

Article

Embodied Environmental and Social Impacts: A Regionalised Sectoral Method for Low-Carbon Construction Materials in Italy

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Abstract

The decarbonisation of the built environment has increased reliance on Environmental Life Cycle Assessment (E-LCA) to evaluate the impacts of construction materials. However, social aspects—particularly those affecting workers—remain underexplored. This study presents a regionalised approach to support socially and environmentally informed decision-making in the Italian construction sector. For this purpose, we have integrated worker health and safety indicators into the E-LCA of two representative building products assessed across key life cycle stages. These indicators are incorporated into the evaluation of Global Warming Potential (GWP), thus serving as a decision-support tool during the design phase. From a design perspective, the aim is to promote a broader understanding of sustainability—encompassing both environmental and social dimensions—within building projects. Methodologically, the contribution is twofold. First, it addresses the current gap in context-specific data on the critical indicator of worker health and safety in the construction sector, an essential requirement for robust and scientifically recognised S-LCA studies. To this end, the study develops a regionalised scoring system based on publicly available occupational health and safety data from the Italian National Accident Database (INAIL), disaggregated by sector and region. Second, we propose a framework to combine these social indicators with LCA-based environmental impact metrics, which remain central to building-scale E-LCA. It is clear that no single region performs best, while a critical need for multi-criteria decision-making in sustainable design is evident.

Keywords: Environmental Life Cycle Assessment; Social Life Cycle Assessment; sustainable construction; occupational health and safety; regionalised data; material selection



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1. Introduction

Reducing greenhouse gas (GHG) emissions to mitigate anthropogenic impacts is a global priority. Sustainable measures, such as decarbonisation and circularity strategies, are being implemented within the construction industry to address some of these challenges. The European Union (EU) targets a 50% reduction in emissions in the building and construction sector by 2030, aiming for an economy with net-zero GHG emissions by 2050. This objective is at the heart of the European Green Deal and is legally mandated by the European Climate Law. A noteworthy strategy in this context involves the transition to net-zero carbon buildings (nZCBs), which has been widely recognised as a promising solution to energy and environmental problems, given that they offer significant advantages in energy efficiency and the reduction of carbon emissions [1,2]. Unlike net-zero

energy buildings (nZEBs), nZCBs focus on achieving net-zero carbon emissions throughout a building's entire life cycle. Net-zero carbon emissions are made up of embodied carbon (EC) (further divided into upfront and whole-life embodied carbon) and operational carbon (OC) (resulting from the emissions linked to operational energy (OE) and water use). Figure 1 illustrates the scopes and life cycle stages, as defined by European standards such as EN 15978:2011 [3].

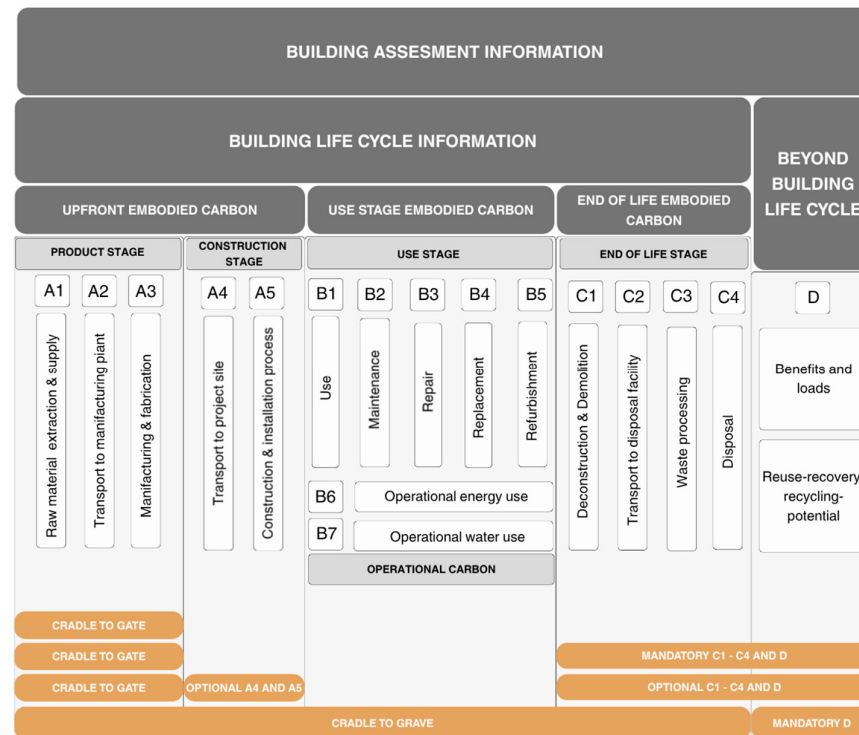


Figure 1. Building life cycle information adapted by EN 15978:2011 [3].

This strategy is consistent with the Whole Life Carbon (WLC) methodology outlined in the revised Energy Performance of Buildings Directive (EPBD) [4], which now includes comprehensive life cycle carbon assessments as a core criterion in evaluating building performance [5], and can serve as a fundamental lever to drive the decarbonisation of the built environment [6].

Recent literature has emphasised the crucial importance of upfront EC, particularly in the product stage, which accounts for approximately 76% of the total EC [7]. Today, product-level environmental data is available through Label Type III, known as Environmental Product Declarations (EPDs). In recent years, the number of EPDs has increased exponentially. In Italy alone, there has been a 29% increase from 420 in 2023 to 542 in 2024 [8]. The uptake of EPDs was primarily seen in companies in the northern part of the country (approx. 70%), followed by companies in the centre (approx. 18.2%) and approximately 10% in the south of Italy [9].

Originally developed to support business-to-business (B2B) communication within supply chains—particularly for procurement and product comparison—Environmental Product Declarations (EPDs) are now widely used as standardised data sources for building-level E-LCAs [10]. However, EPDs are not always available for all products included in a project. They are also not necessarily representative of the specific context of a construction intervention. In addition to production-related impacts, accurately assessing the environmental performance of a product within a given construction scenario requires careful consideration of post-gate phases, particularly those occurring pre-occupancy, such as transport (A4) and installation (A5). These stages can significantly influence overall

environmental outcomes. Furthermore, even a single product with an EPD may require differentiated treatment, as real-world variations in transport and installation conditions can substantially affect its life cycle performance. Likewise, the same raw material may result in different environmental impacts depending on its extraction conditions (A1) or the location of its transformation process (A3).

Alongside environmental impacts, construction supply chains exert substantial influence on the other two pillars of sustainable development—the social and economic dimensions [11]. In terms of social impact, the construction industry has a major influence on local communities, neighbourhoods and cities, construction workers and users, as well as on global communities through the globally interconnected supply chain that sits behind most construction products and building materials. To appreciate these impacts, S-LCA has been developed as a complementary approach to the Environmental Life Cycle Assessment (E-LCA) methodology in order to address social aspects through distinct methodological frameworks [12].

According to the official guidelines of the United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC), first published in 2009 and revised in 2020 (United Nations Environment Programme 2020) [13], the stakeholder categories included in the Social Life Cycle Assessment (S-LCA) are workers, the local community, value-chain actors, consumers, society and children. However, the required data is a complex part of S-LCA, as it includes information on health and safety, working conditions and other issues that are controversial in the industry [14]. Despite strict legislation and efforts by institutions and social partners to improve health and safety conditions, construction is still a risky industry in Italy [15]. Occupational safety is a critical issue in the sector due to frequent exposure to risks such as falls from heights, overexertion, and contact with hazardous materials.

According to the Italian National Institute for Insurance against Accidents at Work (INAIL) data [16], northern Italy accounts for almost 61% of all accidents, followed by central Italy, at 20%, and southern Italy, at 19%.

This study presents a regionalised method to support social and environmental decision-making in the Italian construction sector by integrating worker health and safety indicators into the E-LCA of two representative construction products across key life cycle stages. In this way, these indicators can be integrated into the assessment of Global Warming Potential (GWP), so serving as a decision-support tool in the design process. From a design perspective, the aim is to promote a broader understanding of sustainability—encompassing both environmental and social dimensions—within building projects. Methodologically, the contribution is twofold. First, it addresses the current gap in context-specific data on the critical indicator of worker health and safety in the construction sector, an essential requirement for robust and scientifically recognised S-LCA studies. Second, it proposes a framework to combine these social indicators with LCA-based environmental impact metrics, which remain central to building-scale E-LCA assessments. The proposed method is applied to a pilot building for which potential social hotspots are examined in relation to two construction materials—stone cladding and double glazing—commonly manufactured and employed in Italian building projects.

This approach aligns with recent contributions that emphasise the need to integrate multidimensional criteria into the design process at an early stage in order to support circular transitions in the built environment. In particular, Giordano et al. (2024) have highlighted the central role of LCA-based decision tools and the shift from single-impact assessments to composite indicators, reinforcing the relevance of scalable, data-driven approaches for material selection [17].

This study proposes a regionalised method to support social and environmental decision-making in the Italian construction sector by integrating worker health and safety indicators into the E-LCA of two representative construction products across key life cycle stages. In this way, these indicators can be integrated into the assessment of GWP, so serving as a decision-support tool in the design process.

2. Theoretical Background and Literature Review

To align with the climate objectives of the Paris Agreement and achieve climate neutrality by 2050, Italy has initiated a series of national strategic frameworks across multiple sectors, including the building industry. These cover the Integrated National Energy and Climate Plan (NECP), which sets targets for 2030; the Long-Term Strategy (LTS), which outlines the decarbonisation pathway towards 2050; and the National Strategy for the Energy Renovation of the Building Stock, aimed at enhancing energy efficiency and reducing emissions in the built environment.

However, a recent Buildings Performance Institute Europe (BPIE) report underscores that despite some progress, Italy must significantly intensify and expedite efforts to reduce emissions from its building stock in order to achieve long-term decarbonisation goals [18]. Among the key recommendations outlined by BPIE is the need to leverage the opportunities provided by the EPBD, including the introduction of limit values for GWP across all phases of the building life cycle. This necessitates the systematic quantification of CO₂-equivalent emissions aligned with the WLC framework, which integrates both operational and embodied impacts throughout the building's life cycle. A critical priority in this context is the reduction in EC emissions released prior to occupancy, which are primarily associated with construction products [19,20]. This trend has been corroborated by several recent studies examining the relationship between operational and embodied energy (EE) across diverse building typologies [21,22]. Findings show that in low-energy buildings, enhanced operational performance has led to a proportional increase in EC, which now accounts for approximately 30–60% of total GHG emissions [23]. In response to this shift, the selection of construction materials plays a strategic role in minimising the carbon footprint of buildings. As widely acknowledged in the E-LCA literature, using materials with low EE and EC—together with a greater reliance on locally sourced resources—is among the most effective strategies to mitigate EC impacts. Numerous studies have reported that increasing the use of local materials can significantly reduce EE, primarily by limiting transport-related emissions [24]. In line with these findings, Crishna et al. (2011) [25], in a life cycle assessment of stone production in the UK, demonstrated that locally sourced stone—such as sandstone, granite and slate—has a substantially lower carbon footprint than imported alternatives, emphasising the environmental benefits of reducing transport-related emissions [25].

This argument is further reinforced by long-term projections from the World Green Building Council, which estimate that more than 50% of total carbon emissions from all new buildings constructed globally between 2020 and 2050 will be attributable to EC [26]. From an economic viewpoint, the construction sector is a cornerstone of the European economy, employing approximately 30% of the EU's industrial workforce [27]. Construction workers are the backbone of the sector's workforce and are central to achieving the European Green Deal's ambitious built environment goals [28].

According to UNEP [29], the built environment is responsible for approximately 7% of employment worldwide and 11–13% of gross domestic product (GDP). In Italy, the construction sector represents a significant portion of the Italian GDP in terms of direct value added, contributing to approximately 5.4% of the national GDP. When incorporating the broader real estate industry and related activities, this contribution increases to 25%,

highlighting the sector's critical role in the macroeconomic structure and its substantial impact on national economic performance [30].

However, to transform the opportunities presented by the European Green Deal and the EU Recovery Instrument, NextGenerationEU—the Union's landmark post-pandemic investment plan—into a successful and coherent framework, it must be anchored in all the fundamental pillars of the European Union system. This includes not only sustainable development and environmental protection but also human well-being, social equity and the structural evolution of labour relations [31]. The creation of high-quality jobs within the green job initiatives of the EU Green Deal is closely linked to occupational safety and health (OSH) conditions, as it ensures a sustainable and resilient workforce during the transition to a greener economy.

Although the construction industry has a positive economic impact, it faces high accident rates, causing considerable financial repercussions [27]. Ensuring decent working conditions and good health and safety standards are among the key priorities outlined in the Joint Roadmap for Competitiveness and Decarbonisation in the recent Clean Industrial Deal, also referred to as the Pact for Clean Industry [28].

This initiative establishes a series of strategic measures to support the development and competitiveness of European industries in their decarbonisation pathways. Among these measures is the introduction of a voluntary carbon intensity label for industrial products targeting a 14% increase in material circularity by 2030, in addition to harmonising carbon accounting methodologies, providing greater transparency for consumers and recognising industry commitments towards achieving decarbonisation goals. The primary obstacle to this measure is often the lack of available data, which has left the evaluation of social impacts largely underdeveloped.

Based on the considerations outlined thus far, it is evident that actions aimed at building decarbonisation must be integrated with assessments conducted according to the S-LCA method, with particular attention paid to the worker stakeholder category, especially concerning the health and safety indicator. Although health and safety conditions are recognised as a critical factor in the construction sector, the quantification and assessment of their social impact remain, in our opinion, a methodological and data-related challenge.

2.1. Materials Considered in This Study

Within all material streams contributing to EC in buildings, this study focuses on natural stone and glass. Traditionally regarded as foundational materials in architectural history, stone and other lithic resources continue to play a significant role in contemporary construction. The stone industry has considerable economic significance both in Italy and globally, contributing to local production systems and employment capacities, particularly in specialised geographical areas [32]. Owing to the presence of highly specialised quarrying districts and a diverse lithological resource base, Italy retains a strategic role in the production and exportation of stone materials. According to the 2021 national survey, there are 4168 authorised quarrying sites across the country, with approximately 25% integrated into the natural stone supply chain. Annual extraction volumes reach 6.2 million cubic meters, most of which are used in the construction sector [33].

Recognising the environmental relevance of these materials, the European Commission established specific criteria for natural stone within the EU Ecolabel scheme for hard surface coverings, which was initially introduced in 2009 [34] and revised in 2021 [35]. More recently, natural stone has been identified among six strategic sectors included in Italy's national E-LCA database developed within the Arcadia project, positioning stone as a key element in supporting sustainable public procurement and green purchasing policies and practices [36,37].

Nevertheless, the cradle-to-gate approach adopted in the Arcadia project excludes several essential downstream phases—specifically, distribution to construction sites (A4) and their on-site installation (A5)—which are crucial for a comprehensive environmental assessment of natural stone use in architecture. These phases are particularly important in Italy, where the extraction and processing of natural stone are concentrated in geographically localised quarrying districts, typically situated near major mining sites. Tuscany, Lombardy and the Province of Trento are the regions with the highest extraction volumes—collectively contributing approximately 54.2% of national production—followed by Lazio and Sardinia.

The lithotypes extracted from these districts are determined by distinct geological, technical and cultural attributes and are widely employed in both contemporary architectural projects and interventions involving the restoration and adaptive reuse of existing structures.

Consequently, transportation and installation practices vary significantly across regions, and their environmental impact is strongly influenced by geographic location.

In addition to natural stone cladding systems, the present study also investigates a second envelope component—glass sheets used in window assemblies.

This focus is driven by the recognition that materials with thermal properties capable of significantly reducing a building's operational energy demand, e.g., insulating glass units (IGUs), play a substantial role in reducing the GWP associated with the building's life cycle.

Although windows typically account for only 10–25% of the total building envelope surface area, they are responsible for up to 60% of overall energy losses, primarily due to their comparatively low thermal resistance relative to other envelope components [38]. Furthermore, IGUs contribute directly and significantly to the GWP indicator, with an estimated 50% share by weight compared to other window components [5].

2.2. EPDs as Data Sources for E-LCA

E-LCA has become a crucial tool for measuring the cradle-to-grave environmental impacts of construction products [39,40] and processes, covering every stage from raw material extraction to end-of-life disposal [41]. E-LCA is widely recognised as the most effective scientific method for evaluating environmental impacts across the entire building life cycle, providing reliable, comprehensive and life cycle-spanning quantifications of EE, OE and GWP effects [42]. In the construction sector, this methodology is valuable, as it can help identify the most sustainable design practices, provide guidance for policy and decision-making and improve the building's overall environmental performance [43].

At the time of writing, Italy, unlike other EU countries [44], lacks a national methodology or harmonised framework for conducting E-LCA at the building level. The most significant recent advancement in this direction is the introduction of the Minimum Environmental Criteria (Criteri Ambientali Minimi or CAM) for public buildings, which are currently undergoing revision [45]. In addition, the newly adopted Procurement Code requires the integration of WLC and E-LCA assessments into both new and renovated public construction projects, so aligning with CAM provisions.

With the revision of CAM, a simplified E-LCA approach is being introduced covering system boundaries A1–A4, B4, B6 and C2–C4 to ensure compliance with European standards for environmental performance assessment. E-LCA studies will be based on EN 15643:2021 [46], EN 15978:2011 [3], EN 17680:2023 [47] and EN 15804+A2:2019 [48] so as to correspond with the European framework Level(s) [49], which promotes sustainability in the built environment and supports the integration of life cycle thinking into building design and public policy [49]. Within this framework, EPDs play a fundamental role

in verifying product compliance during construction, enabling site supervisors to assess equivalence in environmental performance between specified and proposed products, as specified in the comparability principle defined by UNI EN 15804+A2:2019 [48].

However, the use of EPDs as input data for E-LCA presents notable methodological challenges. Although EPDs provide standardised metrics regarding the environmental impact of products, their dependence on scenario-specific assumptions may lead to inconsistencies across regional contexts due to variability in assumptions and data quality [50]. The reliability of E-LCA results is therefore contingent on the precision and contextual relevance of the EPDs employed [44]. This issue becomes particularly significant when construction sites are geographically distant from manufacturing facilities. For instance, the environmental footprint of a window produced in northern Italy will differ depending on whether it is installed in the northern or southern parts of the country. These differences stem not only from extended transport distances but also from variations in transport modalities (e.g., vehicle load capacity, Euro emission class) and subsequent life cycle stages after production. Such variability can markedly influence E-LCA outcomes and, by extension, affect decision-making processes in sustainable construction. Although E-LCA remains a key tool for evaluating environmental building performance, it encounters several limitations and critical issues, including its reduced inclusion of social and economic dimensions [51,52]. Some scholars argue that conventional E-LCA methods fail to address environmental impacts on human health and well-being and do not incorporate wider social considerations [53].

2.3. Assessing Social Impacts in Product Systems

S-LCA expands the scope of sustainability evaluation by addressing the social impact of a product or process across its life cycle [54]. Research has shown that S-LCA is a valuable tool for identifying social hotspots and guiding product design and policy development [55]. S-LCA has a technical framework similar to E-LCA, adopting a four-step approach that involves defining the goal, scope and functional unit, as well as establishing the system boundaries in the first stage [56]. Both methodologies rely on a functional unit to define the product system, ensuring consistency in the evaluation (UNEP/SETAC, 2009) [57]. Although the E-LCA framework provides a structured methodology, the input data required for S-LCA differ significantly [58].

The S-LCA framework adopts a stakeholder-based approach, assessing potential impacts—positive and negative—on distinct social groups that form the analytical basis of the evaluation [13]. Social impacts are classified in function of stakeholders, with each group connected to impact subcategories representing socially significant themes or attributes. These subcategories are assessed through impact indicators, and multiple indicators may be used for evaluation (the table in Section 3.2.2). The selection of indicators depends on the specific context of the study. While alternative classifications, such as country-based groupings, may be applied, they must be clearly justified and explained. Each stakeholder category encompasses multiple dimensions of social impact.

The S-LCA Guidelines consider six stakeholder categories—workers, local communities, value chain actors (e.g., suppliers and not including consumers), consumers, children and society [13]. A more detailed classification is provided by the UNEP Guidelines [13].

The social dimension of sustainability is often the most elusive in practical efforts to advance sustainable development [59]. Although conventional discussions in the construction sector tend to underrepresent these aspects, increasing attention is being given to the broader social implications along the entire production chain, notably working conditions. S-LCA frameworks aim to incorporate these considerations more systematically. In particular, workers' health and well-being are among the most frequently assessed indi-

cators, serving as proxies to evaluate key social issues, such as fair wages, working hours, occupational safety, and labour rights. At the product level, S-LCA enables companies to systematically evaluate and communicate the social implications associated with their products across all stages of the value chain from raw material extraction to end of life.

Building on this approach, a promising protocol to reveal socially relevant information is the Social Product Declaration (SPD), a standardised format analogous to EPD. The concept was formally introduced in 2023 through a pilot initiative led by EPD International, RWTH Aachen University, Circular s.r.l. and Hitachi Rail, resulting in the world's first SPD and corresponding Product Category Rules (PCR) [60]. SPDs establish a dedicated framework to capture the specific dimensions of social sustainability, presenting key indicators, e.g., working conditions, labour rights, occupational health and safety, and community impacts in an independently verified, transparent and comparable format. The incorporation of SPDs into existing sustainability assessment frameworks provides a structured basis for enhancing transparency, accountability and evidence-based decision-making, which are consistent with UNEP Guidelines for S-LCA [13]. When deployed alongside EPDs, SPDs contribute to a more integrated representation of product sustainability while encouraging socially responsible practices across industrial value chains.

3. Methodology

To assess their suitability within an appropriate design framework, the proposed methodological approach is tested on a certified Passive House building, selected as representative of NZEB principles and as a reference for embodied GWP assessment. Specifically, the case involves a residential building to be built in Italy that has been extensively analysed in terms of embodied and operational energy in previous research [61]. The focus of the analysis is on two representative construction materials—natural stone and double glazing—selected for their relevance in building envelopes and fenestration systems. As an application context, it is assumed that the natural stone is sourced from Tuscany, a region historically and industrially linked to the extraction and processing of natural stone, with well-established stone districts. For double glazing, the reference region is Lombardy, which hosts numerous production hubs and is widely recognised as a key node in the national construction supply chain. To broaden the geographical scope of the analysis, additional regions were considered: Lazio, Liguria, and the Province of Bolzano, all located within a 500 km radius. These areas were selected to reflect a wider range of production contexts and logistical conditions relevant to the Italian construction sector.

Figure 2, illustrates the implementation of the study across three sequential stages.

- (1) Definition of the goal and scope and system boundaries for both the E-LCA and S-LCA.
- (2) Impact assessment data collection, including
 - (a) collection and selection of E-LCA data sources, such as indicators for natural stone based on a previous study [31] and EPDs for double glazing, along with the definition of appropriate scenarios to conduct the E-LCA;
 - (b) Identification of essential S-LCA elements, including relevant stakeholder categories, impact subcategories and the social inventory required for the analysis.
- (3) Impact characterisation of environmental impacts covering the following life cycle stages:
 - i. Production (A1–A3);
 - ii. Transport (A4), accounting for site-to-site distances specified in step a;
 - iii. Installation (A5) derived from EPD-aligned producer profiles.

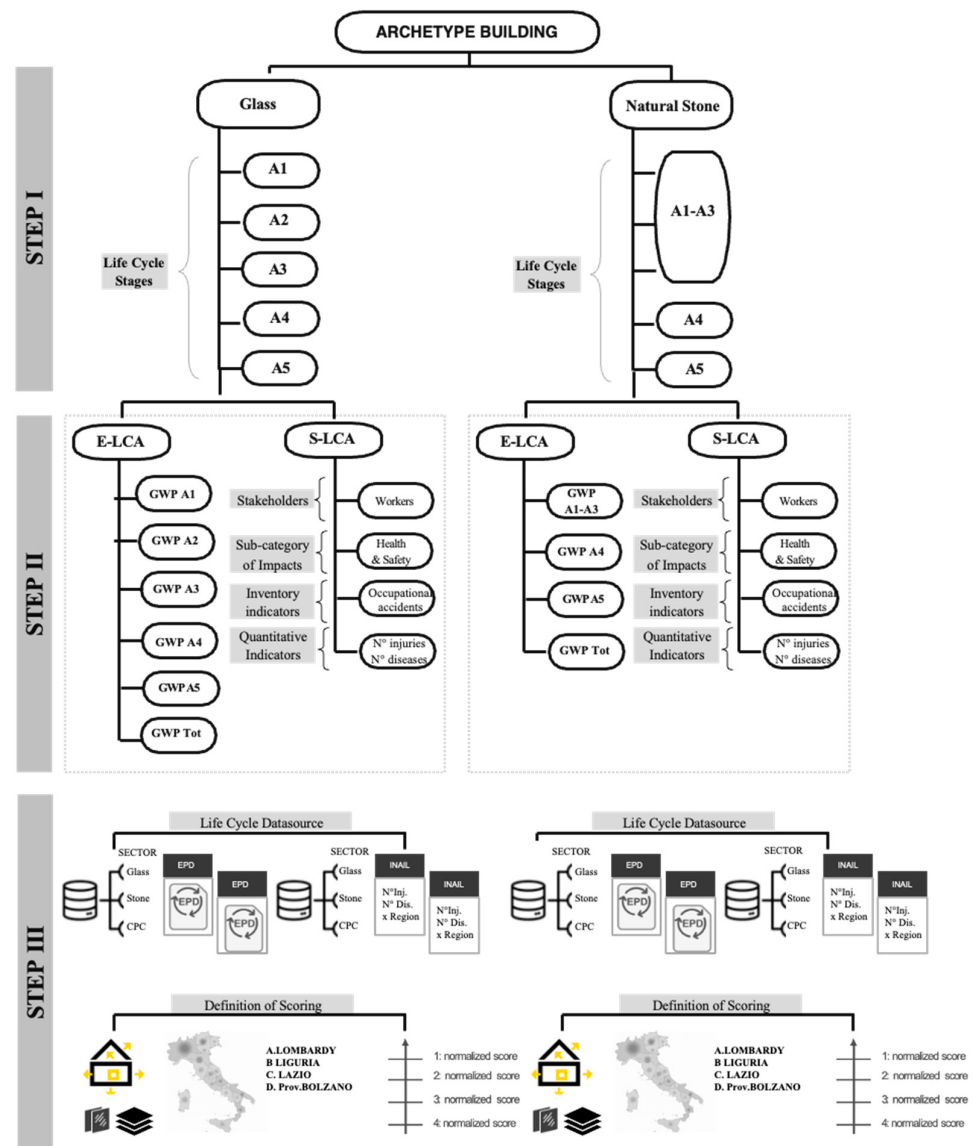


Figure 2. Steps of the proposed methodology.

Social impacts were further examined through regional accident data from the Italian construction industry based on official records provided by INAIL and regarding four regions: Lombardy, Liguria, Lazio and the Province of Bolzano. Subsequently, a normalisation procedure was applied to develop scoring systems for both E-LCA and S-LCA culminating in targeted recommendations aimed at guiding material selection and supporting more sustainable building design decisions.

3.1. Step 1: Definition of the Goal & Scope and System Boundaries

In line with ISO 14040 standards and the UNEP Guidelines for S-LCA methodology [62,63], the first step involves defining the study's purpose by addressing the following questions:

- What are the study's objectives?
- Who is the intended audience?
- What specific aspects are being assessed?
- Does the study contribute to decision-making processes? If so, in which domain?
- Which stakeholders are specifically relevant for S-LCA?

The overarching goal is to facilitate sustainable building design and informed decision-making in the selection of construction materials and products via a life cycle-based methodology integrating both environmental and social dimensions. Although the analysis focuses on two selected materials—ornamental stone for façade cladding and glass for insulated glazing units—the proposed framework is scalable and applicable to a broader spectrum of building materials. It enables a comprehensive evaluation of impacts across the life cycle and supports design decisions that balance environmental performance with social considerations.

The functional unit adopted in this study corresponds to the total installed quantity of each selected material within the case study building, specifically 133 m² of ornamental stone flooring and 15 m² of insulated glazing units, distributed across eight windows and one French door. This building-scale definition reflects real-world procurement and design logic, and supports a comprehensive assessment of environmental and social impacts. Although results are not normalised to 1 m², the approach remains compatible with component-level comparisons and aligns with EN 15804+A2:2019 [48] and ISO 21930:2017 [64] principles.

The life cycle stages addressed include quarrying raw materials (A1), transport to the manufacturing site (A2), manufacturing process (A3), delivery to the building site (A4) and installation (A5) (Figure 3).

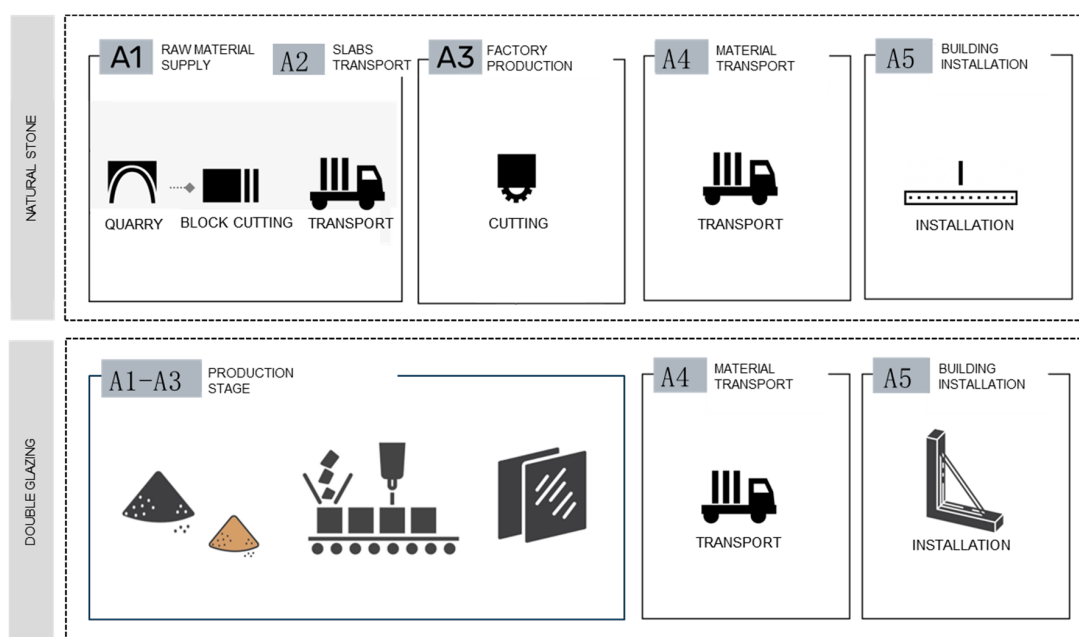


Figure 3. System boundaries adopted for E-LCA and S-LCA integration.

Material quantities from the case study were cross-referenced with EPD data to carry out the full E-LCA process consistent with the four standardised stages. Using the stakeholder-based approach outlined in the UNEP framework, the study identifies *workers* engaged in manufacturing, quarrying and construction as the principal stakeholder category. Within this group, *health and safety* was selected as the key social impact sub-category given its prominence in construction-related lifecycle stages. This choice was informed by a socio-economic analysis and supported by data from Eurostat [65]. These figures highlight that while construction is classified as a strategic sector, it remains the industry with the highest number of non-fatal occupational accidents in Europe.

3.2. Step 2: Data Collection

3.2.1. E-LCA Data Source

The aforementioned work identifies the bill of materials, including their composition and technical characteristics. From this dataset, two materials—double glazing and natural stone cladding—were selected for further analysis. In the second step, their respective quantities were correlated with GWP indicators sourced from two main reference points—(i) a detailed LCA study based on primary data collected both at the quarry and at the production facility of Italian manufacturers regarding cladding stone extracted in Tuscany, and (ii) the EPDs of the double glazing used in the window systems (Table 1). More specifically, in order to carry out the environmental impacts across the four geographical scenarios under investigation, values from the EPDs were adapted for life cycle stages A2 (only for the natural stone), A4 and A5. Stages A1 and A3 were assumed to remain constant, as they are closely tied to core production processes. Table 1 provides a summary of the data utilised to quantify CO₂ equivalent emissions across the relevant life cycle stages for the two selected products.

Table 1. E-LCA assumptions.

Life Cycle Stage	Material Category	Description	Bill of Quantities/Materials Input	Data Types/Collecting Data Method
A1–A3	Double glazing	1 m ² of double-glazing insulating glass, consisting of two laminated glass panes (44.1) and a 16 mm argon-filled cavity, with a total weight of 41.981 kg/m ² . U value = 1.0 W/(m ² ·K). The two laminated glass panes are composed of: 4 mm soda-lime silicate glass pane, 4 mm coated glass pane, treated with a thin layer of metal oxides applied through a cathodic sputtering process conducted under vacuum conditions.	15.7 m ² /0.65 ton	EPD (Source: EPD-IES-0015806.002)
	Natural stone	The modelling of module A2 considers weighted average transport distances of raw materials from suppliers to the manufacturing facility. Transport modes include road, ship, and/or rail, depending on the origin of each material. These modes are not disaggregated individually, but are reported in aggregated form across modules A1–A3, in accordance with EN 15804+A2:2019 [48]. 1 metric ton of natural sandstone, extracted from an Italian quarry, featuring a natural surface and sawn edges, with a density of 2550 kg/m ³ . 1 metric ton of natural sandstone, extracted from an Italian quarry, featuring a natural surface and sawn edges, with a density of 2550 kg/m ³ . The transport process in module A2 refers to the movement of 1 metric ton of sandstone by a 16–32 tonne EURO 5 freight lorry over approx. 0.7 km, corresponding to a short internal transfer within the quarry site.	133 m ² /6.8 ton	E-LCA study (Source: [29])

Table 1. Cont.

Life Cycle Stage	Material Category	Description	Bill of Quantities/Materials Input	Data Types/Collecting Data Method
A4	Double glazing	The assumed transport scenarios estimate a distance range of 141–520 km, carried out by lorry (>32 t). This corresponds approximately to the distances from the manufacturing site to Genoa ($\approx$ 250 km), Milan (170 km), Rome (520 km) and Bolzano (191 km).	659 kg $\times$ distance (141–520) km	Scenario readapted from EPD (Source: EPD-IES-0015806.002)
A4	Natural stone	As scenarios, a transport distance between 313 and 360 km is considered, carried out by lorry (>32 t). This corresponds, respectively, to the distance from the manufacturing site to Genoa (313 km), Milan (317 km), Rome (339 km) and Bolzano (360 km).	6.8 tonnes $\times$ distance (313–360) km	Scenario readapted from EPD (Source: NEPD-2907-1588-EN)
A5	Double glazing	According to the EPD assumption for A5, no waste is generated during installation except for packaging residues, specifically mixed plastics and pressed board, which are allocated for recycling. An average transport distance of 50 km is considered between the customer site and the recycling facility, using a lorry (3.5–7.5 metric tonnes, EURO 5 emission standard) for transportation.	15.7 m ²	EPD (Source: EPD-IES-0015806.002)
A5	Natural stone	The adopted scenario considers installation using cement-based adhesives, with an estimated 10% material spillage occurring during the process. Additionally, packaging waste treatment is integrated into the overall assessment. For each m ² of installed cladding, 5 kg of cement mortar and 1 litre of water are assumed	133 m ²	EPD (Source: NEPD-2907-1588-EN)

The quality of environmental data was systematically assessed using the Data Quality Matrix. Pedigree scores were assigned to modules A1–A5 to ensure transparency regarding the origin, relevance, and technological alignment of the datasets used. The scores reported in Table 1 follow a scale from 1 (very good) to 5 (very poor), with all values ranging between 1 and 2, indicating a good level of data quality and representativeness.

3.2.2. S-LCA Assumptions

Building on the stakeholder-based framework outlined in the UNEP Guidelines [13], the study identifies workers as the principal stakeholder category and selects health and safety as the key social subcategory, given their relevance as one of the most critical issues across the life cycle stages within the system boundaries (Table 2).

The prioritisation of this social indicator stems from an analysis of socio-economic pressures particularly affecting the construction sector, which historically shows high vulnerability to workplace accidents. According to Eurostat [65], the construction industry accounted for 65.6% of all fatal occupational incidents and 43.0% of non-fatal accidents registered within the European Union in 2022. It also represented 21.9% of total reported workplace accidents, surpassing sectors such as transportation and storage (15.6%).

Table 2. Connection between stakeholders, subcategories, indicators, and data collection (Adapted from UNEP [13]).

Stakeholder Category	Subcategories	Indicators	Inventory Indicators	Data Types/Collecting Data Method
Worker	Health and safety		Occupational accidents	Primary data of N° Injuries, fatal incidents and work-related illnesses in Italy per year, per type of incident (e.g., falls, exposure to hazardous substances) by industrial sector and region from National Institute for the Prevention of Accidents at Work (INAIL) work-related accident database

Complementary national data provided by INAIL confirms the sector’s critical status in Italy. In 2023, approximately 40,000 occupational injuries were recorded in construction, marking a 3.4% increase compared to the previous year and positioning the industry among those with the highest accident rates.

3.3. Step 3: The Characterisation of Impacts

3.3.1. Environmental Life Cycle Impacts

The GWP impacts for each life cycle stage derived from the data collected for the case study building are given in Table 3 for the cladding stone (133 m²) and in Table 4 for the double glazing (15.6 m²).

Table 3. GWP indicator across each life cycle stage for natural stone cladding installed in the building, with corresponding regional scores.

GWP Indicator (Kg CO ₂ Equivalent)				
	Lombardy	Lazio	Liguria	Bolzano
A1	8.75	8.75	8.75	8.75
A2	7.46×10^{-1}	7.46×10^{-1}	7.46×10^{-1}	7.46×10^{-1}
A3	7.87	7.87	7.87	7.87
A4	2.39×10^2	2.55×10^2	2.36×10^2	2.72×10^2
A5	1.82×10^2	1.82×10^2	1.82×10^2	1.82×10^2
Total	4.39×10^2	4.55×10^2	4.36×10^2	4.72×10^2
Normalised value	0.93	0.96	0.92	1
Rank	2	3	1	4

To enable comparison across regional contexts, environmental impact values were normalised with respect to the maximum observed benchmark: Bolzano (472 kg CO₂ eq.) for natural stone and Lazio (633 kg CO₂ eq.) for double glazing. Normalisation was performed using the following formula:

$$\text{Normalised value} = \frac{\text{Regional impact}}{\text{Benchmark}}$$

Subsequently, normalised values were recoded onto an ordinal scale ranging from 1 (lowest impact) to 4 (highest impact), in order to facilitate integration with the social indicator and the construction of the composite E-LCA + S-LCA score.

Table 4. GWP indicator by life cycle stage for double glazing applied in the case study building, with corresponding regional scores.

GWP Indicator (Kg CO ₂ Equivalent)				
	Lombardy	Lazio	Liguria	Bolzano
A1–A3	5.69×10^2	5.69×10^2	5.69×10^2	5.69×10^2
A4	2.12×10^1	6.45×10^1	3.03×10^1	2.37×10^1
A5	1.49×10^{-2}	1.49×10^{-2}	1.49×10^{-2}	1.49×10^{-2}
Total	5.90×10^2	6.33×10^2	5.99×10^2	5.92×10^2
Normalised value	0.93	1	0.95	0.94
Rank	1	4	3	2

3.3.2. Social LCA Indicators

Workers' health and safety have been identified as among the most critical S-LCA subcategories in evaluating corporate performance across product life cycles and supply chains [66] (Table 5). The challenges related to workers' health and safety are particularly significant in the construction sector. The study conducted by Hosseini et al. [67] on S-LCA for material selection highlighted that one of the inventory indicators with a strong negative impact during the pre-building stages (raw material acquisition, construction material production) and construction stages is occupational accidents among workers.

Table 5. Mapping of stakeholders, social subcategories and related indicators in the natural stone sector, based on UNEP [13].

LC Stage	Data Type	Italian Region					Source
		Lombardy	Lazio	Liguria	Bolzano	Tuscany *	
A1	No. of Accidents	-	-	-	-	3	Italian National Institute for Social Security (INPS) for Sector 6.1.1.1.0—blasters and explosive techniques in quarries and mines 5-year average 2019–2023
	No. of Workers	-	-	-	-	4036.6	Italian National Institute of Statistics (ISTAT) for sector extraction of stone, sand and clay (ATECO code 81) Single-year value (2022)
A2	No. of Accidents	1683	-	-	-	-	Italian National Institute for Social Security (INPS)—Employment data for the transport sector, extracted from the maximum value in national social security databases for the considered regions) 5-year average 2019–2023
	No. of Vehicle Fleet Distribution	*	*	*	*	306,382.6	Regional vehicle fleet data for Tuscany ACI [68] (exclusive quarry site for natural stone) 5-year average 2019–2023

Table 5. Cont.

LC Stage	Data Type	Italian Region					Source
		Lombardy	Lazio	Liguria	Bolzano	Tuscany *	
A3	No. of Accidents	47	22	16	8	*	National Institute for Social Security (INPS) database of stone cutters and polishers, stonemasons and marble workers (ATECO code 6.1.1.2.0) 5-year average 2019–2023
	No. of Workers	3479	1765	755	278	*	Italian National Institute of Statistics (ISTAT) database for cutting, shaping and finishing in the stone sector (ATECO code 237) Single-year value (2022)
A4	No. of Accidents	1683	693	373	196	*	Italian National Institute for Social Security (INPS)—employment data for the transport sector, extracted from national social security databases 5-year average 2019–2023
	No. of Vehicle Fleet Distribution	620,836	324,370	88,295	174,588	*	Number of circulating vehicles across the five Italian regions included in the study, based on regional data from the Automobile Club of Italy (ACI), 5-year average 2019–2023
A5	No. of Accidents	44	3	5	27	*	National Institute for Social Security (INPS) database of tilers and cladding specialists in stone and similar materials (ATECO code 6.1.3.2.3) 5-year average 2019–2023
	No. of Workers	63,381	31,813	5418	4595	*	ISTAT data on the number of employees in construction of residential and non-residential buildings (Code sector 412) Single-year value (2022)

* Quarry location for natural stone.

3.3.3. Scoring Definition

After collecting data by region and sector—specifically the number of occupational injuries and the corresponding workforce (Table 5 for natural stone and Table 6 for double glazing)—the normalised incidence rate of occupational injuries was calculated for each sector across the life cycle stages A1 to A5, disaggregated by region. As defined in Equation (1), for stages A1, A3, and A5, this rate was determined by dividing the number of recorded injuries in each sector by the number of workers employed in the given sector and region. In parallel, for stages A2 and A4, normalization was based on the number of circulating vehicles (vehicle fleet), reflecting the transport-related dimension of the analysis.

$$Injury\ Rate\ Norm. = \frac{N^{\circ}\ Injuries\ (A1)}{N^{\circ}\ Workers\ (A1)} + \frac{N^{\circ}\ Injuries\ (A2)}{N^{\circ}\ Vehicle\ Fleet\ (A2)} + \frac{N^{\circ}\ Injuries\ (A3)}{N^{\circ}\ Workers\ (A3)} + \frac{N^{\circ}\ Injuries\ (A4)}{N^{\circ}\ Workers\ (A4)} + \frac{N^{\circ}\ Injuries\ (A5)}{N^{\circ}\ Workers\ (A5)} \quad (1)$$

where:

Injury Rate = Occupational Injury Incidence Rate → The frequency of occupational injuries relative to the workforce size.

N° Injuries = Number of Occupational Injuries → Total recorded cases of work-related injuries.

N° Workers = Number of Workers per Sector → Total number of employees within each sector.

N° Vehicle Fleet = Number of Trucks per Region → Total number of trucks registered or operating in each region.

Table 6. Mapping of stakeholders, social subcategories and related indicators in the glass sector, based on UNEP [13].

LC Stage	Data Type	Italian Region				Source
		Lombardy	Lazio	Liguria	Bolzano	
A1–A3	No. of Accidents	43 **	-	-	-	Italian National Institute for Social Security (INPS) database of Sector ATECO code 231—Manufacture of glass and glass products 5-year average 2019–2023
	No. of Workers	5428	-	-	-	Italian National Institute of Statistics (ISTAT) database for the manufacture of glass and glass products and cutting, shaping and finishing in the stone sector (ATECO code 231) Single-year value (2022)
A4	No. of Accidents	1683	693	373	196	Italian National Institute for Social Security (INPS)—Employment data for the transport sector extracted from national social security databases 5-year average 2019–2023
	No. of Vehicle Fleet Distribution	620,836	324,370	88,295	174,588	Number of circulating vehicles across the five Italian regions included in the study, based on regional data from the Automobile Club of Italy (ACI), 5-year average 2019–2023
A5	No. of Accidents	44	3	5	27	National Institute for Social Security (INPS) database of tilers and cladding specialists in stone and similar materials (ATECO code 6.1.3.2.3) 5-year average 2019–2023
	No. of Workers	63,381	31,813	5418	4595	ISTAT data on the number of employees in construction of residential and non-residential buildings (Code sector 412) Single-year value (2022)

** Manufacturing site.

Finally, to enable meaningful comparison among values, a regional scoring system was defined following the data normalisation process.

In line with the approach adopted for the E-LCA component, the social indicator was constructed using the injury rate per number of workers by sector, normalised against the highest observed value across regions. This benchmark-based approach ensures logical consistency within the scoring system and allows for the harmonised integration of environmental and social dimensions. As with the environmental data, normalised values were subsequently classified into four categories ranging from 1 (best performance) to 4 (worst performance). Tables 7 and 8 present the injury rate scores by sector and the corresponding rankings for natural stone and glass, respectively.

Table 7. Normalised Occupational Injury Scores and Sectoral Rankings in the natural stone supply chain.

Life Cycle Stage	Region			
	Lombardy	Lazio	Liguria	Bolzano
A1 (Tuscany)	2.22×10^{-3}	2.22×10^{-3}	2.22×10^{-3}	2.22×10^{-3}
A2 (Tuscany)	5.49×10^{-3}	5.49×10^{-3}	5.49×10^{-3}	5.49×10^{-3}
A3	1.36×10^{-2}	1.22×10^{-2}	2.15×10^{-2}	2.81×10^{-2}
A4	2.71×10^{-3}	2.14×10^{-3}	4.23×10^{-3}	1.12×10^{-3}
A5	6.91×10^{-4}	1.01×10^{-4}	9.23×10^{-4}	5.79×10^{-3}
Total	2.47×10^{-2}	2.22×10^{-2}	3.43×10^{-2}	4.27×10^{-2}
Normalised value	0.58	0.52	0.80	1
Rank	2	1	3	4

Table 8. Normalised occupational injury scores and sectoral rankings in the glass supply chain.

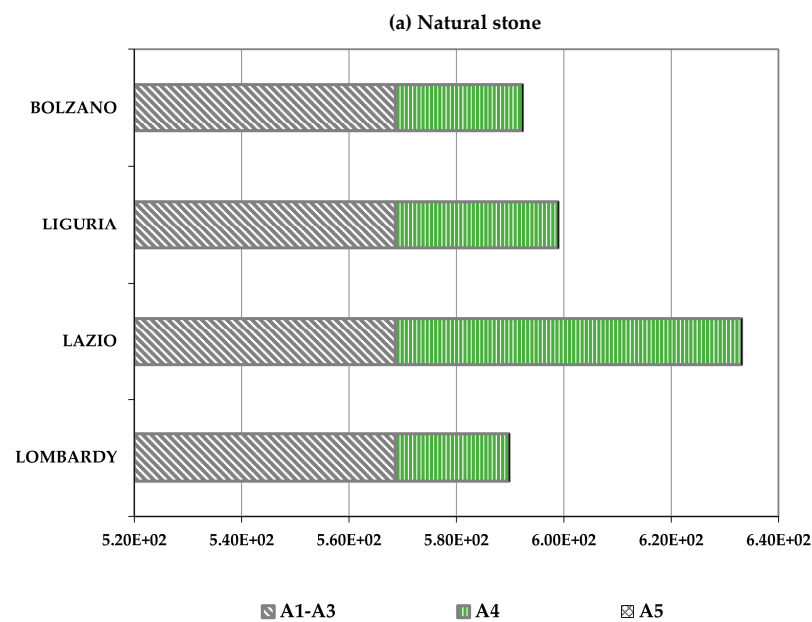
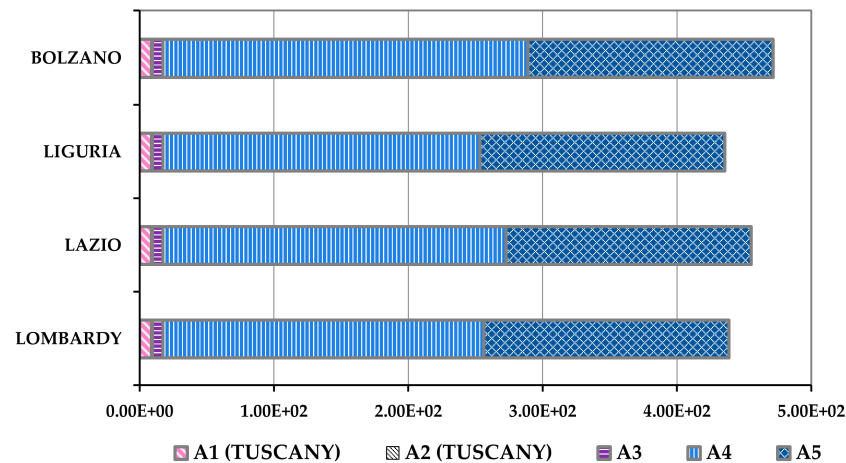
Life Cycle Stage	Region			
	Lombardy	Lazio	Liguria	Bolzano
A1–A3 (Lombardy)	1.34×10^{-2}	1.34×10^{-2}	1.34×10^{-2}	1.34×10^{-2}
A4	2.71×10^{-3}	2.14×10^{-3}	4.23×10^{-3}	1.12×10^{-3}
A5	3.54×10^{-3}	2.41×10^{-3}	9.19×10^{-3}	6.70×10^{-3}
TOTAL	1.94×10^{-2}	1.77×10^{-2}	2.66×10^{-2}	2.10×10^{-2}
Normalised value	0.73	0.67	1	0.79
RANK	2	1	4	3

4. Results

This section describes and analyses the results obtained from the study. First, the E-LCA values of the two products analysed within the case study building are presented for each region. Second, the assessment of social life cycle impacts is illustrated, focusing on the stakeholder category of workers and, particularly, on the health and safety indicator. Third, a comparative analysis is conducted between the combined E-LCA and S-LCA results, disaggregated by material and by region. Finally, a single impact score (E-LCA + S-LCA) is defined for each material and region.

E and S-LCA of Natural Stone Cladding Across Regions

The results of the E-LCA of natural stone extracted from a quarry located in Tuscany show that the variation in environmental impact across different geographical contexts is primarily driven by stage A4, which refers to the transport of the product from the production site to the construction site. This impact is inevitably higher in the Province of Bolzano, due to the greater distance involved, as illustrated in Figure 4a.



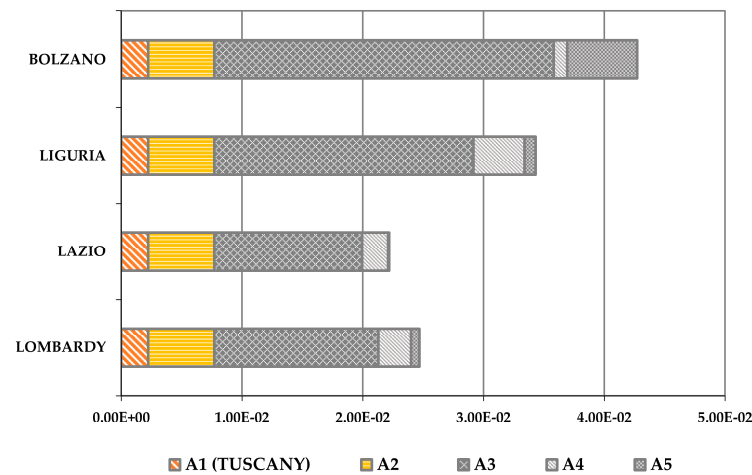
(b) Double glazing

Figure 4. Global Warming Potential (expressed in kg CO₂e) by region for construction stages A1–A5 of (a) natural stone cladding and (b) double-glazing systems.

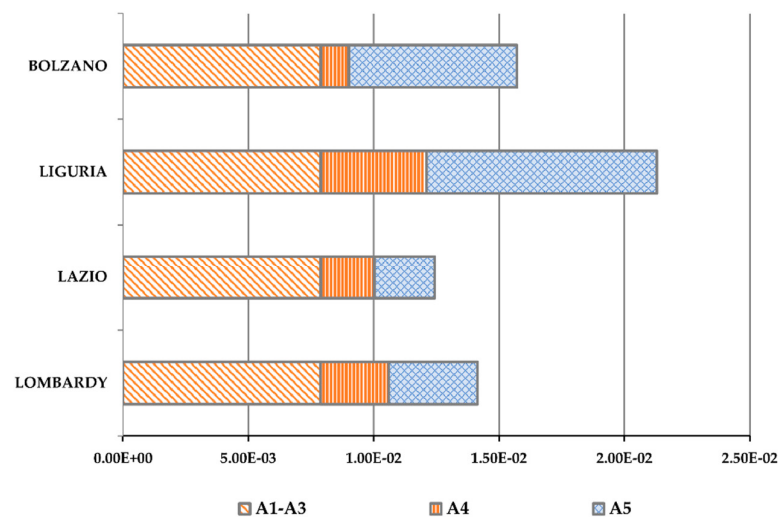
The same applies to glazing, where the production site is located in the Lombardy region. Consequently, the highest transport-related impact (stage A4) is attributed to the Lazio region, which is farthest from the manufacturing site, as shown in Figure 4b. However, the breakdown of the upfront carbon impacts of the two materials is significantly different, with the lion's share being in stages A4 and A5 for stone cladding and in A1–A3, followed by A4, for glass.

With regard to the social dimension related to natural stone (Figure 5a), when social impact values are normalised by the number of workers, and assuming equal contributions

from stages A1 and A2, the highest impact is observed at the production stage (stage A3). This is followed by impacts associated with intermediate transport from the quarry to the manufacturing facility (A2) and final transport from the facility to the construction site (A4). Stage A5 (on-site installation) contributes significantly to the overall social impact, particularly in the Province of Bolzano. Although Bolzano does not report the highest absolute number of occupational accidents during installation—there were 27 incidents, 39% fewer than the 44 reported in Lombardy—the relative impact increases markedly when normalised by workforce size. Given that Bolzano’s workforce is approximately 76% smaller, the accident rate per worker is substantially higher.



(a) Natural stone



(b) Double glazing

Figure 5. Injury rate, normalised by number of workers, by region for construction stages A1–A5 of (a) natural stone cladding; (b) double-glazing systems.

Focusing on double glazing and assuming equal impacts during stages A1–A3 across the four geographical scenarios analysed, the variability in social impacts is primarily determined by the installation stage (A5), followed by stage A4 (transportation).

Despite recording approximately 35% fewer incidents than Lazio and around 77% fewer than the highest value observed in Lombardy, the region with the highest injury rate

is Liguria. Once again, however, this figure becomes significant when normalised by the number of workers (Figure 5b).

To support a clearer interpretation of trade-offs between environmental and social impacts across region–material combinations, a set of comparative visualizations was developed, including radar charts (Figure 6) and a 2×2 quadrant diagram (Figure 7). These tools enable each region to be positioned according to its performance along both dimensions, facilitating the interpretation of contextual profiles and informing procurement strategies.

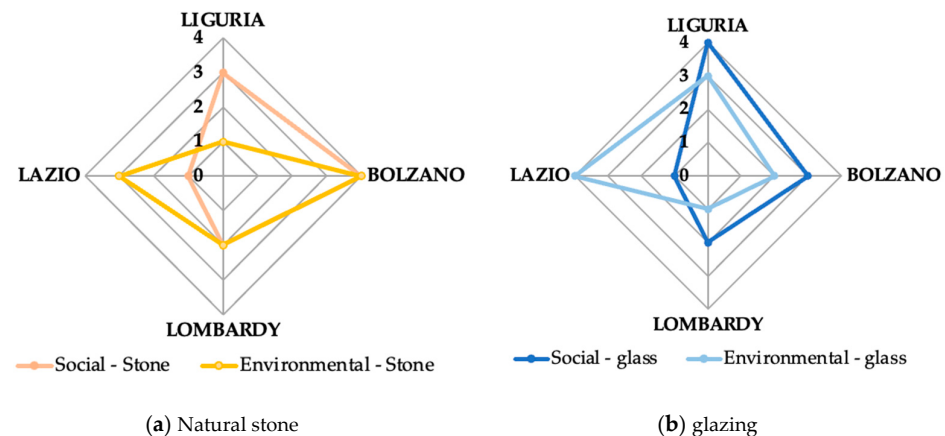


Figure 6. Regional distribution of environmental and social impacts by material type (stone and glass).

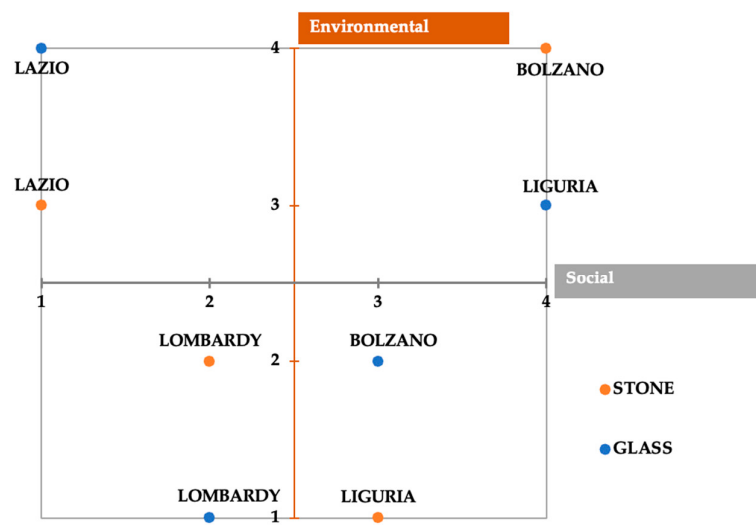


Figure 7. Trade-off analysis of environmental and social impacts across region–material combinations.

In particular, the quadrant diagram in Figure 7 highlights cases where environmental efficiency (i.e., lower A4 values) may coincide with social vulnerability (i.e., higher normalised accident rates). For example, Lazio shows relatively high environmental impact for both materials—with a score of 4 for double glazing and 3 for natural stone—while maintaining low social scores. Bolzano displays more pronounced impacts for stone, both environmentally and socially, whereas Liguria presents a more balanced profile with lower environmental impact for stone and higher social performance for glass.

Finally, in order to provide a more comprehensive visualization of both GWP and social performance—particularly regarding worker health and safety—the next step involved determining a single regional score for each indicator—E (environmental) and S (social). This composite score was obtained by combining previously normalized E-LCA and S-LCA indicators (Figure 6) with sector-specific breakdowns provided in Figure 8a (natural

stone) and 8b (double glazing). The total score is represented by a star symbol ranging from a minimum value of 1 to a maximum of 4 with the star size indicating the score's magnitude. In Figure 8c, stars are labeled with “G” for glazing and “R” for natural stone, while environmental and social indicators are respectively identified by the letters “E” and “S”. As illustrated in Figure 8c—which shows the material-specific scores for stone (S) and glass (G) obtained by summing the normalized scores for each indicator—the contribution in terms of CO₂-equivalent emissions, assuming a shared production site, is predominantly influenced in both sectors by the distance from the production facility to the construction site.

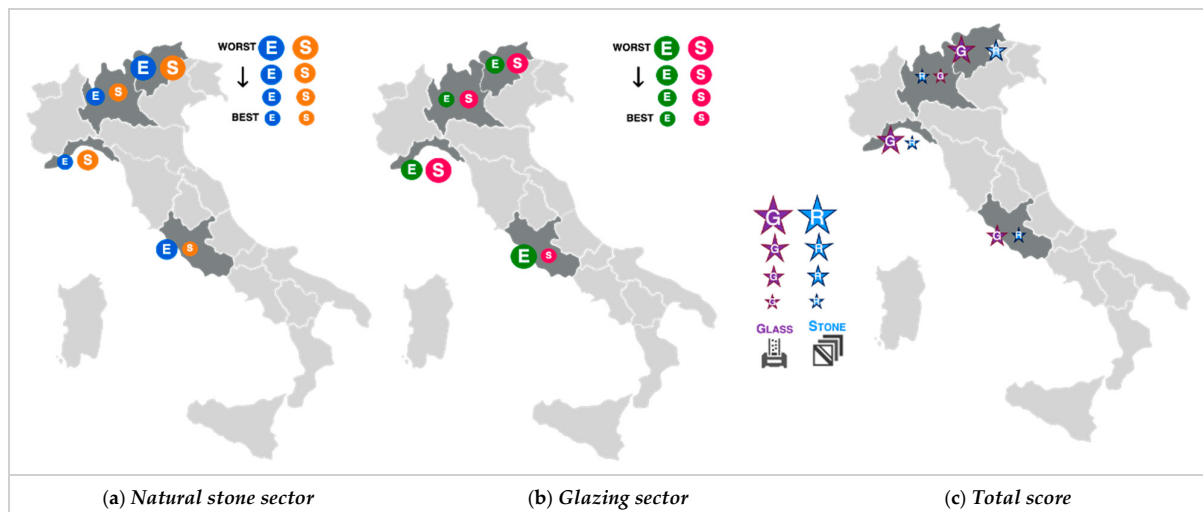


Figure 8. Integrated overview of regional environmental and social performance scores (Stages A1–A5) across the four Italian case study areas (dark gray regions): (a) natural stone cladding; (b) glazing systems; (c) total score. Star symbols are labelled by material type: ‘G’ indicates glazing elements and ‘R’ refers to natural stone components.

Specifically, the highest impact for natural stone is seen in Bolzano (approximately 340 km from the quarry and production site), while for glazing, it is recorded in Lazio (approximately 470 km from the manufacturing facility). With regard to social impacts, the absolute number of workplace accidents per sector and region does not by itself reflect the actual weight of the impact, as this must be normalised by the number of employees involved. The analysis conducted in this study, therefore, showed that regions with a smaller workforce tend to exhibit higher relative impact values. This indicates that a lower number of incidents may correspond to a higher relative risk exposure per worker. These findings highlight the importance of considering both absolute and normalised social indicators when assessing worker-related risks, especially in regions with limited staffing and complex or labour-intensive installation activities.

5. Discussion

The environmental sustainability of a building throughout its life cycle is strongly influenced by the materials used in its construction [69]. However, material selection should extend beyond functional performance requirements and environmental considerations arising during the product life cycle. One such consideration is the impact on worker health, particularly due to occupational accidents, which are notably prevalent in the construction sector.

While worker health and safety are widely recognised in the literature as the most consistently addressed impact category within S-LCA [66], the integration of regional specificities and empirical data remains limited, posing challenges in achieving a more

context-sensitive and realistic evaluation of social impacts. This limitation is partly due to the restricted availability of impact data and the reluctance of stakeholders to disclose such information [14].

Quantitative assessment of social impacts at each stage of the material life cycle is essential not only to incorporate the ‘social dimension’ into sustainable material selection from the early design phase, but also to unlock potential benefits for responsible production and consumption. In this regard, the present study contributes to bridging this gap by proposing a regionalised approach that integrates worker health and safety indicators into the life cycle assessment of construction materials.

In Italy, INAIL has developed an online statistical database that aggregates data at the provincial, regional and national levels on the number of occupational injuries and work-related illnesses, classified according to the ATECO code—the national classification of economic activities. However, the effective application of these data at the building scale requires re-elaboration and contextualisation to ensure alignment with the life cycle stages of construction products and the specific territorial characteristics of Italy and thereby present a useful tool for integrating the social dimension into sustainable design practices. Our finding that transport (stage A4) is a key driver of global warming potential aligns with Crishna et al. (2011) [25] who identified logistics as a dominant contributor to environmental impacts in construction supply chains. Similarly, the sensitivity of social impacts to workforce size and installation complexity (stage A5) introduces a new, regionally differentiated dimension to the challenges previously noted by Hosseini et al. (2014) [67] who emphasised the importance of contextual factors in assessing social risks.

While the study offers significant methodological contributions, several limitations should be acknowledged. First, the analysis is based on only two construction products—natural stone cladding and double glazing—which, although representative, do not capture the full diversity of materials used in the sector. Second, due to the lack of a national dataset, the environmental data for stages A1–A3 rely on a single EPD per material, which may affect the extent to which the results can be generalised. Third, the use of normalised injury rates as social indicators depends on the availability and granularity of public data, which vary across regions and sectors. Finally, the integration of qualitative dimensions—such as workers’ perceptions and lived experiences—remains an open challenge for future research, as also highlighted by Kühnen [63] and other scholars who advocate for mixed-method approaches to capture subjective aspects of social sustainability.

6. Conclusions and Research Outlook

This study introduces a methodological advancement through the integration of E-LCA and SLCA, proposing an approach capable of capturing regional specificities and incorporating the empirical data necessary for a more realistic evaluation of social impacts across construction supply chains.

The analysis of natural stone cladding and double glazing across four regional scenarios reveals that environmental impacts are predominantly influenced by transport distances (stage A4), as reported by Crishna et al. (2011) [25], who identify logistics as a key driver of global warming potential. Social impacts—particularly those related to worker health and safety—are shaped by workforce size and installation complexity (stage A5), adding a new regional dimension to the contextual challenges previously noted by Hosseini et al. (2014) [67].

The integration of environmental and social assessments into a composite regional score highlights the need to consider both absolute and normalised indicators, offering a more nuanced understanding of risk exposure and sustainability performance across construction supply chains. The use of quantitative metrics, such as the number of occupa-

tional injuries and diseases in the two construction-related production sectors, provides a valid approach to quantifying objective and verifiable impacts. However, the use of workforce size as a denominator introduces methodological limitations, particularly in regions with small teams, where even a few incidents can inflate normalised rates.

In line with UNEP guidelines, an alternative approach would be to use hours worked as the denominator (e.g., injuries per million hours worked), which offers a more proportional measure of exposure. This option was not feasible due to the lack of updated and regionally disaggregated data. Available sources were either outdated (e.g., last updated in 2015) or aggregated at the national level, and did not include information on the ratio of part-time to full-time employment, which would be essential for reliable calibration.

The possibility of weighting impacts by injury severity was also explored. However, the dataset proved too generic to support meaningful classification. For example, injuries are reported by anatomical location (e.g., hand, foot), but without specifying the type of damage or degree of impairment. In the absence of a clear correlation between injury type and severity, assigning weights was deemed both methodologically weak and ethically questionable.

Another critical issue concerns the treatment of mixed employee/subcontractor crews, which is particularly relevant in sectors with high subcontracting rates. Current data sources do not distinguish between these categories, but future refinements to the scoring system should address this gap to ensure a more accurate representation of working conditions.

The decision to focus on workers as the primary stakeholder group is consistent with the life cycle stages analysed (A1–A3, A4, A5), where workers' exposure is direct and documentable. This choice also responds to a methodological gap highlighted in the literature and regulatory frameworks, as noted in source [14], regarding the availability of reliable social data in the construction sector.

In line with Kühnen [66] and previous research on the critical gap in social life cycle subcategories, there is a clear need to integrate subjective perceptual indicators to capture workers' lived experiences. This calls for a paradigm shift toward a mixed-method framework incorporating qualitative tools such as structured interviews to explore cognitive and emotional perceptions across life cycles and supply chains. Such an integrated approach would enable a more holistic assessment, combining empirical metrics with psychosocial determinants of workplace well-being and thereby enhancing the depth and accuracy of social sustainability evaluations within the life cycle sustainability assessment framework.

To guide future research, several limitations should be acknowledged. From the environmental perspective, reliance on single product-specific environmental declarations in the absence of national datasets—particularly for modules A1–A3—limits representativeness. The present application is also restricted to two products, which are insufficient to reflect the diversity of the sector. From the social perspective, key challenges include the choice of denominator for exposure metrics and the lack of disaggregated data on hours worked and injury severity. Extending the method to other national contexts by identifying databases equivalent to INAIL and mapping data across life cycle modules would strengthen the validity and transferability of the proposed framework.

Overall, this work presents a replicable methodological approach for integrating the social dimension into sustainable building design, promoting the adoption of composite metrics in decision-making processes and environmental product declarations. However, the results should not be interpreted as comparative evaluations or as a basis for defining performance benchmarks, but rather as a context-sensitive tool to support informed and responsible design choices.

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Abbreviations

The following abbreviations are used in this manuscript:

B2B	Business-to-Business
BPIE	Buildings Performance Institute Europe
CAM	Criteri Ambientali Minimi
E-LCA	Environmental Life Cycle Assessment
EC	Embodied Carbon
EE	Embodied Energy
EPBD	Energy Performance of Buildings Directive
EPD	Environmental Product Declarations
GDP	Gross Domestic Product
GWP	Global Warming Potential
INAIL	Istituto Nazionale per l'Assicurazione contro gli Infortuni sul Lavoro
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LTS	Long-Term Strategy
NECP	National Energy and Climate Plan
nZCB	Net-Zero Carbon Building
nZEB	Net-Zero Energy Building
OC	Operational Carbon
OE	Operational Energy
PCR	Product Category Rules
RE2020	Réglementation Environnementale 2020
S-LCA	Social Life Cycle Assessment
SETAC	Society of Environmental Toxicology and Chemistry
SPD	Social Product Declaration
UNI	Ente Nazionale Italiano di Unificazione
UNEP	United Nations Environment Programme
WLC	Whole Life Carbon

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