailed description of the Hot Box can be found in [34,35]. The employed measuring instruments were made up of internal and external surface temperatures (Ts), using two probes positioned on both surfaces of the sample; indoor air temperature (Tair) inside the Hot Bot; and a heat flux probe (HF), placed on the inner side of the sample (Figure 10).



(**a**) (**b**) (**c**)

Figure 10. (**a**) Internal view of the sample from the top; (**b**) internal side view of the sample; (**c**) external front view of the sample.

The experiments were carried out by setting the temperature of the hot chamber equal to 45 °C and the outside temperature, i.e., the laboratory, at 28 °C. Following the standard ISO 9869 [36], there should be a temperature difference of 15–20 °C between the two surfaces of the sample, to correctly make heat flux measurements. The datalogger acquired data every ten minutes for a total of 72 h, as per regulations. The experimental results obtained in terms of conductance and transmittance (Figure 11) were the following:

- Sample 1: conductance: 2.16 [W/m^{2}K]; transmittance: 1.58 [W/m^{2}K];
- Sample 2: conductance: 2.74 [W/m^{2}K]; transmittance: 1.87 [W/m^{2}K];
- Sample 3: conductance: 2.94 [W/m^{2}K]; transmittance: 1.96 [W/m^{2}K].

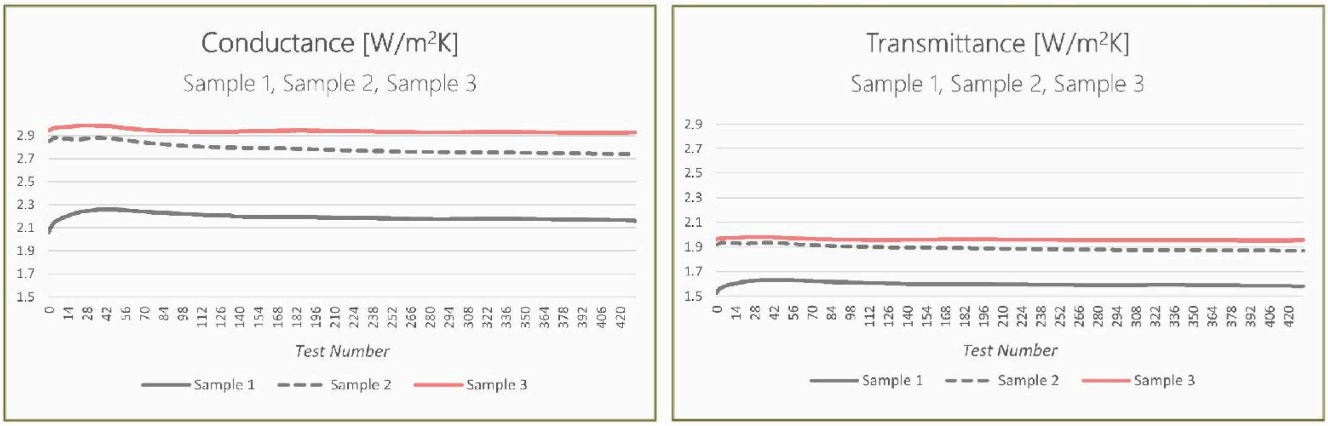


Figure 11. Trend of the conductance and transmittance values of the three samples.

From the analysis and critical reading of the previous data, it emerges that a variation in the grain size of sample 1, sample 2, and sample 3, corresponds to the energy behavior of the wall with a negligible variation. Therefore, the sustainable "dry" envelope behaves homogeneously. This aspect facilitates the construction process, allowing the operator to not have to select the aggregates, reducing the time and costs of the various site activities.

The software analysis was carried out with EdilClima 12.24.08 [36] by comparing two identical vertical closures (vertical closure 1 and vertical closure 2) that differed only in the addition of the sustainable big bag in one of the two (vertical closure 2), in order to verify the advantages in terms of heat capacity of the designed component. One of the regulatory checks, as per the Italian Decree [33], is on the surface mass, calculated as the product of density (kg/m^3) and thickness (m) of material. The reference value imposed by the Italian Decree is 230 kg/m^2. Vertical closure 1, without the big bag, has a surface mass of 85 kg/m^2 (below the 230 kg/m^2 limit, m^2 value below which, according to Italian standards, the wall must be verified in dynamic conditions) and a periodic transmittance of 0.139 W/m^{2}K (exceeding the 0.10 W/m^{2}K limit), thus failing to meet minimum standards [37]. Otherwise, vertical closure 2, with the big bag, exceeds the minimum requirements with a surface mass of 245 kg/m^2 and a periodic transmittance of 0.014 W/m^{2}K. Furthermore, according to ISO 13786 [38], vertical closure 1 falls within the mediocre performance range and performance qualities in class V. The optimized solution, vertical closure 2, exhibits optimal performance and is classified as class I. The results show that the presence of the sustainable big bag is negligible for its contribution to thermal transmittance, but it allows for a significant improvement in heat capacity (Figure 12).

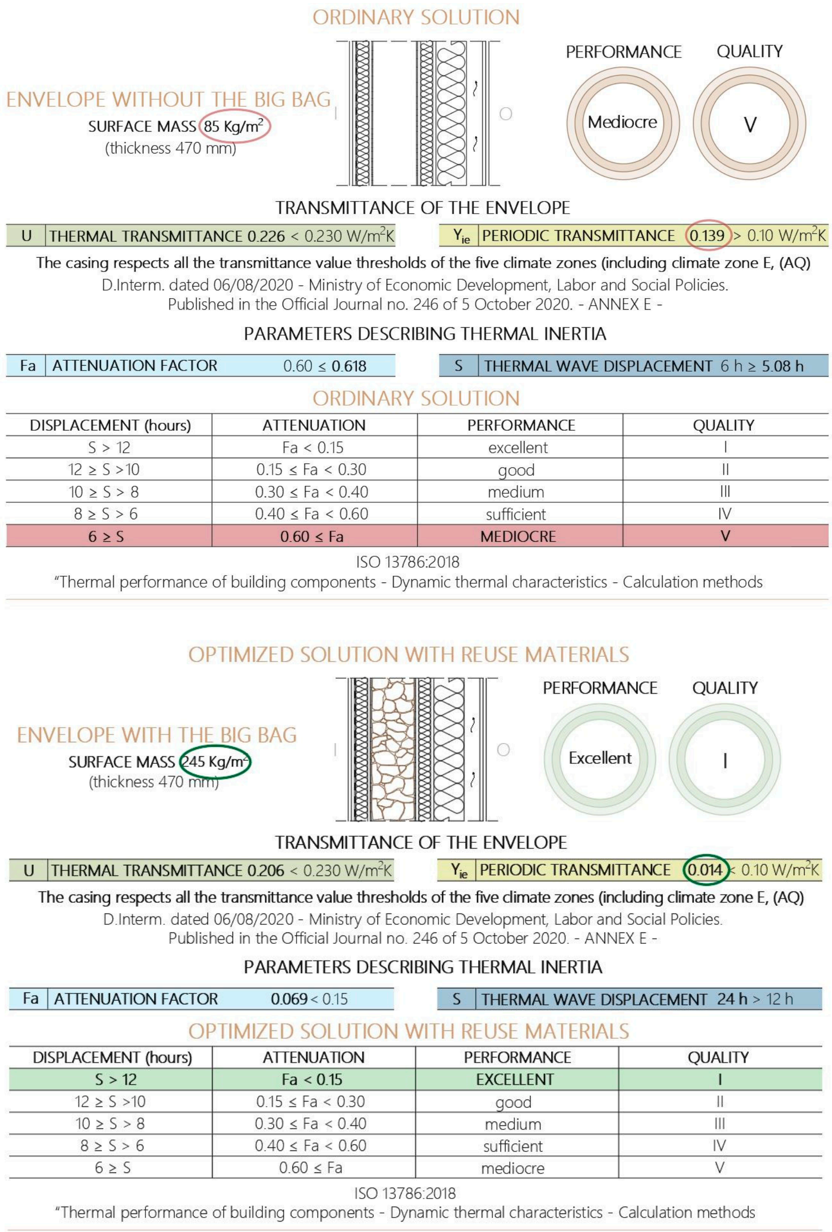


Figure 12. Thermal comparison between vertical closure 1 (without sustainable big bag) and vertical closure 2 (with sustainable big bag).

The quantitative analysis of the transmittance and conductance values has allowed us to define the granulometry of the bag that can contain different types of aggregates based on the demolition materials, avoiding additional time in selecting the filling material but also understanding how, despite the fact that it is a dry technology, by increasing the mass of the wall facing, we can obtain an element that increases the thermal capacity, in favor of the thermal inertia of the wall and energy savings for summer and winter air conditioning.

5. Discussion

Modern construction has now come up with a great challenge: on the one hand, there is a strong demand for new constructions; on the other hand, there is an increasing awareness of the environmental impact of construction choices, so much so that building materials are no longer considered sustainable but a moral obligation. Innovative building materials that can become the basis of a green revolution in the world of construction can be of different types, including the recycled stone that is the subject of this study.

The validity of the construction system on display is part of the advantages of the use of dry systems that can be assembled directly on site. The stone and reused bricks used to fill the bag can easily be reused an infinite number of times, as needed, thus making the construction element very versatile. The implementation time of the system is much reduced compared to traditional construction materials and allows for rapid assembly of the structure with reduced execution times, in favor of reducing safety risks on site and related costs. By using different sizes of bag filling elements, the production of additional materials and, above all, the use of raw materials are reduced throughout the construction site.

Large stone or brick walls have always had excellent performance in terms of insulation and heat capacity, minimizing heat loss in winter and keeping rooms cool in summer, thus actively collaborating in the reduction in energy consumption for air conditioning and lower greenhouse gas emissions. Recycled stone is an excellent alternative to the consumption of natural resources, and above all, if recycled on site, it greatly reduces the production of waste and the related disposal costs. This approach is even more significant if used in areas where significant events have occurred involving the recovery or reconstruction of large, inhabited centers and building interventions, such as during post-earthquake or post-war reconstruction.

The possibility of local supply and the use of natural resources are the first element in promoting environmental sustainability: the assessment of the environmental impact of a building intervention has a significant impact on the use of renewable sources, the percentage of reuse of recycled materials, the use of recycled materials, and the percentage of the weight of materials of local origin compared to the total.

With this system, each of these elements can be assessed as meeting all the criteria required in the Life Cycle Assessment, which favors companies that implement more efficient and eco-sustainable processes but is also an indicator of strong environmental responsibility. Implementing circularity on a larger scale than the construction sector requires the integration of multiple cross-cutting activities with an innovative design and construction approach. It is necessary to identify the selective demolition process and a local supply. The waste status of a good process is determined by the legislation: Reuse is also indirectly encouraged by Directive (EU) 2019/904. The law was implemented in Italy in the Legislative Decree 152/2006 Environmental regulations, in particular with the amendments made by Legislative Decree 116 of 2020. Despite some regulatory references, many critical issues still exist in Italy: in 2018, the UN network proposed the implementation of a process to fill some gaps, but it still remains pending today. This model could have greater significance if we were to speak of "deconstruction" instead of common demolition: it is a matter of providing for the selective disassembly of components already in the design phase, with the indication of all recyclable materials, which can be managed through component exchange platforms that can be integrated into BIM software.

6. Conclusions

The circular economy is the fourth point of the six environmental objectives reported in Article 17 of the "Taxonomy Regulation", which describes the DNSH principle in order to assess elements that do not cause significant damage to the environment. This point pays particular attention to natural resources and raw materials, waste production, and disposal, all measures at the basis of the National Recovery and Resilience Plans (PNRR), so much so that they must be respected for all interventions financed by these European funds. For these reasons and due to the increase in energy costs, the global building market must move towards greater sustainability with a Cradle-to-Cradle (C2C) approach through regenerative design. The approach must be applied at a holistic level, considering economic, industrial, and social factors; reducing waste to a minimum for each intervention; assimilating the materials used with natural elements that can be regenerated.

It is a matter of improving the eco-design strategies of products by evaluating five certification criteria:

1. The healthiness of materials;
2. Reuse;
3. The evaluation of the energy necessary for production;
4. The management of water resources and, finally, social responsibility.

The big bag complies with this methodology and, in more detail,

- It complies with the C2C certification criteria, as the use of its components, dry and easily removable and reassembled, can produce infinite new elements that can be re-applied to as many construction solutions.
- It can be further supported by the use of systems with BIM platforms that identify the recyclable and recycled elements within the models in order to predict their future life developments.
- It allows for obtaining environmental benefits for the reuse of waste materials and the energy optimization of the envelope.
- It simplifies, speeds up, and makes all construction site operations related to both the selective demolition phase of the building and its subsequent redevelopment more economical.

The management of rubble in contexts that have suffered extensive damage over large areas of a territory due to calamitous events such as earthquakes or even destruction due to war represents one of the most important environmental issues, both for the technical criticalities related to the movement of large quantities of materials and for the associated important social, regulatory, and economic implications. The supply chain is very long, and its activities, such as pre-selection, removal, sorting, and selection, are expensive in terms of money and time but still mandatory. This research aims to fulfill the need for removal of such rubble on site, reclassifying it with a further use and respecting the certification criteria. Future development will include the implementation of a study using structural checks of the elements to understand whether they will also be able to fulfill the function of mending the load-bearing elements of parts of collapsed walls. In addition, the relationships between key variables and their influence on performance and the definition of systematic models to connect experimental results with real-word performance will also be explored in future research.

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