Lecture Notes in Civil Engineering

Rossella Corrao · Tiziana Campisi ·
Simona Colajanni · Manfredi Saeli ·
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Proceedings of the 11th International Conference of Ar.Tec. (Scientific Society of Architectural Engineering)

Colloqui.AT.e 2024 - Volume 3

Springer

Lecture Notes in Civil Engineering 612

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ISSN 2366-2557 ISSN 2366-2565 (electronic)
Lecture Notes in Civil Engineering
ISBN 978-3-031-71866-3 ISBN 978-3-031-71867-0 (eBook)
https://doi.org/10.1007/978-3-031-71867-0

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Contents

Key Lecture

Topic C_Building Design and Technologies

Biogenic Local Waste for the Refurbishment of Rural Heritage: The Gualtieri Case Study (Lombardy, Italy)

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Abstract. Can rural buildings be refurbished by exploiting natural waste from local productions? This research aims to achieve implementation and sufficiency objectives by focusing on existing building refurbishment, efficiency improvement, and local natural resources exploitation. The solution being explored is the use of bio-based building materials, which, if well-designed, can offer low or even positive environmental impacts. To avoid land use and ensure not to compete with the food and biofuel sectors, the research focuses on organic waste in a circular approach. The research investigates a replicable workflow for using local bio-based waste in rural refurbishment, from the quantification of waste to the evaluation as building components, to finally assess the impact of their application. The contribution analyzes the state of the art, highlighting the lack of an established methodology for using natural waste in construction. The final goal is to facilitate the integration of these materials into the local construction sector. A case study has been presented to consider a specific geography and government system, starting with examining the Valmalenco Mountain Valley in northern Italy and hypothesizing the refurbishment of the Gualtieri village as a pilot project. The research employed Life Cycle Assessment to investigate the sustainability of different refurbishment scenarios for the case study, employing the semi-static method to determine GWP. Two tiers of study ensued: a primary comparison of biogenic insulation materials based on performance, impact, and cost, and a secondary analysis of three technologies, both conventional and innovative. Finally, a comprehensive examination of impacts was conducted and contrasted with the CasaClima protocol's national performance scale, yielding positive verification.

Keywords: Bio-based Materials · Rural Settlements · Local Organic Waste · Refurbishment Strategies · Data-driven Design

1 Introduction

The combined impact of buildings and construction plays a significant role in the climate crisis, contributing to 36% of global final energy consumption and 39% of energy-related carbon dioxide (CO_2) emissions when accounting for upstream power generation. Although there have been advancements in sustainable buildings and construction,

R. Corrao et al. (Eds.): Colloqui.AT.e 2024, LNCE 612, pp. 708–731, 2025.
https://doi.org/10.1007/978-3-031-71867-0_48

improvements are still not keeping up with the growing buildings sector and rising demand for energy services [1]. While past efforts focused on reducing building operational emissions through energy efficiency and renewable energy use [2, 3], recent studies indicate that greater attention should be given to other stages of the construction life cycle, such as the embodied carbon associated with manufacturing, transportation, and construction processes, to achieve complete decarbonization of the construction industry [4–6]. For those reasons, the decision-making and design stages require increasing efforts to take into account the complexity of requirements and optimize the subsequent phases of resource procurement, construction site, use, and end-of-life of buildings. This complexity increases in the case of existing heritage refurbishment interventions, requiring effective tools for the transparent evaluation of the different ad hoc design options. The first part of the paper is divided into sections, introducing the importance of marginal areas and regenerative solutions, then focusing on circular strategies, possible applications of biogenic materials in construction, and possible methods of quantifying and assessing their impact, as shown in Fig. 1.

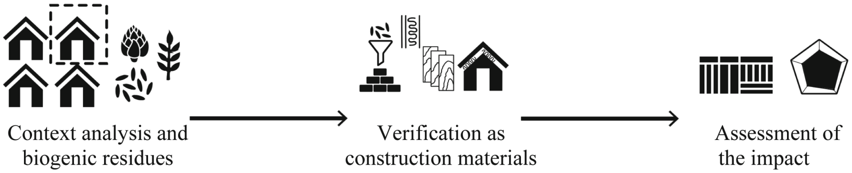


Fig. 1. Graphical diagram of the methodology described in the following paragraphs—2024, authors' production.

1.1 The Role of Marginal Settlements and Regenerative Strategies

Projections from the United Nations Population Fund (UNFPA) anticipate a global population surge, reaching 10.4 billion by 2100. Simultaneously, depopulation trends in Europe, highlighted by the OECD Regional Demography, reveal a concentration of inhabitants in urban areas, leading to the abandonment of smaller towns, causing the aging of the tangible and intangible heritage of marginal areas. Addressing the spatial challenges, the Global Alliance for Building and Construction, International Energy Agency, and United Nations Environment Programme report from 2018 underscores a surging demand for buildings, projecting a doubling of the global buildings sector floor area by 2060, resulting in an addition of over 230 billion square meters [7]. This escalating need for space intertwines with the depopulation issue, as smaller towns experience abandonment, contributing to the aging and neglect of rural centers. To this, it is necessary to offset the current macro-trend and promote sustainable development where new emerging post-pandemic challenges become the drivers for implementing regenerative actions beneficial for residents and marginalized social groups. Additionally, these actions should contribute to the protection and safeguarding of cultural and natural heritage and support the development of small and medium-sized businesses. This can be achieved through creativity and innovation, which should be rooted in culture and local knowledge [8].

For these reasons, the research chooses to focus on areas outside urban centers and urban clusters (areas with at least 5,000 inhabitants and at least 300 per km^2), choosing the definition of EU [9]. Moreover, the definition of minor historic settlement includes pre-modern cores and widespread traditional buildings, encompassing the spaces organized by past generations of farmers to enable the activities of animal farming and agriculture [10]. Italy is characterized by a complex and widespread network of these small settlements, integrated into territories with great scenic and natural values, but with a weak economy. However, if properly refurbished and repurposed, they can nevertheless be transformed into an opportunity to increase the attractiveness of a fragile territory and to create new developments for local populations [11].

At the same time, the EU requires its Member States to develop strategies to achieve a highly energy-efficient and fully decarbonized building stock by 2050. As the energy performance of buildings improves, construction materials become more important as a cause of environmental impact. According to IEA in 2019, this sector represents 11% of the overall energy and process-related CO_2 emissions. Furthermore, in a globalized economy, the potential for interregional solutions grounded in locally available resources often remains untapped. The focus on sustainable products arises from the urgent need to address these issues and transition towards more responsible and environmentally friendly production and consumption practices. Moreover, forecasts indicate the EU ETS price stabilizing around €70/tCO_2 by 2030, with subsequent growth to approximately €130/tCO_2 by 2040. The Market Stability Reserve (MSR) ensures price stability until 2035. Still, results suggest a potential surge in CO_2 prices in the 2040s, emphasizing the need for system redesign [12] (Fig. 2a). In this context, there is a rising interest in bio-based building materials (3BM) driven by their positive environmental attributes (Fig. 2b), including the use of renewable resources, carbon dioxide storage, reduced greenhouse gas emissions, and the promotion of healthier building environments [13–15]. Moreover, these materials offer the potential to stimulate previously untapped local markets and facilitate the transition toward a more circular economy, aligned with the European Commission's vision of resource efficiency.

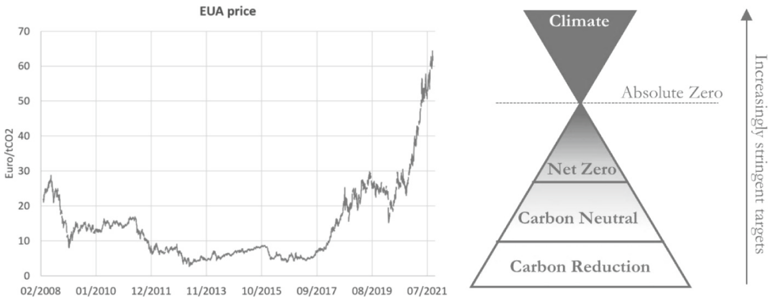


Fig. 2. **a.** Price of CO_2 in the EU Emissions Trading System—2021, Carbon Tax Center—**b.** Construction targets' pyramid—2024, authors' production.

The above is the conceptual and operational framework in which the following research project acts, looking to these marginal settlements and natural waste as a potential resource for the socio-ecological regeneration of the building environment (Fig. 3). Marginal settlements become the test site within which it will be possible to define and test share eco-innovative strategies. Hence, the circular principle is applied both to the reuse of waste materials and the recovery of fragile areas at risk of depopulation. We explore, as an alternative to conventional buildings, the use of bio-based materials as refurbishment systems with the exploitation of organic waste produced in the same area.

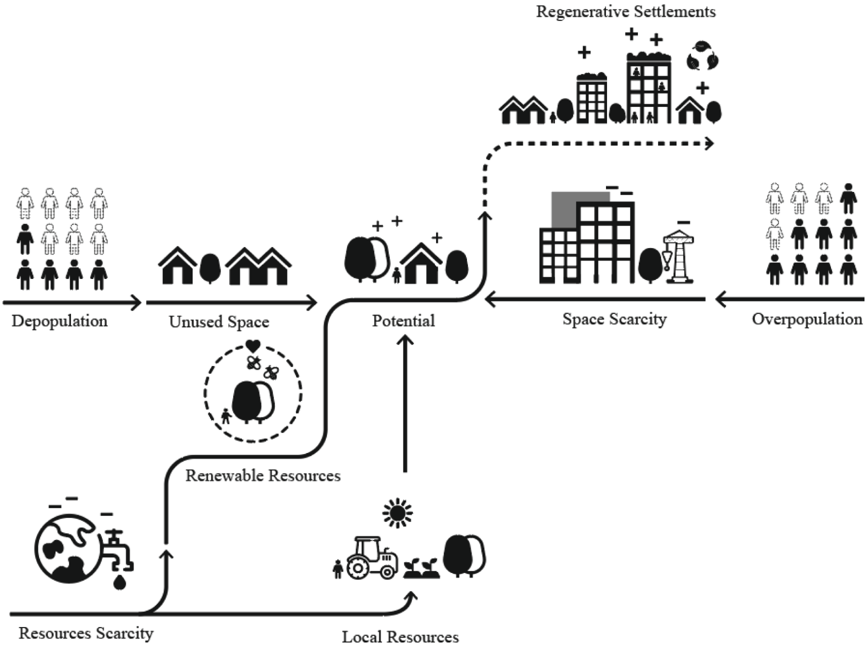


Fig. 3. Conceptual scheme of the problem statement and goal of the research—2024, authors' production.

2 Local Upcycled Waste as Construction Materials

The global extraction of materials has tripled since 1970, and this trend is expected to continue. Simultaneously, waste generation is projected to increase by 70% by the year 2050. This alarming rate of resource consumption and waste generation threatens the Earth's natural systems. Moreover, the impact on biodiversity and water resources is significant. This means that the current practices in material extraction and processing are unsustainable and significantly contribute to the deterioration of ecosystems and water sources. To address this issue, two main strategies can be applied to reduce environmental impacts related to buildings' materials: bio-based materials use and circular building design.

2.1 Regenerative Circular Thinking

Empirical evidence has underscored that solely relying on the reuse of building materials derived from demolition activities is insufficient to reach the sustainability objectives set for 2050, particularly considering the prevalence of new construction projects surpassing demolition activities. The incorporation of bio-based materials, harnessed from renewable sources, emerges as a pivotal strategy with the potential to use buildings as carbon sinks [16]. However, even if bio-based materials generally exert lower environmental impacts than conventional materials for climate change, they may have higher environmental impacts in the categories of land use and eutrophication [17]. While trying to find among bio-based materials those with less environmental impact, we developed a growing interest in natural waste coming from other sectors (mostly primary) and their availability. Up to now, energy use and paper making are the most common methods for the usage of waste [18]. Among the residue types, there are those obtained from the activities of agribusiness industries engaged in the cultivation, production, and processing of the products of primary activities such as agriculture, animal husbandry, and forestry, to make finished products for food. It emerges that the agribusiness sector is a complex economic branch, which includes within it a wide range of activities, occupying a considerable share of the market and a prominent position concerning the economy. Shifting from the circular approach to regenerative circular thinking which includes the life cycle of products coming from other sectors has threefold advantages. Firstly, biogenic wastes undergo a transformative process, precluding their incineration, as they find utility in a novel sector. Secondly, the construction industry, through the incorporation of these materials, mitigates the requisition for non-regenerative resources. Finally, with meticulous design that circumvents non-natural treatments, the natural materials employed in construction can, at the end of their life cycle, be reintegrated into the environment without necessitating additional treatment (Fig. 4).

Rural regions are characterized by high availability of natural resources and production of natural origin waste from agriculture, forestry, and breeding. The fragmentary nature of information has demonstrated that to promote the creation of circular economies is more effective to start from the territory’s characteristics and to identify the residues [19] (Fig. 4).

This research chose to focus on the use of readily available materials, with low economic value, and with no current complete use in the market. The following characteristics for the choice of materials are considered:

- natural waste materials that do not currently have any specific use, therefore destined for disposal for the most part, and that come from existing production systems that are sufficiently widespread in the area;
- materials already prepared for use, with almost no need to undergo further processing operations to create the element, to avoid increased production time and environmental impacts or experimentation of new machinery.

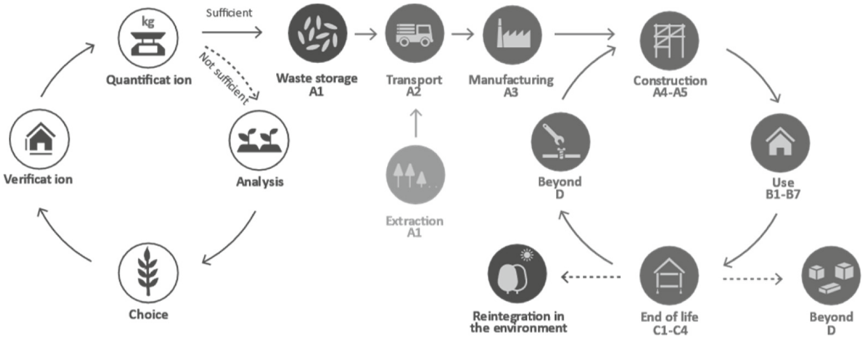


Fig. 4. Building's life cycle circular potential with the exploitation of organic local waste—2024, authors' production.

2.2 Verification as Construction Materials

After choosing the residues it is possible to verify the performances as building application and state which organic waste possesses suitable characteristics for use as a building component.

As already stated, bio-based materials, when applied in construction projects, have the potential to store their embedded CO_2 for the lifetime of the building component [20]. While much of the carbon stored in bio-based construction products is emitted as CO_2 at the end of the building service life, the same amount of carbon can be assumed to be sequestered when the regrowth of plants is completed [21]. Starting from the literature review and materials database, we can appreciate the typologies of products currently available in the European market with a variety of applications to fulfill the functions of structure, insulation, exterior and interior finish, and substrate (Table 1). European biomasses are mostly wood, wheat, rice, grass, hemp, sheep's wool, cellulose, kenaf, cork, seaweed, reeds, multi-biomass composition, and recycled biomass from textile industry waste such as cotton. The biomasses imported and assembled to form European products are bamboo from Asia and South America, recycled jute from the sacks, which are given a second life as insulation material, and coconut, whose fibers lend themselves well to forming sound insulation panels. All of them are obtained from other productions' waste, except hemp, kenaf, and bamboo. A further exception is the use of structural wood and cork, which are grown or used with the primary purpose of application in the construction world. At a first review, we can state that the wider employment of these materials is for insulation elements. Within the spectrum of biogenic materials, those derived from biomass that regenerates within a short time frame of 1 to 5 years, often referred to as fast-growing or herbaceous biomass, hold the greatest potential for addressing climate change. This is due to their ability to sequester carbon at a considerably faster rate than trees [22].

Table 1. Applications of biomass used as construction products in the European market—2023, Authors' reworking from 2021, Carcassi et al. [23].

Biomass used in construction in the European market		Applications									
		Structure		Insulation					External finishes	Interior finishes	Subfloors
			aggregate	roof	floor	interior walls	exterior walls	basement			
Local biomass	**WOOD**										
	Solid wood	X							X	X	
	Wood fiber			X	X	X	X				
	Wood wool			X	X	X	X				
	WHEAT										
	Straw	X					X				
	RICE										
	Rice hull										X
	Rice husk					X	X		X	X	
	Rice straw	X				X	X				
	HERB										
	Herb fiber			X	X	X	X	X			
	HEMP										
	Hemp fiber				X	X	X				
	Canapulus					X	X				

(*continued*)

Table 1. (*continued*)

Biomass used in construction in the European market	Applications									
	Structure		Insulation					External finishes	Interior finishes	Subfloors
		aggregate	roof	floor	interior walls	exterior walls	basement			
SHEEP WOOL										
Sheep wool			X	X	X	X	X			
FLAX										
Flaxboard					X					
CELLULOSE										
Cellulose fibers			X	X	X	X				
KENAF										
Kenaf Fibers			X	X	X	X				
CORK										
Cork			X	X	X	X		X	X	X
MARINE BIOMASS										
Posidonia oceanica			X	X	X	X			X	
Mussel shell		X								
REEDS										

(*continued*)

Table 1. (*continued*)

Biomass used in construction in the European market		Applications									
		Structure		Insulation					External finishes	Interior finishes	Subfloors
			aggregate	roof	floor	interior walls	exterior walls	basement			
	Lacustrine reeds			X		X	X			X	
Imported	**JUTE**										
	Jute fiber			X	X	X	X				
	BAMBOO										
	Bamboo reeds	X									
	Bamboo fibers	X							X	X	
	COCONUT										
	Coconut fibers									X	

2.3 Quantification of Bioregional Waste and Value Generation

After evaluating their viability as construction materials, a key challenge in promoting regenerative solutions' integration into the construction sector is gauging their abundance, quantifying the availability to reach industrial scale-up. Leising et al. [24] define CE in supply chain collaboration as connecting actors through managing data transparency, material flows, responsibilities, predictability, and benefits sharing. However, finding accurate data for residues coming from other sectors is challenging, as many variables are difficult to estimate, including a large number of crop and livestock types, the many treatment methodologies they may undergo, and statistical fluctuations. For this reason, focusing on clusters of regions and small supply chains seems to be easier. Statistical data and interviews are the most common approaches to quantify waste abundance. We found an interesting approach in the Value Chain Generator [25], a platform designed during the Interreg project AlpLinkBioEco to unearth unexploited business opportunities for bio-based value chains. The methodology relies on a knowledge base structured as a pyramid, with three levels: Actors, Descriptors, and Biolinks. The Actors Level contains information about various entities in the bio-based economy. Clusters, which are groups of connected companies within a geographic area, are also included in this level. The Descriptors Level involves expert knowledge about the activities to describe inputs, processing methods, and outputs. Finally, the Biolinks Level represents concrete links between two actors based on shared business opportunities (Fig. 5). Biolinks reflect potential interactions between actors. It ranges from simple ideas for new business opportunities to established economic interactions and new business models. Indeed, the process has two dimensions, the horizontal to match complementary inputs with outputs, and the vertical one, to add alternatives to identified ideas and actors [25]. However, this tool is not open access but is reported in this research as exemplary of a methodology that increases new opportunities for circular economies.

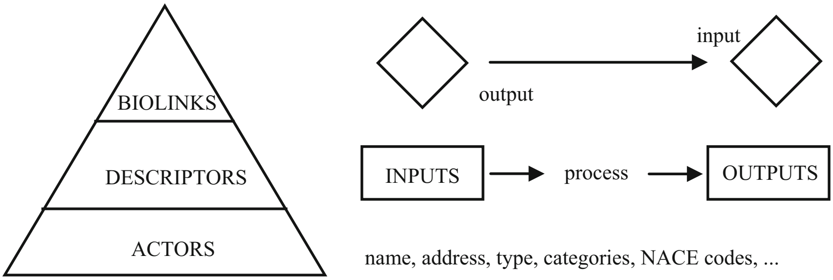


Fig. 5. Schematic diagram of VCG operation—2021, Interreg AlpLinkBioEco.

2.4 Assessment and Research Gap

Even if the use of bio-based solutions in the construction field is well-discussed and has a fast-growing interest in the scientific community, applications are still limited due to their relatively high cost and the lack of knowledge on raw materials' quantity and agribusiness residues, as well as on data for their impact assessment. Up to 80% of a product's environmental impacts can be determined at the design phase, significantly influencing the ultimate performance of buildings, but it is still marked by considerable uncertainty stemming from a lack of information and pending decisions. In the prevailing economic model, cost and market dynamics prioritize manufactured and financial values, neglecting natural, human, and social aspects. This linear economy fosters monoculture, biodiversity loss, and global inequalities. For these reasons, it is crucial to address all these aspects to entirely evaluate the regenerative power of the solutions. To tackle these issues, Porritt's 'five capitals' model [26], emphasizing natural, human, and social values alongside manufactured and financial aspects. LCA is a useful methodology to assess the environmental impact. Generally, in the construction sector, employing data from databases is suitable for conducting evaluations in the early stages of design, whereas data from Environmental Product Declarations (EPDs) are suitable for assessments in advanced design stages. Among the existing databases are Ecoinvent, KBOB, and ICE. Additionally, there are software programs that allow for rapid inventory and analysis, such as SimaPro, the One Click LCA plugin for Revit, and the Bombyx plugin for Grasshopper.

3 The Gualtieri Complex Case Study

We applied the methodology to a case study in Valmalenco, a key lateral valley of Valtellina, in the north of Italy, stretching for 15 km from Sondrio to Chiesa in Valmalenco. The focus is Gualtieri, a historic center under Sondrio Province and Valtellina Mountain Community. The analysis reveals that Valmalenco consists of isolated historic centers undergoing depopulation due to the intellectual capital drain and limited economic growth opportunities. Factors such as the Spriana landslide, unfavorable valley exposure, river Mallero flooding risk, and lack of railway connection to Sondrio contribute to the decline. Strengths include tourism potential and circular economy models for local commerce.

3.1 Agricultural Sector and Waste Quantification

The study delves into the agricultural and livestock sectors of Valtellina and Valmalenco, emphasizing short supply chains characterized by direct sales from local producers to consumers. Historically, both regions sustained their populations through agriculture, adapting to mountainous terrain with techniques like dry stone walls for terracing. However, contemporary challenges, including climate change, have contributed to the decline of high-altitude farming. In this sense it is crucial to mitigate environmental impact through innovative waste management solutions for the considerable by-products generated in these agricultural processes. Methodologies and sources for the quantification of waste have been:

- National and Regional Statistical Data, e.g. for Italy: Istat
- Data Collection from Companies: investigations among companies involved in different productions to gather data on the quantities of residual biomass.

Present-day agricultural activities in the area encompass cereals, vineyards, and innovative crops such as giant American blueberries. Table 2 shows the data of local productions and the amount of by-products or waste generated, with the current destination. Valtellina, renowned for its wine industry, particularly cultivates Nebbiolo grapes on terraced slopes. However, both regions grapple with environmental challenges arising from significant by-products generated in agricultural processes. For example, in the viticulture sector, grape cultivation yields substantial by-products, including grape stems, pomace, and pruning residues. The annual by-product quantity per agricultural enterprise is approximately 2,400 kg, comprising 300–400 kg of grape stems and approximately 5 tons of pruning residues. Considering ten viticultural enterprises in the average Valtellina territory, the total by-product amounts to 24,000 kg for grape processing and around 50 tons for pruning residues, posing challenges for disposal, especially due to the environmental impact of burning certain organic materials. Another crucial production in both Valtellina and Valmalenco is cereals, where cultivation has expanded to include blueberries.

3.2 Gualtieri Refurbishment Design

Contrada Gualtieri, situated in the “Quadra Rurale,” exhibits a rich historical context, influenced by its proximity to Sondrio and Chiesa in Valmalenco. Gualtieri, belonging to the fifth district of Sondrio, exhibited distinct socio-economic individuality from the 12th to the 13th century as a transit and toll area under the guidance of an elected Dean. After the Grisons’ occupation in 1512, the districts of Valmalenco gained significant autonomy, forming the six quadrants of the Magnificent Community of Malenco, actively engaging in artisanal and commercial initiatives. At present, Gualtieri is largely abandoned, with uninhabitable structures, and recent demolitions due to safety concerns (Fig. 6). The external walls of the complex reflect the local heritage, crafted from indigenous stones joined with lime and sand mortar. At times, these walls showcase historical plastered finishes. As for the roofs, they boast wooden frameworks supporting slate known as “piode”. Some renovations, adapting to contemporary needs, introduce materials like clay tiles or corrugated aluminum sheets. Interior inspections reveal a lack of distinct artistic or aesthetic flooring elements, suggesting a practical rather than ornamental approach to flooring in the observed spaces. Gualtieri’s proximity to Sondrio makes it a prime location for experimental initiatives, compensating for its limited agricultural opportunities.

The design hypothesis of the following research involves the inclusion of a technological hub intended for the reuse of biogenic waste materials from the region. Existing structures are recovered entirely, with options for integrated volumes in Cross Laminated Timber (CLT). Indeed, a notable structural strategy involves a “box within a box” made of CLT panels, preserving original lines while acting as structural support. Evolutionary phases include deliberate roof demolition, partial wall removal, and total floor extraction. Research conducted in the Valmalenco area revealed the potential of utilizing agricultural by-products. As outlined in the previous section, these predominantly include grape pomace, stems, fibrous cereal residues such as bran, straw, grass, milk whey, sheep wool, and wood from forest maintenance. Exploring these raw materials, potential applications in the construction sector were identified through scientific articles

Table 2. Local production, by-products, and waste in the Valtellina and Valmalenco regions—Authors' reworking.

Source	Quintals per year harvested	Products	By-products	By-products Current Destination	Waste	Quintals per year	Current Disposal
Grapevine	46 625	Wine	Pomace	Distilleries for grappa production		240	
			Lees	Soil Fertilizer			
					Grape Stalks		Incinerator
					Prunings	500	Incinerator
Rye	520	Grains, Flour, substitute for coffee	Straw	Animal bedding		234	
					Glumes, Rachis, Rests		Dispersed in the soil
Wheat	195	Grain, Flour	Germ	Oil used for soap production		30	
			Bran	Fodder			
			Straw	Animal bedding and papermaking			
Oats	140	Oat milk	Fibers	Bio-packaging		25	
		Grains, Flakes, Flours, Whiskey			Straw, Tegument		Dispersed in the soil
Buckwheat	360	Honey, Grains, Flours	Straw	Fodder animal		48	
					Husk		Dispersed in the soil

(*continued*)

Table 2. (*continued*)

Source	Quintals per year harvested	Products	By-products	By-products Current Destination	Waste	Quintals per year	Current Disposal
Barley	2 444	Grains, Flours, Barley coffee			Straw, Glumes	489	Dispersed in the soil
		Malt for beer and liquor	Threshing	Soil fertilization, animal feed, biogas production			

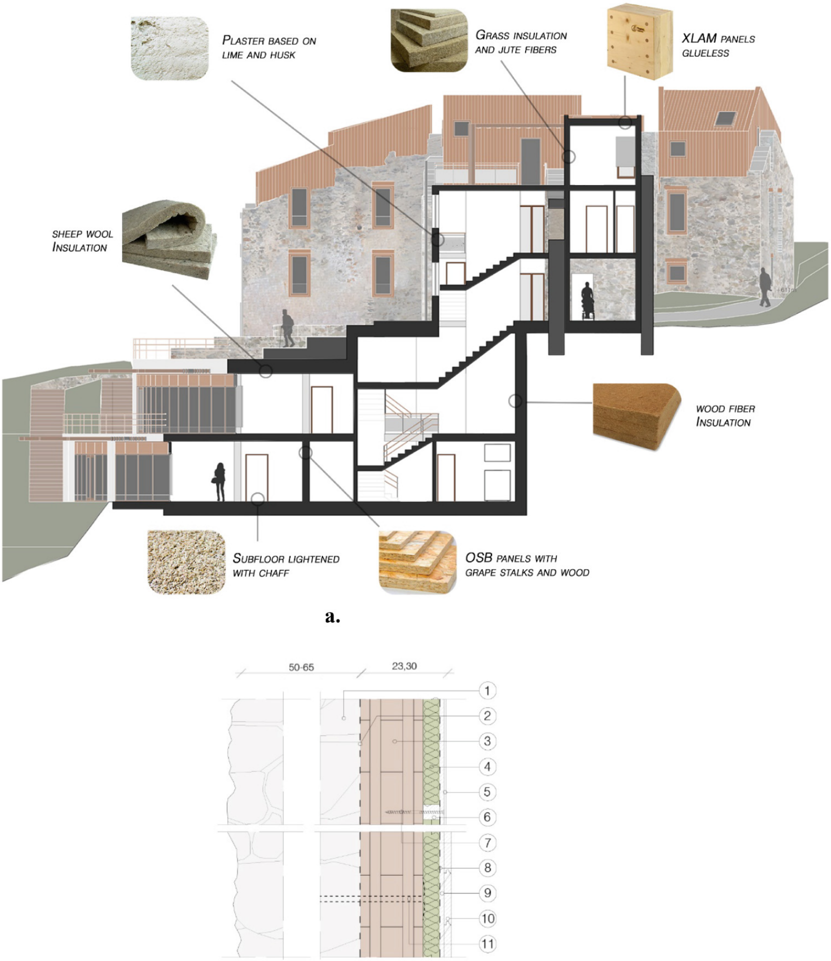
Fig. 6. Site section, technological section, reference plan, emblematic photo of the project area—2023, Cerri and Molina.

and existing products: most of these biomasses are already utilized to produce insulating materials and rigid support or cladding panels, often combined with mineral materials for thermal plasters and screeds. Priority was given to bio-based materials or those with an EPD for their technological choices. Specifically, for existing building renovation, an adhesive-free CLT structure was chosen, with structural slats connected by wooden screws, ensuring complete naturalness and recyclability. CLT not only serves a structural function but also offers thermal and comfort benefits and environmental impact reduction, making it highly suitable for renovation projects (Table 3).

Another prevalent material in a refurbishment design is insulation. The design choice incorporates three different types: grass and jute, wood fiber, and sheep wool insulation. These materials and technologies have been selected after the assessment in terms of performances, environmental impact and cost, as shown in the following section. Finishes and supporting elements predominantly consist of biogenic materials such as wooden slats, OSB panels, cereal fiber plaster, and fibrous waste and mycelium floors (Figs. 7a and 7b).

3.3 LCA as Comparison of Solutions

The case study chooses the LCA as a tool for measuring environmental impact and as a parameter for comparing multiple solutions. The analysis conducted defines two levels of comparison: the first between bio-based insulation materials (Fig. 8) and the second among three technological recovery solutions (Fig. 9). Both comparisons consider material performance, environmental impact, and costs per square meter. As mentioned in the 1.1 chapter, a key feature of bio-based materials is their ability to sequester carbon dioxide during growth through photosynthesis, affecting their carbon balance throughout their lifecycle. Various methods evaluate the carbon balance of biogenic materials, each considering growth, harvesting phases, and end-of-life scenarios. Static approaches assume a constant carbon balance, with two methods commonly used: the "0/0 approach" and the "–1/+1 approach". While these methods quantify the same GWP,



b.

Fig. 7. **a**. Representative section of the bio-based materials employment in the project—2023, Cerri and Molina. **b**. Vertical closure with CLT, bio-based insulation, and plaster or ash cladding on existing stone wall—2023, Cerri and Molina.

they differ in considering carbon sequestration. However, both lack temporal variability. Dynamic approaches, such as Levasseur [27] and Guest [28], account for storage and rotation periods of biogenic carbon. Levasseur's method employs dynamic characterization factors to calculate instantaneous and cumulative impacts over time, correcting the limitations of static methods. Guest's semi-static method, used in subsequent analyses, incorporates storage and rotation periods' influence on biogenic carbon balance, yielding a dynamic approach.

Table 3. Table of layers' properties referred to Fig. 7b—2023, Cerri and Molina.

	Description	T [m]	Density kg/m^3	λ-value W/mK	R m^{2}K/W
1	Existing stone wall	0.60	–	0.6	1.08
2	Waterproof membrane	0.0005	320	0.22	–
3	CLT panel	0.17	450	0.079	2.15
4	Insulating layer—grass panels and jute fibers	0.045	40	0.041	1.10
5	Lime plaster and fibrous waste	0.005	1420	0.065	0.08
6	Wooden lath substructure	0.045	485	0.13	–
8	Vapor barrier layer	0.00015	1330	0.39	–
9	Supporting layer made of OSB panel	0.01	600	0.13	0.08
10	Ash beadboard paneling	0.02	485	0.13	0.15

Regarding the choice of vertical insulation, different materials were compared by imposing a base thermal resistance value (Rt = 1.277 km^2/W), from which the various thicknesses were then derived. We proceeded with the inventory, where the GWP values related to production, construction, and decommissioning materials were evaluated, preferring, where possible, data from EPDs and using data from the databases KBOB and ECOINVENT. To conduct the comparison, it was necessary to standardize the net GWP values of individual insulants relative to the imposed thermal resistance. This normalization process involved the Eq. (1):

$$GWP\frac{kgCO_2eqW}{m^4K} = \frac{GWP\frac{kgCO_2eq}{kg} * \rho * sp}{R_t} \tag{1}$$

Subsequently, these values were compared with the cost per square meter of the respective materials, in some cases deducted from the cost of similar materials. The comparison values are then presented in a table and resulting graph (Fig. 8). It's noteworthy that Cartonlana, an insulation material composed of recycled paper and sheep wool, is not represented in the graph due to its significantly higher GWP values compared to other insulants, leading to its exclusion from consideration. Additionally, E-PLA insulation is not a viable solution due to its high impacts and costs, stemming from its limited market presence that hampers manufacturers from engineering and improving production. Conversely, these bio-based insulants all exhibit excellent performance, showing minimal differentiation in terms of impact, with only natural wool insulation reporting values above zero, but significant differentiation in terms of cost (with blown husk being the most expensive). The straw panel emerges as the preferred insulation material for external vertical closures, balancing performance, impacts, and costs, but it is impractical due to its thickness when applied to existing walls. Wood fiber insulation, while not as efficient as straw, is a suitable alternative due to its reduced thickness, especially for rural building restoration. However, the design strategy already apply wood for structures. The choice shifts to grass and jute panels despite their slightly lower performance. Their use would support the maintenance of surrounding forests, trails, and agricultural fields. Therefore, the grass and jute panel is chosen for external vertical closure systems (Fig. 7b), but other insulating materials may still be used within the project.

Table 4. Table of insulation materials with GWP and cost—2023, Cerri and Molina.

Insulation panel	GWPnet [kgCO$_2$eqW/m^{4}K]	Cost [€/m^2]
E-PLA	6.580	34.96
Natural wool insulation	0.278	15.5
Cartonlana	201.845	20
Wood fiber	–0.776	2.79
Grass and jute panel	–0.683	6.36
Blown-in husk insulation	–0.286	20.8
Straw	–2.411	0.48

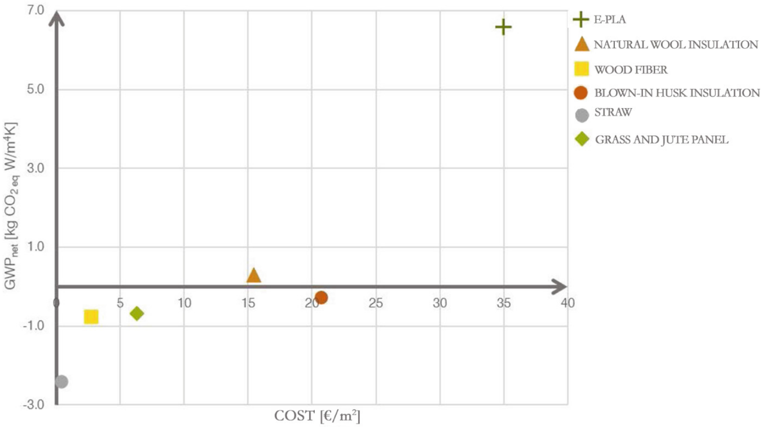


Fig. 8. Graph displaying insulation materials' correlation with GWP and cost per square meter—2023, Cerri and Molina.

Once the choice of insulation material for the vertical closure is made, the comparison between existing renewal solutions applied in previous projects was conducted. The technological unit chosen for comparison is the vertical closure adjacent to the stone wall (Fig. 7b). Three potential solutions have been defined and compared in terms of performance, GWP, and costs, to compare the bio-based option with other possible refurbishment options. These solutions include: Option A, Option B (bio-based solution), and Option C (Fig. 9).

- Option A: Conventional technology with brick structure, rock wool insulation, and plaster cladding, widely used in various recovery projects, especially in rural areas due to its low construction cost.
- Option B: Current project technology, made with bio-based materials and CLT structure, aiming for low environmental impact by utilizing local natural biomass. This solution, with plaster cladding, was chosen for analysis as it's the most common within the project.
- Option C: A technology that is increasingly chosen for rural renewal (such as the Paraloup project [29]) due to reduced thickness and dry technology, making it easier to execute, featuring a steel structure, sheep wool insulation, and local chestnut wood cladding.

The performance analysis ensured all technologies met a baseline transmittance of 0.28 W/m^{2}K, facilitating calculation of phase shift and sound insulation power and executing Glaser analysis, validated for all three conditions. Thickness was a crucial consideration due to rural recovery contexts, emphasizing minimal added thickness. Despite similar phase shifts and sound insulation power, the conventional solution performs best, while option C is less effective. The proposed bio-based material solution sits between the other two options, delivering good phase shift and sound absorption values.

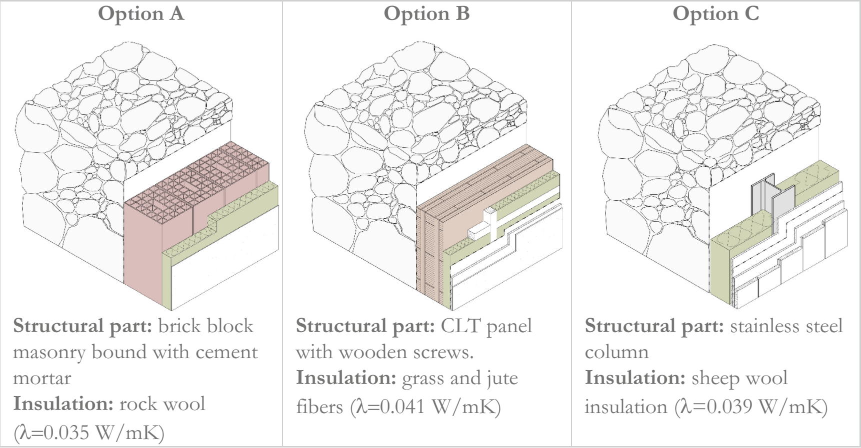


Fig. 9. Axonometric detail sections of the analyzed solutions—2023, Cerri and Molina.

For the environmental impacts assessment, LCA analysis of individual packages was conducted, considering 1 m^2 of technology with a thermal transmittance $U = 0.28$ W/m^{2}K (without considering the stone layer in the calculation). LCA involved analyzing individual option's impacts using the semi-static Guest method, considering fossil contributions statically and dynamic CO_2 biogenic contributions, reflecting natural materials' stored CO_2, ultimately providing net GWP values for comparison. Comparing solutions, the bio-based one (B) exhibits the lowest GWPbio, lowering the overall GWPnet, making it the least impactful. For comprehensive analysis, material costs per square meter and labor costs were assessed, with the traditional solution having the lowest overall cost, as bio-based building materials are still subjected to an ‘economy of scale’s’ focus in the current global economic model.

To establish relationships among various parameters, a comparison matrix was created, assigning scores to each parameter based on comparison scales (Table 4). These scales were developed either from existing standards, such as those outlined in the DM 26/06/2009 regarding phase shift, or from project-specific considerations. The thickness score scale was determined by evaluating the reduction of internal space, thus favoring minimal thicknesses with higher scores, similarly for cost per square meter, favoring lower-cost walls. For assigning scores to the GWP, a scale was devised considering that achieving a neutral or negative balance is not always possible, hence good scores were also assigned to packages with relatively low GWP (Table 5). Subsequently, a comparison matrix was generated by assigning the previous scores in Table 5 to each analyzed category.

The summation of these scores identified the solution with the highest score: option B, the biobased package. Despite its higher cost, it obtained excellent scores in terms of phase shift and environmental impact (Table 6).

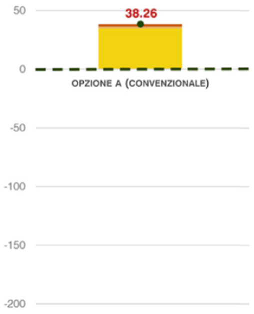
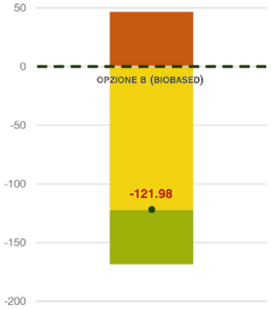
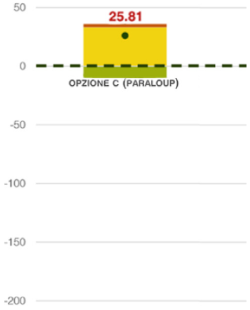
Finally, to validate the technological and energetic strategies adopted, a quantitative sustainability verification was undertaken. Initially, this involved using the “Nature” module of the CasaClima protocol, followed by defining and calculating the total GWP of the entire Gualtieri complex. The obtained value was then classified using the evaluation scale provided by the ProCasaClima software to assess environmental performance. The Nature module, integrated within the ProCasaClima spreadsheet, evaluates sustainability by considering various parameters such as the environmental impact of materials, water impact related to hydraulic system efficiency, indoor air quality, radon gas protection, natural lighting, and acoustic comfort. Certification relies on scoring within each category and bonus points for using locally sourced materials. To achieve certification, a score equal to or below 300 points is required. The module was completed, considering regional material sourcing to benefit from bonus points, resulting in a positive verification.

From the Nature module verification, the total GWP of the construction materials used in the project was obtained. This value was adjusted to account for any missing portions of the structure that were not included in the module. It is crucial to note that the software calculation does not incorporate biogenic CO_2, i.e., carbon dioxide absorbed by natural biomass during its growth period, as it is based on the EN 14067 standard, which lacks a dynamic method for calculating GWP. Consequently, the total GWP value was augmented with the addition of GWP values for the missing materials, calculated using a static approach. Further analysis highlighted the contribution of structural materials to the total GWP, with CLT’s negative balance notably reducing the overall value. Finally, the overall GWP value was converted to kg CO_2 eq/m^2 a, considering the building’s lifespan and project’s usable area. The calculated value, 2.986016 kgCO_2 eq/m^2 a, was compared with the CasaClima protocol’s value scale, confirming the building’s classification within the highest efficiency tier, category A.

Table 5. Table of scores assigned to the parameters considered.

Evaluation	Excellent	Good	Medium	Sufficient	Mediocre	Insuffi-cient
SCORE	**5**	**4**	**3**	**2**	**1**	**0**
Thickness (cm)	$t < 15$	$15 < t < 20$	$20 < t < 25$	$25 < t < 30$	$t > 30$	
Thermal lag (h)	$tl > 12$	$12 > tl > 10$	$10 > tl > 8$	$8 > tl > 6$	$tl < 6$	
GWP_{net} ($kgCO_{2\ eq}$)	$GWP < 0$	$0 < GWP < 10$	$10 < GWP < 20$	$20 < GWP < 30$	$GWP > 30$	
Total cost (€/m^2)	$c < 80$	$80 < c < 120$	$120 < c < 160$	$160 < c < 200$	$200 < c < 240$	$c > 240$

Table 6. Comparison matrix between the three options assessed—2023, Cerri and Molina.

Option A	Score	Option B	Score	Option C	Score
Thickness = 35 cm	**1**	Thickness = 23 cm	**3**	Thickness = 16 cm	**4**
Thermal lag = 13.34 h	**5**	Thermal lag = 12.95 h	**5**	Thermal lag = 9.23 h	**3**
GWPnet = 38.26 $kgCO_2$ eq		GWPnet = –121.98 $kgCO_2$ eq		GWP_{net} = 25.81 $kgCO_{2\ eq}$	
	**1**		**5**		**2**
Material cost = 42.57 €/m^2		Material cost = 120.86 €/m^2		Material cost = 58.70 €/m^2	
Labor cost = 47.45 €/m^2		Labor cost = 116.84 €/m^2		Labor cost = 213.93 €/m^2	
Total cost = 90.02 €/m^2	**4**	Total cost = 237.70 €/m^2	**1**	Total cost = 272. 63 €/m^2	**0**
TOTAL SCORE	**11**		**14**		**9**

4 Conclusions and Further Developments

The research aims to characterize rural areas to identify strategies for improving the adaptation of the building stock, preserving its cultural heritage while making it more adaptive to climate change, by using climate-neutral resources and promoting new circular economies through the activation of cross-sector synergies, in a multiscale and multidisciplinary approach. The study analyzes methods to quantify and assess different local materials and technological solutions, demonstrating that local bio-based solutions perform the best in terms of environmental impact and performances, but in terms of cost are still less advantageous than traditional technologies, still subjected to an 'economy of scale's' focus in the current global economic model.

Future developments include the establishment of a specific framework with the development of a matrix of KPIs for evaluating the use of regional biogenic waste in construction in environmental, social, and economic terms.

Acknowledgments. The authors would like to thank Victoria Cerri and Eleonora Molina (Politecnico di Milano) for their valuable support given during their master thesis for data collection and outcomes.

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