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The Carbon Footprint of Thermal Insulation: The Added Value of Circular Models Using Recycled Textile Waste

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Abstract: The goal of climate neutrality by 2050 drives the building sector towards stricter control of processes and products, leading to a substantial reduction of embodied carbon throughout the life cycle. Many of the most used insulation materials have a high carbon footprint, mainly due to the production phase (from cradle to gate). The need to reduce these impacts has led to the implementation of materials whose predominant raw material is recycled material in order to reduce the embodied carbon. The contribution presents the results of a research work that analysed the potential of insulation materials obtained from textile waste, evaluating not only their energy performance but also, above all, their environmental impact in terms of carbon footprint. It starts from a state-of-the-art analysis of the main traditional and new-generation thermal insulation materials, not only in relation to performance but also to environmental impacts, in order to investigate the opportunities offered using insulation materials designed according to circular models (10R) and produced with industrial and/or post-consumer waste fabrics, through a carbon footprint comparison. To support the choice of this type of insulation, a multi-criteria evaluation method is proposed through which the comparative analysis of the most significant insulation products selected is carried out.

Keywords: thermal insulation; carbon footprint; embodied carbon; textile waste; whole life carbon; life cycle assessment; circular model

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1. Introduction

"The European Union is committed to developing a sustainable, competitive, secure and decarbonised energy system" is the complex declaration of intent enshrined in the entire latest generation of EU energy and climate directives. It is promoted as a shared objective by Italian Plans (Research National Plan 21–27 and National Recovery and Resilience Plan), European Programmes (Next Generation EU, European Green Deal, FIT for 55, ...) and international strategies (SDGs, Climate-ADAPT, ...) that currently engage the European socio-political and economic landscape. The word energy is always associated with the word climate, implying that relational nexus that links energy needs (and therefore production systems) to climate-changing emissions, to the point of feeling the need to think far-sightedly about energy as resilient [1] for a competitive and climate-neutral economy [2].

Therein lies the triangulation: Environment, Economy and Society that should guide the Green Transition of the building sector. However, Climate Change goals cannot be achieved with energy-efficient technologies alone. The building sector must implement a paradigm shift. While the energy consumption attributed to buildings in the operational phase has been managed and reduced by the various laws that have succeeded one another over the last 20 years, the greenhouse gas emissions embodied in building materials represent a non-negligible part of the carbon footprint of the building life cycle and the binding regulatory instruments governing their necessary drastic reduction are not yet fully operational.

The first step is the awareness of the damage we potentially cause by over-consumption and the second is the attempt to satisfy our ever-decreasing needs with goods (materials and energy) produced in a circular approach, thus extending the resource value chain [3].

2. Strategies to Reduce Consumption and Emissions

The material-energy pair links the processes of the green transition to those of the energy transition aiming for climate neutrality by 2050. This pushes the building sector towards stricter control of the processes and products involved in the construction of a building, leading to a substantial reduction of embodied carbon throughout the life cycle.

According to the 2019 Global Report released by the International Energy Agency (IEA) and the United Nations [4], the building sector accounts for 39% of global CO_2 emissions, making it one of the sectors where action is most urgently needed.

In Europe, the need to reduce the energy and environmental impacts of the built environment has, over the last two decades, favoured the definition of multiple regulatory instruments, the most important of which have been the various Energy Performance of Building Directives (EPBDs) with which criteria for analysing and evaluating the construction qualities of buildings have been progressively put into place in order to produce projects that improve their performance. The EPBDs that have followed one another periodically have first investigated aspects relating to the energy efficiency of the building-installation system (2002/91/EC), summer comfort and zero energy balance (2010/31/EU), up to contemplating requirements for decarbonisation of the built environment, the fight against energy poverty (2018/844/EU) and zero emission buildings (New EPBD Green House), all of which are in any case aimed at addressing the performance criticalities of the opaque and transparent components of the envelope. The aim is to identify the most "effective" types of interventions and materials in view of a retrofit project that is valid both in terms of energy and the environment in a broader sense.

The European Green Deal was entrusted with the arduous task of transforming the EU economy, making it resource-efficient, with the ambitious goal of achieving zero climate impact by 2050. This goal became binding thanks to the new European Climate Act (EEC/EU Regulation No. 1119 of 30 June 2021).

Recognising that these goals cannot be achieved without an effective campaign to renovate the existing building stock, the EU has also put in place the Renovation Wave Strategy (RWS). The RWS, an integral part of the European Green Deal, aims to double the rate of renovation of the building stock over the next 10 years, with the goal of improving the energy performance of buildings and reducing primary energy needs through increased energy and resource efficiency.

In strategies to reduce consumption and emissions, the use of passive solutions, including improving the performance of the building envelope, must always be the main option. Thermal insulation, which is fundamental to ensure the control of energy flows and comfort, and to contain operational carbon as much as possible, is a key factor in reducing the environmental impact of buildings, but it must be reinterpreted in light of the increasingly felt need to contain embodied carbon as well.

By 2050, all new and existing assets must be net zero across the whole life cycle, including operational and embodied emissions [5].

Any strategy to improve the energy performance of buildings should therefore be made with Whole Life Carbon (WLC) in mind. WLC emissions are the entire amount of carbon produced by a building in its life cycle, including both operational and embodied [5].

A detailed Whole Life Carbon Analysis, although desirable, is still little used, not least because of the limited information available for cradle-to-gate carbon data [6].

The insulation materials market is still dominated by a few categories such as mineral wool, expanded and extruded polystyrene, and glass fibre [7,8], some of which cause significant impacts on the environment at one or more stages of the life cycle. The greatest impacts are generally attributable to the production phase, in terms of the use of non-renewable raw materials and fossil energy, and to the disposal phase, due to the problems of re-use or recycling of products at the end of their life.

It is precisely the need to reduce these impacts, especially those related to the initial phase of the life cycle, that has driven the implementation of materials whose predominant raw material is recycled material.

The RWS itself emphasises the need to increase the market for sustainable construction products and services based on the principles of the circular economy, including the integration of new materials and the reuse of waste materials. Therefore, great attention is given not only to the shift from synthetic to natural materials but also to the exploitation of the use of waste and recycled materials for insulation [9].

In order to increase the dissemination and use of these materials, the implementation of evaluation methods, which consider the performance of insulation materials while also considering environmental impacts in the life cycle, is crucial.

If until a few years ago the energy attributable to the operational phase, i.e., that connected to maintaining comfort conditions (heating, cooling, lighting, etc.), represented the most significant item, of the total life cycle energy, the reduction of operational energy is leading to a shift of impacts from one phase to the other. Embodied energy, especially cradle-to-gate energy, is therefore tending to become increasingly important in assessing the actual sustainability of the building [10].

Therefore, effective and immediate actions are needed to reduce the carbon embodied in buildings to avoid undermining the carbon reductions achieved through energy efficiency [11].

This is especially true for buildings housing universities, as these are organisations engaged in education, research and community services, and should play a key role in addressing climate and environmental challenges [12]. Therefore, when assessing the sustainability of university buildings, it is relevant to also calculate the carbon footprint [13] in order to be able to identify the most suitable strategies to make such buildings truly sustainable.

Life Cycle Assessment (LCA) is one of the most effective tools to monitor environmental impacts at all stages of the life cycle and to calculate the carbon footprint. It is a tool, increasingly used in different areas of the construction sector, which aims to assess impacts on ecosystems, natural resources and human health, through a standardised approach to model, assess and quantify the impacts of a product or process over a complete time horizon extended to the useful life of products [14]. Consequently, it can be a useful tool to support the building sector in the transition towards carbon-neutral buildings (CNB).

A carbon-neutral building, although there is no internationally agreed official definition, must achieve a net quantity of carbon dioxide equivalent ($CO_{2\text{-eq}}$) emissions related to the life cycle of the entire building, equal to zero [15].

In achieving the ambitious "carbon neutral building" goal, the role of the materials used, especially in relation to their carbon footprint and the environmental impacts they cause, plays an increasingly central and decisive role.

3. Classification, Characteristics and Environmental Impacts of Thermal Insulation Materials

The first step in reducing a building's primary energy demand is to reduce the Net Energy Demand by optimising the building envelope. In this direction, insulating materials, which can contribute significantly to reducing heat loss in buildings and thus energy demand, play a key role in the energy efficiency of the building sector.

There is a wide variety of insulators on the market that can be classified according to different criteria, ranging from the origin of the material, the internal structure, thermal characteristics and performance (conductivity, density, specific heat, etc.). It cannot be overlooked, however, that many of the insulation materials currently on the market have a high carbon footprint [16].

For this reason, there is an increasing amount of research aiming at the development of new insulation materials that can provide similar or even better performance than traditional insulation materials but with a reduced environmental impact and a smaller carbon footprint.

The choice of insulation material, then, takes on strategic importance and must be made based on multiple criteria that are not only based on performance and economic reasons, as was the case in the past but must also integrate ecological considerations.

The abundant availability of insulation materials on the market makes it difficult to make an informed decision on the best type of insulation for a given construction [17]. The CO_2 emissions associated with the material's life cycle and in particular those associated with the production phase become an important selection criterion.

Most insulating materials are mainly polymeric materials, as polymers generally have good insulating properties due to their stable physical and chemical properties, and fillers and other additives, e.g., composite materials [18].

Many studies have been performed to create new insulation materials, or to improve the characteristics of traditional ones, by changing the type of polymer, and/or fillers and/or additives, in order to achieve good energy performance, while safeguarding human health and the environment.

To assess the thermal insulation performance of single or combined homogeneous materials, the most used indicators are thermal conductivity and thermal transmittance, respectively. Thermal conductivity (l) is defined by ASTM as the time rate of steady state heat flow (W) through a unit area of 1 m thick homogeneous material in a direction perpendicular to isothermal planes, induced by a unit (1 K) temperature difference.

For a material to be considered a thermal insulator, it should have a conductivity of less than 0.07 W/mK [7]. For many insulating materials, thermal conductivity can vary with changing temperature, humidity or density.

Thermal transmittance, also called U-value, is the rate of heat flow through a unit surface area of a component with unit (1 K) temperature difference between the surfaces of the two sides of the component and is expressed in W/m^2K.

However, these are not the only parameters to assess the energy performance of a thermal insulator. Other properties such as density (kg/m^3) and specific heat (J/kgK) must be considered. Furthermore, very important for the thermal inertia of an opaque building component, and thus for summer comfort, is the thermal diffusivity of the insulating material, i.e., the property of the material that characterises the propagation speed of the conductive thermal flux caused by the variation in temperature over time. Thermal diffusivity is the thermal conductivity divided by density and specific heat capacity at constant pressure [19].

Numerous international standards relating to thermal insulators (ASTM, ISO, EN, DIN, etc.) propose various classifications of insulating materials from different perspectives, tests and specifications of all kinds [18].

The insulation materials on the market today can in fact be classified with respect to several factors [10]:

- Material structure (cellular, fibrous, porous),
- Chemical composition (organic and inorganic),
- Origin (vegetable, animal, mineral, synthetic; derived from new, partially or totally recycled raw materials),
- Specific weight (generally ranging from 12 kg/m^3 up to about 600 kg/m^3),
- Thermal conductivity (ranging from less than 0.03 W/mK to over 0.065 W/m K),
- Density (ranging from 16 to 380 kg/m^3),
- Resistance to physical agents (humidity, high temperature, UV radiation, pressure, shear, and other forces),
- Resistance to chemical factors (presence of organic solvents, humidity, oxidation, reaction to fire, . . .).

With respect to material structure, the classification is between cellular, fibrous, and porous materials. Cellular materials can in turn be divided into alveolar and granular.

With respect to chemical composition, insulation materials can be divided between organic, which are derived from renewable materials, and inorganic, which are obtained through a chemical process. Organics can be natural, such as wood fibre, mineralised wood fibre, vegetable fibre (hemp, coconut, jute), cellulose fibre, cork, or synthetic, i.e., of natural origin, but treated by artificial production processes. The latter include sintered expanded polystyrene (EPS), one of the most widespread thermal insulators, a thermoplastic polymer obtained from styrene and composed of carbon, hydrogen and air (98%).

Organic fibrous materials, such as cellulose, cotton, and wood, are generally good thermal insulators, as they trap air within the fibres, preventing heat transmission by convection and limiting the conduction of gaseous heat [18].

Following a thorough literature review, Fuschl et al. [20] reports a widespread classification between inorganic (rock wool and glass wool), organic non-renewable (EPS, XPS, and PUR) and renewable-based materials.

Currently, two product groups are most popular in the European insulation materials market, inorganic fibrous materials, especially glass and rock wool, and organic foam materials, especially EPS, XPS, and PUR [18].

The classification according to origin, initially based on materials of natural (plant, animal, mineral) and synthetic origin, must now consider and highlight whether the material is derived from new, partially or fully recycled raw materials [10].

A study on unconventional sustainable building insulation materials [7] reports on the state of the art of the main innovative thermal insulation materials, made from natural and/or recycled materials, which are still little available on the market or in an experimental phase. In addition to providing energy performance parameters (conductivity, density, specific heat), it proposes an analysis of the sustainability of these materials.

It should be noted that the performance of materials claimed by researchers for traditional thermal insulators is not always consistent with what is stated in international standards, e.g., ASTM [18].

Conventional insulation materials, while helping to reduce the energy and carbon footprint of the operational phase, also have a high impact on the environment.

Those from petrochemical products, such as polystyrene, cause impacts mainly in terms of resource use, and those from natural sources, such as rock or glass wool, mainly in terms of energy used for the production processes. Not to mention the considerable impacts attributable to the disposal phase, due to problems with reuse and recycling of products at the end of their life [21].

Life Cycle Assessment data are required for the environmental impacts of these materials. LCA is a rational approach to quantifying the environmental impacts of a product over its entire life cycle and can provide an objective measure of the environmental impacts of buildings and individual components [10].

Several studies [7–23] have identified the impact of climate change as a key impact category for insulation materials.

An important indicator for assessing this impact, especially with respect to the Carbon Neutral Building objective, is the carbon footprint, which allows the measurement of the environmental impacts determined by the production of climate-altering gases originating from anthropogenic activities on the climate. It expresses the total greenhouse gas emissions that are associated directly or indirectly with a product, service or organisation and is expressed in terms of the amount of carbon dioxide emitted or its equivalent of other greenhouse gases. It is defined in units of CO_2-equivalent ($CO_{2\text{-eq}}$.). Emissions are evaluated based on the most important greenhouse gas: CO_2 [10].

To calculate the carbon footprint of a thermal insulation and more generally of a building material over its life cycle, the embodied energy and carbon must be measured using LCA according to the international standard ISO 14044:2006, which defines the four key stages of LCA as "Goal and Scope Definition", "Life Cycle Inventory Analysis" (LCI), "Impact Assessment", and "Interpretation". In the assessment, cradle-to-grave impacts can be considered by calculating the embodied energy and carbon in four steps:

A1—3 Product
A4—5 Construction Process

B1—7 Use
C1—4 End of life

This excludes "operational energy" used inside the building when in use.

However, the evaluation may focus on only one or more phases of the life cycle in relation to the impacts generated and the aspects to be emphasised.

Assessing the environmental impacts of an insulation material often narrows the boundaries of the assessment to the cradle-to-gate phase, i.e., the extraction of raw materials and the production of the material, before the product is transported to customers.

Studies have shown that the analysis of the total environmental impact for different types of thermal insulation at different stages of the life cycle (production, construction, use, and end-of-life) revealed that generally, the stage with the highest environmental impact is the production stage [8].

The most widely used method in the UK only considers the impact of greenhouse gases and energy and only from the cradle-to-gate stage of the product [24].

A quantitative comparison of 15 insulation materials was carried out by [10]. This comparison, shown in Table 1 in addition to considering thermal performance aspects, also evaluated the carbon footprint, which was calculated based on the actual level of thermal insulation, considering the specific weight of each material, as well as differences in their thermal conductivity (λ), using 1 kg of the specific thermal insulation material as the Functional Unit (EN 15804:2012 + A1:2013) for the calculation. The evaluation was limited to the cradle-to-gate phase, and the use and disposal phases of the product were neglected due to a lack of reliable data. The quantity of the specific insulating material was calculated as a function of the thermal transmittance to be achieved for the wall, set at 2.0 W/m^{2}K. This limit value can be considered adequate for a Mediterranean climate zone C. This value is calculated assuming that the insulating layer is added to a reinforced concrete wall (thermal conductivity of 2.04 W/mK with a thickness of 15 cm, which on one side was plastered with a cement plaster 2 cm thick and thermal conductivity of 0.85 W/mK. Values of thermal resistance for inner (Ri) and outer (Re) air were taken as 0.125 m^2 K/W and 0.043 m^2 K/W, respectively. The results obtained by Kunic have been restated in Table 1.

Kumar et al. [25] carries out a comparative analysis of the properties of building insulation materials, also in relation to different climate zones, and proposes four criteria to select the optimum insulation:

(1) Energy
(2) Environment
(3) Economic Efficiency
(4) Comfort.

The study uses the following indicators for environmental aspects: Operational Energy and Carbon and Embodied Energy and Carbon. The comparison is made for the different types of walls proposed in relation also to the energy requirements needed to maintain adequate comfort conditions. The authors do not consider LCA data for estimating environmental performance and do not consider the main environmental impact indicators.

In [17] the environmental performance of 21 insulators using the LCA method are evaluated. In accordance with ISO 14040 and ISO 14044, they analyse the impacts associated with the entire life of the insulation material, from extraction, through manufacture, use, end-of-life treatment, and disposal. The proposed method assigns an environmental score by combining the impacts associated with the production phase of the material with those due to CO_2 to cover energy requirements, then summing embodied and operational carbon. The assessment includes four environmental impact indicators (Global warming potential, Ozone depletion potential, Photochemical ozone creation, and Acidification potential of land and water). The insulation material with the best environmental performance is cellulose, which was obtained from recycled newspapers.

Table 1. Comparative table of physical properties and carbon footprint between thermal insulation made from textile waste and other insulation materials.

Thermal Insulation Classification	Thermal Insulation Material	Density *	Thermal Conductivity *	Required Thickness of Thermal Insulation **	Carbon Footprint Per Mass of Most Used Material for Building Envelopes	Required Weight of Thermal Insulation Per Surface (1 m^2), for U = 0.20 W/(m^2 K)	Carbon Footprint of Thermal Insulation Per Surface Unit (1 m^2), for U = 0.20 W/(m^2 K)	Data Source
		Kg/m^3	W/mK	m	kg $CO_{2\text{-eq}}$./kg	kg/m^2	kg $CO_{2\text{-eq}}$./m^2	
Organic fossil fuel derived	EPS	16	0.037	0.175	4.205	2.803	11.8	Kunic, 2017 [10]
	EPS with reflective additives	16	0.032	0.152	4.400	2.424	10.7	
	XPS	32	0.038	0.18	5.840	5.757	33.6	
	PU polyurethane	45	0.025	0.118	4.307	5.326	22.9	
Inorganic mineral derived	Glass wool-low density	22	0.036	0.17	1.494	3.750	5.6	
	Glass wool-high density	80	0.038	0.18	1.380	14.393	19.9	
	Rock wool-low density	70	0.040	0.189	1.082	13.256	14.3	
	Rock wool-high density	155	0.045	0.213	0.920	33.023	30.4	
	Foam glass	170	0.060	0.284	1.565	48.292	76.6	
Organic plants derived	Wood fibre wool-low density	120	0.050	0.237	0.062	28.407	1.8	
	Wood fibre wool-high density	380	0.090	0.426	0.062	161.919	10.0	
	Cork	160	0.050	0.237	1.156	37.876	43.8	
Innovative	Cellulose-recycled	60	0.044	0.208	0.367	12.499	4.6	
	Aerogel	140	0.017	0.08	4.200	11.268	47.3	
	VIP	170	0.06	0.028	8.551	4.829	41.3	
	Insulation material made of recycled textile fibres from a short supply chain	50	0.0358	0.17	0.863	8.5	7.3	technical material data sheet
		60				10.2	8.8	
		80				13.6	11.7	

* (Most used for building envelopes); ** for thermal transmittance (U value) of 0.20 W/(m^2 K), for most used densities and thermal conductivities of thermal insulations.

In [6] the whol- life carbon performance of eight current market available insulation materials is analyzed. In order to compare the environmental impact of different insulation materials, they analyse the carbon emissions per unit area of the wall. The comparison is made with respect to the following parameters: thermal conductivity, density, cradle-to-gate embodied carbon and service life. The whole-life carbon analysis in this study considered the following life cycle phases: product phase (A1–A3), construction process phase (A4 transport to project site), use phase (B4 replacement and B6 operational energy consumption) and end-of-life phase (C2 transport to disposal facility). The analysis showed that considering a distance of 50 km from the production site to the construction site, carbon emissions for the transport of materials (gate to site) are almost negligible (less than 1.1%) when compared to those from the cradle to the gate, for all insulation materials. These percentages increase with increasing distance.

For the evaluation of thermal insulation materials, the environmental load is often measured using the mass of material required to achieve a thermal resistance of 1 m^2K/W as the Functional Unit and using as indicators the cumulative energy demand (CED), i.e., the primary energy consumed during the entire life cycle, measured in MJ per functional unit and the global warming potential (IPPC GWP 2007). The latter indicator calculates the greenhouse gas emissions attributable to the functional unit of the material (kilograms of CO_2 equivalent per functional unit), during its life cycle over three time horizons (20, 50 and 100 years) [7].

In [26], which carried out a comparative life cycle assessment (LCA) of the environmental impacts of different insulation materials (polyurethane, extruded polystyrene and mineral wool) in the continental Mediterranean climate, showed that PU polyurethane presented the highest environmental impact during the production phase, while XPS was found to have the worst environmental performance of all materials evaluated.

A literature review on the LCA for insulation materials [20] showed that the main cause of environmental impact for non-renewable organic materials is the raw material and for inorganic materials the production process, while the most common impact factor for renewable-based materials is binders and additives.

In recent years, many studies have been conducted with the aim of reducing the environmental impacts associated with the initial phase of the life cycle of insulation materials by replacing traditionally used raw materials with recycled materials.

This approach can make a significant contribution to the implementation of the guidelines of the Circular Economy concept, helping to reduce on the one hand the critical issues related to the disposal of certain types of waste and on the other, the use of non-renewable resources.

Considering an estimated increase in global raw material consumption, which is expected to almost double by 2060 [27], material efficiency strategies, including the use of recycled materials, are required to reduce greenhouse gas emissions associated with building materials. The application of such strategies could result in a reduction of greenhouse gas emissions in the material cycle of residential buildings by more than 80 per cent in 2050 in the G7 countries alone [11].

In this direction, for example, there has been a growing trend to develop innovative multifunctional composites produced from new polymers, derived neither from food nor from natural materials, but rather from by-products and waste from agricultural, forestry, livestock and marine activities [28].

Recycling of synthetic materials or industrial by-products can also be a sustainable strategy to reduce the use of virgin material on the one hand and landfill disposal on the other. With respect to thermal insulation performance, products made from recycled materials are generally better than natural ones [7].

Several studies [21] conducted a literature survey on the thermal conductivity of natural materials, mostly represented by agricultural waste: apple leaves, pine leaves, wheat straw, rice straw, rice husk, coconut fibre, sugar cane milling and pressing residue, date palm fibre, maize cellulose granules, and then compared them with the thermal performance of traditional insulation materials. For example, a chipboard with pineapple leaves was tested for which conductivity values varying between 0.043 and 0.035 W/mK were observed.

Lacoste et al. [29] produced low-density insulation boards made from hot-pressed coconut husk and bagasse, manufactured without the use of chemical binding additives. Coconut husk is a waste material available in large quantities as coconut residue. The bagasse, which plays the role of a natural binder within the panel as it is rich in cellulose, is also a waste material, a by-product of sugar production. The thermal conductivity of the panel with a density of 350 kg/m^3, measured according to ISO 8301, found values between 0.046 and 0.068 W/mK.

The use of plant/agricultural waste material offers several advantages [10]:

- The embodied energy and life-cycle costs of natural materials are significantly lower than those of conventional insulation materials;
- The production of natural materials is less harmful to the environment than the toxic materials used to produce some conventional insulation boards;
- The use of these natural materials poses no threat to human or environmental health.

4. Thermal Insulation Made from Textile Waste

Population growth and changing consumption patterns have led to an ever-increasing number of textile products, which cause considerable environmental impacts in their life cycle, and also due to textile waste management [30].

The European Parliament and the Council (2011) [31] defined textile products as "any raw, semi-worked, worked, manufactured, semi-manufactured or made-up product composed exclusively of textile fibres, regardless of the mixing or assembly process employed".

Every year millions of tonnes of textile waste consisting of production waste and post-consumer garments end up in landfills, causing severe environmental pollution [13].

Textile waste is generally divided into three groups: production waste, pre-consumer waste and post-consumer waste [32]. To these, waste consisting of synthetic fibres used not in the textile sector but in other sectors such as construction [33] should be added.

During decomposition, textile waste pollutes groundwater by forming greenhouse gases, methane in the case of biodegradable textile waste and ammonia in the case of wool. Synthetic textiles, on the other hand, are of particular concern due to their non-biodegradability, and toxicity, also in relation to the ever-increasing production quantity [34].

The percentage of textile waste that is recycled and reused is still quite low. In the EU out of about 5.8 tonnes of textile waste, the percentage is about 25%, compared to a potential of 95% [33,34]. An interesting perspective to reduce the amount of textile waste going to landfills "is the transformation into fibres that, although not fully suitable for reuse in the textile industry, can successfully become raw material in the building insulation sector" [35].

At the same time, the growing need to reduce the environmental impact caused by insulation materials is directing research, even before the market, towards new, more sustainable and environmentally friendly products. In this direction, interest in the use of textile waste as thermal insulators is growing, not only because of their good thermal properties but also, above all, to try to reduce the enormous amount of textile waste that is lost to the environment every year.

In this regard, studies and experiments have been undertaken to analyse heat transmission phenomena through different types of textile waste, because in order to optimise their use as thermal insulation in building construction, knowledge of their thermal, mechanical and physical performance is indispensable.

The thermal characterisation of an insulation material made from recycled textile fibres for building applications is the first step in verifying the technical feasibility of such a product type. Ref. [36] conducted experimental and numerical studies to determine the radiative flux ratio of fibrous insulation materials made from inhomogeneous recycled textile waste (i.e., characterised by different fibre types and sizes) in order to determine both radiative and effective thermal conductivity. Studies on heat propagation in fibrous insulation materials have shown that exchanges occur mainly by radiation and conduction, while those by convection are generally negligible.

Ref. [7] pointed out that textile materials are characterised by low thermal conductivity but also low density, making their insulation performance comparable to that of lightweight synthetic materials such as expanded polystyrene (EPS) and extruded polystyrene (XPS).

In [37] the thermal insulation potential of woven fabric waste (WFW) and a waste of this residue, named woven fabric subwaste (WFS), applied on an external double wall model was studied. Using measurement methods in accordance with ISO 9869, they found thermal conductivity values for WFW of 0.044 W/mK, which are quite similar to those of traditional insulation materials such as expanded polystyrene (EPS), extruded polystyrene (XPS), and mineral wool (MW). For insulation made from WFS, on the other hand, the thermal conductivity is 0.103 W/mK, so the thermal performance is lower than WFW, but still close to that of other insulation materials such as clay granules, vermiculite or expanded perlite.

Ref. [38] did several experiments on the reuse of textile waste, and proposed an insulation material made from cotton waste and sunflower stalks, using epoxy resin as a binder.

In [39], experiments with the use of textile waste for the thermal insulation of buildings have been described. In particular, they tested the performance in terms of both thermal transmittance and diffusivity of two samples waste linter (WL) and tablecloth (WT) were produced by shredding and mixing. For the former, they reported a thermal transmittance of 0.033 W/mK and thermal diffusivity was found to be about 5.8×10^{-3} m^2/h. For the second, the thermal transmittance was found to be 0.039 W/mK and thermal diffusivity was about 3.8 $m^2/h \cdot 10^{-3}$.

In [33], thermal insulation from waste polyester fibres and bicomponent fibres was studied, and their performance was evaluated. Conductivity was verified at different temperatures through laboratory tests performed on samples with 20 per cent two-component fibres and apparent densities of 65, 80 and 95 kg/m^3. Values between 0.04319 (for the sample with a density of 95 kg/m^3 at 10 °C) and 0.05598 (for the sample with a density of 65 kg/m^3 at 40 °C) were found.

The potential of the application of textile waste in the insulation of buildings in the form of woven-nonwoven has also been assessed with regard to the effects of porosity and density on the properties of needle-punched woven-nonwoven fabrics. Ref. [40] specifically studied acrylic and wool-based nonwoven waste using the needle-punched technique, for which a thermal conductivity between 0.03745 and 0.04581 W/mK was found.

In [28], thermal insulation based on wood fibres and textile waste from recycled jeans was tested; there used sodium alginate extracted from brown algae as an adhesive binder. The tests showed a thermal conductivity in the range of 0.078 ÷ 0.089 W/m/K for an average density in the range of 308 ÷ 333 kg/m^3 depending on the bio-composite considered.

Experimental tests have been conducted by [35] on thermal insulation materials made from textile scraps and recycled plastic waste fibres, which integrate natural fibres of plant or animal origin. These materials, produced by carding-folding technology, are based on the use of different composite products comprising combed sheep's wool, siliconized cellulosic fibre, recycled polyethylene terephthalate (rPET) and polyester (rPES) waste, converted into fibres. Specifically, the proposed material incorporates 55% recycled materials (25% rPET and 30% rPES), 30% wool by-products or virgin wool with low-quality fibre that cannot be used in the textile industry, and 15% siliconized cellulosic fibre. The experiments were carried out on six heat-insulating mattresses which, although produced using the same fibre mix, had different apparent densities and thicknesses. The following experimental results were reported:

- Heat transfer coefficient of 0.032 ÷ 0.050 W/mK;
- Water vapour permeance in the range 8.83 ÷ 18.43 $m/mhPa^2$;
- Vapour resistance in the range 0.06 ÷ 0.11 mPa/mg^2;
- Water vapour permeability, δ, in the range 0.31 ÷ 0.75 mg/mhPa;
- Water vapour diffusion resistance factor, μ, in the range 0.95 ÷ 2.32.

These thermal insulating materials have also been shown to contribute to improved indoor air quality as well as offer greater biological resistance to worm and insect attack than similar thermal insulators made solely of sheep's wool [35].

Interesting results resulted from a study [41] that experimented with a new type of lightweight cladding mortars made from cement-based composites reinforced with textile scraps that partially replaced sand. One of the aims of using textiles in cement mixtures was to improve their thermal resistance, as well as their mechanical resistance. As the percentage of incorporated fibres increased, thermal conductivity decreased. A 15% decrease was achieved compared to smooth mortar by incorporating 10% textile fibres into the mix until a 42% lower conductivity was achieved for mixes with 40% textile fibres. The benefits also concerned thermal diffusivity, with a 21% reduction compared to smooth mortar. The addition of 40 per cent textile fibre waste in cement mortar achieved a thermal diffusivity of 0.97 mm^2/s. This also brings significant benefits for the control of summer conditions.

In [42], new environmentally friendly thermal insulation panels produced using waste sheep's wool as a "matrix" and other waste fibres playing the role of "filler" were tested. The latter, preferably of natural origin, must already be available in the reference territory, and come from existing local agro-industrial and textile production. The thermal conductivity of the manufactured samples varies from 0.054 to 0.061 W/mK.

An analysis of the literature has shown that sufficient data are not always available to adequately assess the energy performance of the material. Data on specific heat, which are crucial for dynamic behaviour, are often missing. There are also still very little data available for the reaction to fire and the vapour resistance factor.

Moreover, there is often insufficient information to make a comparison with traditional insulators that also take environmental aspects into account.

To this end, a performance and carbon footprint comparison was made between some insulation materials and a product made in Italy consisting of 100 per cent textile fibres from textile industry processing waste and the recycling of discarded textiles.

For this insulation material, the manufacturer has declared:

- Conductivity $\lambda = 0.0358$ W/mK for densities from 50 to 80 kg/m^3
- Resistance to water vapour diffusion (panel only) $\mu = 2.2$ (UNI EN 12086:2013)
- Vapour permeability $\delta = 0.33$

The LCA assessment carried out in accordance with ISO 14044, considering the system boundaries to be those from cradle to grave and excluding the use phase, certified a carbon footprint of 0.863 Kg CO_{2eq} (GWP 100), and an energy consumption of 9.814 MJ (non-renewable CED). The study's conformity to the ISO 14044 standard was certified by Rina Service and approved by the Ministry for the Environment and Protection of Land and Sea within the framework of the National Carbon Footprint Assessment Programme. The data were calculated on 1 kg of product.

With respect to end-of-life, the material is classifiable as non-hazardous waste and can be fully recovered for recycling or reuse if not polluted by other materials.

Table 1 shows the comparison between the panels made from textile waste and the other insulation materials analysed by [10].

In order to make the comparison, the thickness necessary to obtain a transmittance of 2.0 W/m^2K in the stratigraphy assumed by [10] was calculated: a thickness of 17 cm is required. The carbon footprint was calculated for three different densities available on the market: 50, 60 and 80 kg/m^3. The comparison shows that this type of insulation offers interesting prospects in terms of both energy performance and carbon footprint.

Avoided impacts related to the incineration of textile waste must also be considered when assessing the reduction of impacts.

Regarding the end-of-life of insulation material, ref. [35] tested the resistance to soil action for samples made from natural fibres and recycled polyethylene terephthalate (rPET) and polyester (rPES) waste by leaving them in the soil and verifying the effects over time. Already after one month, the first signs of degradation were recorded, which became substantial over the following six months, showing that the materials made represented a favourable environment for microorganisms and worms and could, in combination with soil and specific nutrient substrates, allow the development of favourable substrates for plant cultivation.

5. Criticalities and Potentials of the 10R Model

The need to address the challenges related to the environmental impacts caused by textile waste has increased interest in all strategies that promote its reuse and recycling. Scientific research has seen in this an opportunity to innovate by experimenting with new materials that respond to as many R-strategies (Figure 1) as possible. The starting point is the need to orientate the production cycle from the linear to the circular model, through a radical change in the process, right from the design phase of the building material. The possibility to implement *Refuse, Rethink*, and *Reduce* strategies implies a high level of creativity, assessable in terms of the ability to make process innovation starting from the way of designing the product and its integrability to the building envelope.

Product design implies full and conscious control of all process inputs (material and energy), where transdisciplinary knowledge, scientific research and appropriate experimentation are part of the concept. This design approach has positive effects that are particularly evident in the retrofit of existing buildings where, often, the coexistence of different building types, historical stratifications, and partial replacements that have occurred over time result in significant differences in the stratigraphy of the various technical elements of which the envelope system is composed, which make a single technological solution inefficient and inappropriate.

The appropriate technological design of the envelope invites the designer to design the stratigraphy of a building element (e.g., a vertical perimeter wall) in a differentiated way, taking into account the different exposures (north-south-south-east-west), the own and brought shadows, the shape and the spatial porosity strictly functional to the real (and not standard) conditions that determine the requirements of thermal flow control, starting from the Audit. In this way, the characteristics of the thermal insulation can be differentiated and respond to the *Refuse* strategy: "If you don't need it, you don't need to buy it" [43].

Similarly, the use of specialised software to support technical choices and certify the performance of building components will be rethought as an ongoing design tool and not just an ex-post control tool. The possibility of evaluating element by element the thicknesses of the insulation material layer, actually necessary to meet the minimum requirements dictated by the standard, will make it possible to reduce both the energy demand during the building's operation phase and the quantity of material used [44]. An optimal thickness can reduce CO_2 and SO_2 emissions and annual energy consumption by up to 89% depending on the type of insulation [45].

The second step is, on the other hand, related to the *Consumption* variable, which mainly invites material producers to change their offer by expanding and orienting the market through genuine product innovation. The possibility of managing waste by reintroducing it into a new production cycle is generally considered a preferable option to incineration and landfilling [46]. The first step for the implementation of such a strategy is the identification of the main material flows in relation to the preferable options for recycling, also in relation to the different process types and their impacts. Analysing textile waste recycling processes, they can be mechanical, chemical, thermal, or combinations of them [47]. The textile wastes that affect the construction sector are mainly post-industrial wastes, generated during the production process, which usually include off-cuts of clothing, excess fabrics and waste due to quality problems (serious production defects), which are so-called "clean" because they are not used [48]. In fact, it is not always possible to find suitable recycling solutions for post-industrial textile waste in the fashion sector, also due to different sizes, shapes, conditions, compositions, and properties [37]. Therefore, sustainability efforts to date have paid more attention to the management of post-consumer textile waste [32], neglecting the management of post-industrial textile waste [34]. However, post-consumer waste can also be of great interest to produce insulation materials, especially when the rate of use is such that reuse in fashion is no longer viable.

Analysing the reuse potential of textile waste, what for the fashion sector is a downcycling, as the value of the material obtained is lower than the value of the material entering the production cycle, for the construction sector can be considered a virtuous process, especially if evaluated in the cradle-to-gate phase. Therefore, one of the indicators for evaluating the effectiveness of the process is certainly "the value of the textile waste", which must be as low as possible (e.g., fabrics that cannot be recovered due to too short fibre or too small a size). In this case, the delta value between material input and material output from the process can be minimised or even positive.

With reference to R-strategies (Figure 1), the sufficiency approach is rewarding: "Sufficiency differs from efficiency and circularity... it may achieve significant cuts in resources and carbon by providing for 'needs' not 'wants', while reducing absolute consumption" [49]. In our country, cultural resistance to demolish and rebuild has become a strong point. Once again, the drive for innovation starts from demand and directs it towards quality achieved with minimal consumption of goods and resources.

In addition, the use-value should be assessed together with the time of use of the good and increasing this value, also by passing through different production cycles, increases the level of sustainability of industrial development.

With specific reference to the Embodied Energy and Carbon of building insulation materials, the European Commission has proposed that a design/product/material lifetime of 50 years is appropriate to calculate the product's environmental footprint [50]. The production of materials with high durability, reparability and replaceability meets the criteria of circularity in the operational phase. The use of waste materials in the cradle, which are also recyclable or reusable in the grave (at the end of their useful life) ensures compliance with the fully regenerative cradle-to-cradle approach.

If the entire design process follows the cradle-to-cradle (C2C) approach, the synergistic relationship between a building and its environment increases, including through an energy and environmental balance in which the total energy consumption of the building over its entire life cycle is equalled and, in some cases, exceeded by the energy produced by the building itself.

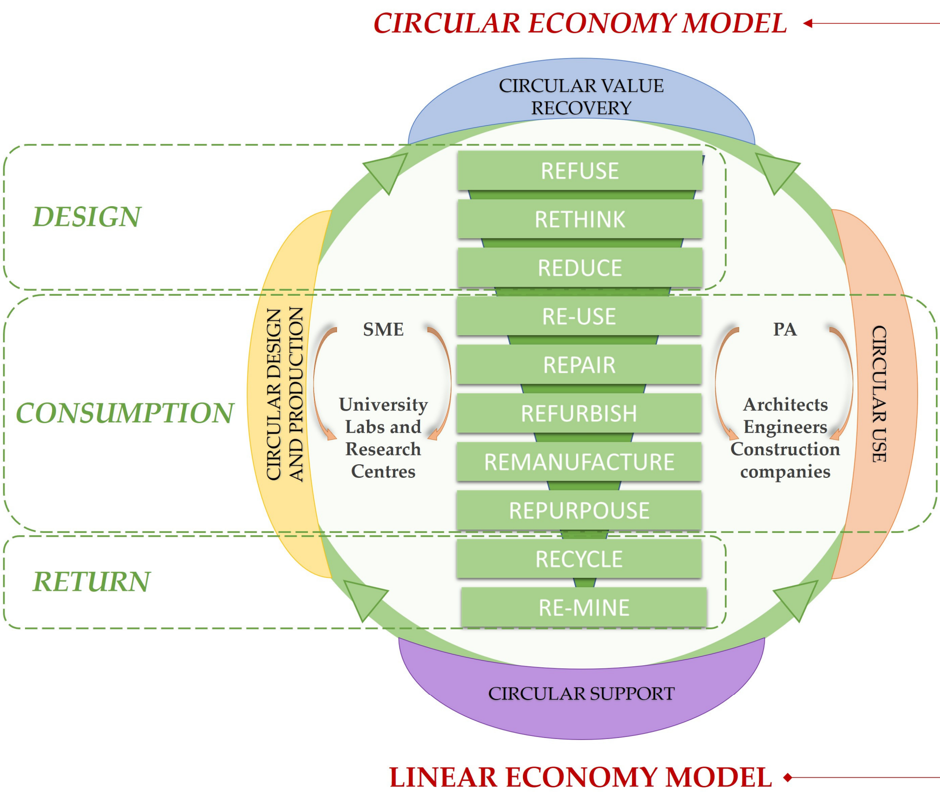

Figure 1. 10R strategies to transition from a linear to a circular economy model.

6. The Research Methodology

This research investigates the opportunities offered by the use of insulation materials produced from industrial and/or post-consumer waste fabrics, evaluated in comparison with traditional, sustainable and regenerative insulation materials through a comparative multi-criteria evaluation. The focus was on materials and their use, rather than design integration with the building. In fact, the priority objective of the research work is to analyse the potential of insulating materials made from textile waste, evaluating not only their energy performance but also, above all, considering their environmental impact in terms of carbon footprint and ability to reduce the energy needs of buildings. Indeed, the use of thermal insulation based on textile waste can play an important role in reducing embodied energy and reducing environmental pollution in buildings [13]. Sheep's wool and recycled cotton, together with traditionally used mineral wool and glass wool, have been shown to offer very high eco-efficient performance by achieving reductions of up to 40% in energy requirements compared to regulatory standards [44].

The first phase of the research delved into the study of insulation materials, analysed according to their classification, characteristics and environmental impacts, as summarised in the previous section.

The analysis focused on their specific performance, also with reference to climate zones [51], as the evaluation of technical parameters with reference to summer and winter conditions was considered relevant. Only issues related to thermo-hygrometric performance were examined in depth, while acoustic aspects were neglected.

In order to make a qualitative and quantitative comparison between different thermal insulators, taking into account not only performance but also environmental impacts, the research highlighted the prevalent importance of embodied energy from cradle to gate, as this is the most critical phase about which there is the least data availability. Furthermore, over the past 20 years the various Energy Performance of Buildings Directives (EPBD) have achieved a progressive reduction in energy use for standard building uses almost exclusively in the Operational phase and this has made the need to reduce resource consumption in the initial phase, in which the foundations are laid for proper management of the final (grave) phase of the process (Design for Dismantling), even more urgent and relevant today. In fact, the greatest environmental impacts today are related to the consumption of energy resources in the initial phase, once EPBD strategies are reducing operational energy.

It is agreed with [10] that the evaluation of the carbon footprint of an insulation material cannot be set on the weight component alone. The evaluation of parameters such as Thermal Conductivity and Density can lead to more appropriate choices and, above all, must be made with the same guaranteed Thermal Transmittance. Furthermore, the eco-oriented approach to design choices must prefer materials that have a low intrinsic environmental impact. Therefore, with the same Thermal transmittance (minimum requirement of the mandatory standards), the design challenge is to choose thermal insulators that meet 10 R strategies. It is true that from the design point of view, thickness is a relevant parameter, especially in the case of retrofits on existing buildings, which have construction and distribution constraints; but the green transition process invites us to prioritise the use of natural, recycled and recyclable materials.

An important aspect of the evaluation is the identification of the functional unit for the LCA, i.e., the reference measure used to compare different products. The FU serves to quantify the identified functions of a product and to provide a reference flow to which inputs and outputs are related (ISO 14044: 2006).

The functional unit used in this research is 1 m^2 of wall, setting the thermal transmittance (U) parameter at 0.20 W/m^2 K appropriate for a Mediterranean climate zone C.

According to [20], the most common Functional Unit (FU) used in the studies reviewed is the mass measured in kg of insulation material required to provide the same thermal resistance R or its reciprocal heat transfer coefficient U over a given area. Indeed,

$$FU = R \times \lambda \times \rho \times A$$

where:

R is the thermal resistance (m^2 K/W)
λ is the thermal conductivity of the material (W/mK)
ρ is the density of the material (Kg/m^3)
A is the area of 1 m^2.

The European Construction Materials Manufacturers Council proposed this FU for insulation materials (CEPMC, 2000) [20] as it reflects the main physical characteristics of insulation materials. However, as previously mentioned, the time variable (assessable in terms of durability) is relevant for assessing the performance of a material over its entire life cycle.

In this work, the FU considered to make the comparison between different insulation types relative to one square metre of building envelope. The methodology used for the assessment of environmental impacts is based on EN 15804.

About the boundaries of the evaluation system, impacts related to the early phase of the life cycle, i.e., cradle-to-gate (Cradle-to-Gate) and life cycle stages A1 to A3 were evaluated (Figure 2):

A1—Raw material supply,
A2—Transport,
A3—Thermal insulation manufacturing.

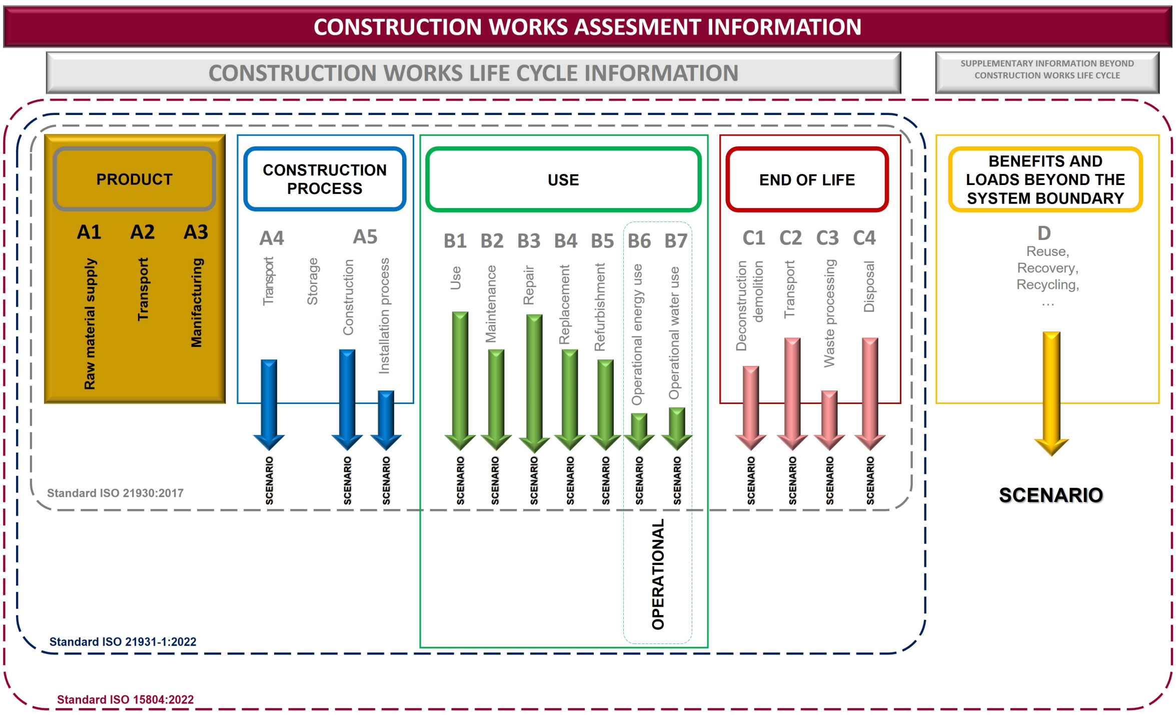

Figure 2. Life cycle stages—DIN EN 15804:2022-03.

This choice of field is motivated by the need to guide technological choices at the design stage, on which the sustainability of all other stages of the process depends. "The approximation of impacts during and after the life of the building would become even more uncertain" [24].

The main limitation of the research was not being able to consider the useful life of insulation materials, because reliable data are not available, especially for non-conventional materials.

The proposed method is intended to be configured as an adapted process LCA tool that serves as decision support at the Meta-design stage, rather than a tool for evaluating the embodied carbon in buildings after construction.

This is a useful tool to support the designer in the choice of insulation material with respect to the environmental impacts of phase A, i.e., from cradle to gate.

Concerning the choice of impact indicator (EN 15804), the impact of climate change was considered prevalent, as indicated by several [22,23].

The principles governing the identification of products with renewable and recycled content are contained in UNI EN ISO 14021:2021 "Environmental labels and declarations. Self-declared environmental claims".

The thermal performance was considered constant even though it is well known that insulating materials are subject to physical and functional obsolescence, which progressively reduces their ability to perform their role in resisting the passage of heat over time.

For the thermophysical properties and carbon footprint of the insulation materials analysed in Table 1, reference was made to [10].

For the thermophysical properties and carbon footprint of the insulation materials made from textile waste analysed in Table 1, reference was made to the data sheets provided by the manufacturer.

The results of experimental research on thermal insulation with textile waste suggest a classification in terms of standard related uses and cutting-edge performance. Certainly, the future scenarios are going to develop. Actually, according to most people, they appear as utopias, but they are boosted by the engine of innovation and sustained by the "Environmental Friendly Behaviour" principle.

7. The Proposed Model

This model was structured to support informed choices based on performance and environmental impact [17].

With this point of view, the Vitruvian concept of architectural being, structured with the human being in an analogical way, is not overcome, but it evolves involving not only architectural components and systems as independent parts that are functionally well defined but also as a complex holistic system towards the approach of the living building. However, we can see the overcoming of the Aristotelian conception that nature sets two great categories of beings one against the other: natural and artificial beings (traditionally buildings and the completely hand-made capitals).

The former is considered as linked with the concept of becoming (which enjoys four essential causes: immanent-material substance, cause agent, formal-intrinsic cause to the being itself and final cause—the last aim prefixed within nature towards all beings tends to their becoming), while the latter are generally linked with the static concept of non-becoming.

7.1. From Concept to Evaluation Structure

This second assertion is challenged by new frontiers of technological design that consider the building as a living organism, which interacts, adapts, evolves, protects and takes full advantage of context. It uses the sun's energy and utilises the resources of the soil, produces oxygen and sequesters CO_2, closes the cycle of water and waste, breathes, suits several seasons, and is built from recycled materials which will be recyclable at the end of their useful life (the "Cradle-to-Cradle" approach).

Let us analyse the steps made towards this future architectural scenario that comes from a constantly increasing performing demand. The starting point is represented by yesterday's architectural scenario, the so-called "Code" phase, the traditionally designed and built architecture belongs to, which is widely overcome. The increasing demand for comfort and efficiency brought the building sector to promote the so-called homeostatic architecture, the whole class of "high-performance building", among which are "Nearly Zero Energy Building (NZEB)", "Plus-Energy Building", "Zero Waste Building", etc. These represent today's architectural scenario and define the qualitative standards of the "Sustainable" phase. "Green Design focuses on single issues, for example, the inclusion of recycled or recyclable plastic, or consideration of energy consumption.

According to Eco-design, environmental considerations are considered at each stage of the design process. Design for sustainability considers the environmental (for example, resource use, end-of-life impact) and social impact of a product (for example usability, responsible use). Instead, sustainability is considered to be more of a direction than a destination that we will actually reach". Eco-oriented planning choices acting on the "hardware" component of the building are preferred, positively affecting environmental costs of the "cradle" and "grave" phases (materials and components from renewable source, recycled/recycling, reused/reusable), but experimentation aims at optimising the "software" component with mechanical/home automation systems that stimulate natural processes.

Indicators must consider and calculate all life-cycle stages and define the main aspects (see ISO 21929-1: 2011) that could have potential impacts on the areas of protection (i.e., "Use of non-renewable resources"), primary (direct) impacts on natural resources and secondary (indirect) impacts on ecosystem and economic prosperity.

The research project evaluates three categories of material (Figure 3):

Category 1. Traditional (yellow line);

Category 2. Bio-based/nature-based, aiming at the only performance optimisation in the operational phase (green line) or also making eco-oriented design choices, that have had a positive impact on the environmental balance in the cradle and grave phases (blue line);

Category 3. Innovative (blue line).

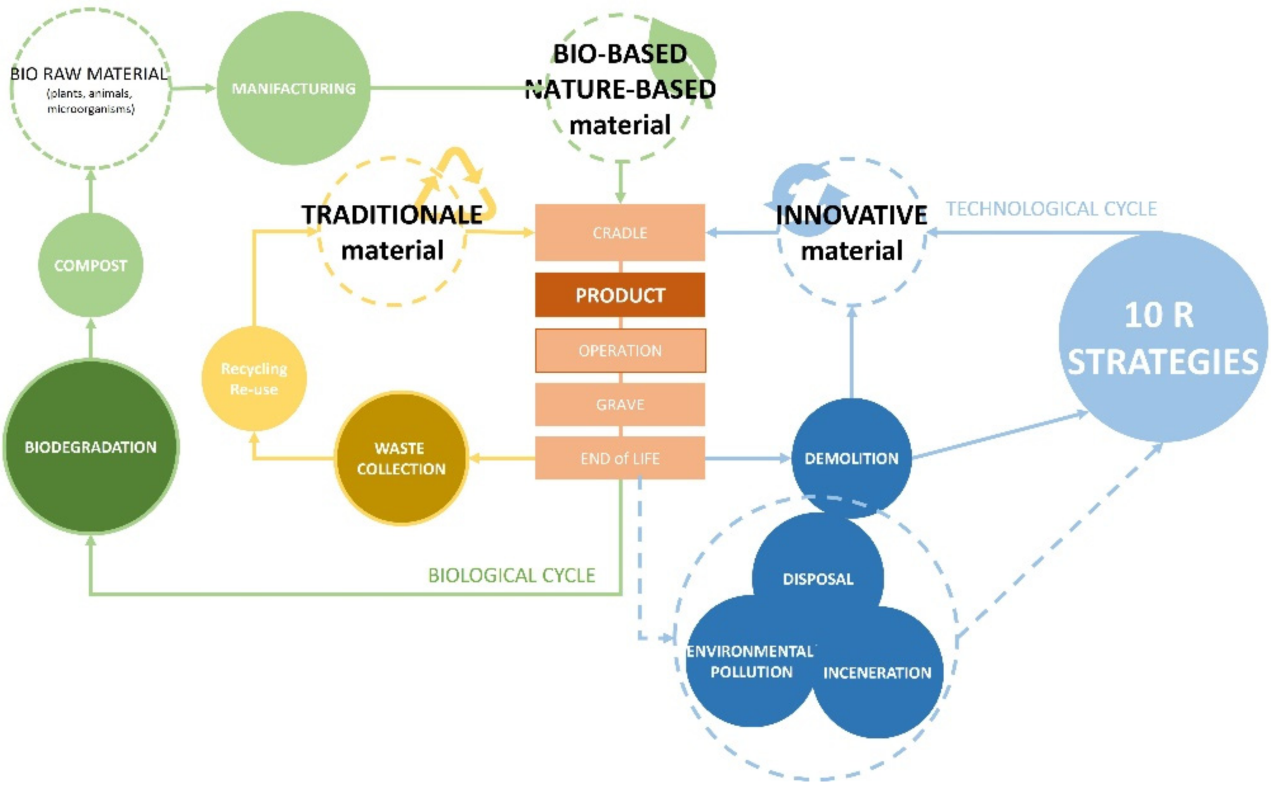

Figure 3. The different categories of materials.

In Table 2, the three categories of insulation materials, selected for illustrative purposes, are qualitatively compared with respect to the four life cycle phases.

Table 2. Evaluation of the three categories of insulation materials with respect to the four life cycle phases.

	Criteria	Range	C1	C2	C3
PRODUCTION	Raw material supply	1. From no renewable source and low availability 2. From no renewable source and high availability 3. From no renewable source with low regenerative potential 4. From renewable source with high regenerative potential 5. From waste of renewable/not renewable materials	1	4	5
	Transport [Distance/Availability].	1. Maximum distance and minimum availability 2. Maximum distance and medium availability 3. Medium distance and medium availability 4. Minimum distance and high availability 5. No distance and maximum availability	1	3	4
	Manufacturing [Complexity manufacturing process/Source supply].	1. High complexity in manufacturing process/High source supply 2. Medium complexity in manufacturing process/High source supply 3. Medium complexity in manufacturing process/Medium source supply 4. Minimum complexity in manufacturing process/Medium source supply 5. Minimum complexity in manufacturing process/Minimum source supply	1	2	5
	Carbon footprint of thermal insulation per surface unit (1 m^2), for U = 0.20 W/(m^2 K)	Min > Max	11.8	43.8	8.8
CONSTRUCTION	Transport to site	1. International distance 2. National distance 3. Regional distance 4. Local distance 5. No distance (grown in site)	2	2	5
	Construction/Installation process [Waste/Source supply].	1. Maximum waste/Maximum source supply 2. Medium waste/Medium source supply 3. Minimum waste/Medium source supply 4. No waste/Minimum source supply 5. Self-construction	4	4	5
OPERATION	Use [Reactivity]	1. Keeping unchanged intrinsic properties 2. Reacting by modifying the surrounding environment properties 3. Reducing the energy demand without energy production 4. Not reducing the energy demand but producing energy 5. Reducing the energy demand and producing energy	1	1	1
	Management [Maintenance of performances during time].	1. High intervention need to keep its performance unchanged over time 2. Medium intervention need to keep unchanged its performances during time 3. Low intervention need to keep its performance unchanged over time 4. To keep its performances unchanged without maintenance 5. Self-management (regenerative behaviour)	4	4	4
ENDOF LIFE	Recycling/Re-use	1. No re-use/No recycling 2. Partial re-use/Partial recycling 3. No re-use/Recycling 4. Re-use/No recycling 5. Re-use/Recycling	3	3	5
	Disposal	1. 100% disposal (special waste) 2. 100% disposal (ordinary waste) 3. Partial disposal 4. Biological decomposition 5. Re-inserting in the LCA	2	4	4

The research work compares three examples of thermal insulation belonging to the three categories. Below, we will analyse the components selected for comparison.

7.2. Comparative Analysis of the Most Significant Insulation Products Selected Using the Proposed Method

A wide variety of insulating materials is available on the international market, essentially grouped into two types of classification by origin (natural-artificial) or by structure (cellular, fibrous and porous).

In recent years, employment margins and installation diversification have allowed very extensive experimentation oriented essentially towards a reduction in insulation thickness—with the same thermal performance—and integration of insulation performance with improved air quality (reduction of volatile emissions, hygroscopicity, and antibacteriality).

This hypothesis appears unquestionably true when evaluating these materials in their operational phase but becomes very different when considering the building system during its entire life cycle.

For this research, three materials were considered as examples of the three main categories (Table 2) compared:

C1-Traditional-EPS (Expanded Polystyrene);
C2-Nature-based-cork (from FSC);
C3-Innovative-insulation from textile waste.

The evaluation immediately shows a substantial coincidence in the performance of these materials during operation, based on concrete performance stability over time and at the same time a very low need for maintenance to ensure durability. What changes substantially is the thickness: minimal in the traditional insulation and greater in the other two. All materials score low in terms of reactivity to external conditions and high in terms of maintenance.

However, the data comparison system makes it possible to distinguish a substantial difference in the performance of these materials during their cradle phase.

EPS (C1 alternative in Table 2), which is derived from a complex expansion of chemical polymer processing, has low scores because it is derived from non-renewable sources and its production is characterised by a huge use of energy and resources. In contrast, the processing of EPS is widespread on an international scale, which allows it to score well in the categories related to the transport of the processed product to the site. At the same time, the large-scale distribution of multiple product sizes allows for excellent adaptability in the installation phase, which takes place with minimal use of resources and reduced waste.

As anticipated, the operational phase follows a linear behaviour with high durability, while the negative impacts of the disposal phase need to be highlighted [18].

EPS, like most polymeric materials, is not reusable once disassembled but is completely recyclable and is often melted to be reintroduced into the technological production cycle due to its good mechanical resistance. Moreover, the polymer recycling operation entails a significant environmental impact due to the massive use of water and energy for molecular rearrangement.

Much more frequently, design choices identify directions based on the environmental compatibility of building materials, also thanks to a positive circuit of building certifications. For this research, natural cork was chosen as a representative of the nature-based materials category. Cork is very versatile and widely used as thermal and acoustic insulation.

Cork (C2 alternative in Table 2) is classified as a renewable source with a high regeneration potential and therefore achieves a high score in terms of raw material supply. At the same time, the good distribution of this resource allows medium distances to be travelled for the subsequent processing stages, which are characterised by processes of medium complexity, but which require a rather high use of resources (mainly due to cooking).

Transport to the site, as well as installation, is a low-impact phase (it is comparable to the performance of EPS) also in terms of reducing the volume of waste produced. The operational phase is linear and long-lasting, thanks to the positioning, generally internal to the envelope stratigraphy.

The end-of-life phase shows positive scores in terms of recycling data and the extension of its useful life is achieved through its reintroduction into the biological production cycle, due to its positive full biological decomposition.

The material resulting from experimentation by the CNB research group was selected as the innovative material (C3 alternative in Table 2). This material, initially conceived for packaging, has enormous potential in applications as an insulation panel for the building industry. It is produced from textile waste and mycelium. The mycelium is the natural fibre-reinforcing agent that combines shredded textile waste the growth process of the mycelium takes place indoors, in the dark, in about two weeks. The resulting fungal material is then dried to stop the growth, so it is considered a biotic process. This property makes it possible to assume a static performance in operational use over a long period of time without any maintenance.

The LCA analysis shows a substantial increase in the outermost stages of material performance (the cradle and the grave). In fact, during procurement, transport and production, the impact of the process is considered positive, as it reduces environmental pollution due to textile waste and mushroom cultivation takes place with minimal use of resources (water and energy).

Adding to the high Cradle scores is the self-production value (cultivated on site): in fact, thanks to the simplicity of laying and rapid stabilisation (about five days) it can be made in the insulating formwork on site, eliminating the transport phase to the building site and the waste of laying.

The disposal of this material, which cannot be reused as it is, but after simple crushing can become part of the production cycle.

In conclusion, we can highlight two other significant results of the comparison: firstly, against a substantial correspondence of operational performance, sustainable materials present a lower impact in the Cradle phase but maintain a relative limitation in the End of Life phase.

Secondly, Innovative materials present an almost common production process, which effectively cancels the Cradle phase and, unlike the previous category, allows for a wide range of disposal possibilities.

What substantially changes is the embodied carbon, which is maximised in innovative and bio-based insulators to the point of being considered carbon sinks.

8. Conclusions

This paper illustrates the conceptual framework of the valuation model between different types of thermal insulation materials evaluated in relation to their environmental impact in terms of carbon footprint and their ability to reduce the energy demand of buildings. The research started with an analysis of the main characteristics and environmental impacts of thermal insulation materials on the market, classified as Organic fossil fuel derived, Inorganic mineral derived, Organic plants derived and Innovative. Among the Innovative materials, particular attention was given to thermal insulation made from textile waste. The comparison shows that this kind of insulation offers interesting prospects both in terms of energy performance and carbon footprint. Particularly relevant is the positive environmental impact resulting from the non-incineration of textile waste at the end of its life, which is not sent to disposal sites but reinserted in a new Technological Cycle (C2C) according to the circular model.

Following this consideration, the research tackled the issue of circularity of processes, investigating the different ways of moving from a linear to a circular model of production by experimenting with new materials that respond to as many R-strategies as possible. About R-strategies, the sufficiency approach was found to be rewarding.

One of the globally recognised criteria is the reduction of embodied energy and carbon, the calculation of which must be part of the design information needed to make the right decisions for the built environment as recommended in the IGT Report [1].

However, a side consideration leads one to consider that the increase in the global population will lead to an increase in the number of buildings on the one hand, from which more and more comfort conditions will be demanded, and consumer products (e.g., textiles for clothing) on the other. The solution of using textile waste to produce insulation materials, therefore, becomes strategic: simultaneously decarbonising buildings and reducing the impacts of textile industry waste. However, for it to be economically viable "the value of textile waste" must be as low as possible.

The "percentage of recycled material fed into the production chain" determines the environmental properties of the insulation material and becomes an extremely relevant parameter. The criteria set by the environmental policy instruments: Green Public Procurement (GPP) in Europe and the new Minimum Environmental Criteria for buildings (MEC) in Italy (current framework, evolution and scenarios) confirm that the construction sector is a sector in which the research work carried out is widely spendable. Considering the new MEC (introduced by Ministerial Decree 256 of 23 June 2022 and entered into force on 4 December 2022) with which the Italian government intends to regulate public procurement in the construction sector, the parameter of the percentage of recycled material in the composition of building materials becomes extremely relevant. The designer in the MEC Report must justify the criterion with which he has chosen the material and the content of recycled or recovered material or by-products, producing the certificate in which the required percentage value is clearly stated, by:

1. Type III Environmental Product Declaration (EPD), compliant with UNI EN 15804 and UNI EN ISO 14025 (e.g., EPD© or EPDItaly©, specifying the calculation methodology);
2. "ReMade in Italy®" certification;
3. The "Plastic Second Life" label;
4. For PVC products, a product certification based on the criteria 4.1 "Use of recycled PVC" and 4.2 "Use of PVC by-products", of the VinylPlus Product Label, with attestation of the specific delivery;
5. A product certification, based on material traceability and mass balance, issued by a conformity assessment body;
6. A product certification, issued by a Conformity Assessment Body, in compliance with UNI/PdR 88 practice "Requirements for verifying the recycled and/or recovered and/or by-product content of products" if the material falls within the scope of this practice (Annex of Ministerial Decree 23 June 2022 no. 256). Of great interest are:

- The End-of-Life Plan, listing all materials, building components and prefabricated elements that can later be reused or recycled;
- The Plan for selective disassembly and demolition, based on ISO 20,887 "Sustainability in buildings and civil engineering works- Design for disassembly and adaptability-Principles, requirements and guidance", or the UNI/PdR 75 "Selective deconstruction-Methodology for selective deconstruction and waste recovery with a view to the circular economy" in which the designer must foresee that at least 70% of the weight of the building components and prefabricated elements used in the project (excluding installations) can be subjected to selective disassembly or demolition (deconstruction) at the end of their life in order to be prepared for reuse, recycling or other recovery operations.

The limitation of the research lies in the scarcity of data available for the assessment of GWP and the verification of the real useful life of these innovative materials. Furthermore, despite the potential of insulation materials made from textile waste, and the numerous research and experiments undertaken on this type of product, there is still little market penetration.

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References

1. European Commission. *Energy Union Package. A Framework Strategy for A Resilient Energy Union with a Forward-Looking Climate Change Policy*; COM(2015), 80; Final, Brussels, 25.2.2015; European Commission: Brussels, Belgium, 2015. Available online: https://eur-lex.europa.eu/resource.html?uri=cellar:1bd46c90-bdd4-11e4-bbe1-01aa75ed71a1.0018.01/DOC_1&format=PDF (accessed on 21 June 2023).
2. European Commission. *A Clean Planet for All. A European Strategic Long-Term Vision for a Prosperous, Modern, Competitive and Climate Neutral Economy*; COM(2018), 773; Final, Brussels, 28.11.2018; European Commission: Brussels, Belgium, 2018. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52018DC0773 (accessed on 21 June 2023).
3. Violano, A.; Cannaviello, M. Bio-based thinking: Research innovation on carbon-zero materials for the circular economy. In *BASES—Well-Being, Environment, Sustainability, Energy, Health. Planning and Designing in Transition*; Ferrante, T., Tucci, F., Eds.; AAVV; Franco Angeli: Milan, Italy, 2022; pp. 387–395.
4. Global Alliance for Buildings and Construction; International Energy Agency. *Global Status Report*; No: 978-92-807-3729-5; United Nations Environment Programme: Nairobi, Kenya, 2019.
5. Marrakech Partnership for Global Climate Action [MPGCA] 2021. Available online: https://unfccc.int/climate-action/marrakech-partnership-for-global-climate-action (accessed on 21 June 2023).
6. Li, X.; Densley Tingley, D. Solid wall insulation of the Victorian house stock in England: A whole life carbon perspective. *Build. Environ.* **2021**, *191*, 107595. [CrossRef]
7. Asdrubali, F.; D'Alessandro, F.; Schiavoni, S. A review of unconventional sustainable building insulation materials. *Sustain. Mater. Technol.* **2015**, *4*, 1–17. [CrossRef]
8. Ata-Ali, N.; Penadés-Plà, V.; Martínez-Muñoz, D.; Yepes, V. Recycled versus non-recycled insulation alternatives: LCA analysis for different climatic conditions in Spain. *Resour. Conserv. Recycl.* **2021**, *175*, 105838. [CrossRef]
9. Majumder, A.; Canale, L.; Mastino, C.C.; Pacitto, A.; Frattolillo, A.; Dell'Isola, M. Thermal Characterization of Recycled Materials for Building Insulation. *Energies* **2021**, *14*, 3564. [CrossRef]
10. Kunič, R. Carbon footprint of thermal insulation materials in building envelopes. *Energy Effic.* **2017**, *10*, 1511–1528. [CrossRef]
11. Global Status Report for Buildings and Construction. 2022. Available online: https://www.unep.org/resources/publication/2022-global-status-report-buildings-and-construction (accessed on 21 June 2023).
12. Valls-Val, K.; Bovea, M.D. Carbon footprint in Higher Education Institutions: A literature review and prospects for future research. *Clean Technol. Environ. Policy* **2021**, *23*, 2523–2542. [CrossRef]
13. Islam, S.; Bhat, G. Environmentally friendly thermal and acoustic insulation materials from recycled textiles. *J. Environ. Manag.* **2019**, *251*, 109536. [CrossRef] [PubMed]
14. Vanderwilde, C.P.; Newell, J.P. Ecosystem services and life cycle assessment: A bibliometric review. *Resour. Conserv. Recycl.* **2021**, *169*, 105461. [CrossRef]
15. Causone, F.; Tatti, A.; Alongi, A. From Nearly Zero Energy to Carbon-Neutral: Case Study of a Hospitality building. *Appl. Sci.* **2021**, *11*, 10148. [CrossRef]
16. Bourguiba, A.; Touati, K.; Sebaibi, N.; Boutouil, M.; Khadraoui, F. Recycled duvets for building thermal insulation. *J. Build. Eng.* **2020**, *31*, 101378. [CrossRef]
17. Dickson, T.; Pavía, S. Energy performance, environmental impact and cost of a range of insulation materials. *Renew. Sustain. Energy Rev.* **2021**, *140*, 110752. [CrossRef]

18. Abu-Jdayil, B.; Mourad, A.; Hittini, W.; Hassan, M.; Hameedi, S. Traditional, state-of-the-art and renewable thermal building insulation materials: An overview. *Constr. Build. Mater.* **2019**, *214*, 709–735. [CrossRef]
19. Cannaviello, M. NZEBOX. Product innovation to reduce carbon footprint of the construction site. In *Pro-Innovation—Process Production Product, Collana Project—Essays and Researches*; De Giovanni, G., Scalisi, F., Eds.; Palermo University Press: Palermo, Italy, 2019; Volume 2, pp. 185–197.
20. Füchsl, S.; Rheude, F.; Röder, H. Life cycle assessment (LCA) of thermal insulation materials: A critical review. *Clean. Mater.* **2022**, *5*, 100119. [CrossRef]
21. Dikmen, N.; Ozkan, S.T.E. Unconventional insulation materials. *Intech Open Sci.* **2016**, 3–23. [CrossRef]
22. Schiavoni, S.; D'Alessandro, F.; Bianchi, F.; Asdrubali, F. Insulation materials for the building sector: A review and comparative analysis. *Renew. Sustain. Energy Rev.* **2016**, *62*, 988–1011. [CrossRef]
23. Wiprächtiger, M.; Haupt, M.; Heeren, N.; Waser, E.; Hellweg, S. A framework for sustainable and circular system design: Development and application on thermal insulation materials. *Resour. Conserv. Recycl.* **2020**, *154*, 104631. [CrossRef]
24. Moncaster et Symons, A method and tool for 'cradle to grave' embodied carbon and energy impacts of UK buildings in compliance with the new TC350 standards. *Energy Build.* **2013**, *66*, 514–523. [CrossRef]
25. Kumar, D.; Alam, M.; Zou, P.X.W.; Sanjayan, J.G.; Memon, R.A. Comparative analysis of building insulation material properties and performance. *Renew. Sustain. Energy Rev.* **2020**, *131*, 110038. [CrossRef]
26. Llantoy, N.; Chàfer, M.; Cabeza, L.F. A comparative life cycle assessment (LCA) of different insulation materials for buildings in the continental Mediterranean climate. *Energy Build.* **2020**, *225*, 110323. [CrossRef]
27. OECD. *Can Social Protection Be an Engine for Inclusive Growth? Development Centre Studies*; OECD Publishing: Paris, France, 2019. [CrossRef]
28. Lacoste, C.; El Hage, R.; Bergeret, A.; Corn, S.; Lacroix, P. Sodium alginate adhesives as binders in wood fibers/textile waste fibers biocomposites for building insulation. *Carbohydr. Polym.* **2018**, *184*, 1–8. [CrossRef]
29. Panyakaew, S.; Fotios, S. New thermal insulation boards made from coconut husk and bagasse. *Energy Build.* **2011**, *43*, 1732–1739. [CrossRef]
30. Triollet, R. *JRC Annual Report 2021*; Foreman, A., Barry, G., Alvarez Martinez, A.F., Mondello, S., Eds.; Publications Office of the European Union: Luxembourg, 2022; ISBN 978-92-76-51231-8. [CrossRef]
31. Regulation (EU) No 1007/2011 of the European Parliament and of the Council of 27 September 2011 on Textile Fibre Names and Related Labelling and Marking of the Fibre Composition of Textile Products and Repealing Council Directive 73/44/EEC and Directives 96/73/EC and 2008/121/EC of the European Parliament and of the Council. Available online: https://eur-lex.europa.eu/eli/reg/2011/1007/oj (accessed on 21 June 2023).
32. Yalcin-Enis, I.; Kucukali-Ozturk, M.; Sezgin, H. Risks and Management of Textile Waste. In *Nanoscience and Biotechnology for Environmental Applications. Environmental Chemistry for a Sustainable World*; Gothandam, K., Ranjan, S., Dasgupta, N., Lichtfouse, E., Eds.; Springer: Cham, Switzerland, 2019; Volume 22. [CrossRef]
33. Drochytka, R.; Dvorakova, M.; Hodn, J. Performance Evaluation and Research of Alternative Thermal Insulation Based on Waste Polyester Fibres. *Procedia Eng.* **2017**, *195*, 236–243. [CrossRef]
34. Dissanayake, D.G.K.; Weerasinghe Wijesinghe, K.A.P.; Kalpage, K.M.D.M.P. Developing a compression moulded thermal insulation panel using post-industrial textile waste. *Waste Manag.* **2018**, *79*, 356–361. [CrossRef] [PubMed]
35. Hegyi, A.; Vermes, H.; Lazarescu, A.-V.; Petcu, C.; Bulacu, C. Thermal Insulation Mattresses Based on Textile Waste and Recycled Plastic Waste Fibres, Integrating Natural Fibres of Vegetable or Animal Origin. *Materials* **2022**, *15*, 1348. [CrossRef]
36. Tilioua, A.; Libessart, L.; Lassue, S. Characterization of the thermal properties of fibrous insulation materials made from recycled textile fibers for building applications: Theoretical and experimental analyses. *Appl. Therm. Eng.* **2018**, *142*, 56–67. [CrossRef]
37. Briga-Sá, A.; Nascimento, D.; Teixeira, N.; Pinto, J.; Caldeira, F.; Varum, H.; Paiva, A. Textile waste as an alternative thermal insulation building material solution. *Constr. Build. Mater.* **2013**, *38*, 155–160. [CrossRef]
38. Binici, H.; Eken, M.; Dolaz, M.; Aksogan, O.; Kara, M. An environmentally friendly thermal insulation material from sunflower stalk, textile waste and stubble fibres. *Constr. Build. Mater.* **2014**, *51*, 24–33. [CrossRef]
39. Hadded, A.; Benltoufa, S.; Fayala, F.; Jemni, A.M. Thermo physical characterisation of recycled textile materials used for building insulating. *J. Build. Eng.* **2016**, *5*, 34–40. [CrossRef]
40. ElWazna, M.; El Fatihi, M.; El Bouari, A.; Cherkaoui, O. Thermo physical characterization of sustainable insulation materials made from textile waste. *J. Build. Eng.* **2017**, *12*, 196–201. [CrossRef]
41. Ayed, R.; Bouadila, S.; Skouri, S.; Boquera, L.; Cabeza, L.F.; Lazaar, M. Recycling Textile Waste to Enhance Building Thermal Insulation and Reduce Carbon Emissions: Experimentation and Model-Based Dynamic Assessment. *Buildings* **2023**, *13*, 535. [CrossRef]
42. Savio, L.; Pennacchio, R.; Patrucco, A.; Manni, V.; Bosia, D. Natural Fibre Insulation Materials: Use of Textile and Agri-food Waste in a Circular Economy Perspective. *Mater. Circ. Econ.* **2022**, *4*, 6. [CrossRef]
43. Ong, R. 10Rs of Circular Economy: Strategies Sustainable Businesses Use. 2022. Available online: https://zenbird.media/10rs-of-circular-economy-strategies-sustainable-businesses-use-to-make-products/ (accessed on 21 June 2023).
44. Braulio-Gonzalo, M.; Bovea, M.D. Environmental and cost performance of building's envelope insulation materials to reduce energy demand: Thickness optimization. *Energy Build.* **2017**, *150*, 527–545. [CrossRef]

45. Ozel, M. Cost analysis for optimum thicknesses and environmental impacts of different insulation materials. *Energy Build.* **2012**, *49*, 552–559. [CrossRef]
46. Cramer, J. How network governance powers the Circular Economy. In *Ten Guiding Principles for Building a Circular Economy, Based on Dutch Experience*; Publication of the Amsterdam Economic Board: Amsterdam, The Netherlands, 2020; ISBN 978-90-90-33928-3.
47. Sandin, G.; Peters, G.M. Environmental impact of textile reuse and recycling—A review. *J. Clean. Prod.* **2018**, *184*, 353–365. [CrossRef]
48. Tomovska, E.; Jordeva, S.; Trajković, D.; Zafirova, K. Attitudes towards managing post-industrial apparel cuttings waste. *J. Text. Inst.* **2016**, *108*, 172–177. [CrossRef]
49. Ness, D. Towards sufficiency and solidarity: COP27 implications for construction and property. *Build. Cities* **2022**, *3*, 912–919. [CrossRef]
50. Commission Recommendation (EU) 2021/2279 of 15 December 2021 on the Use of the Environmental Footprint Methods to Measure and Communicate the Life Cycle Environmental Performance of Products and Organisations. C/2021/9332. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32021H2279 (accessed on 21 June 2023).
51. Violano, A.; Capobianco, L.; Cannaviello, M. The future now: An adaptive tailor-made prefabricated Zero Energy Building. *TECHNE—J. Technol. Archit. Environ.* **2021**, *2*, 122–127. [CrossRef]