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DOTTORATO DI RICERCA IN FISICA TECNICA AMBIENTALE

(XXIV CICLO)

ENVIRONMENTAL AND ENERGY PERFORMANCES OF BUILDING PRODUCTS: A WORKING CHAIN BASED ANALYSIS

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Forwards

The present work is aimed at investigating the environmental and energy performances of products to be utilized in buildings. Specifically, marble (Section 1), granite (Section 2) and natural materials (Section 3) will be analyzed.

The marble features are here studied on the basis of a field working chain audit. Particularly, two representative firms of the Custonaci productive basin (Trapani) have been considered. Their working chain have been investigated, by the point of view of the energy and materials flows, with a classical Life Cycle Assessment (LCA) approach. Moreover, the social and economic impacts of such materials have also been assessed by means of the Life Cycle Costing (LCC) and Social Life Cycle Assessment (S-LCA) approaches. By the way, the here presented S-LCA study represents one of the few presently available in the literature.

The granite has been analyzed by an energy and materials point of view, in the aim of singling out the possibility of reducing the amount of energy involved in the productive process along with the potentiality for reusing the waste materials resulting from the present working chain. The study refers to Spanish firms, due to the period that the author spent in this country, thanks to a PhD fellowship granted by the University of Palermo.

The possibility of utilizing natural materials, like hay and hemp, has been finally investigated by means of an experimental approach. The studies was conducted in the laboratory for indoor and building materials currently operating within the Department DEIM of the University of Palermo.

SECTION 1: The marble

Chapter 1
The marble working chain

1 Introduction

Sustainability is today an overused word in different political and scientific contexts.
The ambitious target of sustainable development, that according to Bruthland report, "means a development that meets the present generation needs without compromising the opportunity of the future generations to meet their owns" is the main objective of local and national governments. This goal is getting particular important for the building sector that presents a high economic, mainly positive, and environmental, mainly negative, impact.
Sustainable development includes the balance of social, economic and environmental factors and the only possible development, which can guarantee the same opportunities and quality of life to the present generation and to the future ones. It guarantees a balance among environmental protection, resource use and technology development [1].
Building sector is considered a strategic compartment for achieving a sustainability production and consumption; in fact its energy use is about 40% of the world energy one.
Building products include several kinds of products such as building materials and buildings themselves. Its variety makes this sector particularly interesting to assess in term of sustainability performances.
Among others, marble products play a significant role for Italian economy. The marble is a natural material, widely used both in greenbuilding and in new bioclimatic building, because of its resistant and aesthetic properties.
Italy is one of the world's largest exporters of raw and processed marble, as outlined in Table 1 and Fig. 1.

Table 1. International exports of raw and processed marble in 2009 [2].

Marble export (ton)							
Austria	7.490	Germany	80.970	Norway*	7.060	Spain	1.254.070
Belgium	169.200	Japan	520	Netherlands	27.420	USA	155.560
Brasile	11.760	Greece*	430.030	Poland	2.950	South Africa*	1.920
Canada	970	Hong Kong*	29.300	Portugal	585.780	Sweden*	1.160
China	2.763.330	India	294.864	U. K.*	3.619	Switzerland	1.250
Croatia	53.880	**Italy**	**2.744.710**	Russland	10.020	Thailand	1.320
Denmark	1.030	Kazakhstan	170	Singapore	5.460	Turkey	5.715.690
France	17.280	Lithuania	1.310	Slovenia	7.081	Ukraine	50

Note: * source of data is the authorized Italian Statistics Institute for 2007 (official data concerning only the last year areavailable).

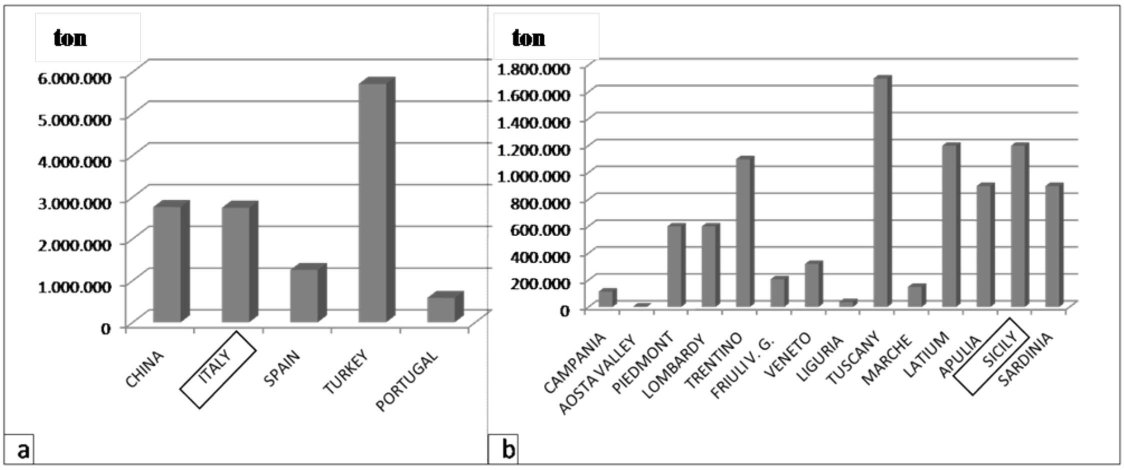


Fig. 1. a) The largest raw and processed marble's world exporters; b) The Italian production of raw marble, by regions. Data reported in both graphs are referred to 2009 [2].

There are two Italian main basins that are considered the first and the second more productive areas: Massa & Carrara basin (north of Italy) and Custonaci basin (Trapani, Sicilian province). The first one is well known and its main product, "Bianco di Carrara", has been used and exported in all parts of the world for centuries. Its use and extraction can already be found during Roman Empire (48-44 a.C.). In the recent years, "Perlato di Sicilia", the most important marble extracted in Custonaci basin, has improved its position in the market. It represents a meaningful resource for the Sicilian economy that it is mainly based on the tertiary and agriculture sectors.

In spite of this background few studies have been developed to assess the sustainability performance of this important building material [3].

Hence the focus of this work is the assessment of sustainability performance of "Perlato di Sicilia".

In fact, as it is well known, the building sector represents one of the most important elements in the economy of the developed countries, being responsible of a large amount of pollutant releases in the atmosphere and requiring a significant part of resources consumption [4].
In addition, the quarry related activities of material typically used in buildings, are characterized by a high environmental impact and by a severe footprint on the territory [3, 5]. Similarly, operations involved in the production of marble cause a high impact on the involved territory [6].
In Sicily, in fact, the diffuse presence of marble quarries and manufacturing plants is raising a big concern about the environmental compatibility of such plants.
Several methodologies and tools have been carried out and implemented for assessing sustainability performances in different sectors. A new meaningful contribution for assessing products and processes is represented by Life Cycle Sustainability Assessment (LCSA). This methodology assesses sustainability performance of a product through its entire life cycle, from the extraction of raw materials, to production, use and disposal. This methodology integrates all three pillars of sustainability, by measuring positive and negative impacts to environment, economy and society at microeconomic level.
A first publication to guide a Life Cycle Assessment (LCA) practitioner in the LCSA was published from UNEP/SETAC LCI [7] at the beginning of 2012. In this study, marble [8] has been taken into consideration as a representative example.
The application of this methodology to marble product is presented in Chapter 2.
LCSA methodology application and the marble case study have pointed out many weak elements of this methodology, so in Chapter 3 the strong and weak points of the LCSA methodology are introduced. In order to reach a detailed analysis, the three steps (LCA, Life Cycle Costing (LCC) and Social Life Cycle Assessment (S-LCA)) are individually analyzed. Obviously the purpose of this work is not to solve the difficulties in the LCSA implementation, but to present in a clear framework some of the open questions that a practitioner of LCSA have to face up in the process of carrying out a LCSA of product.
An eco-label award for marble used in building sector clearly represents a strong commercial tool for communicating the sustainability performances of this important material, provided that the criteria utilized for awarding the firms are really capable of capturing all the impacts related to its productive chain. With this aim, in this work a

critical analysis of the current Decision concerning hard coverings [9] has been preliminary conducted for verifying whether it is actually viable for the natural products, like marble. This verification highlighted some critical points of this Document when applied to marble. This analysis is presented in Chapter 4.

In Chapter 4, it is also presented a quick comparison between the European standard eco-label [9] and one of the Italian standards for the certification of products and materials in green building. In particular, the Italian standard presented by the National Bio-ecological Architecture (ANAB) and the Institute for Ethical and Environmental Certification (ICEA) [10] is taken into consideration. The aim is to point out analogies and differences between these two standards and to identify possible strong and weak points, towards the establishment of a more comprehensive and powerful brand for marble.

Nowadays, as already mentioned, marble processing takes place by a production cycle that requires large amounts of energy and that involves the release of large amounts of waste materials. Moreover, marble quarries don't have much in common with other forms of underground mines (the dimension of openings, the method of excavation, the form of the excavated material, the support method etc). We need, therefore, to have methods for the assessment of environmental and energetical performance of the processes which take place in marble quarries and sawmills. Such methods , moreover, should be characterized by a simplicity of application which allows an easy to use even by non-technical operators. This will allow, on one hand, the managers of marble quarries to evaluate environmental performance of mining activities implemented, on the other hand, local governments to assess the impacts on environment made by the production of materials for building. The study, reported in Chapter 5, is an attempt to provide concrete answers to these needs by suggesting a simple method of environmental assessment of the marble productive cycle.

In order to get a good understanding of this study about the "Perlato di Sicilia", it is propaedeutic the knowledge of its processing cycle; then, after a brief description, in the following Paragraph, of the development of stone industry in Sicily, in Paragraph 3 a detailed description of the processing cycle is presented.

2 The stone industry in Sicily: the Custonaci basin

As already mentioned, one of the main productive activities of the region of Sicily is that of quarry joined to extraction and initial working processing destined to the trade of lithoid and not lithoid rocks, non-worthless mining, that is to say materials classified as second-class.

In Fig. 2, all of the quarries present in the Sicilian Region are shown, as they are spread in the territory, including the marble ones; currently, there exist 557 quarries in operation and 691 worn-out quarries [11].

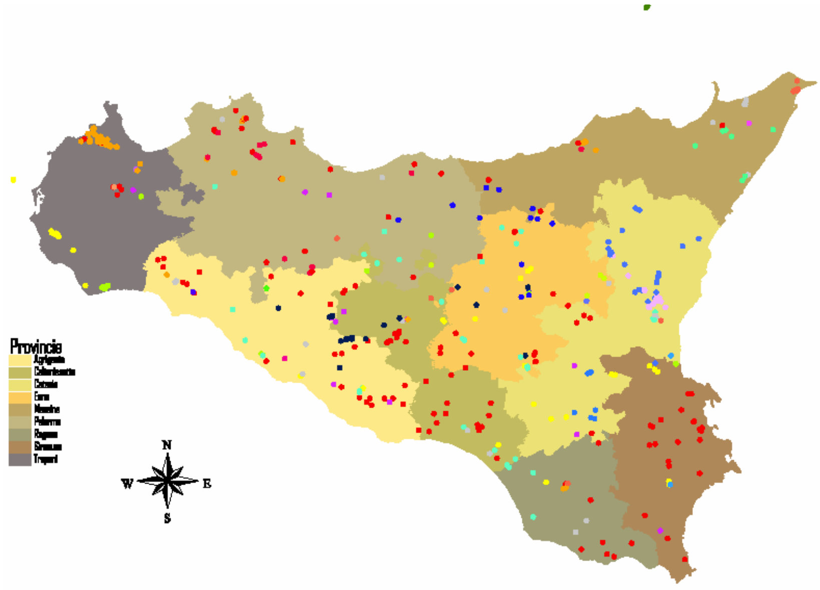


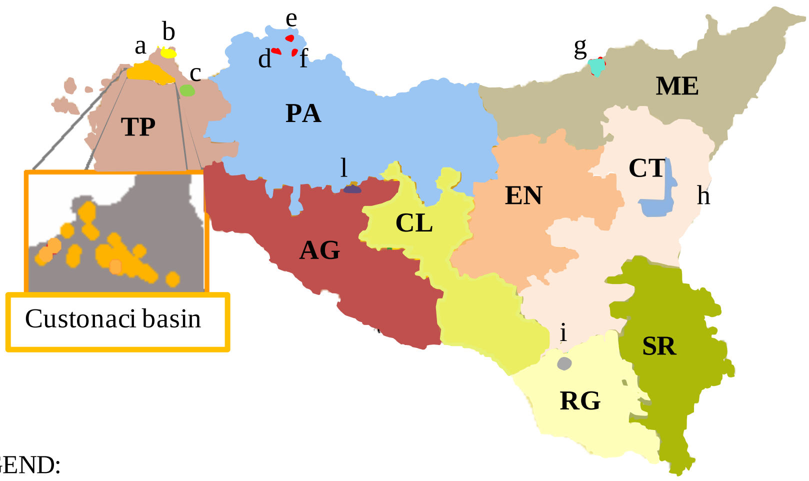
Fig. 2. Distribution of the quarries in operation in Sicily.

The geologic characteristics of Sicily make it one of the most productive area of marble product.

As showed in Fig. 3 several kinds of marble are extracted in Sicily.

The Custonaci basin in Sicily is comprised of approximately 54 marble quarries located in an area of 69 km^2 [12].

Custonaci streches across the north-west tip of Sicily, facing the Tyrrhenian Sea and bordering the municipality of San Vito Lo Capo to the north-east, that of Valderice to the south-west, and those of Buseto Palizzolo and Castellammare del Golfo to the south. The marble field, which includes the municipalities of Custonaci, Trapani, Paceco, San Vito Lo Capo, Castellamare del Golfo, Valderice and Buseto Palizzolo, now covers an area of approximately three square kilometres. Thanks to its geological conformation, characterized by extensive outcrops of limestones of Mesozoic Dolomitic limestones, the territory of Custonaci contains wide deposits of precious stone material that have been exploited for century and have contributed to creation of landscape marked by human presence where the dominant features are quarries. The importance of these deposits has been known for centuries, thanks to the variety of precious marble used in the great architectural works of the past and preferred by many artists and architects both Italy and abroad.



LEGEND:
a = Avorio Venato, Botticino and Breccia di Sicilia, Perlato and Perlatino di Sicilia, Libeccio and Libeccio antico
b = Spuma di mare, Rosso S. Vito, Grigio San Vito
c = Rosso M. Inici
d = Rosso Montecitorio, Rosso Kumeta, Verde Kumeta
e = Grigio Billiemi
f = Alabastro
g = Grigio and Grigio Reale S. Marco, Brecciato Normanno and Rosso S. Marco
h = Basalto da Taglio
i = Pietra di Comiso
l= Avorio di Agrigento

Fig. 3. Sicilian marbles.

Actually Custonaci industrial area produces about 85% of Sicilian marble, it is accounts for 15,7% in Italy and 2,7% in the world [13].

Analysis of marble manufacturing industry reveals an excessive discrepancy between the productive capacities of the quarries and the working of the raw material.

Manufacturing activity is limited to the production of semi-worked and/or raw products, which offer the most competitive market opportunities. This however neglects the production of precious worked materials, which could be more easily placed on niche markets, which are certainly more refined and more remunerative [14].

The importance of this sector drives to inquire into its environmental impacts and to single out the related weak points, in environmental terms, of the production chain of these products.

The marble from Custonaci is made by sedimentary rocks consisting of 98% calcite and 2% dolomite, apatite, illite, goethite and quartz. They were originated from several phenomena of deterioration, compression, erosion, entrainment and deposit of detritus from pre-existent rocks and/or animal and vegetable remains in marine habitat. Thus, in some cases, the diastrophism and tectonic evolution have created polygenic rocks, such as “Libeccio” and “Libeccio Antico”, polychrome marbles that are much appreciated for the decorative and aesthetic quality. The main marbles extracted in marble field of Custonaci include several types such as: “Perlato di Sicilia” (pale ivory in colour with patches of pure calcite), “Avorio Venato” (ivory in colour with pink glints and interspersed with gold-coloured goethite), “Perlatino di Sicilia”, “Libeccio”, etc (see Fig. 2).

As already mentioned, in this study the marble considered is “Perlato di Sicilia”.

“Perlato di Sicilia” appeared on the market around 1950-51, mainly to meet local demand for white Carrara marble, which was becoming difficult and costly to supply.

This marble, which was of a novel color and appearance, was immediately very well received. Production increased year by year and in fact is still growing.

The success was well justified by the excellent technical characteristics of this stone (see Table 2).

In the next Paragraph we will proceed to a detailed description of working cycle of “Perlato di Sicilia”.

Table 2. Main technical data of Custonaci marble ("Perlato di Sicilia").

Quarrying area	Custonaci, Castellammare del Golfo, Valderice
Prevalent use	Floors, indoor and outdoor covering, stues and fountains
Treatments	Water-repellent, oil repellent, satinizing
Volume unit weight [g/m^3]	2,665 - 2,69
Imbibition coefficient [%]	0,298 – 0,91
Simple Compression breaking stress [kg/cm^2]	982 - 2009
Wear index [Mm/km]	0,4 - 4
Compression breaking stress [kg/cm^2]	2002
After freeze treatment [kg/cm^2]	2088
Water absorption coeff. [%]	0,9
With bending stress [kg/cm^2]	139
Impact esistance [cm]	29
Wear byfriction [mm]	0,57

Source: study of Architectura Department of University of Palermo.

3 Main phases of the manufacturing of the Sicilian marble "Perlato di Sicilia"

The analysis of the "Perlato di Sicilia" marble manufacturing process might be conducted dividing the whole process into its three main phases:

- quarry: raw material extraction;
- sawmill (step 1): marble processing;
- sawmill (step 2): finishing operations.

3.1 Extraction of raw materials in the quarry

In the stones industry the production process begins with the raw materials extraction which is carried out entirely in quarry.

Fig. 4 outlines the different operations carried out in the quarry in the specific case of a Sicilian marble, along with the indication of the input, output and by-products for each operation.

To extract the raw material either explosives or steel tip excavators hammer are used.

Fig. 5 shows the extraction of the "Perlato di Sicilia" executed using explosive.

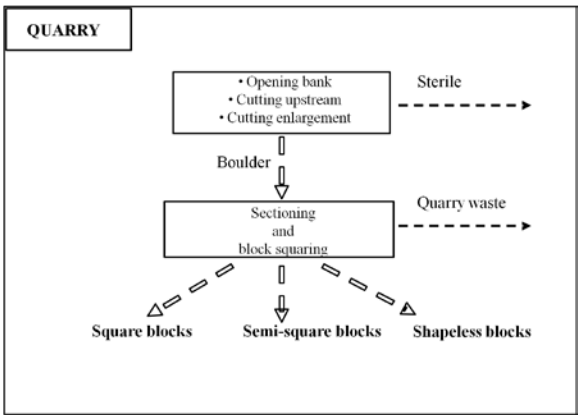


Fig. 4. Diagram of different operations carried out in the quarry.

Fig. 5. Extraction through the use of explosives.

More specifically, the excavation of the Sicilian marble comprises the three following phases: 1. cutting of big banks[1] of rock, 2. tipping of the cylinder banks on the quarry, and 3. squaring of cylinder banks in blocks according to commercial size. Fig. 6 shows graphically the sequences of these three phases.

Fig. 6. Description of the phases cited in Fig. 4: tipping and sectioning of the slice.

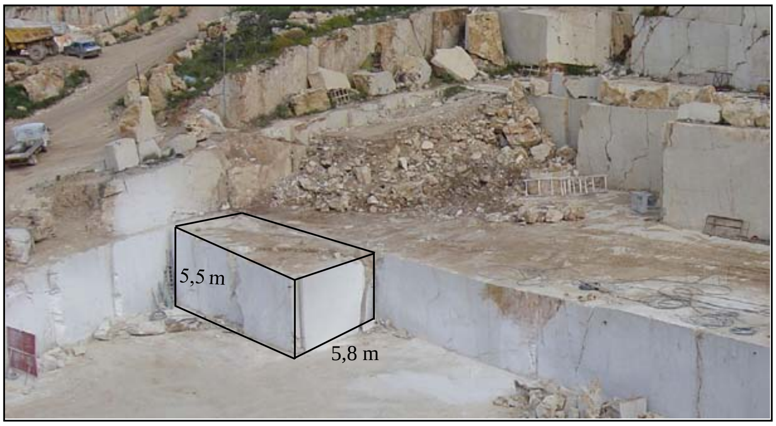


Fig. 7. Detail of the quarry with the slice still on site.

[1]**Bank**: part of a boulder compact which extends horizontally, bounded by two horizontal planes, one visible and the other hypothetical parallel at the bottom, which represents the horizontal slice.

As regards the opening of the cylinder bank (phase 1), it occurs excavating a trapezoidal trench (slice) whose typical dimensions are: height 5,5 m, length 12,0 m, base 5,8 m (see Fig. 7). The first step consists of making a vertical hole at the corner of the inside corner by the drill then two other horizontal holes are made at the bottom on the two vertical walls, of about 10 cm diameter which reach the large vertical hole in the case of a slice cut. Through these holes a diamond wire is introduced, which makes three cuts: the first one is horizontal, in fact, the wire passes through these two horizontal holes isolating the slice from the mount to the basis, while the other two cuts are vertical so the wire goes through the vertical and horizontal hole, respectively.

Afterwards, the classification of materials that is the separation based on blocks size, is made through fixed grids, vibrating screens, rotating screens, hydraulic or centrifugal force classifiers. At the end of these treatments products have a well-defined grain size. Different sizes (sand, crushed stone, crushed rock, half breach, etc.), inert products are used for the production and packaging of cement conglomerates and asphalt in different types. These treatments aim at producing blocks whose dimension are suitable for loading, often in containers, and transport (approximately 1,8 x 1,8 x 2,9 m).

As Fig. 8 clearly shows, blocks obtained by the three above described phases, are then treated in the sawmill (as described in Paragraph 3.2), whereas the inert material produced during the extraction (the crushed material), which is, actually, a by-product of the extraction process, is treated in a crushing plant, with one or more initial stages of mechanical preparation of the extracted materials.

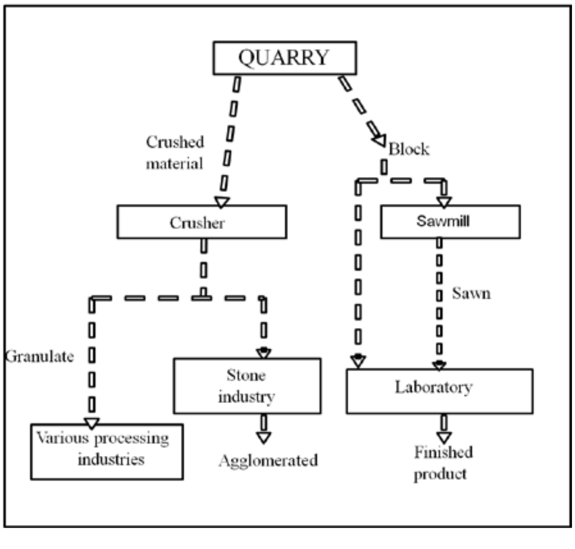


Fig. 8. General description of the operation performed outside the quarry.

3.2 Marble processing and finishing operation in the sawmill (steps 1 and 2)

As mentioned earlier, blocks sourced by banks are then treated in the sawmill. Fig. 9 schematically describes operations performed in the sawmill where, therefore, the second phase of the manufacturing process of marble takes place.

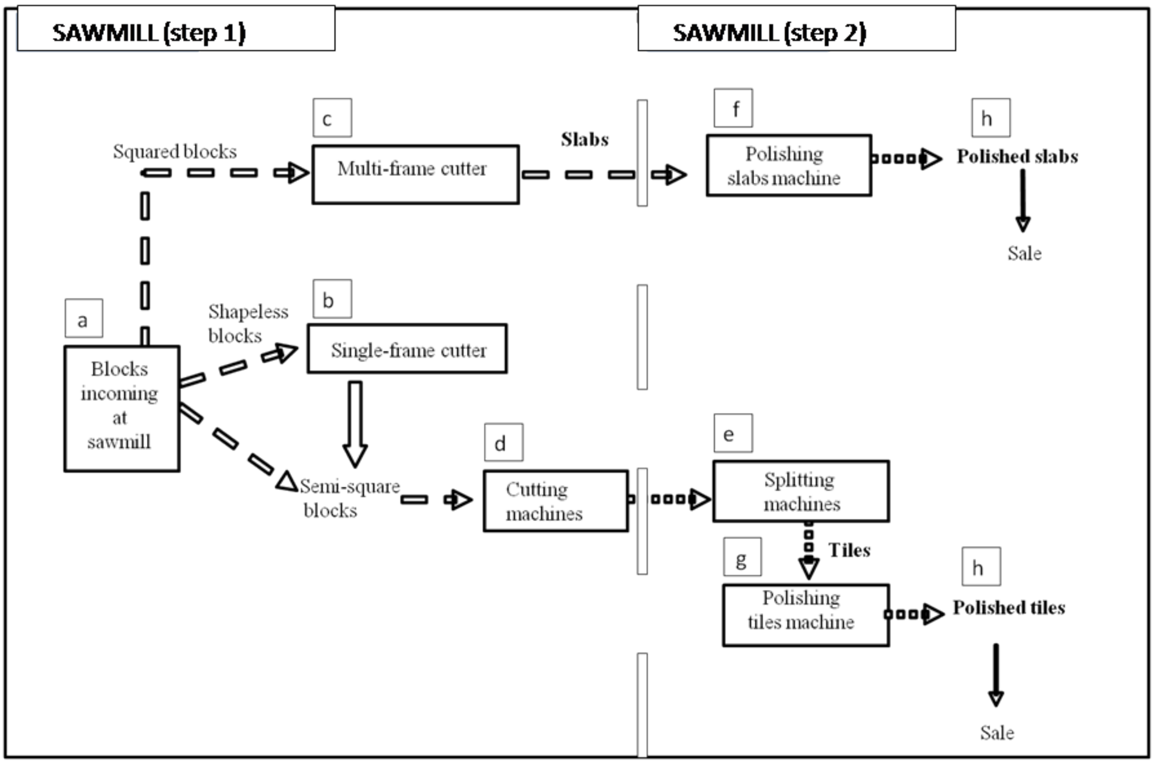


Fig. 9. Diagram of the operations performed in the sawmill.

The process begins with sawing stones into either great size “slabs” or “tiles” with a width up to a maximum of 50 cm and of any thickness. The slabs are obtained from squared blocks that, sawn with “multi-blade” frame, are used to make large products. The tiles, however, obtained from semi-squared blocks of smaller dimensions (called “shapeless”) are cut by “cut blocks equipments” with two circular diamond discs (saws): one that cuts vertically and the other one horizontally (each cut corresponds to a tiles), as reported in Fig. 10 (a, b, c, d, e).

The other processes involved in the whole marble working chain are the following:

- sharpening whose purpose is to obtain regular slabs/tiles of a certain size. This operation is performed through water-cooled diamond disks. Individual slabs/tiles are squared and divided into regular and square slabs/tiles;

- grouting by means of which marble products are checked and possibly repaired with a polyester resin;
- finishing, which is a dry operation with hand tools to correct any imperfections present on the slab/tile (edges, corners, coasts) or on the whole surface as a result of previous processing.

Most of these operations are performed manually in a special room and separated from grinding area, using electrical equipment (pads, chisels, sanders, etc.).

The last process consists of polishing (f, g, h in Fig. 10). This process is carried out manually using appropriate electric tools and water constant; only for small details it can also be performed dry through tools for manual grinding. Abrasive wheels, which are used at this stage to polish properly, have different hardness based on magnesium oxide, magnesium chloride (Sorel cement) and silicon carbide to roughing and potassium oxalate. Alternatively, in case of some specific aesthetic effects specifically requested by the client, it is used the hammering which produces surfaces with imperfections; this operation occurs in dry environment either manually or through power tools.

Fig. 10. Description of the phases indicated in Fig. 9. a) Storage of blocks incoming at sawmill, b) single-blade frame, c) multi-blade frame, d) cutting machine, e) splitting machine, f) polishing slabs machine, g) polishing tiles machine, h) polished slab and tile.

Chapter 2

Life Cycle Sustainability Assessment: an implementation to marble products

1 Introduction

The focus of this Chapter is the assessment of sustainability performance of “Perlato di Sicilia”.

The sustainability performance of “Perlato di Sicilia” been assessed by a life cycle thinking approach, where the entire product life cycle has been considered [15]. The procedure used here is called, as already mentioned, Life Cycle Sustainability Assessment (LCSA) and a set of indicators to consider social, economic and environmental factors has been identified and implemented here.

LCSA can be formally defined as [16, 17, 18]:

LCSA = LCA +LCC + S-LCA [1]

Where LCA is Life Cycle Assessment, procedure standardized by ISO 14040-44 [19, 20, 21], LCC is Life Cycle Costing [22] that focuses on the economic impacts along the product life cycle, and Social Life Cycle Assessment (S-LCA) that focuses on social impact [23] and it is considered the less developed among these three procedures.

Because only few studies have been carried out on this product until now and they mainly focused on the environmental performances, primary data have been collected and a specific set of indicators for measuring the economic and social dimensions have been identified. The primary data have been collected by two representative companies, called, for privacy reason, A and B through this work, sited both in the Custonaci basin.

2 Life Cycle Assessment to marble

LCA has already been implemented for other natural stone floor coverings and an implementation has been carried out on the “Perlato di Sicilia” [6].

The Life Cycle Assessment (LCA) methodology, as it is well known, is able to evaluate the (potential) impacts on the environment of a product/service along its entire life cycle [18, 24]. It is a well-known approach, as already mentioned, with a standardized procedure which consists of the following steps: goal and scope definition, inventory analysis, impact assessment, results interpretation.

By applying the LCA to the manufacturing plant of marble slabs and marble tiles of “Perlato di Sicilia”, a “cradle to gate” approach was applied to the product life cycle, instead of the “cradle to grave” one [17, 25], since the segment regarding the life cycle from the “gate to the grave” is generally affected by uncertainties, mainly related to the different disposal policies adopted by the site. In the following, the study carried out is briefly described, by illustrating its main features and by defining the involved components.

Functional Unit. The selected functional unit (FU), here considered, was 1 cubic meter (m^3) of marble [26] at the gate of the manufacturing plant.

System Boundaries. Concerning the system boundaries for the application, as mentioned earlier, we assessed a partial product life cycle (a “cradle to gate” segment instead of the “cradle to grave” one). The following productive phases were then considered:

- raw material extraction (cradle);
- cutting and polishing of finishing products, along with the transportation operations occurring within the plant (factory’s gate).

The utilization and disposal phases involving the product were omitted in the analysis. The first one is here discarded because the potential impact of the marble’s duty phase is believed to be very low, since the only involved operations consist of surface washing and polishing; actually, these impacts, elated to the duty cycle of the product, should be more suitably computed in the frame of the environmental balance of buildings where marble is mounted. Whereas, as regards the disposal phase, it has been omitted because generally it is geographically and timely far away from the manufacturing site; therefore, the evaluation would result quite difficult and unviable. In fact, it must be considered that, since marble is produced in a relatively few sites while it is exported all over the world, the gathering of these data could be a particularly complex operation.

Assumptions. Certain assumptions have been taken during this LCA analysis, that is:

- the transportation of scrap and spoil to the landfill is included in the system boundaries;
- all scraps from quarry and sawmills are discarded in a dedicated landfill;
- the water used for cooling the diamond wires and saws in the quarry is not recycled;
- the water used in the sawmill is recycled, so causing a production of sawing sludge;

— although the sawing sludge disposal could be used for environmental recovery of worn-out quarries [27], this is not considered in this work [28].

Inventory Analysis. As regards the inventory, primary data were obtained by directly contacting the management of the considered firms.

Impact Assessment. The impact assessment has been effected by using the characterization factors contained in the CML-IA database [29] and in the SimaPro© database [30]. The selection of two different databases is justified by the various assumptions to which each of them refers [31], in this way approaching in a more complete way the singling out of the environmental impacts.

It was possible to get more detailed information for the firm A, where the all input and output have been differentiated for each group of products: tiles and slabs. Instead for the firm B, all data referred to both products and, consequently, a differentiation have not been done (Fig. 11) according to data availability.

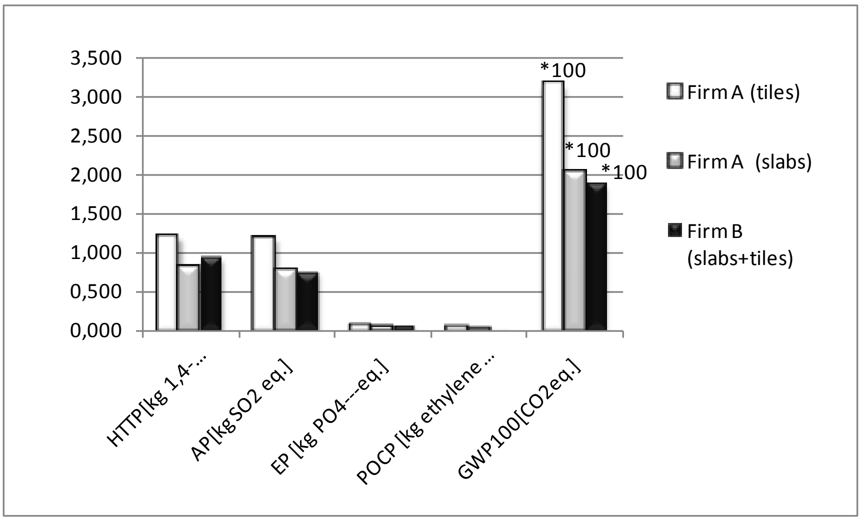


Fig. 11. Comparison of LCA results of A and B firms. (HTTP = Human Toxicity Potential; AP = Acidification Potential; EP = Eutrophication Potential; POCP = Photochemical Oxidation; GWP = Global Warming Potential).

Anyway, the comparison of the two companies shows that the firm A has a higher environmental impact than the firm B. This probably is due to a better choice of the equipment and to a more careful management regarding energy and fuel use.

LCA considers more indicators than those reported in Fig. 11, but here only the indicators of the occurred environmental impact of marble are reported.

3 Life Cycle Costing to marble

The LCC is a procedure to assess all costs and revenues that occur along the product life cycle. This procedure is complementary to LCA and it should be implemented to the same system. It has not been standardised yet but a handbook and a code of practice have been published [32, 33]. The LCC includes also the externalities such as carbon taxes, waste costs and similar. In this application, as externalities the waste management costs have been considered; as matter of the fact according to the regional and national laws these are the main environmental costs that occur by these kinds of industrial activities. All costs included in this assessment are reported in the Fig. 12. For each category reported in the Fig. 12, the difference between the two product life cycles is small. This is justified by the fact that both activities are in the same basin and regional contest and the equipment level is quite similar.

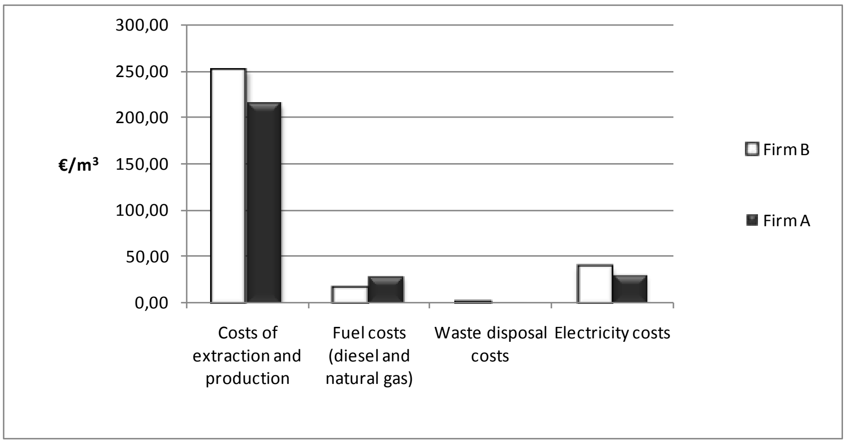


Fig. 12. All costs included in the LCC of "Perlato di Sicilia".

4 Social Life Cycle Assessment to marble

The third component of sustainability assessment consists of the Social Life Cycle Assessment (S-LCA). It is defined as the social impacts assessment of all product life cycle [34, 35]. It is still considered in its infancy, if it is compared to the methodological development level of the other two components, but a lot of efforts and improvements have been made by the scientific community to define this evaluation in the last years.

Two main approaches can be identified: the first related to the Danish school that considers the S-LCA more related to the company behaviour and, consequently, the evaluation is focused more on social conducts of the company and its main suppliers [36, 37] without necessarily taking into account all product life cycle. The second approach has been introduced by the S-LCA guidelines carried out by UNEP/SETAC Life Cycle Initiative [38]. In this second case the S-LCA is conducted in parallel to the LCA, by following the same steps but where instead of environmental impact, the social ones are evaluated. This second approach has been preferred in this work because the main goal is to obtain a complete sustainability assessment of the considered product. According to guideline five groups of main stakeholders have been identified: workers, consumers, local communities, society, and value chain actors. For each stakeholders group different social impacts subcategories have been identified and a methodological sheet for each subcategory have already been drafted [38]. According to guidelines a screening to identify the most impacted stakeholders have been carried out and all relative stakeholder categories have been considered. In this study, the most affected stakeholder group according to the activity is workers. The guidelines do not establish which set of indicators should be used for each subcategory, but in the methodological sheets draft some direction and suggestions are given. In this application a combined top-down and bottom-up approach has been implemented to identify a valid set of indicators [39]. It manages to consider all aspects assumed as valuable for the society and the ideal indicators are matched with data availability. All results have been reported for functional unit of product according to the other two assessments. The best social performance has been obtained by the B firm as it is shown by the Figs. 13 and 14. The average monthly salary per working hour and per employee is from 1.265,39 to 2.009,01 €. Both values are acceptable according to the minimum wage for the extraction and manufacturing of natural stone materials imposed by the regional law.

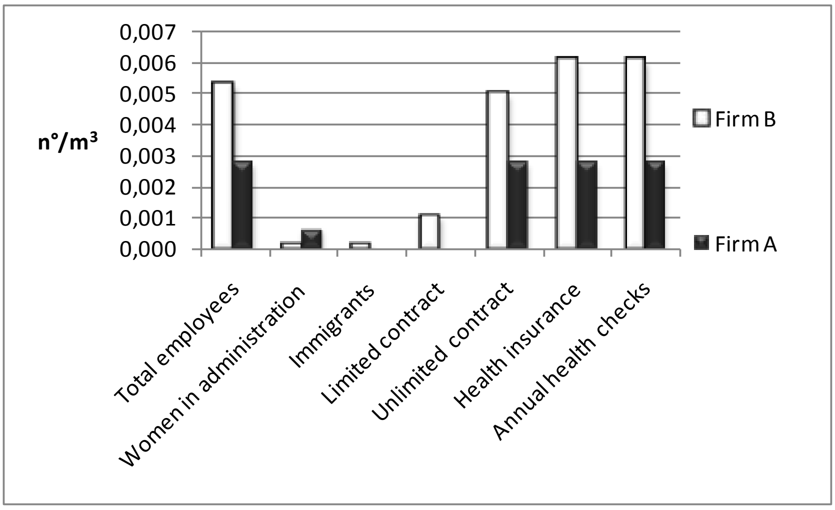


Fig. 13. Social indicators of workers stakeholder category.

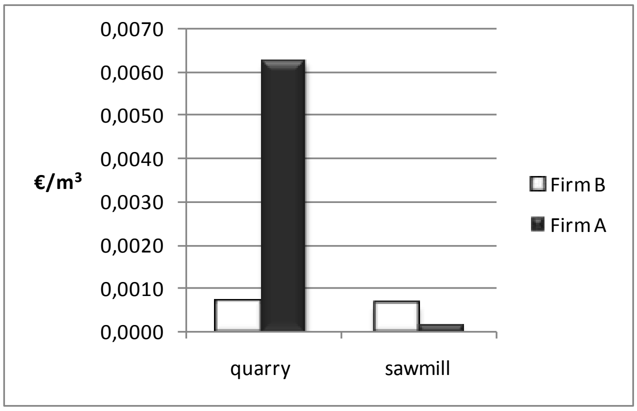


Fig. 14. Monthly salary of employee of quarry and sawmill.

5 Life Cycle SustainabilityAssessment to marble

A complete Life Cycle Sustainability Assessment of the product is obtained by the parallel implementation of all three methodologies introduced in the previous Paragraphs [15]. All three evaluations have been carried out to the same systems and all indicators have been reported to the same functional unit, m^3 of marble. The collection of the data has been carried out in the same period, by questionnaires and surveys of the assessed plants and their workers. The evaluation has shown that the best environmental performance has been reached by the firm B, although this company has the worst economic one. The firm B has also reached the best social performance except for the average wage per hours and number of women employees: both values are in lower than firm A ones.

The obtained results are not so straight forward to identify the best product for all three pillars of sustainability, so further considerations should be made. According to the LCA procedure the assessment should not be made to decide which product is better, but only to compare the products on the base of a transparent procedure that can support decision-makers towards a more sustainable product.

Than, actually the results could be summarized in one or more aggregated indexes that in few values show the aggregated sustainability performance [40]. It can not be done without some considerations about how weight all indicators. The weighting procedure should be carried out with support of a consultation process that involves the affected stakeholders [41]; that is why a flexible and easy to use tool should be implemented to support decision-makers. It concerns another important point of LCSA implementation but it will, however, not be considered in this article both because the point has not yet been thoroughly enough discussed in the LCA community and it could be too early.

6 Conclusions

The LCSA has been implemented for the first time to marble products to evaluate and to compare two production processes of “Perlato di Sicilia” by a life cycle approach. This product has been chosen because it represents a meaningful industrial activity for the economy of Sicilian region and any study was implemented so far for assessing its sustainability performances. A meaningful part of this work regards the data collection; all data presented in this work are primary data and have been directly collected from two representative production plants of Custonaci basin. It represents the second most productive basin of Italy and the first of Sicily.

This first implementation allows identifying strengths and weakness of the products and their life cycle, but it also limits and potentialities of LCSA methodology. According to the reference, the LCSA has been implemented by a combined implementation of LCA, LCC and S-LCA. All procedures have been implemented to the same system and the results are related to the same functional unit. The main difficulties are regarding to the S-LCA, where a definitive and commonly accepted set of indicators has still missed. A set of indicators has been identified by combined top-down and bottom-up approach and then the obtained results of social impacts of “Perlato di Sicilia” have been presented in this work.

The obtained results have shown that the B firm presents a better environmental and social performances but, in the same time, it has the highest costs and the lowest average salary for employees and working hours. These results are meaningful to address each company to improve their performances and to introduce a competitive market towards a sustainable production.

Chapter 3

Life Cycle Sustainability Assessment: strengths and weakness of a practical implementation

1 Introduction

The aim of this Chapter is to present lights and shadows of practical implementation of LCSA for identifying further steps towards a standardized methodology.This Chapter does not aim to solve the difficulties in the LCSA implementation, but to present in a clear framework some of the open questions that a practitioner of LCSA have to face up into carrying out a LCSA of product.

Because the unique standardized methodology is the (environmental) Life Cycle Assessment, the strengths and weakness are clustered following the ISO 14040. The guidelines published by the UNEP/SETAC LCI on social life cycle assessment (S-LCA) and the publication for practitioners on sustainability assessment, “Towards Life Cycle Sustainability Assessment” [7], where the other two dimensions have been integrated, are important scheme to refer in this critical review of results of the LCSA of marble. Moreover the recent progress on S-LCA and LCSA have been considered to formulate comments and suggestions for the practitioner of LCSA. Suggestions are clustered in tables for each step of LCSA. A qualitative evaluation has been given for each step of the implementation with a score and colour scale (from weakness (1) to strength (5)) to distinguish those steps that are already fully developed from the other that need further efforts.

In the goal and scope, a meaningful role is played by the identification of stakeholder groups according to the assessment is made. The stakeholder group determined issues and indicators that have to be considered in the assessment. The obtained results are strongly dependents on the selected stakeholder group.

The Life Cycle Sustainability Impact Assessment is still implemented differently for each technique, in fact this phase is considered one of the most challenging with the evaluation value of (1) weakness.

The interpretation phase needs a strong and communicative supporting tool. The LCSA can plays a significant role to address sustainable production and consumption but for that porpoise it needs that the results can be understood from expert and non experts of LCA.

Even if the LCSA is recognized as a valid method to assess sustainability performances of a product several efforts have to be still paid to fully develop it in particular in the social assessment and in the Life Cycle Impact Assessment. Particular attention has to be paid to identify a set of indicators to standardize and facilitate the Life Cycle Inventory. More applications of LCSA should be implemented to create a robust database. Moreover a tool to handle with the three dimensions of sustainability in the interpretation step is desirable to present the results in an understandable but still comprehensive way.

2 Life Cycle Sustainability Assessment – strengths and weakness

As already mentioned, the definition of LCSA is presented with the formal equation LCSA=LCA+LCC+S-LCA.

For each step a table is presented where e description of relative strengths and weakness have been given, a relative score and in the last column an advice to improve the methodology according to new scientific development. A score and a colour scale have been defined to rank each step of the methodology in term of weakness dark grey (5) to strength white (1).

Goal and scope: as already mentioned, according to the ISO 14040 the first step is to identify the goal and scope of the assessment, relative system boundary, functional unit, audience to whom the assessment should be presented, and a first scheme of data and factors that should be included in the case study.

The goal of the case study is a comprehensive sustainability assessment of the marble life cycle, therefore all stakeholder groups that can be affected should be considered in the assessment. In fact, the social and economic impacts of the product strongly depend on the chosen stakeholder group, and the choice of the stakeholder groups depends on the aim of the study.

As it is shown in Table 3, the role of the stakeholders group is more significant in the S-LCA and LCC, where the results of the case study strongly depends on the stakeholder group chosen, the stakeholder analysis should be made according to the main goal and the necessity of LCC and S-LCA.

The chosen stakeholders of the marble case study, as already mentioned, are the companies involved in the marble manufacturing for the economic assessment and the following stakeholders strictly related to them in the social analysis: worker and value chain actors [38].

According to the S-LCA, the local community is another important stakeholder group, strongly affected by the social positive and negative impacts of marble. As matter of fact, the quarries and sawmills have positive as well as negative impacts on the local communities, such as: local employment, access to material resources, reduction of healthy conditions, delocalization and so on. In this work, the practicability of the implementation and measurability of factors were a priority in the study; therefore the lack of data related to the above mentioned social impacts of marble on local community led to neglect this stakeholder group.

Consumers have not been considered because the marble does not have a meaningful impact at social, economic and environmental level during its use phase.

The next challenge is the definition of the system boundary. According to the publication "Towards Life Cycle Sustainability Assessment" edited by UNEP/SETAC LCI [7], *"…all unit processes relevant for at least one of the techniques"* must be included in the system boundary. Consequently each factor that affects at least one of the three dimensions should be included in the Life Cycle Inventory. The system boundary has been defined as the three main production plants (quarry, sawmill, polishing plant and transports) and the relative environmental, economic and social inputs and outputs of these three plants have been considered. Analysing more in detail the case study, all environmental impacts and all money flows of the organizations, from extraction of raw materials to the production of the marble, have been considered, including the environmental impacts generated by the fuel production and the costs generated to buy them (e.g. it indirectly includes all costs afforded by electricity producer). What about the social impacts of them? Should the workers of the energy system plants, manufacturing plants of diesel and so on be considered too?

To be consistent with the life thinking approach all workers involved in each unit process should be included and their social impacts measured. In the present case study, once again, the gap of data availability has not allowed to assess the social impacts caused by the other materials and energy inputs of the marble life cycle. An extensive research on statistic data related to the social aspects of energy system at regional level has been conducted to identify social hotspots of this process unit, but unfortunately no data of subcategories of workers stakeholder has been found.

The functional unit should represent the technical utility and social utility of the product. According to that it has been has a cubic meter (m^3) of marble, which has the function to cover, and insulated a building, to make the flat/house more valuable and improve its aesthetic quality. The definition of a functional unit of marble by considering the three dimension of sustainability was not particularly challenging, but of course it strongly depends on the product and its function on society.

A common accepted set of indicators for LCSA has not yet been defined. In fact, international agreement has been found mainly for the economic and environmental indicators [32], but the scientific community is still struggling to define the social ones. Because our focus is the social impacts of workers according to the International Law Organization, Universal Declaration of Human Rights as well as more specific references such as S-LCA guidelines [38] and methodological sheets [42] the following topics must be assessed: child labour, force labour, fair wage, freedom of association and collective bargaining, health and safety conditions, equal opportunity and discrimination.

The indicators that can be used to measure these topics strongly depend on data availability and the goal of the study. In fact when the main goal is an external communication of the results to customers or partners preferred used indicators of social issues are related to risk reduction (that it gives a more positive message on these critical topics) as opposed to if the study is used for the internal assessment, raw percentages and number of injuries or discrimination cases should be directly monitored.

2.1 Life Cycle Inventory

The Life Cycle Inventory should already be carried out in the first moment by encompassing environmental, economic and social aspects. In particular, have contemporarily carried out a questionnaire to assess the three dimensions. The collection of the data has been carried out in the same period, by questionnaires, audits and surveys of the assessed plants and their workers.

In particular for collecting social data some questions to check the plausibility of the data have been added.

The collection of true social data is a challenge because they touch topics that can destroy the image of the organization and have penal consequences. On the other hand, it is important to have the right data to draw the current social status of the employees. In the case study, some of the utilized data have been collected by means of field analysis and by directly reviewing the documents of the company.

Because it is not always possible to visit and assess directly the plant, a good screening process is suggested by using several references and company´s documents, such as: assessment of the sustainability report of the company if it is available; a hotspot analysis according to the Social Hotspot Database [43] to obtain the framework of the main social risk of the considered country/sector; collection of data and indicator at country and regional levels as suggested by the methodological sheets [34] in the generic analysis. For collecting primary data an easy and comprehensive questionnaire was carried out. When it is possible the questionnaire should be specific for the product and should focus on the hotspots factors identified by generic analysis. Several references are available for supporting the environmental life cycle inventory such as ELCD, Directive on European Flower. A good support for the Life Cycle Costing Inventory is represented by the new SETAC publication "Environmental Life Cycle Costing: Code of Practice" [32], where a practicable example in the automobile sector have been reported and the indicators used described in detail. The good news on the economic indicators are all expressed in monetary units so no characterization factors are needed to translate them into impact categories.

The main challenge remains the Social Life Cycle Inventory where most of the data until now is available for a hotspot analysis and a lot of effort still have to be paid to collecting primary data at company level, for each company involved in the product life cycle. In Table 4 some examples of data sources are reported.

For marble no secondary data is available in neither of the two main databases mentioned in Table 4 (Gabi® and SimaPro®) but in their modelling process examples of economic and social indicators have already been set up to support the practitioners in the inventory phase. The units of social indicators reported in the GaBi5® are working hours for all indicators already inserted in the software. In other words issues like child labour, forced labour and health issues are all measured in working hours worked for example by children or working hours lost for injuries and diseases. Were directly used as indicators the percentage and/or number of cases (related to child labour, forced labour, discrimination), average of salary, number of employees per gender and age and so on. If the data used in the marble case study is more intuitive and easier to collect on the other hand it needs to be translated into impacts and (or directly) interpreted.

2.2 Life Cycle Sustainability Impact Assessment

The Life Cycle Sustainability Impacts Assessment can be clearly defined only for the environmental [20, 44, 45] dimension. For the economic one, we do not need the translation in the impact categories because in general "the life cycle cost is a number expressed in monetary units and the comparative assessment is easily done indeed a lower cost is always better" [32].

The social dimension is the most complex one and the less defined in the impact assessment step. On one hand, it is true that some of the social issues already have a theoretical intrinsic value according to common understanding of the well-being and human rights, indeed no child labour, no force labour, no discrimination must occur. On the other hand, according to local conditions it is not always possible to establish in which impact categories the abolition of these bad practices bring the improvement of workers social conditions. The example of child labour reported to Joergensen et al. [37] and Dreyer et al. [35] explains how difficult the definition of the impact pathway of this even conventionally condemned social issue is. When, for example, child labour occurs the health, the education and the future of the child can be badly affected. However, since children are generally forced to work due to poverty [46] the ban of child labour could force them to take other, potentially worse jobs [37] with no consequential improvements of their social and health conditions.

In the case study, because knew the local conditions, the LCI results have been directly used as representative indicators of the impact assessment and how much they touch on the sustainability performance has been considered directly through Life Cycle Sustainability Dashboard (LCSD) in the interpretation phase.

3 Interpretation of Life Cycle Sustainability Assessment results

The interpretation phase should aim to have a clear vision of the comprehensive sustainability impacts of the product together with the ability to identify the main factors that affect the results.

The general scope of the LCSA is to support decision-making processes where it is possible that experts and non-experts of LCA take a part in the decision. To summarize, according to the current state of the methodology, no common agreement has been found to translate economic and social mid-point categories into impacts on the comprehensive area of protection well-being and human dignity [35]. At the conclusion of LCSA we have to handle the results of several impact indicators in order to elaborate a technical suggestion for the decision-makers.

A possible solution to it, when more than one same group of products has been assessed and the most sustainable solution have to be identified is the Life Cycle Sustainability Dashboard (LCSD). Traverso et al [40] have presented this new version of Dashboard of as a valid tool to compare the LCSA results of more similar products and to present the results to a expert and non-expert audience. This tool has been used for other products [40, 47] and the results of the marble case study [8] have been shortly presented, as already mentioned, in the UNEP/SETAC [7] publications. One of the strengths of this tool is the ability to present the comparison results through a score and an intuitive colour scale that identify the best performance of the products considered in comparison to 1000 points and dark green and the worst one with 0 points and dark red. The score of the intermediate value is obtained with the linear interpolation of these two extremes and the colour varies from light red to yellow to light green. According to LCSD it is possible to insert some weights to give more importance to one or more indicators according to the decision-makers perspective and/or stakeholders interest.

The weighting procedure should be carried out with support of a consultation process that involves the affected stakeholders [48]. In the case study of marble the same weighting has been used for all indicators to evaluate all indicators with same importance.

The obtained results of LCSA of marble have been presented by LCSD to the companies, which were involved in the data collection. The ability to present the results through a colour scale and contemporarily without losing the original data was successful in presenting positive and negative impacts of the “Perlato di Sicilia” marble (from Custonaci) compared to “Bianco di Carrara” [7]. An example is reported in Fig. 15 where a comparison of environmental LCA among three different marbles is shown. Analogue visualization can be presented for the LCC and S-LCA results as well as for the aggregated evaluation of the three pillars for each product. As suggested by Traverso et al. [40] it is still preferable to the interpretation phase of LCSA by LCSD the non-aggregated version of it where the value of the comparison for each indicator (e.g. GWP) is presented.

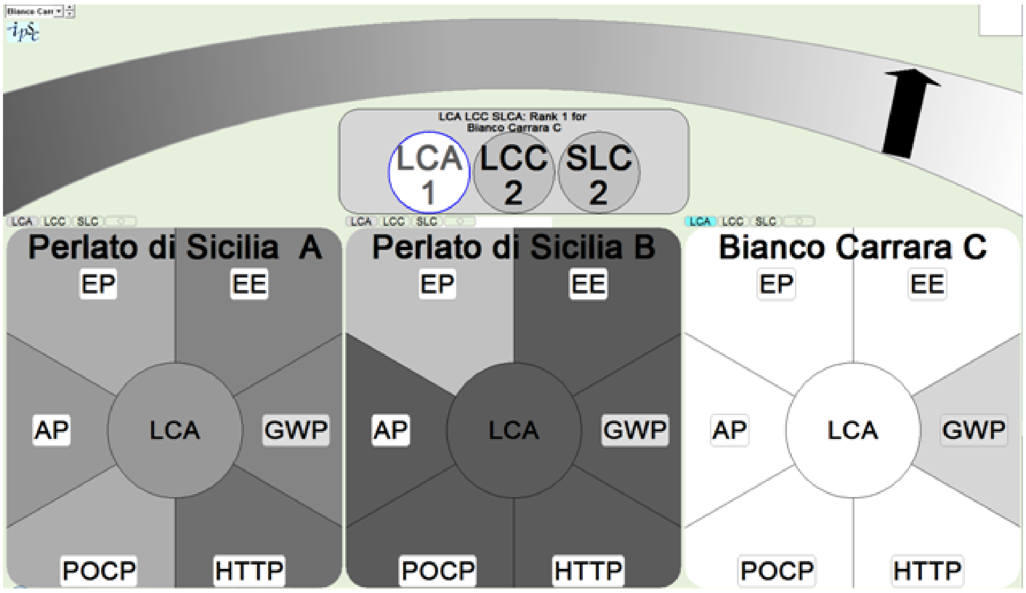


Fig. 15. Example of LCSA results interpreted and shown by Life Cycle Sustainability Dashboard

4 Discussion and conclusions

This Chapter analysed step by step a practical implementation of LCSA to marble in order to identify limits and potentialities of the methodology as well as the practical implementation. In Tables 3, 4, 5, 6 a summary of strengths and weaknesses of each implementation phase is presented. To summarize the entire assessment of marble according to the current state of the art of the methodology, each phase has been assessed. The summary of the evaluation results are reported in Table 7 with a colour and score that represents the level of weakness (1) towards strength (5). According to the obtained results still a lot of effort has to be paid to reach complete definition of the LCSA in particular related to the definition of a set of indicators and the availability of primary and secondary data. In addition to the lack of data a more standard methodology for the impact assessment of the social dimension and the interpretation of the overall sustainability performance should be developed.

Table 3. Strengths and Weaknesses of the goal and scope definition

Step	Stregth/Weakness	Evaluation	Comment/Suggestion
LCSA	Each product has to be contemporarily assessed by the three techniques.	Strength (5)	We have to implement at the beginning the three techniques (LCA, LCC and S-LCA).
	The opportunity to carry out a contemporary assessment of the three dimensions, improve the efficiency of the results, allows the practitioners to identify trade-offs of the three pillars.	Strength (5)	
Goal and scope of the study	The comprehensive goal of the study to assess the sustainability impacts of a marble introduces complexity and reduces the practicability of the study.	Weakness (2)	The assumptions should be as transparent and justifiable as possible and all consequences should be evaluated to reduce the subjectivity and to improve the reproducibility of the study.
	A comprehensive goal and scope for the three dimensions of sustainability allows a more complete assessment of the sustainability performances of products and avoids the shifting of the impacts from one dimension to the others.	Strength (5)	
Identification of the Stakeholder group	It strongly depends on the goal of the study and strongly affects the system boundary and factors and relative indicators used for the assessment.	Weakness (2)	Transparent approach with the report of the justified choices met in the assessment. A Stakeholder analysis related to the product should be carried out at the beginning of the study to identify the stakeholders mainly affected by the product life cycle assessment
Stakeholder group affects the results of the assessment	The LCC and S-LCA results strongly depend on the stakeholder group,	Strength/ Weakness (3)	The chosen stakeholder group should be consistent to the main goal of the LCSA assessment, and the exclusion of one should be transparently reported and justified.
	The stakeholders group considered in the marble study is Workers.	Strength/ Weakness (3)	A stakeholder analysis identified workers and local community as the main affected ones, but the lack of data led us to focus our attention on workers for which valid primary and secondary data have been collected.
Functional unit	According to the publication of UNEP/SETAC LCI about LCSA it is recommended that the functional unit describes both the technical social utility of the product.	Strength/ Weakness (3)	Identify the social utility of the product's life cycle could be difficult and strongly depends on the goal and the considered stakeholder group
	The cubic meter of marble that has the functionality of covering, insulating and aesthetically improving a surface.	Strength (4)	The importance of insulating and improving the aesthetic values of a building causes social, environmental and economic consequences.
System boundary	It consists of all unit processes which have meaningful impacts on at least one of the three pillars.	Strength (4)	It is enough that each unit process has an impact in at least one of the three dimensions of the sustainability to be included in the system boundary of the product.
	In the study the system boundary mainly includes the production phase. The use phase does not have high sustainability impacts but the end of life could have meaningful impacts	Strength (4)	The end of life in this case has been neglected because in the most cases it is temporary and geographically very far from the production phase and no specific data is available for the marble. An explanation of the reason that leads to neglect some product life cycle phase should be given
Issues/Indicators	A standard set of environmental, social and economic indicators has not been defined yet but a first proposal of it has been given in the case study of marble.	Strength/ Weakness (3)	The main challenge is the selection of social indicators. The methodological sheets and other references could be considered to select a valid set of indicators [23, 35, 42].
	The data have to be related to the functional unit. How do we deal with social qualitative indicators?	Weakness (2)	The social indicators could be qualitative and semi-quantitative, so it could be very difficult to integrate them into a further comprehensive sustainability assessment of the product. In the case of qualitative and semi-quantitative indicators the introduction of evaluation scale or a multi-criteria assessment is suggested to translate the qualitative evaluation into score [49].
Data considered in the assessment	All data of environmental, economic and social factors have to be collected related to the functional unit.	Strength/ Weakness (3)	Not so much social primary data is available and it is always a challenge to collect it at a unit process level. A hotspot analysis could be carried out for identifying the main risks and potentialities of the product at sector and country level- and consequently to the result of social hotspot analysis a more detailed primary data should be collected for the main identified social risks and opportunities.
	The data has to be collected for the entire product life cycle (from extraction of raw material and considering the production of all materials and components)	Weakness (2)	Social data related to all material inputs have to be considered. In the case study the social data is referred to as the main unit processes without considering the production of the electricity and diesel.

Table 4. Strengths and weaknesses of Life Cycle Inventory

Step	Strength/Weakness	Evaluation	Suggestion
Hotspots Analysis	The social Hotspots analysis can be implemented to have a first social impact of the product at country or sectorial level.	Strength (4)	Social Hotspots Database [43], World Bank, UNICEF, ISTAT and other official social databanks can be used to have a first s-LCA at sector, country or regional level. Of course the data sources have to be transparent. The social hotspot analysis should take into account the different geographical level of the data, by giving priority and more importance to the ones that are at local and sectorial level and that are more product specific.
Collection of primary data	Sustainability Data of each unit process has to be collected. That means social data of the entire supply chain of the product has to be considered.	Strength/ Weakness (2)	Difficulties can be met in having social data for each unit process and particular attention has to be paid to the allocation phase. In the case study we had direct data for each unit process and no allocation.
Use of secondary data for environmental and economic life cycle inventory	The use of secondary data is possible for both dimensions. The huge amount of environmental input and output data are available in several softwares for assessing the environmental dimensions. The economic one needs probably further efforts, where data is available for specific case studies.	Strength/ Weakness (3)	Software such as GaBi or SimaPro can be used for the environmental and economic assessment.
Use of secondary data for social inventory	No secondary data is available for the social dimensions.	Weakness (1)	The only possibility to have secondary data when primary data is not available is to derive data at product level with a macroeconomic analysis of the specific product sector by using Input and Output analysis [50]. The data sources are more or less the same for the hotspot analysis but in this case data at sector level should be considered.
Data referred to FU	At the end data has been reported to the functional unit.	Strength/ Weakness (3)	Even if the social and economic inputs and outputs are very small related to the selected FU.

Table 5:Strength and weaknesses of Life Cycle Sustainability Impact Assessment

Step	Strength/ Weakness	Evaluation	Suggestion
Classification/ Characterization	It has been done for the environmental LCA because the characterization factors are available only for this pillar. The indicators of economic LCI are all reported in the euro, and they already represent the impact.	Strength (5)	
	The characterization factors for the S-LCA have not been defined yet and the case study mainly uses the LCI indicator to measure the impact.	Weakness (1)	Several theoretical approaches have been presented [37, 49, 51, 52] but unfortunately no agreement has been reached in the scientific community yet.

Table 6: Strengths and weaknesses of interpretation phase.

Step	Stregth/ Weakness	Evaluation	Suggestion
Integration of the three dimension	Life Cycle Sustainability Dashboard has been used in this assessment to report the comparison of more than one product.	Strength (4)	LCSD is only one of the possible tools to support the interpretation of LCSA results.
Weighting	In the case study the same weight for all indicators has been used to assess the sustainability assessment of the marble. Also if it is not recommended the weighting process is often applied.	Strength/ Weakness (3)	A transparent weighting process is recommended to make the interpretation reasonable and justified.

Table 7. Summary of the evaluation of each phase of LCSA in terms of weakness and strengths.

Step (goal an scope)	**Score**
LCSA	5
Goal and scope of the study	3
Identification of the Stakeholder group	2
Stakeholder group affects the results of the assessment	3
Functional unit	3
System boundary	4
Issues/Indicators	2
Data considered in the assessment	2
Step (Life Cycle Inventory)	
Hotspot Analysis	4
Collection of primary data	2
Use of secondary data	2
Data referred to FU	3
Step (Life Cycle Sustainability Impact assessment)	
Classification/Characterization	3
Step (LCSA Interpretation)	
Integration of the three dimension	4
Weightining	3

Legend	
Very good (Strength)	5
Good (Strengh>Challenge)	4
Medium (Strengh/Challenge)	3
Bad (Stregth < Challenge)	2
Very Bad (Challenge)	1

The importance to develop LCSA and S-LCA to assess product performances when there are other tools such as CSR, Global Reporting Initiative guidelines that have been already implemented and accepted at company level is often questioned. In fact, the social impacts are mainly related to the behaviour of the companies involved in the product life cycle and the social impacts of a company have been quite well addressed by Global Reporting Initiative guidelines [53], United Nation Global compact guidelines and so on. If it is true that these tools already exist and are used at company level, it is also true that they are mainly used to assess the company political strategy that is not necessary related to the application of it to each plant and site. Moreover, the assessment of it at product level supports users and consumers towards a more sustainable consumption by identifying "bad" and "good" products of the same group. The main risk of a social assessment at product level, as emphasised by Zamagni et al. [54], is that even if all the companies involved in the product life cycle do not caus any violations of human and labour rights in the specific plants where the product is manufactured, that does not mean that they carry responsibility in all sites of the company. On the other hand, tracing the sustainability performance of a product is a strong step to sensitise the producers and force them to improve their performance by starting with at least one of their products and to make the consumer more and more aware of the responsibility of his choice.

Chapter 4

Is the eco-label EU Decision for hard coverings really capable of capturing the environmental performances of the marble productive chain? A field verification by means of a life cycle approach

1 Introduction

This Chapter intends to show whether the eco-label EU Decision for hard coverings, is really capable of capturing the environmental performances of the marble productive chain, in other words whether it is actually viable for the natural products, like marble.
In fact, it must be noted that building materials, within a general approach aimed at the improvement of the energy efficiency of this sector [55], are increasingly called to achieve quality brands that, generally, aim at the energy and environmental certification of such materials [56].
The socio-economic context in which companies ha1ve to operate is in constant and rapid transformation due to several factors, among which the most important are: the technological innovation, the constant changes of market and its globalization, the European integration and the evolution of demand joined to a new way of customer's expectations (need for transparency, service development, sensitivity to environmental impact). Therefore, all companies, in different sectors, are called to give accurate signals to market making organizational and managerial choices that represent the necessary response to changes required by market. Then, for example in building industry the different materials used, with particular reference to those of the so called bio-architecture, today require certifications which communicate their quality and environmental performance.
Within the European scheme for awarding building products with the eco-label [57] brand, marble is contemplated among hard coverings, as a "natural product". In fact, the European Commission Decision 607 of 9th July 2009, establishing ecological criteria for awarding hard coverings by the Community eco-label, subdivided these products into two major groups: "natural products" and "processed products"."Natural products" are materials existing in the environment which include marble, granite and other stones that can be found in nature. Whereas, the group "processed products" can be further divided into two sub-groups, that is "hardened" and "cooked" products. The first ones are agglomerated stones, like concrete blocks and terraces, while the latter are ceramic

tiles and bricks [9]. According to this classification, marble belongs to the class of natural products.

In sight of the identification of the firms eligible for an eco-label award, a preliminary verification of the EU Decision 2009/607/CE, in terms of their environmental performances should be conducted, in order of verifying the full compatibility of criteria present in the Decision with impacts associated to the working chain of marble. On the basis of this preliminary analysis of the structure and criteria of the Decision referring to the phases of a working chain belonging to the marble District in Sicily, certain limitations of the Decision in catching all impacts exerted by this productive chain seems to arise. The marble processing cycle is described in Paragraph 2 of the Chapter 1. Furthermore, these limitations are checked by means of an "in the field" application of a classical LCA methodology to a firm belonging to the marble Custonaci basin, where they seem to be confirmed.

As regards previous studies on this particular topic(eco-label criteria), to the best of our knowledge, no research work is currently available in the scientific literature, apart the work carried out by Baldo et al. [58], which consisted in using LCA to develop eco-label criteria for hard floor coverings whose results have been then published in the EU Decision 272/2002 [59], which represents the previous version of the Decision 607/2009 here analysed.

In the next Paragraph criteria for the label of building materials will be analyzed at the light also of the life cycle analysis.

2 Analyzing the European Commission Decision 607/2009 with respect to a typical marble working chain

The first European Directive on the posting of a Community mark for construction products (CE) dates back to December 21st, 1988 [60]. It aimed to remove technical barriers to trade in field of construction products in order to enhance their free movement in the internal market.

In order to achieve that objective, Directive 89/106/EEC provided for establishment of harmonized standards for construction products and for granting of European technical approvals. This Directive has been modified by Directive 93/68 [61], Directive 98/34 [62] and Regulation 1882/2003 [63]. Finally, in order to simplify and clarify the existing framework, and improve transparency and effectiveness of measures in force, it was appropriate to replace Directive 89/106/EC with the recently adopted Regulation 305/2011 [64]. Furthermore, following what has been stated several times in this paper, Regulation 305/2011 suggests that in order to assess the performance of a construction product you should take into account all the aspects related to life cycle of the product. Of course, all manufacturers who want to affix the CE brand on their products must draw up a declaration of performance in accordance with Regulation 305/2011. Always the same regulation states that the CE marking is the only marking which certifies the construction product is consonant to the declared performance and has the applicable requirements relating to the Union harmonization legislation. It also states that other markings may be used on condition they help to improve its performance.

Criteria contained in the EU Decision 2009/607/CE for the EU eco-label of hard coverings are here analyzed, in order of checking their applicability to marble and natural stones, in general.

The EU eco-label we are referring to is the European brand [57] assigned to the products and services which are characterized by high environmental performance over their entire life cycle. It is a strong communication tool by means of which such products/services can be quickly and easily recognized by the market, that requires products characterized by higher and higher performance standards.

The European Commission Decision 607 of 2009 establishes the ecological criteria for awarding hard coverings by the Community eco-label.

A schematic description of the Decision is reported in Table 8 where, for each criterion, is provided its identification number, its object, the class of products to which the criterion refers, the sub criteria of which each criterion is composed and the pertinent working phase.

Criteria in the range 6 to 10 are not included in the present analysis, since the corresponding phases do not apply to the productive site but belong to external segments of the productive chain. As that, in the following criteria from 1 to 5 of the Decision are analyzed with respect to the above mentioned productive chain of the "Perlato di Sicilia", which are extraction in quarry, processing in sawmill and finishing operation in laboratory. In Table 8 criteria referring to natural stones that will be analyzed in the present work are those reported in bold.

In more details, criteria 1, 2 and 5 (that is “raw material extraction”, “raw materials selection” and “waste management”, respectively) referring to the extraction phase in quarry (see the last column of the Table 8), will be discussed in the Paragraph 2.1. The manufacturing process of slabs and tiles in sawmill will be discussed in Paragraph 2.2. Whereas criteria 3 and 5 (that is “finishing operation” and “waste management”) referring to the finishing operations (see the last column of the Table 8) will be treated in Paragraph 2.3.

Table 8. Schematic description of the Decision Commission 607/2009/EC [9].

Criterion n°	*Object*	*Class of products*	*Sub-criterion*	*Pertinent working phase*
1	**Raw material extraction**	Natural products	**1.1. Extraction management (a)**	Quarry
		All hard covering products	1.2. Extraction management	
2	**Raw materials selection**	All hard coverings products	**2.1. Absence of risk phrases in raw materials**	Quarry
		Glazed tiles	2.2. Limitation of the presence of some substances in the additives	----------
		All hard coverings products	**2.3. Limitation of the presence of asbestos and polyester resins in the materials**	Quarry
3	**Finishing operations**	Natural products	----------	Laboratory
4	Production process	Processed products	4.1. Energy consumption	----------
		Processed products	4.2. Water consumption and use	
		Processed products	4.3. Emissions to air	
		Processed products	4.4. Emissions to water	
		Processed products	4.5. Cement	
5	**Waste management**	Natural products	**5.1 Waste management**	Quarry and laboratory
		Processed products	5.2. Recovery of waste	----------
6	Use phase	Glazed tiles	6.1. Release of dangerous substances	----------
7	Packaging	----------	----------	----------
8	Fitness for use	----------	----------	----------
9	Consumer information	----------	----------	----------
10	Information appearing on the eco-label	All (natural and processed) products	----------	----------

(a) Six main indicators are here identified: I1: Water recycling ratio; I2: Quarry impact ratio; I3: Natural resource waste; I4: Air quality; I5: Water quality; I6: Noise.

2.1 Analysis of criteria for quarry operations

In this Paragraph criteria referring to typical operations occurring in marble quarries are analyzed. They involve: criterion 1 ("raw material extraction"), criterion 2 ("raw materials selection") and criterion 5 ("waste management").

Criterion 1, "raw material extraction".

The Decision assumes that raw material extraction management for natural stones shall be evaluated using a matrix of six main indicators, that is: I1, "water recycling ratio"; I2, "quarry impact ratio"; I3, "natural resource waste"; I4, "air quality"; I5, "water quality"; I6, "noise". The raw material extraction management shall be scored according to a matrix of these indicators. The main features of each of the six indicators are shortly reported in the following.

I1, "water recycling ratio". This indicator is calculated as the ratio between the waste water recycled and the total water that exits the process (every active quarry must ensure, in fact, a proper supply). For waste water is here meant only water used in processing plants, not comprehensive of the fresh water coming from rain and subsoil water. The related calculation algorithm is in the form:

$$\frac{\text{m}^3\text{of waste water recycled}}{\text{m}^3\text{of total water leaving the process}}[\%].$$

I2, "quarry impact ratio". Its calculation is based on the measurement of both affected (which includes quarry front and active dump areas) and the authorized areas. Then, the calculation algorithm is the form:

$$\frac{\text{m}^2\text{of affected area (quarry front + active dump)}}{\text{m}^2\text{of authorised area}}[\%].$$

I3, "natural resource waste". This indicator is calculated as the ratio between the usable material and the total volume extracted yearly. Usable material refers to the whole volume which can be used in any process: for the case of marble, commercial blocks, aggregate materials and everything else suitable for further processing and use. The pertinent calculation algorithm is in the form:

$$\frac{\text{m}^3\text{ usable material}}{\text{m}^3\text{extracted material}}[\%].$$

I4, "air quality". According to the Decision, the calculation consists of the measurement, along the border of the quarry area, of PM_{10} suspended particles based on specific requirements of the general provisions of Directive 1999/30/EC [65] and of the test method defined in UNI EN 12341 [66].

I5, "water quality". This indicator considers the total emissions of suspended solids occurring after surface water treatment flowing out of the mine site. To calculate this indicator the measurement of total suspended solids [mg/l] using the test method reported in ISO 5667-17 [67] is needed.

I6, "noise". This indicator considers the noise level (on impulsive noises) recorded along the border of the quarry area. To calculate the I6 value, the measurement of the noise [dB(A)] using the test method reported in ISO 1996-1 [68] is needed.

To be eligible for the EU eco-label, mines must obtain a weighted score of at least 19 points over the six indicators. In addition, the score of each indicator must be higher or lower than a threshold specified as appropriate [9]. The total score achieved, within the Decision's scheme, shall be based on the sum of individual scores given for each indicator, multiplied by its corrective weighting (W). The values of these weighting factors are indicated in the EU Decision depending on three different categories , that is the soil use class (W1), the density of settlements (W2) and the interference with surface water bodies (W3).

Anyway, for the application to the marble working chain the above indicators need to be further discussed.

With reference to indicator I4 ("air quality"), it must be observed that apparently it is not exhaustive enough for marble, because it only requires to calculate PM_{10}, in this way neglecting all of other pollutant emissions which, actually, occur in a marble quarry. In fact, use of electricity and consumption of fossil fuels (typically, diesel oil), which is involved in the extraction activities, also lead to the releasing of gaseous pollutants into the atmosphere such as NOx, SO_2, CO and CO_2, that are recognized as important causes of the worsening of the environmental quality [69]. Therefore, it would be important that the Regulation for the EU eco-label for hard coverings would also account for these emissions and would sets threshold values, not only for PM_{10} but also for these other pollutant components.

Another important point to be further considered is given by a fundamental field analysis [70] provided by an Italian environmental institution, that signals in the marble district of Carrara the presence of $PM_{2,5}$ (fine suspended particulate); actually the analysis revealed that as far as 93% of the fine particulate in the area is represented by $PM_{2,5}$, while in the Italian towns they account for 50% of the whole particulate matters. Moreover, high percentage of breathing diseases have been noticed among in habitants of Carrara; these values are surprisingly not in line with the national average values [71]. This fine particulate is capable to penetrate deeply into lungs during breathing and, despite the detailed mechanism with which it interferes with body's organisms is not completely clear yet, it is known that the smaller the size is, the highest the possibility of biologic interaction is. Among the main problems caused by fine and ultrafine particulate (PM_{10} and, especially, $PM_{2,5}$), acute and chronic pathologies involving both the breathing system (asthma, bronchitis, emphysema, allergy, tumors) and cardiovascular system in predisposed subjects must be contemplated [72, 73].

Based on the above considerations, the indicator "air quality" would need to be modified aimed to account for all pollutant emissions in atmosphere caused by the marble production activities.

As far the possible introduction of new indicators is in question for marble, a parameter accounting for the amount of blocks extracted and sent to the sawmill with respect to the total amount of material extracted, should be also introduced. Actually, such an indicator was already present in the above cited first version of the Decision [59], but it was then deleted in the version now in use.

Moreover, an indicator that quantifies the relevant volume of materials disposed in landfills should be further introduced, since it appears indispensible for a comprehensive assessment of the environmental performances of the product.

Another indicator, able to take into account the use of explosive in quarry, should be added as well. In fact, explosives are often used in marble quarries to remove the vegetation layer below which the raw material is placed. Problems caused by the use of explosive are different: both the environmental impacts generated by the use of this energy source and the potential consequences on workers (the safety levels in working places) must be considered. Therefore, an analysis about the type of explosive utilized and about its effect on the environment and people are recommended [74]. Type and quantities of explosives used must be therefore defined with respect to the amount of materials removed (m^3).

The possible introduction of such new indicators will be described in more detail in Paragraph 4.

Criterion 2, "raw materials selection".

The eco-label regulation establishes that raw materials must not contain substances or preparations that are assigned any of the 18 risk phrases reported in the same Decision (e.g. substances with risk code R45, which may cause cancer are not allowed). Moreover, it states that either raw materials used for natural products cannot contain asbestos and the use of polyester resins in production is limited to the 10% of the total weight raw materials.

These requisites confirm the full suitability of criterion 2 also for marble.

Criterion 5, "waste management".

The Decision establishes that the waste deriving from quarrying should be properly treated. Particularly, in sub-criterion 5.1 ("waste management") it refers to the extraction and polishing operations, while all the cutting procedures occurring in sawmill are neglected. Moreover, no criteria accounting for the recovery and/or reuse of waste are present, despite the extraction phase of marble is characterized by a significant recovery of waste material. These materials are mainly constituted of marble blocks of various size, that can be usefully recovered and commercialized [75, 76].

As that, this criterion seems to be applicable to marble with some modifications, as discussed in Paragraph 4.

2.2 Analysis of criteria for sawmill operations

In the Decision for the EU eco-label for hard coverings, no criteria accounting for the whole production process of marble blocks in sawmill are contemplated. Actually, this represents an important weakness in the Decision, since plant cutting operations, typically occurring in sawmill, are significantly energy consuming [5].

Manufacturing processes of marble such as cutting to suitable sizes and polishing for ornamental purposes, produce marble dust and aggregate as by-products. In fact, during the cutting process 20 ÷ 30% of the marble blocks turn into dust [77].

Unfortunately, as previously noticed, no criteria are present in the Decision with respect to the manufacturing process of marble slabs and tiles in sawmill. Therefore, neither energy and resources consumption nor air and water pollutant emissions, occurring in this phase, are taken into account. This lack doesn't allow a suitable evaluation of impacts caused by the production process of marble.

Moreover, as regards criterion 5, which is concerned with the waste management, it simply regards the management of waste deriving from quarrying and finishing operations, in this way totally neglecting the waste from processing operations (occurring in sawmill), although the production of marble slabs and tiles results in a significant amount of sludge and by-product.

Besides, also in this case, as noticed for quarry, the waste recovery is not considered, although the sawing sludge could also be used for environmental recovery of worn-out quarries [27, 28].

At the light of the previous considerations, the inclusion of a new criterion which accounts for the whole impacts of the production process of marble is suggested, as will be introduced and discussed in Paragraph 4.

2.3 Analysis of criteria for finishing operations

In this Paragraph, criteria referring to the finishing operations, are analyzed, that is criteria 3 ("finishing operations") and 5 ("waste management").

<u>Criterion 3, "finishing operations".</u>

Specifically in the case of marble, finishing operations consist of polishing and (possible) resin tapping of finished products.

The Decision requires measuring particulate emission into air (PM_{10} and styrene), water recycling ratio and emission into water (suspended solid, Cd, Cr (VI), Fe and Pb). Anyway, the criterion, although accounting for the environmental impacts generated by finishing operations (mostly emissions in water), does not consider the energy consumption due to the different equipment utilized in this phase .

A proposed modification of this criterion will be introduced and discussed in Paragraph 4.

<u>Criterion 5, "waste management".</u>

In this criterion the Decision establishes that the waste deriving from finishing operations should be properly treated. As that, it fully applicable to marble.

3 Field verification of the suitability to marble of EU Decision 2009/607/EC by means of a Life Cycle Analysis approach

As observed earlier, some criticisms have been found during the checking of the suitability of the Decision to the working chain of marble. Clearly, an "on the field" verification of the manufacturing process of the marble, from both energy and environmental perspectives, is useful to confirm or not this preliminary analysis.

In Chapter 2, Paragraph 2, LCA methodology(purpose, functional unit,assumptions,etc.) applied to "Perlato di Sicilia" is represented. There are also the results of an analysis referred to two companies working in Custonaci basin. In this part of the work the results of the LCA methodology will be analyzed just for one of the two companies (firm A).

The amounts of the energy required to produce 1 m^3 of marble [31] at the factory's gate were then calculated and split in three main components: the energy in quarry and in sawmill (step 1 and 2), respectively, as reported in Fig. 16 where typical values of the daily treated materials are also reported.

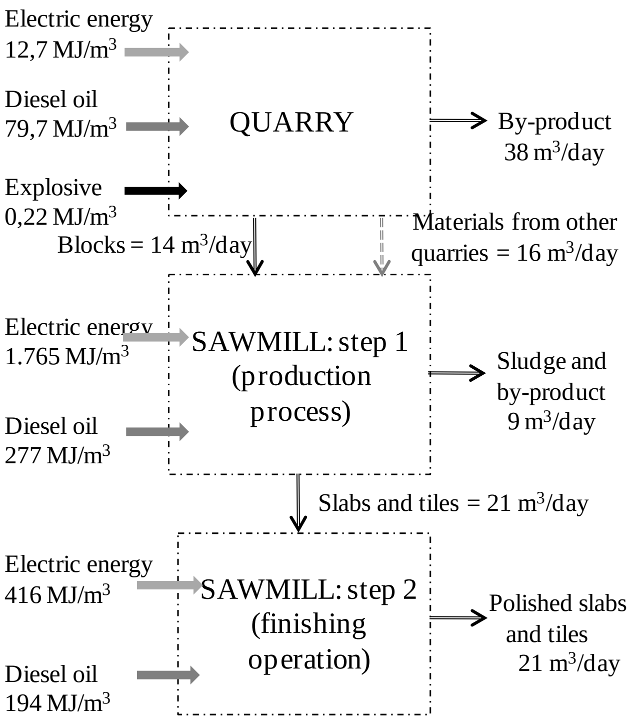


Fig. 16. Specific (MJ/m^3) energy amounts involved in the manufacturing process of firm A, subdivided by quarry and sawmill (step 1 and 2).

The related pollutant emissions per functional unit occurring in quarry and sawmill (step 1 and 2) were calculated by cumulating the emissions caused by the use of each single energy source (electric energy and diesel oil) and explosive used in the different phases of the productive chain (Table 9) during the whole life cycle. For indirectly computing these emissions, the proper emission factors of the energy sources were applied (Table 10).

Table 9. Pollutant emissions (g/m^3) per functional unit related to the consumption of the involved energy sources and explosive, in quarry and sawmill (step 1 and 2).

	QUARRY			SAWMILL(step 1)		SAWMILL (step 2)	
	Electric energy	Diesel oil	Explosive	Electric energy	Diesel oil	Electric energy	Diesel oil
CO_2	2,547	5,901	23.73	354,035	20,483	83,385	14,372
NO_x	2.54	63.08	0.00	353.03	218.96	83.15	153.63
SO_2	6.60	1.83	7.67	916.91	6.37	215.96	4.47
CO	2.47	15.65	5.04	343.23	54.31	80.84	38.11
HC	0.02	0.16	-------	3.00	0.55	0.71	0.39
PM_{10}	4.78	4.69	-------	664.39	16.28	156.48	11.42
SOV	-------	16.78	-------	-------	58.26	-------	40.88
K_2O	-------	-------	16.43	-------	-------	-------	-------
K_2S	-------	-------	12.85	-------	-------	-------	-------
$PM_{2,5}$	-------	4.22	-------	-------	14.64	-------	10.27

Table 10. Emission factors (g/MJ) for electric energy, diesel oil and explosive [78].

Emission factors	CO_2	NO_x	SO_2	CO	HC	PM_{10}	SOV	K_2O	K_2S	$PM_{2,5}$
Electric energy	200.5	0.2	0.52	0.19	0.002	0.38	----	----	----	----
Diesel oil	74	0.79	0.02	0.20	0.002	0.06	0.21	----	----	0.0529
Explosive	108.33	----	35	23	----	----	----	75	58.67	----

The resulting potential impact of 1 m^3 of marble produced in the examined firm are already reported in Fig. 11 of Chapter 2.

This LCA application to the working operations occurring in a typical marble firm of the Sicilian productive district does confirm the criticisms that the preliminary analysis of the Decision 607/2009 have arisen. In fact, the "on the field" checking of this marble productive site singled out the involvement of pollutant emissions and the releasing of fine particulate (with a radius < 2.5 μm) in quarry, that wasn't taken into account in the criteria of the Decision. Furthermore, the sawmill operations involve a large amount of energy and, in turn, of pollutant emissions that are not considered in the current version of the Decision. Moreover, the sludge and scraps production of sawmill are not considered as well. Finally, the energy consumption involved in the finishing operations of marble is omitted in the present Decision structure.

4 Discussion and proposals

From the preceding analysis and considerations the need for a revision of the European Decision actually in force for hard coverings has arisen, in order of render it more suitable for marble and for natural stones that show a working chain similar to the marble one.

4.1 Criterion 1 - "raw material extraction"

In the current release of the Decision criterion 1 ("raw material extraction") is composed by six indicators. Anyway, in order of better evaluating the environmental performances of productive chains of marble, possible new indicators should be included in the Decision's structure, while some of the existing ones should be suitably modified. By summarizing the results of the analysis (Paragraph 2) of the structure of the Decision and of the field investigation of a marble productive site (Paragraph 3) previously presented, it is here proposed that:

- indicator I4 should be properly modified, by taking into account the pollutant releases in the atmosphere of all the working activities;
- a new parameter (indicator I7) should be introduced to account for the amount of commercially utilizable blocks, extracted and addressed to sawmill, with respect to the total extracted material; this parameter can be assumed as a general measure of the efficiency of the marble production site;
- a new parameter (indicator I8) should be introduced to account for the relevant volume of materials disposed in landfills;
- a new parameter (indicator I9) should be finally introduced to account for the use of explosive in marble quarry.

As a result of these considerations regarding the criterion 1 and its sub-indicators, a new matrix of pertinent scores is here proposed (Table 11), where all changes and/or integrations to the original matrix are reported in the dashed boxes.

Table 11. New matrix proposed to score the raw material extraction management in the case of marble.

Indicator		Score				
		5 (excellent)	3 (good)	1 (sufficient)	Threshold	Relative weights
I1Water recycling ratio (%)		> 80	80 - 70	69 - 65	< 65	W3
I2 Quarry impact ratio (%)		< 15	15 - 30	31 - 50	> 50	W1, W2
I3 Natural resource appreciation (%)		**> 60**	**60 - 45**	**44 - 35**	**< 35**	-----
I4 Air quality (μg/m[3])	PM_{10}	**< 15**	**15 - 30**	**31 – 40**	**> 40 [a]**	W2
	NO_x	**< 10**	**10 - 20**	**21 - 30**	**> 30 [a]**	**W2**
	$PM_{2.5}$	**< 10**	**10 - 15**	**16 – 25**	**> 25 [a]**	**W2**
	SO_2	**< 40**	**40 - 80**	**81 – 125**	**> 125 [b]**	**SO_2**
	CO (g/m[3])	**< 3**	**3 - 6**	**7 – 10**	**> 10 [b]**	**W2**
I5 Water quality (mg/l)		< 15	15 - 30	31 – 40	> 40	W1, W2, W3
I6 Noise (dB(A))		< 30	30 - 55	56 – 60	> 60	W2
I7 Blocks recovery (%)		**> 40**	**40 - 30**	**29 - 20**	**< 20**	-----
I8 Quarrywaste(%)		**< 20**	**20 - 30**	**31 – 40**	**> 40**	-----
I9 Use of explosives (kg/m[3])		**-----**	**-----**	**-----**	**-----**	**-----**

[a]yearly limit; [b]daily limit.

Benchmarks related to indicator I3 have been modified. In this case again, the proposed benchmarks are those included in the previous version of the Decision whose stricter values seem to better apply to sustainability criteria.

The benchmarks for pollutants (indicator I4) refer to yearly, daily and warning values, as indicated in the Italian standard concerning this sector [79]. This selection, obviously, depends on the law situation of the marble district of Custonaci. For a general use of the table, values referring to each pollutant should be those established by technical standards and regulations issued in the country where the productive site is located.

The benchmarks attributed to the new proposed indicators I7 and I8 ("blocks recovery" and "quarry waste") have those referring to the previous release of the Decision, where an indicator accounting for the "block recovery" was actually present.

As regards indicator I9, at the present state, it must be observed that benchmarks referring to the amount of explosive utilized to destroy the superficial vegetation layer below which marble blocks are positioned cannot be attributed. In fact a standard concerning limit values of explosive to be utilized in quarries do not exit so far. Currently, an "in field" analysis is being carried out by present authors in the Custonaci productive district, to collect data concerning the amount of explosive used and to identify average and, possibly, limit values. At the moment, the simple indication of the amount of explosive used (kg/m^3) could be required to firms, in order to be eligible for the eco-label award.

With reference to indicator I4, a more extensive evaluation of the pollutant emissions produced by the extraction operations in quarry is proposed. These considered added emissions are reported in Fig. 17, not only for firm A but also for the firm B. Although firm B, as already mentioned, differs slightly in the productive chain from firm A, it is in the same way representative of the production practices of this marble district, and both then show the same materials flow distribution. Because such emissions are generated nearby the quarry, they can be calculated along the perimeter of the sites area, using a direct method, based on test methods present in the pertinent standards, that is UNI EN 12341 [66] for PM_{10}, UNI EN 14791 [80] for SO_2, UNI EN 14792 [81] for NO_x, UNI EN 14907 [82] for $PM_{2,5}$ and UNI EN 14626 [83] for CO.

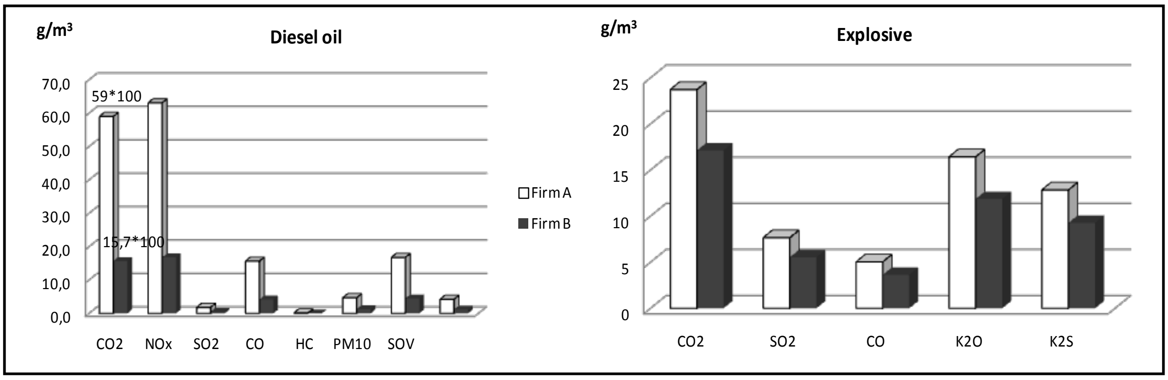


Fig. 17. Total emission in quarry for firm A and firm B for unitary volume of material.

As can be observed in Fig. 17, two firms, although characterized by comparable mass flows in quarry, present different pollutant releases in the atmosphere, with emissions of firm B lower than the ones of firm A. Such a difference can be explained by considering the more advanced technological equipment present in firm B. In fact, this firm uses, other than the energy sources already mentioned, also photovoltaic generated electric energy, that determines a lower amount of pollutant emissions.

Since, as already mentioned (see Fig. 16), also the electricity is contemplated among the energy sources used, an estimation of the pollutant emissions produced during the production cycle of this form of energy must be done. In this case, of course, pollutants are not emitted nearby the quarry but at the site of the thermal power plant generating the electric energy; therefore, these emissions can be only indirectly evaluated (Fig. 18). The emission factors of each single energy source, that are available in literature [78] and already reported in Table 10, can be usefully adopted on this purpose.

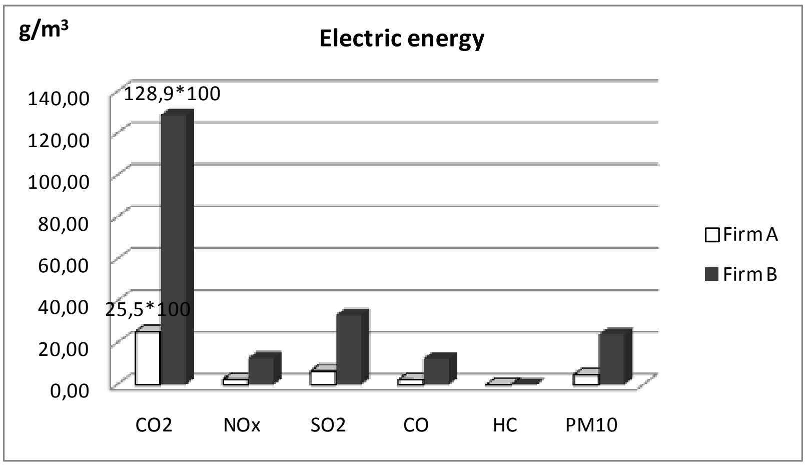


Fig. 18. Total emissions generated in to the production cycle of the electric energy used in firms A and B.

The typical distribution of mass flows in quarry, in percentage values, valid for both firms, is reported in Fig. 19. More specifically, the total extracted material "a", consists of commercial blocks, "b" (this part accounts for 30% of total extracted material), and by-products, "c" (this part accounts for 70%); the latter is made, in turn, of disposal material, "d" (this part accounts for 30%) and usable material, "e" (this part accounts for 70%).

Starting from this distribution of mass flows, indicator I3 (already present in the Decision) and indicators I7 and I8 (here proposed) can be computed for firms A and B.

$$I3 = \frac{commercial\ blocks + usable\ materials}{total\ extracted\ material} = \frac{b+e}{a} \cong 30\%;$$

$$I7 = \frac{commercial\ blocks}{total\ extracted\ material} = \frac{b}{a} \cong 70\%;$$

$$I8 = \frac{disposable\ material}{total\ extracted\ material} = \frac{d}{a} \cong 21\ \%\ .$$

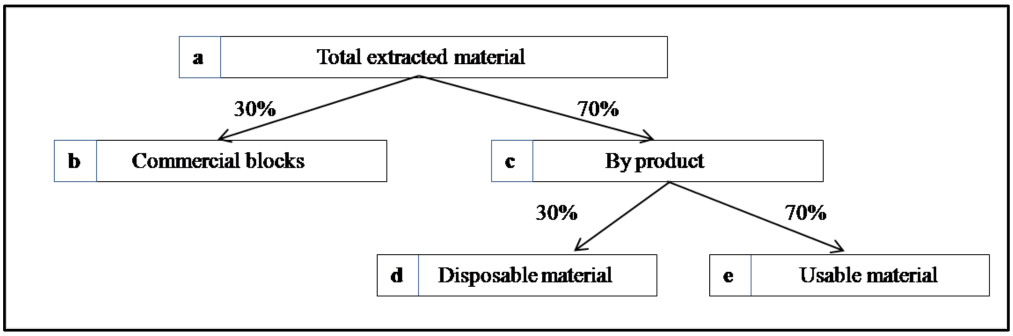


Fig. 19. Typical distribution of mass flows in quarry, in percentage terms, as result of the "in field" analysis of both firms.

As regards indicator I9, it has been calculated for the two considered firms as ratio between the amount of used explosive and the amount of removed material. It resulted to be 0.07 kg/m^3 for firm A and 0.02 kg/m^3 for firm B.
According to the Decision 607/2009, as already mentioned in Paragraph 2.1, quarries must obtain, with regards to criterion 1, a weighed score of at least 19 points to be eligible for the eco-label award. Based on the changes and new proposals regarding on the matrix, this weighted score cannot be confirmed so far. Tentatively, by considering that in the current matrix for each of six indicators a mean value of approximately 3 points is required, in this new proposed version of the matrix, composed by 9 indicators, a total score of 28 points could be reasonably proposed.

4.2 Criterion 2 - "raw material selection"

As regards criterion 2 ("raw material selection"), no modifications are proposed here because relevant weaknesses did not emerge through the present analysis.

4.3 Criterion 3 - "finishing operation"

With respect to criterion 3 ("finishing operation"), the environmental impacts generated by the finishing operations certainly need to be evaluated more accurately and the energy consumption related to the use of the several different involved equipment must be accounted for. In fact, our application of a LCA analysis to the "Perlato di Sicilia" has shown that energy consumption related to the for polishing and resin tapping operations accounts for as far as 30% of the whole amount of energy utilized in sawmill. Therefore, the calculation of this energy consumption should be also included among the Decision parameters. This energy consumption could be usefully calculated, as suggested in the Decision, like "Process Energy Requirement" (PER). Clearly, the threshold and the test method to be used have to be established as well. Ranges already present in criterion 4 ("production process") could be used with this purpose; they, in fact, even though refer to processed products, can be similarly applied in case of marble and natural stones. The PER limit, in this case, should not exceed the level of 1.6 MJ/kg.

4.4 Criterion 4 - “production process”

Actually, this criterion have not been treated in the previous analysis, since it refers only to processed products and not to natural products, as marble is. Anyway, some of the sub-criteria included in it in the current version of the Decision could be considered for inclusion in a new release of the award scheme.

In fact, a criterion for air emissions, that takes into account all of the pollutant emissions generated during the manufacturing process of marble in sawmill, should be present in a scheme for natural stones and marble. Actually, in the Decision a criterion (sub-criterion 4.3 in Table 8) referred to the working process is already present, but it is referred only to processed materials excluding all natural products like marble. Therefore, this criterion might be extended, with the due modifications, to natural products.

A summary of the energy consumption related to the sawmill operations (step 1) is shown in Fig. 20, compared with some available literature data referring to other marble products. The graph shows that energy consumption for the production of 1 m^3 of “Perlato di Sicilia” of firm A is considerably higher than energy consumption for the production of 1 m^3 of “Carrara marble” [26]; Nicoletti *et al.*[3] and the “Greek marble” analyzed by Gazi et al.[5]. While the energy consumption of “Perlato di Sicilia” of firm B is slightly higher than “Carrara marble” and “Greek marble”.

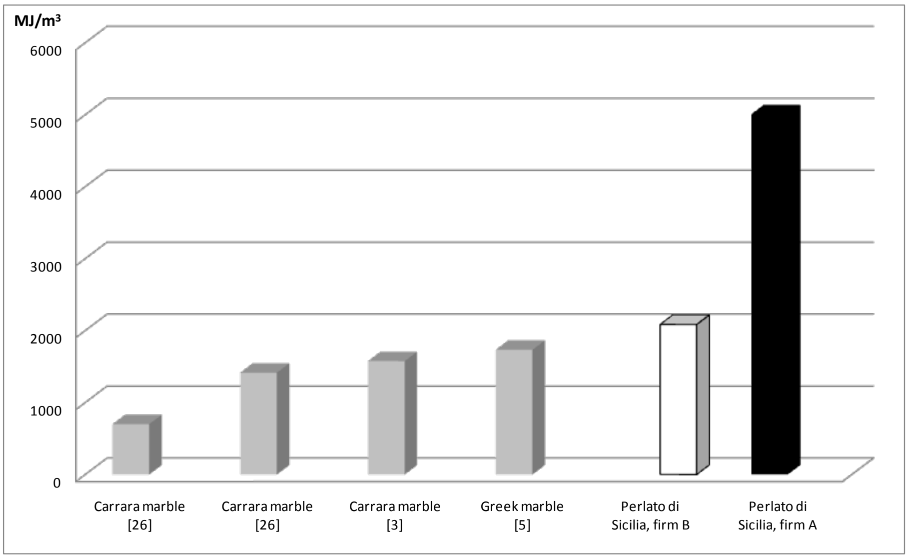


Fig. 20. Range of energy consumption of marble products.

Moreover, since in the Decision no indicators that take into account the possible use of renewable sources are present, a new parameter could be thus introduced to measure the pollutant emissions saved depending on the possible use of renewable sources.

4.5 Criterion 5 - "waste management"

As regards criterion 5 ("waste management"), it should be properly modified to consider both the managing of waste deriving from the manufacturing process of marble slabs and tiles and the recycling of by-product materials that, in this case, accounts for approximately 70% of the treated product [84]. Again, such waste production should be suitably taken into account. Therefore, an extension to marble of sub-criterion 5.2 "waste recovery" (see Table 8) is suggested.

As regards the production of marble blocks that takes place in sawmill, a criterion accounting for the energy and resources consumption occurring in this phase along with their resultant impacts, should be also introduced. Indeed cutting operation, leading to production of slabs and tiles of marble, makes a significant amount of sludge, the so-called "marmettola" (made only in sawmill) and by-product, the so-called "cocciame" (made both in quarry and sawmill). These products when subjected to particular treatments could be used for example to build embankments and road foundations or as waterproofing materials for foundations of MSW landfill [80, 81], such as "topsoil" for environmental rehabilitation of quarries and compromised sites [82] or even in building industry [83, 84, 85, 86, 87].

5 Standard eco-label versus "materiale per la bioedilizia": a comparison

In this Paragraph we want to present a quick comparison between the European standard, already analyzed, and an Italian standard for the certification of products and materials for green building. Specifically, it was analyzed an Italian standard presented by the National Bio-ecological Architecture Association (ANAB) and the Institute for Ethical and Environmental Certification (ICEA).

This standard specifies general and special conditions in order to get authorization to affix to products and materials for green building the "materiale per la bioedilizia" (material for green building) label in accordance with the objectives, principles, practices, and requirements of UNI EN ISO 14024 [88]: "Environmental labels and declarations - Type 1 eco-labeling - Principles and Procedures" and the ANAB mark [10]. The aim is to highlight similarities and differences between these standards and identify possible strengths and weaknesses, considering a possible definition of a more comprehensive and high-performance mark towards, at least, marble.

At this point, in order to have an immediate visualization of differences and similarities between the two considered standards, taking into consideration the entire production cycle of marble (quarry, sawmill (steps 1 and 2)), in Table 12 a schematization is presented.

Table 12. Similarities and differences of the two standards.

	Eco-label standard	***Materiale per la bioedilizia***
Presence of a criterion related to the extraction phase with corresponding thresholds	✓	---
Presence of a criterion related to production process with corresponding thresholds	---	---
Presence of a criterion related to finishing operations with corresponding thresholds	✓	---
Presence of indicators related to the extraction phase with corresponding thresholds	✓	---
Presence of indicators related to production process with corresponding thresholds	---	---
Presence of indicators related to finishing operations with corresponding thresholds	---	---
Assessment of all general impacts	---	✓
Assessment of energy consumption during the extraction of raw materials	✓	✓
Assessment of energy consumption of the production process	---	✓
Assessment of energy consumption of finishing treatment	---	✓
Evaluation of all emissions of pollutants in water, air , soil and subsoil related to the phases of: extraction of raw materials, production process and finishing treatments	---	✓
Evaluation and management of waste production at all phases of life cycle	---	✓
Presence of threshold values which compare the results obtained	✓	---

It is clear that the main strong point of material for green building standard is to capture all impacts related to each phase of production cycle of marble, but its weak point is not to predict any threshold values of reference which compare with the results obtained from the analysis of life cycle of the analyzed product. The strong point of eco-label standard, however, is the presence of an easy understanding and application structure (thanks to the presence of indicators and criteria) and the possibility to compare the results obtained with the threshold values of reference.

On the contrary, its main weak point, as already mentioned several times, is to neglect many impacts related to the different phases of the production cycle, in particular not to consider all impacts related to the stage of processing in sawmill.

However there is not a clear dominance of one standard over the other, because each one has advantages and limitations of different issues of different activities. Then, the idea of integrating the strong points of the two methodologies was born, in order to propose guidelines that contain the best criteria of the two standards.

These guidelines may be simply identified by combining the strong points of the two methodologies in order to eliminate completely the weak points.

These guidelines could be structured in this way:

- presence of a criterion for each phase of life cycle, just as the European standard, but which takes into account, however, all the environmental impacts for each phase, ie: energy consumption, pollutant emissions and production/management and recovery of waste and scraps producted. Then, it should be requested an application of LCA methodology to be sure to include all impacts;
- for each criterion and sub-criterion and any indication, there should be a threshold value of reference. Of course, if the product exceeds this value it cannot receive the mark;
- For each criterion it should be given a score depending on the result. That is to say, you should have some reference imposed which can have assigned a relative score. Obviously the sum of each score let us determine whether the product deserves/does not deserve the mark/certification of quality.

Table 13 shows an example of this proposal referred to a generic Criterion “X”. For this criterion a threshold value of “90” has been suggested (see the last column of Table 13). then, you could for example give a score 1 (sufficient), 3 (good), or 5 (excellent) depending on the range which it belongs to.

For example if you have 10 criteria, the maximum possible score got by the product is 50 (5 points for each criterion), while the minimum is 10 (one point for each criterion). At this point you need to determine the minimum score to have the certification (for example, according to the limits imposed by the Decision, the limit in this case could be 31).

Table 13. Example of scoring for the generic criterion "X".

	1 (sufficient)	3 (good)	5 (excellent)	threshold value
Criterion "X"	60 - 90	30 - 60	< 30	90

An approach like this makes clear and immediate the display of the result (thanks to a single benchmark score); ensure the complete impact assessment (through an analysis of life cycle) allows to compare the results obtained with limits set by local, national or international Regulations (eliminating any superficial comparison of results obtained with those obtained by similar products or database of the field).

Then, this leads to a higher reliability of conducted analysis and a guarantee on performance of quality reached by the product candidate to the release of the mark/certification of quality.

6 Conclusions

An eco-label award for marble used in building sector clearly represents a strong commercial tool for communicating the sustainability performances of this important material, provided that the criteria utilized for awarding the firms are really capable of capturing all the impacts related to its productive chain. With this aim, in this work a critical analysis of the current Decision concerning hard coverings has been preliminary conducted for verifying whether it is actually viable for the natural products, like marble. This verification highlighted some critical points of this Document when applied to marble.

Moreover, a field-study has been performed, by examining the whole productive chain of a couple of firms treating the "Perlato di Sicilia" marble, which includes either the extraction and processing phases, and finishing operations. The application of a classical LCA methodology, enabling the accounting for all of the emissions due to the production chain, was utilized in this aim.

The current version of the Decision seems to present some serious limitations when applied to marble and the natural stones, that have a productive chain similar to the marble one, such as granite [89, 90] for example.

The analysis of the structure of the Decision and the field checking on two firms of the Custonaci marble district in Sicily, has risen the following considerations:

a. the introduction of new environmental indicators (I7, I8, and I9) referring to the criterion “raw material extraction” is suggested, in order of better describing the operations involved in this phase;
b. as regards the criteria “raw material selection”, “finishing operation” and “waste management”, a certain number of modifications, essentially concerning aspects that are typical of the marble working process and that weren’t properly indicated in the Decision, have been also proposed here;
c. with respect to the criterion “production process”, its extension to natural products has been proposed, provided that suitable changes are introduced;
d. the indication of the quantity of explosive utilized in quarry should be reported by firms that are candidate to apply for the excellence brand;
e. the percentage of energy (electric as well thermal) produced by renewable sources should be included in the evaluation of the environmental performances of a given firm.

Clearly, further investigations are needed in order to better assess the proposed scheme, especially in terms of thresholds values of pollutant releases and use of explosive, that are actually specific for the marble productive chain. Moreover, additional analyses should be addressed to a better particularization to marble of the weighting factors W1, W2 and W3 applied in the quarry operations.

Despite these still open questions, the changes here introduced can represent a useful indication toward a more suitable scheme of the EU eco-label for marble, at least. In fact, the present modified version of the standard has been proposed to the Sicilian administration in order to be voluntary adopted by marble productive sites of the region, in the aim of extensively verifying its suitability.

Chapter 5

Environmental appraisal of marble production: a simple method for field evaluations

1 Introduction

Marble, among materials frequently used in building, also needs environmental analysis, since its processing takes place by mining and a processing cycle which requires considerable amounts of energy and which involves a release of significant quantities of scrap materials. Moreover, marble quarries do not have much in common with other forms of underground mines (the dimension of openings, the method of excavation, the form of the excavated material, the support method, etc.) then several techniques for rehabilitation of the exploited land [91] have been developed and these could be suitably used in the case of marble quarries. In fact, for instance, limestone quarrying has the potential to cause a particular set of two impacts to the karstic nature of the terrains, therefore it requires special care [92, 93].

In mining activity scraps represent a significant part of the production process. In fact, during the manufacturing process only 20-25 % of total extract is transformed into finished product, while the remaining 70-75 % is composed of scraps of production [79]. This simple fact justifies the interest in methods for assessing the environmental performance of marble quarries and processes that lead to finished product.

This greatly complicates the attempt to assess the environmental impact of quarrying activities and cutting and finishing marble activities. In addition it is important to outline that because of the nature of mining settlements and the traditional approach which they are managed with, these sophisticated analyzes must often be made by personnel not specifically trained to evaluation of environmental performance.

Then, it is necessary to have simple and reliable methods of evaluating environmental and energetical performance of processes which take place in marble quarries and sawmills.

In Paragraph 2 we will proceed to an environmental analysis of the “Perlato di Sicilia” through the proposal of a simple method of evaluation.

2 Evaluation of significance of environmental aspects/impacts

As already mentioned, in this Chapter, we will look for identifying operational tools which allow companies in Custonaci basin (TP, Italy) to embark on a virtuous path of improving environmental performance. Therefore, we propose a simple tool to assess environmental significance of some work cycle services.

In order to show a general and sintetic representation of environmental features involved in each activity, in Table 14 a matrix of interactions is represented with a list of activities and environmental features involved. This matrix was built taking into account the results of LCA described in Chapter 2, Paragraph 2.

It is important to say that activities developped at the site (first colomn of Table 14) have been summarized in three main phases, the quarry where extraction of raw materials occurs, the sawmill (step 1) where cutting operations take place and the sawmill (step 2) where final processing takes place.

Table 14. Correlation matrix between activities in the site and environmental aspects [94].

Activities carried out in the site		List of environmental issues																	
		water consumption	electricity consumption	fuel consumption	dangerous substance	asbestos	contamination of soil and subsoil	traffic	radioactive sources	electromagnetic	vibration	waste water	thermic central	air conditioning plant	waste	atmospheric emissions	noises	odour	dusts
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
QUARRY	cutting of first material	X	X		X		X				X	X			X	X	X	X	X
	squaring	X	X	X			X				X	X			X		X		X
	transport blocks to sawmill and waste to landfill			X			X	X								X			X
SAWMILL (phase 1)	storage		X				X										X		
	cutting blocks	X	X				X					X			X		X		X
	resin tapping				X		X								X	X		X	
	treatment of refluent water		X		X		X								X				
	transport to sawmill (phase 2)			X			X	X								X			X
	office activities	X	X									X			X				
SAWMILL (phase 2)	resin tapping				X	X	X								X	X		X	
	polishing	X	X				X								X		X		
	treatment of refluent water		X		X		X								X				
	distribution of finished product			X				X								X			

The relative environmental impact and significance level was evaluated in the following conditions:

- *normal operating conditions* are those in which no production phase determines specific situations in the site, in productive context and outdoor activities connected with them. Normal conditions are, therefore, those of ordinary administration;
- *unexpected conditions* and possible emergency or abnormal situations are those situations where you cannot do further predictions and, at the same time, these situations can change environmental aspects, already seen under normal conditions.

In relation to each of environmental aspects related to the company activity, a level of significance according to criteria defined below has been defined.

An impact is defined not significant, when medium-long term consequences of contaminant factor on environment, are not to be held into serious consideration, since quality and/or quantity of pollutants. Vice versa, a significant impact is defined when immediate medium-long term consequences of contaminant factors on the environment, are to be held into serious consideration since quality and/or quantity of pollutants .

Therefore, when all environmental aspects are identified, by the already mentioned environmental analysis, we will proceed to their significance evaluation. There is not, unfortunately, a defined or standard methodology. It is a free choice of a company that should find the best method suited to it. It is very important that a company chooses, even at this early stage, what methodology is the best suited its needs, in fact later, this assessment needs to be carried out every year. In this work, in order to evaluate the significance of each aspect/impact, we will take into account a methodology which refers to the known equation proposed and developed by Ehrlich, Holdren and Commoner in the early 1970 [95, 96, 97, 98], that is:

$$\boldsymbol{I} = \boldsymbol{P} \times \boldsymbol{A} \times \boldsymbol{T}$$

that states that the human impact (***I***) on the natural environment equals the product of population (***P***), affluence (***A***,that is theconsumption per capita) and technology (***T***, that is the environmental impact per consumption unit).

Sometimes, because of the difficulty in estimating *A* and *T,* per capita energy use is employed as a surrogate for their product [99]. Some equate *T* with impact per unit of economic activity [100], and for others T is a rather fuzzy category covering all sources of variation apart from population and affluence [101].

The impact equation was introduced in a paper by Ehrlich and Holdren in 1971 in the form:

$$\boldsymbol{I} = \boldsymbol{P} \times \boldsymbol{F}$$

where F is a function that measures per capita impact [102].

Following the simplified approach which is represented here, the terms of the equation of impact valuation are dimensionless. Values which refer to the conventional scale scores are also attributed to them. These values are in relation to the extent of pressure exerted by each term.

In our case, the parameters of the equation have the following meanings:

I= the significance of impact

P= degree of impact, depending on extension

A = frequency of environmental impact

T = importance of the aspect and its relative impact, considering possible law and values more or less near to the threshold value.

In order to have a significance of environmental aspects, in Table 15 there is a grid of assigning impact levels for extension (P), frequency (A) and size (T) parameters.

Table 15. Description of the terms of the impact equation, with the pertinent ranks [94].

Component of the original impact equation	Characteristic of the impact in this aprroach	Ranking	Range of the ranking	Specification
P Population	Extension	3	High	The interested area exceeds the farm site
		2	Medium	The interested area coincides with the farm site
		1	Not significant	The interested area is not significant
A Affluence	Frequency	3	High	Occurring at every working cycle
		2	Medium	Occurring at periodic frequency, for exemple, monthly
		1	Not significant	Rarely occurring
T Technology	Entity	3	High	Values are outside the standard limits
		2	Medium	Values are within the standard limits
		1	Not significant	Not subject to the current standards

Underlining that impact *I* is calculated by the relation I = P × A × T and taking into account the proposed parameters in Table 14, it is easy to identify that *I* will vary from a minimum of 1 (ie P = A = T = 1) to a maximum of 27 (ie P = A = T = 3) then, the values range of impact *I* can be grouped under three major categories (low, medium and high), as indicated inTable 16.

Table 16. Impact ranks for the adopted judgement ranges [94].

Numerical value of the impact	Judgement attributed to the impact
1-9	Low
10-18	Medium
19-27	High

In this Chapter, it is considered that all environmental aspects, subject to regulations, that exceed the limits set by regulations in force [27, 103], are considered to be significant environmental impacts. In environmental management system, significant impact will be taken into account.

However the detected elements, although not strictly significant, will still be taken into account, according to a scale of priorities, in order to improve the environmental performance of the organization anyway.

This simple evaluation process allow to define the significance of environmental aspects by a single numerical indicator *I*. In this way, the company can immediately realize any environmental aspects on which acting first following a scale of priorities, in order to improve their performance. At the same time the company realizes those aspect that can be faced later.

Tables 17, 18 and 19 show, in reference to individual activities at the site, the relevant aspects/impacts and the level of significance associated with normal and emergency conditions according to criteria discussed above, in particular the Table 17 refers to quarrying, while Tables 18 and 19 relate to operations carried out in the sawmill (separeted by step 1 and 2).

These matrices must be seen as a tool to establish prior objectives to be included in the environmental program.

Tables 17, 18 and 19 are a direct application of Table 14 and of the ranges of parameters contained in it. For instance, in the case of "accidental oil spillage on the soil" in quarry during cutting operations (see Table 17), you can attribute:

- to P the value 2, because the extent of impact, ie, the area affected by the impact, coincides with the farm site;
- to A the value 1, because frequency of the occurrence of environmental aspect is minimal, since it takes place only in case of accidents;
- to T the value 3, because values are outside the standard limits.

Table 17 let us infer the company, in relation to quarry activities, should pay special attention to these following issues, for which there is the highest rating of impact for:

- consumption of electric energy,
- production of special waste from scraps of cutting upstream blocks,
- dusts emission,
- emissions of gaseous pollutants,
- production of special waste from operations of squaring blocks.

Table 18 let us infer the company, in relation to sawmill activities (step 1), should pay special attention only to:

- production of dangerous waste from waste products relating to loom operations; in fact it is only forth is environmental aspect that it is pointed out a high impact.

Table 19 let us infer the company, in relation to sawmill activities (step 2) should pay particular attention to issues for which there is the highest rating of impact, namely:

- consumption of electric energy,
- production of special waste (waste processing, grinding wheel sand sludge),

both coming from polishing phase of marble slabs and tiles.

Table 17. Environmental aspects/impacts and their significance for quarry [94].

QUARRY							
Activity	**Operating conditions**	**Environmental aspect**	**Environmental impact**	**Significance (aspect/impact)**			
				P	***A***	*T*	***I***
1. Cutting and widening of the cut of first material	N	electricity consumption	depletion of natural resources	3	3	3	**27**
	N	water consumption	depletion of natural resources	2	3	3	18
	N	production of special waste (waste from processing)	any abandonment of waste in environment because of an incorrect management resulting in occupation of soil	3	3	3	**27**
	N	noise	noise pollution	2	3	3	18
	N	water discharge	groundwater pollution	3	3	2	18
	E	accidental spillage of oil on the soil	contamination of soil and subsoil and groundwater	2	1	3	6
	A	accidental spillage of oil on the soil due to maintenance	contamination of soil and subsoil contamination of groundwater	2	1	3	6
	N	dusts	atmosphere pollution	3	3	3	**27**
	N	gaseous emissions in atm	atmosphere pollution	3	3	3	**27**
	N	vibration	any soil instability	2	3	1	6
2. Squaring	N	water consumption	depletion of natural resources	2	3	3	18
	N	electricity consumption	depletion of natural resources	3	3	3	**27**
	N	fuel consumption	air pollution (exhaust gas) and depletion of natural resources	2	3	2	12
	N	production special waste (scraps)	any abandonment of waste in environment because of an incorrect management resulting in the occupation of soil	3	3	3	**27**
	N	noise	noise pollution	2	3	3	18
	E	accidental spillage of oil on soil	contamination of soil and subsoil and groundwater	2	1	3	6
	A	accidental spillage of oil on soil due to maintenance	contamination of soil and subsoil and groundwater	2	1	3	6
	N	water discharge	groundwater pollution	3	3	2	18
3. Transport to sawmill	**N**	fuel consumption	atmosphere pollution (exhaust gas) and depletion of natural resources	3	3	2	18
	E	accidental spillage of oil or diesel fuel on soil	contamination of soil and subsoil and groundwater	2	1	3	6
	N	dusts	atmosphere pollution	3	3	2	18
	A	accidental spillage of oil on soil due to maintenance	contamination of soil and subsoil and possible contamination of groundwater	2	1	3	6

LEGEND		
N = normal operating conditions	*P* = degree of impact	1 - 9: reduced impact
E = emergency situations	*A* = frequency of impact	10 - 18: average impact
I = significance of impact	*T* = importance of impact	**19 - 27**: high impact

Table 18. Environmental aspects/impacts and their significance for sawmill, step 1 [94].

SAWMILL (Phase 1)							
Activity	**Operating conditions**	**Environmental aspect**	**Environmental impact**	**Significance (aspect/impact)**			
				P	***A***	*T*	***I***
1. Storage	**N**	electricity consumption	depletion of natural resources	3	3	2	18
	N	noise	noise pollution	2	3	3	18
	E	accidental spillage of oil on soil	contamination of soil	2	1	3	6
	A	accidental spillage of oil on the soil due to maintenance	contamination of soil and subsoil	2	1	3	6
2. Operations loom	**N**	water consumption	depletion of natural resources	1	3	2	6
	N	electricity consumption	depletion of natural resources	3	3	2	18
	N	production special waste (scraps)	any abandonment of waste in environment because of an incorrect management resulting in occupation of soil	3	3	3	**27**
	N	noise	noise pollution	2	3	3	18
	N	dusts	atmosphere pollution	1	3	2	6
	N	water discharge	pollution of surface and groundwater	1	3	2	6
	A	accidental spillage of oil on the soil due to maintenance	contamination of soil and subsoil	2	1	3	6
3. Resin tapping	**N**	use of dangerous substances	contamination of soil	1	3	3	9
	N	odour	atmosphere pollution	3	3	2	18
	N	production of special waste	any spillage of waste in environment because of an incorrect management	3	3	2	18
4. Transportation to sawmill (step 2)	**N**	fuel consumption	atmosphere pollution (exhaust gas) and depletion of natural resources	2	3	1	6
	N	dusts	atmosphere pollution	2	3	1	6
	A	accidental spillage of oil on the soil due to maintenance	contamination of soil and subsoil and groundwater	2	1	3	6
5. Different office activities	**N**	water consumption	depletion of natural resources	1	3	3	9
	N	electricity consumption	depletion of natural resources	1	3	1	3
	N	production of urban waste (paper, etc.) and production of special waste (toner cartridges)	any spillage of waste in environment because of an incorrect management	2	2	3	12
	N	water discharge (pit imoff)	groundwater pollution	2	3	2	12
6. Wastewater treatment	**N**	waste	any abandonment of waste in environment because of an incorrect management resulting in occupation of soil	1	3	2	6
	A	spillage of contaminated water (maintenance)	groundwater pollution	3	1	2	6
	E	spillage of contaminated water	groundwater pollution	3	1	3	9

LEGEND		
N = normal operating conditions	*P* = degree of impact	1 - 9: reduced impact
E = emergency situations	*A* = frequency of impact	10 - 18: average impact
I = significance of impact	*T* = importance of impact	**19 - 27**: high impact

Table 19. Environmental aspects/impacts and their significance for sawmill, step 2 [94].

SAWMILL (Phase 2)							
Activity	**Operating conditions**	**Environmental aspect**	**Environmental impact**	**Significance (aspect/impact)**			
				P	***A***	*T*	***I***
1. Resin tapping	**N**	use of dangerous substances	soil contamination	1	3	3	9
	N	odour	atmospheric pollution	3	3	2	18
	E	production special waste	any spillage of waste in environment because of an incorrect management	3	3	2	18
2. Polishing	**N**	water consumption	depletion of natural resources	1	3	2	6
	N	electricity consumption	depletion of natural resources	3	3	3	**27**
	N	production of special waste (waste processing, grinding wheels, sludge)	any spillage of waste in environment because of an incorrect management	3	3	3	**27**
	N	noise	noise pollution	2	3	3	18
	N	water discharge	pollution of surface and groundwater	1	3	2	6
	E	accidental spillage of oil on soil	soil contamination	2	1	3	6
	A	accidental spillage of oil on the soil due to maintenance	contamination of soil and subsoil	2	1	3	6
3. Distribution of finished product	N	fuel consumption	atmosphere pollution (exhaust gas) and depletion of natural resources	3	3	1	9
4. Wastewater treatment	**N**	waste	any spillage of waste in environment because of an incorrect management resulting in occupation of soil	1	3	3	9
	A	spillage of contaminated water (maintenance)	groundwater pollution	3	1	2	6
	E	spillage of contaminated water (maintenance)	groundwater pollution	3	1	3	9

LEGEND		
N = normal operating conditions	*P* = degree of impact	1 - 9: reduced impact
E = emergency situations	*A* = frequency of impact	10 - 18: average impact
I = significance of impact	*T* = importance of impact	**19 - 27**: high impact

3 Conclusions

This work presented here comes from the desire of companies of Italian marble beds in Custonaci (TP) to undertake a process of enhancing environmental performance of their life-cycle, also in response to the European Union and the national government requests. As regard this point, it is important to outline that environmental performance of products are becoming a strong element of communication toward outside, giving greater value and, therefore, more trade attraction to the product. The desire of companies to undertake an environmental improvement of their production chain is based on these considerations.

Then, in reference to some companies in the already mentioned area, in this paper, after pointing out the importance of assessing the significance of impacts related to production cycle of the "Perlato di Sicilia", we proceeded according to this following study scheme:

- identification (through the creation of a correlation matrix, see Table 14) of environmental aspects involved in every stage of production (differentiating, always, quarry processes from sawmill processes);
- identification (through special cards, Tables 17, 18 and 19) of environmental impacts related to previously selected aspects;
- calculation of the significance of each impact, through the application of the known equation ($I = P \times A \times T$). These were reported in the schedules about resource use and environmental impacts resulting from the production process of marble mentioned above (see Tables 17, 18 and 19).

This tool can be used to identify the business best solutions in relation to impacts on environment made by the work chain.

Because of their relative ease of use, the methods of analysis presented here can apply as self-assessment tools for companies who intend to pursue a virtuous environmental policy, giving in this way a particular added value to a material for construction industry which is currently suffering of high energy costs and marked polluting emissions. This study has showed, however, awareness that in mining of marble there are very wide margins of improvement, both in terms of saving energy resources and in limiting of pressure in environment exerted by working process of this important economic sector. Therefore, in future analysis appropriate solutions will be searched in order to reduce energy consumption and waste producted in different phases of marble working cycle.

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SECTION 2: The granite

Chapter 1

Environmental management of granite slab production

1 Introduction

Building sector is considered as a key in Spanish economic development, as a major player in Spanish economy and a whole, and the effect that causes drag on the rest of economic sectors, exercising a powerful effect on the economic activity and the creation of direct and indirect employment [1].

In particular, the natural stone sector falls within what is called “modern mining”, it is a relatively young and modern sector (as result of different industries), but it already has a great economic significance, as it employs directly more than half a million people worldwide and, above all, because it offers many opportunities for growth in future; this is because natural stone is a material (because of its quality) day by day more appreciated and used for covering, flooring, funeral, crafts, decorating and building in general. In this sector, the granite industry is the only industry which has been more dynamic in recent years and has a huge potential for development [2].

In particular, this sector is considered one of the most productive in the Galicia region (see Paragraph 2).

The guidelines established by the European Commission (EC) for awarding an eco-label to hard coverings [3, 4] to stimulate “ecological behavior” among producers and consumers are therefore of great importance to the granite industry. The provision of complete Life Cycle Inventories (LCI) is an essential prerequisite for to facilitate the comprehensive characterization of products environmental performance and an accurate identification of hot-spots for environmental improvement. A complete cradle-to-gate LCI of granite production has recently been developed by Mendoza et al. [5]. The LCI dataset indicates that granite sawing is the most environmentally relevant unit process in the entire production chain, accounting for 54% (15.4 kWh) of the chain’s electricity demand, 35% (34.7 l) of its water consumption, 77% (77.1 kg) of its material requirements and 81% (25.1 kg) of granite waste generation per net square meter of polished granite tile production.

So, in this Chapter focuses on analysing the potential environmental improvements achievable at the sawing unit process, and subsequently at the level of the processing stage and at the entire granite production chain, by promoting a technological pathway towards the use of diamond multi-wire saws in substitution of traditional gangsaws for granite slabs production. Also, given that cooling water is an indispensable input and granite sludge an inevitable output of granite sawing, whatever the technology applied, the paper integrates the assessment of the potential for rainwater harvesting for industrial use to limit the consumption and potential pollution of groundwater reservoirs whereas a review of potential alternatives to promote material recovery of granite sludge into by-products complete the research.

The promotion of cleaner sawing technologies which contribute to maximize the economic output at a minimum environmental cost is essential for improving the competitiveness of the granite industry.

2 The stone industry in Galicia

Granite is an igneous compact stone containing major mineral components of quartz, feldspar and mica. Its natural hardness, durability and aesthetics make granite a traditional high-quality material used widely in construction, where it competes with a variety of alternatives for different applications, especially indoor and outdoor cladding and paving, masonry and decoration [6].

In Spain there are about 645 mining companies; these, 645 companies extract quarry materials including granite, marble, calcareous stones, sandstones and slate, although excluding ashlar stone used for remodeling works, building refurbishment and restoration. The extraction of marble and calcareous stone of ornamental quality totaled 5.659.624 tonnes and accounted for 66% of total natural stone production. This is followed by granite extraction with 1.948.497 tonnes (23% of the total) and slate extraction with 963.371 tonnes (11%), accounting for 100% of the sector [7].

Galicia, because of its geological characteristics, has the greatest potential of ornamental stone deposits in the country, supplying the most important world markets, either raw or in processed product. In Galician Community, Pontevedra is the most important province in this sector, excelling Vigo and Porriño as leading centres of extraction and processing. Quarries in other two centres in provinces of Lugo and Ourense are also important, although they are at a lower level [8].

In particular, activities of granite in Galicia represent a significant part of Galicia's dynamic business, hence, a group of companies is made around this raw material, creating a cluster, that is to say a group of companies, from the same area or sector which are intertwined with others that they support and that are directly related to the core of the group referenced [8].

In addition, in Galicia there is the greatest number of companies engaged in the extraction (278), Galicia is followed by Andalucia, Castilla, León and Valencia. The Valencia Region accounts for 41% of export volume of natural stone, followed by Galicia, with 31%, Castilla, León and Murcia (both 8%) and Catalonia, Andalucia (both 4%) complete the ranking [1].

Considering the foreign trade of rough granite from different Spanish regions, Galicia monopolizes domestic raw granite. Specifically, 62% of the volume and 77% of the monetary value exported from Galicia. Among the provinces, the ranking is headed by Pontevedra which exports 90% of weight in comparison with the national total and 75% of monetary value. As rough granite, Galicia is the first region for exports with the 71% of volume and 59% of monetary value. Among provinces, Pontevedra ranks first with 68% of weight of the national total and 56% of monetary value [9].

3 Analysis and results

Fig. 1 shows the case scenario under assessment, from which the study's methodological framework and the presentation and discussion of the results are articulated.

In particular, the granite production chain is divided into the unit processes of quarrying (in which a granite bench is successively subdivided until commercial granite blocks are obtained), sawing (a commercial granite block is cut into large granite slabs), finishing (surface treatment is performed to create a specific stone texture) and cutting (granite slabs are cut into suitably sized granite tiles for construction).

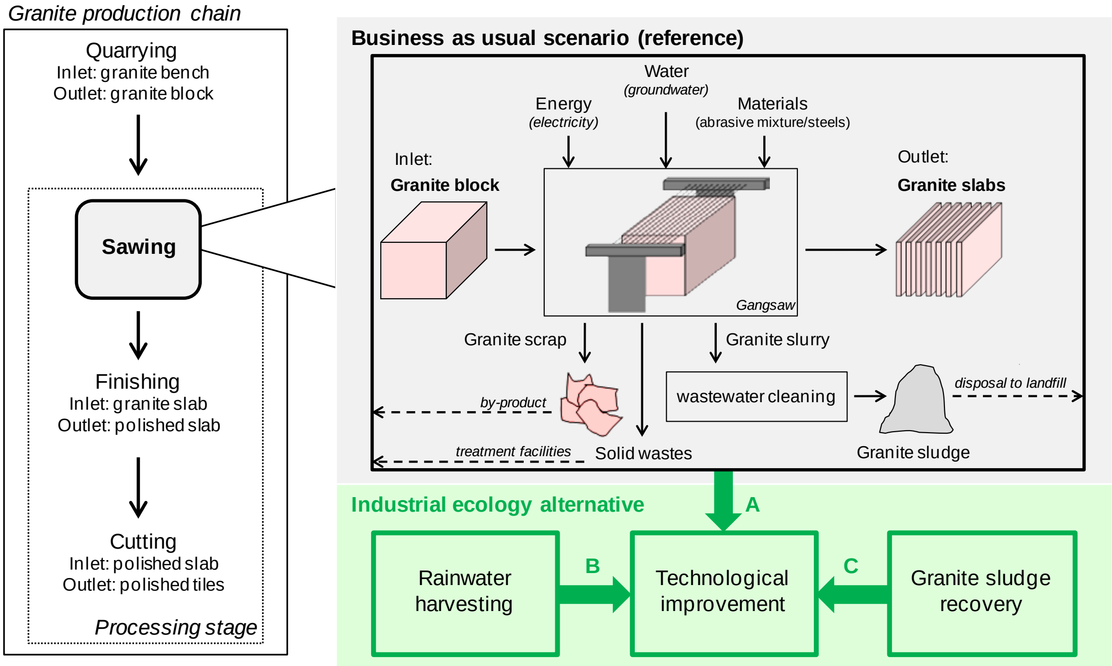

Fig. 1. Case scenario and system boundaries under assessment.

3.1 LCI of granite slab production

The first methodological step involves compiling and calculating the inputs and outputs related to the production of granite slabs using optimized sawing technologies. The analyzed technologies consist of an optimized multi-blade gangsaw with 180 steel blades (MBGS 180), a diamond multi-wire saw with 35 wires (DMWS 35) and a diamond multi-wire saw with 100 wires (DMWS 100). The sawing technologies under consideration have been proposed by experts from processing facilities that participated in the research providing technical support. The sawing technologies being considered are modern, competitive and representative. The applied procedure to develop the LCI dataset of each sawing technology is based on the requirements and guidelines specified by ISO 14044 [10]. The environmental characterization of sawing technologies is addressed only with life cycle inventory analysis. The functional unit (FU) is defined as the production of one square meter of 2–cm-thick granite slabs, which is the thickness that is most commonly produced by processing plants. LCI data from Mendoza et al. [5] are used as a reference to determine the potential for environmental improvement at the processing stage level and the entire granite production chain by promoting the optimization of sawing technologies.

To provide a complete overview of the magnitude of energy, water and ancillary material requirements and granite waste generation related to the operation of the MBGS 180, DMWS 35 and DMWS 100 technologies, Fig. 2 summarizes the LCI results for a sawn granite block.

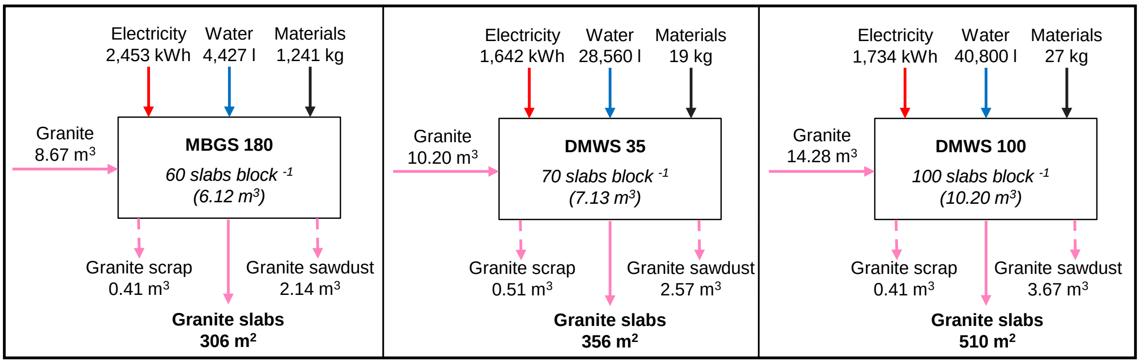

Fig. 2. Energy, water and material requirements, granite waste generation and net granite slab production per block sawn using MBGS and DMWS technologies.

All sawing technologies are electrically powered. Nevertheless, minor diesel inputs are also required to address the on-site transportation of granite slabs and scrap. Approximately 15.6 MJ of diesel are consumed per m^3 of granite transported. Regarding water inputs, it is important to differentiate between water use and water consumption. The water utilized in processing facilities circulates through a closed-loop cleaning process. The water use corresponds to the flow of cooling water required during operation, while the water consumption corresponds to the required additions supplied to the closed-loop circuit to compensate for water losses in the form of evaporation and moisture content in the granite sludge generated after wastewater cleaning.

Approximately 14.167 liters of water are used per granite block sawn using the MBGS 180, whereas a significantly higher amount of water is used by the DMWS 35 and DMWS 100, corresponding to 190.400 liters and 272.000 liters, respectively. The water consumption (water losses) of each sawing technology corresponds to approximately 15% of the total water used during the operation. The MBGS 180 consumes an extra quantity of approximately 2.302 liters $block^{-1}$ due to the addition of the abrasive mixture required for cutting stone. In terms of ancillary material requirements, they represent a minor input compared to the magnitudes of the energy and water inputs, especially for the DMWS technologies, in which these materials are almost negligible compared to the net production of granite slabs per sawn block. The resource efficiency of the sawing technologies accounts for approximately 70%. Table 1 presents the complete LCI dataset allocated per square meter of granite slab production for each sawing technology. The LCI data related to the MBGS 180 are used as a reference to analyze the potential for environmental improvement by using the DMWS technology instead.

Table 1. LCI dataset per square meter of granite slab production for each sawing technology.

INPUT			**MBGS 180**	ref.	**DMWS 35**	dif. %	**DMWS 100**	dif. %
ENERGY		Electricity, low voltage (kWh)	8.02E+00	-	4.61E+00	- 43	3.40E+00	- 58
		Diesel (MJ)	3.33E-01	-	3.34E-01	+ 0.5	3.24E-01	- 3
WATER		Cooling water (kg)	1.45E+01	-	8.02E+01	+ 454	8.00E+01	+ 453
MATERIALS	*Cutting tools*	Steel (kg)	1.28E+00	-	3.39E-02	- 97	3.36E-02	- 97
	Abrasive admixture	Steel grit (kg)	1.76E+00	-	0.00E+00	- 100	0.00E+00	- 100
		Hydrated lime (kg)	9.10E-01	-	0.00E+00	- 100	0.00E+00	- 100
	Wastewater cleaning agents	Coagulants and flocculants (kg)	9.36E-03	-	3.40E-03	- 64	3.41E-03	- 64
		CO_2 (kg)	8.14E-02	-	0.00E+00	- 100	0.00E+00	- 100
	Maintenance	Oil and grease (kg)	1.15E-02	-	1.67E-02	+ 45	1.67E-02	+ 45
GRANITE		Gross granite (kg)	7.65E+01	-	7.73E+01	+ 1	7.56E+01	+ 1
OUTPUT			**MBGS 180**	ref.	**DMWS 35**	dif. **%**	**DMWS 100**	dif. %
GRANITE		**Granite slab (kg/m²):** *product*	**5.40E+01**	-	**5.40E+01**	0	**5.40E+01**	0
		Granite scrap (kg): *by-product*	3.60E+00	-	3.87E+00	+ 7	2.16E+00	- 40
		Granite sawdust (kg) – *emitted to air*	9.45E-01	-	9.72E-01	+ 3	9.72E-01	+ 3
		Granite sludge (kg) – *waste*	3.35E+01	-	3.05E+01	- 9	3.05E+01	- 9
WATER		Water to air (kg) – *evaporated*	2.17E+00	-	6.81E+01	+ 3040	6.80E+01	+ 3033
OTHER WASTES		Steel scrap (kg)	8.10E-01	-	3.39E-02	- 96	3.36E-02	- 96
		Residual oil (kg)	6.51E-03	-	1.00E-02	+ 54	1.00E-02	+ 54

Energy DMWS 100 represents the best technological alternative to reducing energy consumption. Approximately 4.6 kWh of electricity can be saved per sawn square meter compared to the MBGS 180 and approximately 3.4 kWh m^{-2} are saved if the DMWS 35 is used instead. Although the total power required by the DMWS 100 is a factor of 1.8 and 2.1 higher than the power required by the DMWS 35 and MBGS 180, respectively, sawing an entire granite block into slabs using the DMWS 100 takes less than 7 hours, whereas it takes twice that long with the DMWS 35 and more than two days when using the MBGS 180.

Cooling water The DMWS 100 and DMWS 35 technologies consume the same amount of water per net unit of production, which is 66 liters m^{-2} higher than water consumed by the MBGS 180. In terms of water use, approximately 534 liters m^{-2} are demanded by the DMWS machines, whereas only 46 liters m^{-2} (-91%) are required by the MBGS 180.

Each diamond wire requires a water flow of 400 liters h^{-1}, of which 60 liters h^{-1} are consumed. As diamond steel wires offer a significantly higher cutting speed than steel blades (0.75 m^2 h^{-1} vs. 0.10 m^2 h^{-1}), they require a higher amount of water to dissipate the heat generated and facilitate stone cutting.

Ancillary materials The total material inputs related to the DMWS technologies are almost negligible (0.1 kg m^{-2}) compared to that of the MBGS 180 (4.1 kg m^{-2}). It is relevant to note that the abrasive mixture required by the MBGS 180 accounts for 66% of its material requirements. With regard to the DMWS technologies, because no abrasive mixture is required in production (only cooling water), the input of stainless steel (for diamond wires) is the only material directly required in production. As the service life of diamond wires is approximately three times higher than that of steel blades, the consumption of stainless steel per unit of product is much smaller than the MBGS 180's carbon steel requirements.

Wastes A quarter of the amount of raw granite entering the sawing process is wasted as sawdust (19 kg m^{-2}). Approximately 5% of this granite sawdust is considered emitted to the air and the remainder is removed by the stream of cooling water, which is subsequently subjected to a cleaning process resulting in granite sludge. Descriptive information on the wastewater cleaning process can be found in Mendoza et al. [5]. The granite sludge produced when using the MBGS 180 is composed of worn steel grit and lime, steel fines from the erosion of the cutting blades, granite fines and cleaning water agents. The granite sludge generated by the DMWS technology is composed only of granite fines and the elements used for wastewater cleaning. The stainless steel of the diamond wires leaves the unit process in the form of steel scrap. Granite sludge has a moisture content of 35% - 40% by weight. In this way, approximately 85% of the water consumption related to the MBGS 180 leaves the unit process in the form of moisture content in the granite sludge, while the remaining 15% leaves the system as evaporation. The opposite occurs for water consumption related to the DMWS technologies. A proportion (≈ 40%) of the oil and grease required for maintenance is considered lost through leaks in machinery.

According to Mendoza et al. [5], every polished granite slab (measuring 5.1 m^2 $slab^{-1}$) can be cut into 16 granite tiles of 60 cm x 40 cm that account for 3.8 net m^2. In this way, the LCI data presented in Table 1 can be allocated per square meter of polished tiles by applying a factor of≈ 1.33. Figures 3, 4 and 5 show the variations in energy, water and material consumption per square meter of granite produced in the sawing unit process, during the processing stage and over the entire production chain when using the MBGS 180, DMWS 35 and DMWS 100 technologies as substitutes forventional gangsaw technology mix (the reference technology). The energy demand is represented in terms of electricity consumption. Diesel requirements and granite waste generation are excluded from the scope because they are unaffected by the substitution in sawing technology.

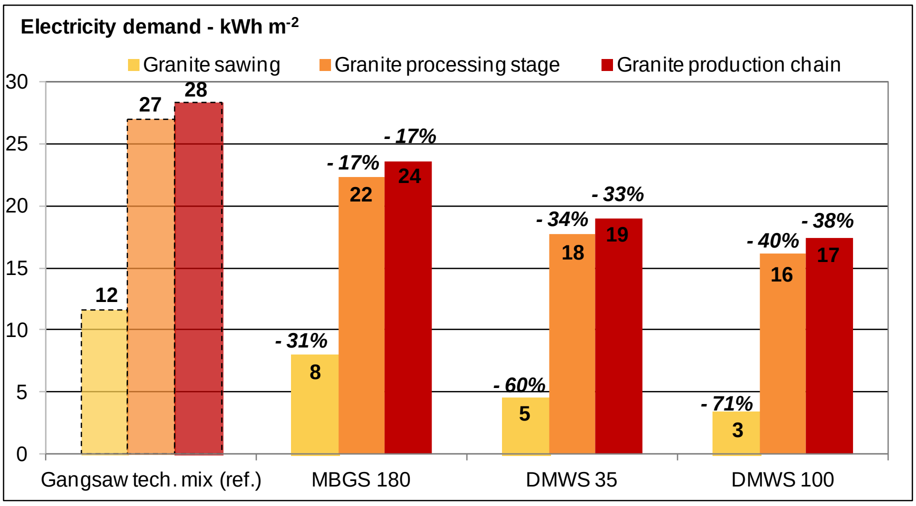

Fig. 3. Variability in energy consumption per square meter of granite production when using the MBGS 180, DMWS 35 and DMWS 100 technologies for granite sawing.

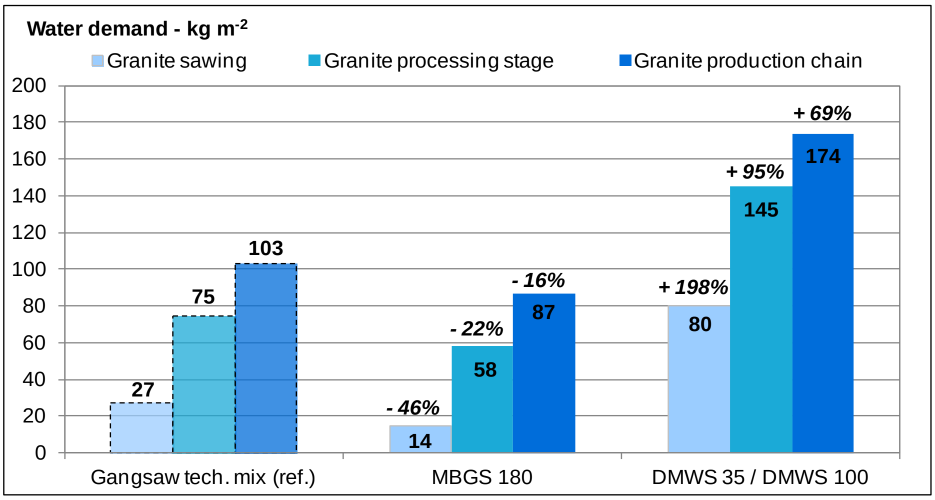

Fig. 4. Variability in water consumption per square meter of granite production when using the MBGS 180, DMWS 35 and DMWS 100 technologies for granite sawing.

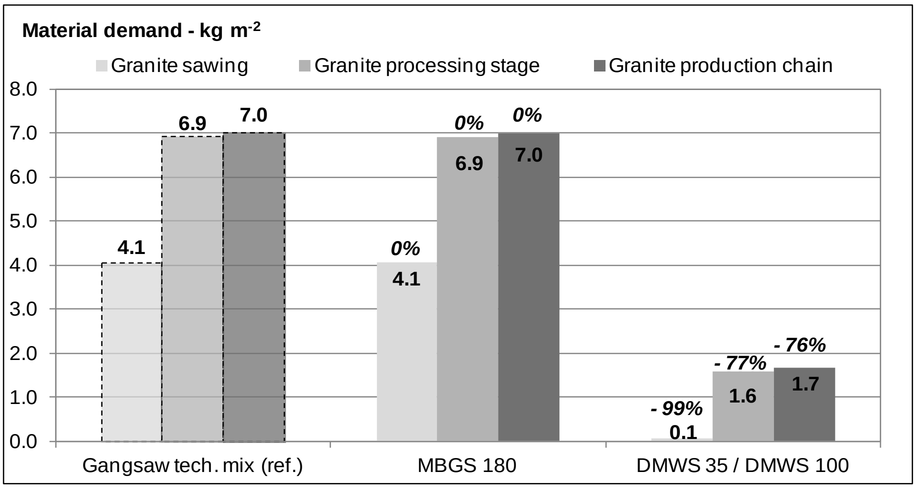

Fig. 5. Variability in material consumption per square meter of granite production when using the MBGS 180, DMWS 35 and DMWS 100 technologies for granite sawing.

The results indicate that the use of optimized gangsaw technology such as the MBGS 180 contributes to generating over 15% of the electricity and water savings in the entire granite production chain compared to the application of a conventional gangsaw mix for granite slab production. The material requirements, however, are not appreciably affected. The DMWS technologies stand out as the best solution for generating significant energy and material savings in the granite production chain. The total electricity demand related to the production of polished granite tiles can be reduced from 30% (9 kWh m^{-2}) to 40% (11 kWh m^{-2}). The total ancillary materials requirements are reduced by three-quarters (-5.3 kg m^{-2}). As the material requirements are reduced, solid waste generation is also reduced. Nevertheless, the water consumption over the entire granite production chain increases greatly, by almost 70% (+71 l m^{-2}). The LCI results demonstrate that DMWS technologies can contribute to generating relevant energy and material savings, although at a significantly higher water cost and with no improvement in resource efficiency. The DMWS technologies cannot, therefore, be considered a cleaner production alternative overall. Complementary water and granite waste management alternatives should be jointly implemented to address all of the relevant environmental aspects from granite sawing and truly contribute to cleaner production.

3.2 Rain water recycling in the granite sawing process

The second methodological step analyzes the potential for rainwater harvesting (RWH) to satisfy the daily water consumption of sawing technologies, as a substitute groundwater and tap water inputs. The RWH potential is determined by applying the software Plugrisost® [11], which is an analytical simulation model based on system dynamics that facilitates the technical, economic and environmental evaluation of rainwater supply systems. The software, although developed primarily to analyze RWH potential at different urban scales, integrates the assessment of rainwater supply for non-residential large surfaces such as industrial facilities or areas. The sizing of rainwater storage tanks is an essential factor to be considered in the analysis of the technical, economic and environmental feasibility of RWH systems [12, 13, 14]. The optimal sizing of rainwater storage tanks is a function of rainwater catchment and rainwater demand. Rainwater catchment, in turn, is a function of the useful catchment surfaces available (roofs and/or paved areas) and rainfall. A basic description of the analytical model has been presented in Gabarrell et al. [15]. Overall, 30 scenarios are modeled to determine the optimum rainwater storage tank size. The criteria applied are meant to achieve a rainwater supply equivalent to at least 50% of the daily water requirements of sawing technologies.

The average results from the data are summarized in Table 2. The results from Table 2 indicate that, depending on the extension of the industrial surface dedicated to rainwater catchment, the daily water consumption by the sawing technologies could be fully satisfied in both the Atlantic and Mediterranean climatic geographies by using rainwater. Thus, RWH could account for a complete substitution of groundwater and tap water inputs. However, not all available rainwater can be harvested. RWH is highly dependent on the daily dynamic between rainwater availability and storage tank sizing.

Table 3 shows the optimal size (volume) of rainwater tanks that would satisfy half of the daily average water consumption by sawing technologies.

Table 2. Potential daily rainwater availability for use in granite sawing.

Potential daily rainwater availability		Atlantic climate geography	Mediterranean climate geography
RAINFALL	Precipitation (l m^{-2} $year^{-1}$)	1,951	614
	Rainy days (days $year^{-1}$)	149	81
	Frequency of precipitation (days $year^{-1}$)	2.4	4.5
	Average rainfall per rainy day (l m^{-2})	13.1	7.6
	Average rainfall per day (l m^{-2})	5.3	1.7
RAINWATER CATCHMENT	Sawmill roof (liters/2,000 m^2)	8,658	2,724
	Industrial plot (liters/28,500 m^2)	123,380	38,812
	Industrial area (liters/574,000 m^2)	2,485,343	781,828
WATER CONSUMPTION	MBGS 180 (liters day^{-1})	6,000	
	DMWS 35 – DMWS 35* (liters day^{-1})	42,840 – 28,560(*)	
	DMWS 100 – DMWS 100* (liters day^{-1})	122,400 – 40,800(*)	
COVERAGE OF WATER CONSUMPTION USING RAINWATER	MBGS 180 (min % to max %)	100	45 to 100
	DMWS 35 – DMWS 35* (min % to max %)	20 to 100 – 30 to 100(*)	6 to 100 – 10 to 100(*)
	DMWS 100 – DMWS 100* (min % to max %)	7 to 100 – 20 to 100(*)	2 to 100 – 7 to 100(*)

NOTE: (*) considers one daily sawing stage.

The results presented in Table 3 provide a complementary perception of the water intensity of sawing technologies while indicating the optimum size of the rainwater tanks required to supply at least 3.000 liters for the MBGS 180, 21.420 liters for the DMWS 35 and 61.200 liters for the DMWS 100 technologies (or 14.280 liters for the DMWS 35 and 20,400 liters for the DMWS 100, if both are used for one sawing stage per day).

Table 3. Optimal rainwater tank size required to satisfy approximately 50% of the daily water consumption by the sawing technologies.

Optimum rainwater tank size		**MBGS 180**		**DMWS 35**		**DMWS 100**		**DMWS 35***		**DMWS 100***	
CATCHMENT SURFACE	Sawmill roof	25 m^3	$\geq$ 40 m^3 (30%)	$\geq$ 50 m^3 (20%)	$\geq$ 50 m^3 (5%)	$\geq$ 50 m^3 (7%)	$\geq$ 50 m^3 (2%)	> 50 m^3 (30%)	$\geq$ 50 m^3 (10%)	> 50 m^3 (20%)	$\geq$ 50 m^3 (7%)
	Industrial plot	15 m^3	30 m^3	150 m^3	500 m^3	700 m^3	> 200 m^3 (25%)	100 m^3	250 m^3	150 m^3	450 m^3
	Industrial area	10 m^3	25 m^3	100 m^3	200 m^3	300 m^3	700 m^3	50 m^3	150 m^3	100 m^3	200 m^3
CLIMATE		A	M	A	M	A	M	A	M	A	M

NOTE: (*) considers one daily sawing stage, (A) is the Atlantic climate, (M) is the Mediterranean climate and red numbers refer to the maximum possible RWH potential.

Higher water consumption by the sawing technologies requires a larger RWH system (in terms of catchment surface and tank size). Given that granite sawing is a highly water-intensive unit process, the use of the sawmill roof as a rainwater catchment surface would be not sufficient to meet the 50% goal for daily rainwater supply. In this case, the implementation of a rainwater tank with 25 m^3 of storage capacity would be enough to satisfy half of the daily water requirements. If granite sawing is addressed in a Mediterranean climate, a maximum of 30% (1.800 liters) of the daily water consumption will be satisfied by supplying rainwater stored in a 40 m^3 tank. The implementation of larger tanks would not contribute to any relevant increase in RWH as the relationship between rainfall, catchment surface and water demand would not change. In the case of DMWS technologies used for 24 h/day in an Atlantic climate geography, the implementation of 50-m^3 rainwater tanks would satisfy a maximum of 20% (8.568 liters) of the DMWS 35's daily water requirement and 7% (same amount) of the DMWS 100's requirement. In Mediterranean climate geographies, the same rainwater tank would supply only 5% (2.142 liters) and 2% (2.448 liters) of the daily water consumption by the DMWS 35 and DMWS 100, respectively. Any increase in tank size would generate equivalent RWH values. If the DMWS technologies were used only to address one sawing stage per day, the share of daily water consumption satisfied by using rainwater stored in a 50-m^3 tank would increase. However, it would not correspond to an increased amount of harvested rainwater. The water depends on the daily dynamics regarding rainwater availability and demand according to tank size. In this case, the RWH results indicate that this size of rainwater storage tank offers higher performance when the daily water requirements of the sawing technologies are increased. It is worth noting that, given the high water intensity of these sawing technologies, the satisfaction of a small share of daily water consumption using harvested rainwater would be a major achievement in terms of groundwater conservation and pollution prevention. If the industrial surface dedicated to rainwater catchment increases, there will be more rainwater available for granite sawing in both the Atlantic and Mediterranean climatic geographies. The RWH results indicate the potential to satisfy 50% of the daily water consumption by sawing technologies if the entire built surface related to the industrial plot or industrial area is used for rainwater catchment. Larger rainfall and catchment surfaces correspond to a reduced rainwater storage tank size. In these cases, it is possible to achieve higher RWH values by increasing the volume of the rainwater storage tanks. Nevertheless, the final selection of an optimal RWH system design will depend on the economic and environmental performance of rainwater infrastructure requirements compared to conventional water supply systems.

3.3 Granite sludge material recovery

The last methodological step consists of a comprehensive review of scientific literature in which the potential for the material recovery of granite sludge is analyzed. The information provided is aimed at being useful for hypothesizing and scheduling the promotion of industrial synergies and symbiosis that could contribute to a major systematic material recovery of granite sludge and significant economies in joint environmental management.

Granite sludge (GS) is a fine-grained, low-plasticity inert waste whose major chemical constituents consist of silica (SiO_2) and alumina (Al_2O_3), followed by iron oxide (Fe_2O_3), lime (CaO) and alkaline oxides (K_2O and Na_2O) and, to a lesser extent, MgO, TiO_2, MnO and P_2O_5. This composition is consistent with the lithology of the processed rock [16]. The sludge's lime and, especially, iron oxide content can relevantly increase when using MBGS technology due to the presence of the worn abrasive mixture. The most significant chemical constituents of GS are basic elements used by the construction industry, and can have useful applications in other economic activities. Fig. 6 provides an overview of potential current opportunities for promoting granite sludge recovery (GSR). The values expressed as wt% represent the percentage by weight of GS that can be use as an input in industrial batch compositions.

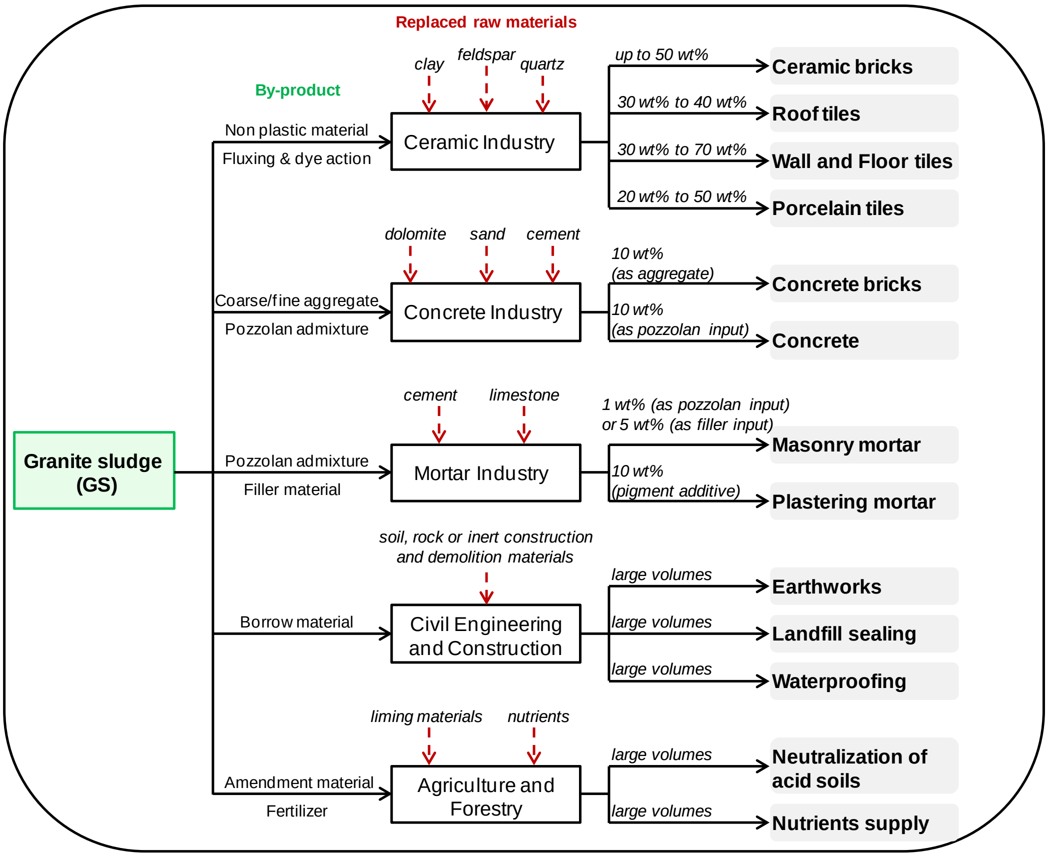

Fig. 6. Summary of potential alternatives for promoting the material recovery of granite sludge.

A large portion of the public scientific literature focused on the analysis of GS recovery practices has suggested that it can be widely used in the production of traditional clay-based materials [17, 18, 19, 20, 21, 22, 23, 24, 25, 26]. The raw materials used by the ceramic industry are divided into three basic categories given the distinctive roles they play during processing [20, 21]: plastic components (clays), fluxing components (feldspars) and inert components (sands). In particular, GS acts as a fluxing agent (source of alkaline oxides derived from feldspars and micaceous mineral content) that improves the sinterability of ceramic bodies (the former glassy phase) in a reaction with silica and alumina. In this way, GS can act as a complete or nearly complete substitute for feldspar and sand inputs and replace a portion of the clay mineral requirements. The iron content of GS is responsiblefor the reddish color of the ceramic bodies after firing. Consequently, the use of pigment additives (when required) can be reduced or even avoided. Researchers have also indicated that the use of GS could also contribute to important energy and water savings in ceramics production. The use of GS facilitates the drying stage through the decrease in working water and the linear shrinkage that can allow for the lower heating temperatures in drying and firing operations. Sintered ceramics using GS have similar or even superior technical properties to conventional products. According to Hamza et al. [27], large quantities of GS can be used to replace a proportional distribution of conventional coarse (dolomite) and fine (sand) aggregates in the production of concrete bricks that yield similar mechanical (compressive strength) and physical (density and absorption) properties to conventional materials. A key aspect highlighting the good performance of GS as an industrial by-product lies in its grain size distribution and filler effect. However, GS is also considered to possess useful pozzolanic activity based on its argillaceous mineral content. GS can therefore be used to replace a share of the cement inputs required to produce conventional concrete. A study by Pereira et al. [28] has indicated that an addition of 10 wt% facilitates better results, allowing for a share of the more expensive and environmentally relevant component used in concrete production to be substituted with this waste material. GS can also be applied in the production of cement-based mortars, giving them retained or improved mechanical properties compared to conventional formulations [29]. GS can account for 1 wt% of masonry mortar batch compositions when it replaces Portland cement, which is not negligible because this replacement is equivalent to a substitution of 10% of the total cement requirements. Rather, GS can serve as a filler material accounting for a maximum of 5 wt%, which is equivalent to the full replacement of limestone consumption. At the same time, GS can be used to fully replace the $CaCO_3$ filler inputs in the production of plastering mortar, with thecomplementary function of providing color to the mortar. Based on a complete geochemical and geotechnical characterization of granite sludge samples, Barrientos et al. [16] have stated that GS can be an appropriate, long- lasting application for earthworks, including earth fills and embankments, a sealing material for municipal waste landfills and a waterproof solution due to its low expansion and low permeability, good load-bearing capacity, acceptable shear strength, rapid settlement, negligible organic content and security offered when placed beside or beneath concrete structures. According to Silva et al. [30], GS can also be aneffective alternative to the traditional liming materials used in the acid neutralization of agricultural and forest soils, while also acting as a source of essential nutrients to plants.

GS provides a rapid release of basic cations (Ca, Mg, Na and K) exposed on the surface of soils with a predominance of siliceous substrates. Other potential applications of GS have involved using it in the manufacture of colored glass to replace silica sand inputs, or as a filler material in the molding of plastics such as PVC [31]. From an industrial ecology standpoint, Fig. 6 gives an overview of a range of opportunities that can be considered for the promotion of industrial synergies, understood as a unilateral exchange, in which one type of material or energy output from one industrial facility becomes an input for another industry (also called by-product synergy), and/or as industrial symbiosis, which involves different organizations becoming engaged in mutual exchanges that contribute to generating a collective benefit greater than the sum of the individual benefits that could be achieved by acting alone [32]. All the GSR practices presented in this case study are technically feasible. It is now essential to start promoting the analysis of the appropriateness of these industrial synergies for local and regional implementation based on the characterization of economically feasible potentials for environmental improvement. The promotion of a by-product synergy between the granite and ceramic industries is can be especially important. Menesez et al. [26] has suggested that ceramics industries in some regions could enable the material recovery of practically all the GS generated by stone processing facilities, without expensive investments in equipment or new technology, though transportation distances should be acceptable. Nevertheless, the Reference Document on Best Available Techniques (BAT) in the Ceramic Manufacturing Industry [4] has not integrated this type of by-product synergy as a BAT for cleaner production. Moreover, there is no such reference document focused on natural stone production. According to Chertow [32, 33], inter-firmnetworking could lead to significant economies in environmental management, related to by-product (re)use, utility and/or infrastructure sharing for the management of commonly used resources, information and expertise flows, the joint provision of services for meeting common ancillary activity needs across firms, well-planned joint transportation networks and regulatory enforcement.

4 Conclusions

This Chapter focuses on analyzing the potential for environmental improvement to the sawing unit process, and consequently at the processing stage level and over the entire granite production chain, by promoting a technological pathway for the adoption of diamond multi-wire saws as a substitute for the gangsaw technology used in the mass production of granite slabs. Given that cooling water is an indispensable requirement and granite sludge an inevitable outcome, regardless of the sawing technology applied, the study integrates an assessment of the potential for rainwater harvesting for industrial use and closes with a review of potential alternatives to promote the material recovery of granite sludge.

The LCI results demonstrated that the use of DMWS technology could contribute to generating significant energy and material savings, but at the expense of greater water consumption and no improvements in resource efficiency. Complementary water and granite waste management alternatives should be jointly implemented at the sawing stage to truly bring about cleaner granite production. The implementation of RWH systems represents an important water management alternative to actively alleviating consumption of groundwater and tap water sources. As the water consumed by MBGS technology is reduced, the implementation of RWH systems could be easier due to the reduction of rainwater infrastructure requirements. The chemical and technical properties of GS make it a suitable by-product for use in a range of different applications by replacing conventional raw materials. In this way, granite waste landfilling would be avoided while generating important environmental improvements in the receptor systems where it is used as an alternative raw material. RWH and GSR strategies are applicable to both DMWS and MBGS technologies. DMWS technology cannot be considered as a cleaner production alternative on its own. The water consumed by it will be always greater than that consumed by MBGS technology, even when implementing RWH systems, because these systems are not water-saving strategies. Due to the global preponderance of water shortages and changing policies regarding water usage, water saving is integral to achieving sustainable practices in any industry. Water consumption stands, therefore, as the keyenvironmental aspect to be considered when determining the best technological solution for cleaner granite production.

Based on the results obtained from the research, the selection of the best technological solution for achieving cleaner production of granite slabs will depend on the following three situations.

- If water saving strategies were implemented for DMWS technology that reduced its water requirements to below MBGS technology water consumption, then

DMWS technology would clearly stand out as the best option for achieving cleaner production of granite slabs and improving the environmental performance of the entire granite production chain.

- If water saving strategies were not applied, then the best technological solution for achieving cleaner production would depend on the way the environmental impact assessment of sawing technologies is addressed. The environmental decision would be highly conditioned by the impact characterization method applied to analyze the relationship between electricity and water consumption. In this way, geographical coverage is a key aspect that must be considered. If the environmental burden associated with electricity consumption is reduced due to a clean energy mix used in the production of electricity (i.e., low carbon) and the environmental impact of water consumption is high due to the importance given to water footprints andcontributions to water scarcity (especially in areas where it does not exist in abundance) then the environmental impacts of each sawing technology could be equivalent or favor MBGS technology (depending on the environmental burden related to ancillary material consumption).
- Our findings in terms of LCI analysis allow us to state that the best option for achieving cleaner production of granite slabs could be supported by sectorizing the use of sawing technologies by geographical region based on water availability. Sawing technologies would be complemented by RWH systems and the promotion of GS material recovery, including the implementation of water-saving or energy- saving strategies as needed (Fig. 7).

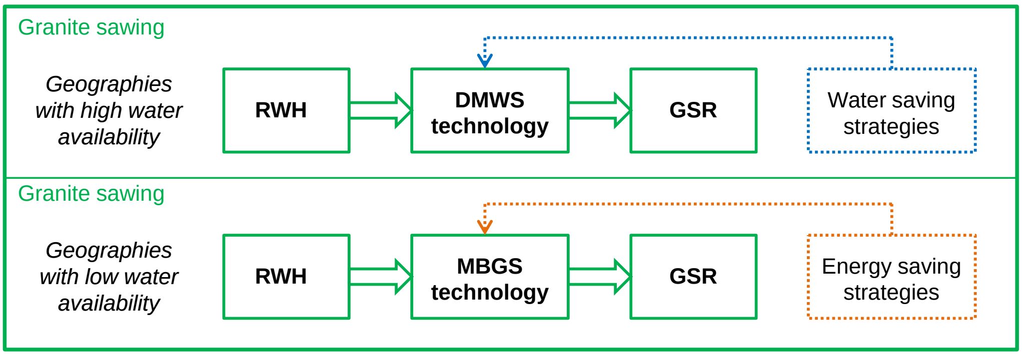

Fig. 7. Proposed cleaner production scenarios for the sawing of granite blocks into slabs

Water-saving strategies could take the form of an improvement to the process's cooling water spray systems to avoid excess water use, the recovery of evaporated water through the implementation of condensation systems or the recovery of water byimproving the GS drying process. Energy-saving strategies could include promoting the implementation of highly efficient electric motors, heat recovery from compressors, the implementation of renewable electricity production systems such as photovoltaic panels connected to the grid or the implementation of dynamic energy management systems. Both water- and energy-saving strategies must, however, be technically, economically and environmentally analyzed to characterize their suitability for implementation. It is also very important to complementarily promote the development of comprehensive industrial ecology studies focused on the identification and analysis of potential industrial symbioses in which the granite industry (and natural stone sector) could participate, especially those strategies that could serve as a starting point for springboarding different exchanges with and between other local and regional industrial agents, that would lead to a global increase in resource efficiency.

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SECTION 3: Natural insulating materials

Chapter 1

Thermal and structural properties of a hemp-lime biocomposite

1 Introduction

Worldwide reduction policies of the pressure exerted by the building sector on the environment are leading toward the construction of eco-compatible buildings [1], that is buildings characterized by low environmental impact and ensuring health conditions to inhabitants [2]. This effort is particularly evident in the search for new technical standards, capable of providing criteria in terms both of energy and environmental performances of buildings [3, 4]. In the bioecological conscious planning, a particular attention has to be devoted to the utilization of low environmental impact materials, that is materials not releasing toxic substances in the environment, presenting good thermo-physical properties and low energy content [5].

In this regard, natural materials seem to have all the above mentioned properties and they will probably represent a viable option to currently used building materials in a few years, both for the possibility to find them near the utilization sites and for their higher environmental compatibility with respect to more sophisticated materials that can undergo chemical alterations or high energy demanding processes.

Many researchers have approached the study of natural materials, especially investigating their thermal insulating properties. The most studied materials are jute [6, 7, 8], cork [9], corn cob [10, 11], hay [12], sugarcane [12, 13], wood wool and rock wool [14], cellulose loose-fill [15], flax [6, 16, 17, 18, 19], straw bales [20, 21, 22], coconut [23, 24, 25, 26] and hemp [6, 17, 18, 19, 27, 28, 29, 30, 31].

Beyond high environmental performances, a good natural material should also respect traditional quality criteria, like transpirability, hygroscopicity, fire resistance, moulds and fungi resistance, odourless, lack of radioactivity and dangerous substances, electrical neutrality and recyclability [32, 33].

Another aspect that has to be taken into account about the utilization of natural materials in buildings is the change of some of their properties, according to the considered material [34], depending on the zone of provenience, harvest time, extraction methods, attacks from alkaline and biological substances, deterioration due to high temperatures or humidity (natural fibres are generally hydrophilic) [6].

In Table 1, density and thermal conductivity values of some natural materials are reported.

Table 1. Density and thermal conductivity values of some natural materials

Fibre raw material	Bulk density (kg/m^3)	Thermal conductivity λ (W/mK)
Cork [9]	120 - 180	0.045
Corn cob panels [10]		0.139
Sugarcane [12]	100 - 125	0.0469 - 0.0496
Stone wool [14]		0.039
Cellulose loose-fill [15]		0.05
Flax [19]	5-50	0.038 - 0.075
Cellulose (recycled paper) [19]	30	0.041
Hemp [19], *	20 - 45	0.040 - 0.060
Straw bales [20]	102.6	0.067
Coconut [26]	85	0.058

* Measured value by present authors of the raw material: 25 kg/m^3

In this Chapter, a first analysis of the thermal and structural behaviour of a biocomposite concrete, constituted by a mineral matrix (lime) with the addition of vegetal fibres (hemp), has been carried out, with particular attention to the amount of fibres and its granulometry in the mixture [35, 36].
Hemp is a plant that can be perfectly cultivated in regions like Sicily (Italy) thanks to its climate. Furthermore, the *Regione Siciliana* [37] has proposed a plan to promote a supply chain that could invest different sectors, starting from the agricultural one. In fact, hemp could be conveniently used in abandoned fields, to recover field polluted by plant protection products, to produce energy from biomass or combustible oils from seeds, and in the building sector to produce insulating panels or lime-hemp concrete. In particular, for the production of lime-hemp concrete only the shives are used, while the fibres, that are the most valuable part of the plant, can be used for other aims.
The analysis carried out shows that hemp can be used both for the realization of insulation panel (hemp fibres alone) and as a construction material (hemp bast and concrete mix). This biocomposite has shown good insulation properties and some mechanical resistance. However, the results show that further analyses should be carried out on the drying process of the material, as it can greatly influences thermal and mechanical properties.

2 Hemp: characteristics and possible uses

The term hemp is used for the strain of the plant *Cannabis Sativa*, an annual crop with a high (until 4 meters) and thin stalk, with the apical part covered with foliage [38]. Hemp is characterized by very good thermo-acoustic properties and its transpirability and hygroscopicity makes it a good regulator of the indoor moisture content [29]. Furthermore, as it does not contain proteins, it is unlikely attacked by insects and moths. In the building sector, hemp is used for the realization of construction panels for interspaces in wooden structures, internal walls coating, ventilated coverings, internal partition walls, false ceilings and floors. Such panels are characterized by a very low specific weight and a high tensile, compressive and flexural strength. Hemp can also be used as plaster for outside walls or as insulating substrate in green coverings. Finally, by means of specific working processes, a fireproof material can be obtained [34, 35].

Hemp does not contain harmful substances nor is dangerous for health both in production and laying phases.

Hemp has to be processed before its utilization. In summer, plants are cut and dried in the sun for two weeks; then they are swingled for separating the bast (that is fibres located in the outer stalk) from shive, that is the wooden inner part (Fig. 1).

Fig. 1. Hemp fibres, said bast (left) and wooden part, said shive (right).

3 Experimental phase: the laboratory

Hemp has been characterized in the Natural Materials Laboratory located in the Department of DEIM of the Università degli Studi di Palermo, Italy. Tests have been carried out both on hemp alone and a biocomposite material. In the first analysis, only the bast has been used to make samples for the calculation of the thermal conductivity of the material, while in the second one the wooden part, the shives, have been mixed with inorganic bindings and then both thermal and mechanic tests have been carried out.

In the following, a list of the main equipments used is reported:

- custom moulds (composed by a tile as bottom and wooden boards as side walls);
- cylindrical moulds;
- cutting mill Retsch™ SM 100 Comfort;
- electronic balance RADWAG™ WLC 30/C1/K;
- mortar mixer Matest™ E095;
- thermostatic chamber ACS™ Inter Continental;
- heat flow meter LaserComp™ FOX 314;
- universal testing machine Zwick Roell™ Z600.

4 Hemp bast panels

The first tests have been performed on the hemp fibres, said bast. The EN 12664 standard [39], that specifies principles and process to test thermal conductivity by means of heat flow meters, has been carefully followed utilizing the equipments present in our laboratory, so disregarding some parameters, mainly concerning the geometric characteristics of samples like faces parallelism and roughness. However, a particular attention in making samples has been devoted to such aspects in order to minimize them as much as possible.

Between the different aims of such analysis, we single out:

- observing the behaviour of bast coming into contact with water;
- assessing bast characteristics after its processing, particularly as far as rigidity and compressibility are concerned;
- evaluating the amount of materials needed for making samples by means of a first rough estimate of the density;
- setting the procedure to follow for making the panels to test in the heat flow meter.

4.1 Screening phase

The first step of the analysis has been a preliminary screening to investigate some parameters of the mixture, like bast granulometry, water content, rigidity and drying duration. After this screening, samples with four different granulometry (being respectively 2, 4, 6 and 8 mm the maximum linear dimension of shives) have been made. Such samples (Fig. 2) have been made mixing bast and water in a ratio 5/1; after a week, they have been removed from their mould and let dry at environment temperature for further 16-22 days until the stabilization of the weight.

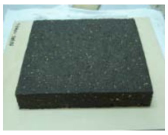
Fig. 2. Positioning of bast-water mixture in the mould (left) and drying of the sample (right).

The drying process is strongly affected by the climatic conditions of the place. Therefore, in order to allow test repeatability, a thermostatic chamber could be conveniently used for drying samples. From the performed tests, it has been observed that a thermostatic chamber can halve the drying process.

4.2 The experimental protocol

Thanks to the results obtained from the screening phase, it has been possible to drawn up a protocol to be followed for sample preparation and performance of thermal conductivity test to allow test repeatability. This experimental protocol is here reported: after chopping hemp fibres of the desired granulometry, they have been mixed with water in a ratio 5:1, then the mixture has been distributed in the mould. After 24 hours, the sample has been removed from the mould and, after further 4 days, put in a thermostatic chamber at 50 °C for 24 hours. Then, it has been daily weighed until the stabilization of the weight. Finally, the surfaces have been smoothed and the thermal test has been carried out by means of a heat flow meter, with the two plates temperature respectively at 5 °C and 25 °C, obtaining the thermal conductivity of the sample. In Table 2, a list of the samples undertaken to experimental tests is reported, while in Fig. 3, the time depending mass is shown.

Table 2. Identification code of all the tested samples.

Sample image	**Sample ID**	**Dimensions (mm × mm × mm)** Ø (mm) / h (mm)	**Density (kg/m^3)**	**Performed test**
	**H2A**	290 × 288 × 31	237	Thermal tests
	H2B	293 × 283 × 44	248	
	H4A	284 × 287 × 31	242	
	H4B	285 × 282 × 49	228	
	H6A	287 × 290 × 34	229	
	H6B	288 × 292 × 42	246	
	H8A	277 × 280 × 48	212	
	H8B	287 × 286 × 51	212	
	**4-20-A**	290 × 290 × 56	603	Thermal tests
	4-20-B	290 × 290 × 37	611	
	4-30-A	292 × 292 × 53	449	
	4-30-B	291 × 291 × 40	415	
	2-20-A	293 × 291 × 58	605	
	2-20-B	292 × 291 × 40	608	
	2-30-A	290 × 290 × 52	475	
	2-30-B	289 × 290 × 39	472	
	2-40-A	288 × 289 × 55	369	
	2-40-B	287 × 288 × 36	377	
	**4-20-A.1**	200 × 50 × 56	571	Flexural tests
	4-20-A.2	201 × 50 × 56	595	
	4-20-A.3	202 × 50 × 56	610	
	4-20-A.4	201 × 51 × 56	592	
	2-20-A.1	199 × 55 × 58	591	
	2-20-A.2	199 × 48 × 58	578	
	2-20-A.3	199 × 49 × 58	592	
	2-20-A.4	198 × 45 × 58	600	
	**4-20-C**	97/97	607	Compressive tests
	4-20-D	97/97	614	
	4-30-C	100/99	435	
	4-30-D	100/99	442	
	2-20-C	99/99	604	
	2-20-D	98/99	610	
	2-30-C	99/98	462	
	2-30-D	98/98	480	
	2-40-C	97/98	328	
	2-40-D	97/98	328	
	Reference sample	99/95	955	

Each sample has an identifying code. For hemp alone panels, it is a three digit code where the first digit stands for the type of material (Hemp), the second for its granulometry (in mm) and the third for identifying similar panels with the same characteristics. For hemp-lime panels/cylinders, instead, the first digit stands for the granulometry of hemp (in mm), followed by the amount of shives in the mixture (percentage in weight) and a final letter identifying similar panels (A and B) or cylinders (C and D) with the same characteristics. Note that the hemp-lime panels have been cut in stripes to obtain proper samples for the flexural tests that have the same identifying code of the panels they come from with a final number added to identify the stripes.

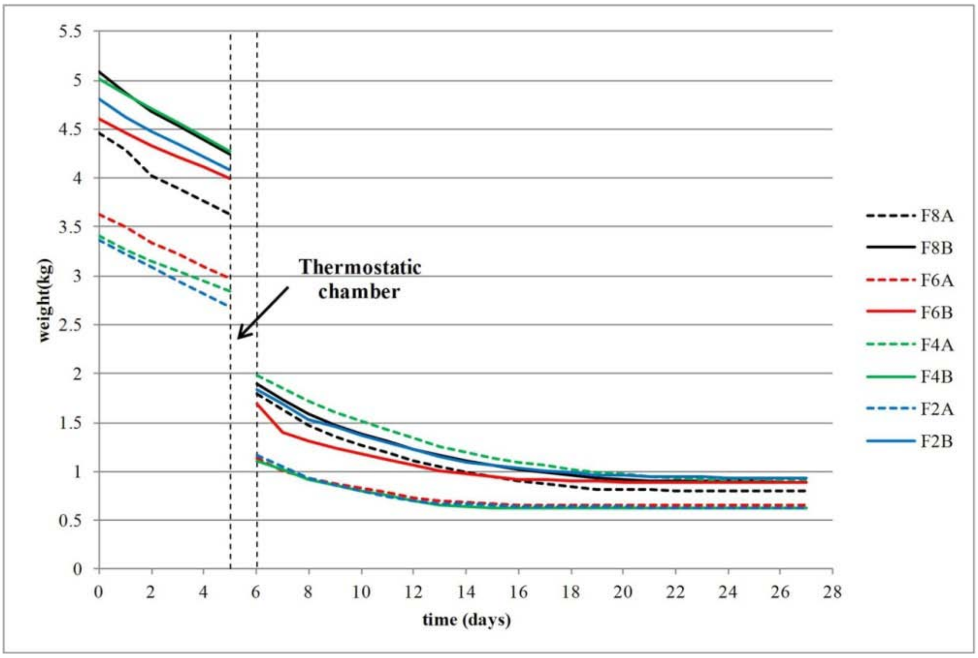


Fig. 3. Time depending mass of the fibres panels.

4.3 Thermal tests results

Thermal tests have been performed by means of a heat flow meter. A test consists of several blocks of 512 measurements at the end of which an average value of temperature and heat flow are calculated for each plate; the test is stopped when steady-state flow conditions through the sample have been reached, that is when the following three conditions are met:

- the temperature equilibrium: the average temperature of each plate in the block must be close to the plate's setpoint temperature, within a given set deviation;

- the percentage equilibrium: the transducers average signals of two successive blocks must be close, within a given set value;
- inflexion criterion: the test should be stopped when the heat flow is in a stationary point, that is the average values of three successive blocks that meet percent equilibrium criterion must first increase and then decrease or vice versa.

In Table 3, a list of the tested samples and their characteristics is reported.

Table 3. List of tested samples and their thermal and physical characteristics.

Sample ID	Density ρ (kg/m^3)	Thermal conductivity λ (W/mK)
H2A	237	0.0777
H2B	248	0.0775
H4A	242	0.0809
H4B	228	0.0854
H6A	229	0.0805
H6B	246	0.0915
H8A	212	0.0866
H8B	212	0.0830

The obtained values of the thermal conductivity are greater that the ones reported in literature [19], that is 0.04-0.06 W/mK. This is likely due to the different process used for the realization of samples. In particular, our samples have been placed in a thermostatic chamber for one day at 50 °C.

5 The hemp-lime biocomposite

The goal of this analysis is to obtain a light material, containing natural fibres, that has at the same time very good thermal insulating and mechanical properties.

Only the shives have been used for the preparation of the samples, chopped to a granulometry ranging between 2 and 8 mm in order to obtain a workable and homogeneous material.

5.1 Screening phase

Two types of moulds have been used for samples preparation: the one to be used in conductivity and flexural tests is a parallelepiped with a square base of 30 cm and heights of 4 and 6 cm respectively, while the one used for mechanical (compressive) tests is a cylinder with a diameter base equal to 10.2 cm and a height of 16.6 cm (Fig. 4). The real dimensions of the samples are slightly different from that of the moulds because of shrinkage.

Fig. 4. Cast of hemp-lime mixture in the moulds (upper raw) and samples after the drying and smoothing process (lower raw).

Two types of lime have been used for samples preparation: CL-70S (hydrated lime) and NHL-5 (hydraulic lime) as identified by EN 459-1 [40]. From the analysis carried out, some considerations can be pointed out:

- mixture containing shives with a granulometry higher than 4 mm are too brittle and easily exfoliate even for low quantities of shive;
- the maximum quantity of shives that can be added to a mixture before it is no longer compact is 30% and 40% by weight, respectively for shives granulometry of 2 and 4 mm;
- mixtures density varies in a range from 300 to 700 kg/m^3.

For each selected mixture, four samples, two panels and two cylinders, have been prepared.

5.2 The experimental protocol

In the following, the protocol used for samples preparation is reported:

after chopping hemp basts of the desired granulometry, they have been mixed with water, hydraulic lime and hydrated lime (in a ratio 4:1), then the mixture has been distributed in the mould previously covered with concrete release agent. After 4 days, the sample has been removed from the mould and, after further 7 days, put in a thermostatic chamber at 50 °C for 6 days. Then, it has been daily weighed until the stabilization of the weight. Finally, the surfaces have been smoothed and the thermal test has been carried out by means of a heat flow meter, with the two plates temperature respectively at 5 °C and 25 °C, obtaining the thermal conductivity of the sample. Finally, the mechanical tests have been performed in the following way: for the compressive tests, the cylindrical samples have been cut to obtain a height/diameter ratio 1:1, then positioned between the plates of the universal testing machine and the test started until crushing of the sample, obtaining the . For the flexural tests, instead, the panels have been cut in stripes having dimensions 20 × 5 × 5 cm, then a three points flexural test has been performed in the universal testing machine.

The above reported steps have been deduced in analogy with those reported in the technical standard UNI EN 12390 [41] for concrete samples. The selected value of the height/diameter ratio allows to directly obtain the cubic resistance.

In Fig. 5, the time depending mass of the hemp-lime cyliders is reported.

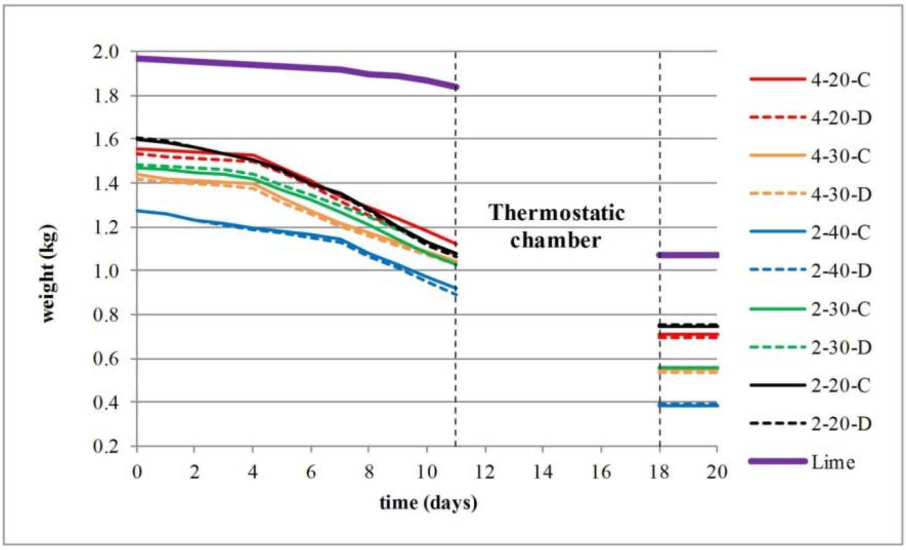


Fig. 5. Time depending mass of the hemp-lime cylinders

5.3 Thermal test results

Thermal tests have been performed as described in Paragraph 4.3. In Table 4, thermal and physical characteristics of the analyzed samples are reported. The sample identification code has the same meaning of Table 2 as described in Paragraph 4.2.

In Fig. 6, the found dependence of thermal conductivity of materials from its density (that is the content in hemp) is reported.

As we expected, the more the percentage in weight of shives in the mixture increases, that is the more the density decreases, the more the thermal conductivity decreases.

Table 4. Thermal and physics characteristics of hemp-lime samples

Sample ID	Hemp granulometry (mm)	Hemp percentage in weight (%)	Dimensions (mm × mm × mm)	Density (kg/m^3)	Thermal conductivity λ (W/mK)
4-20-A	4	20	290 × 290 × 56	603	0.1406
4-20-B	4	20	290 × 290 × 37	611	0.1408
4-30-A	4	30	292 × 292 × 53	449	0.1033
4-30-B	4	30	291 × 291 × 40	415	0.0972
2-20-A	2	20	293 × 291 × 58	605	0.1321
2-20-B	2	20	292 × 291 × 40	608	0.1366
2-30-A	2	30	290 × 290 × 52	475	0.1038
2-30-B	2	30	289 × 290 × 39	472	0.1079
2-40-A	2	40	288 × 289 × 55	369	0.0947
2-40-B	2	40	287 × 288 × 36	377	0.0899

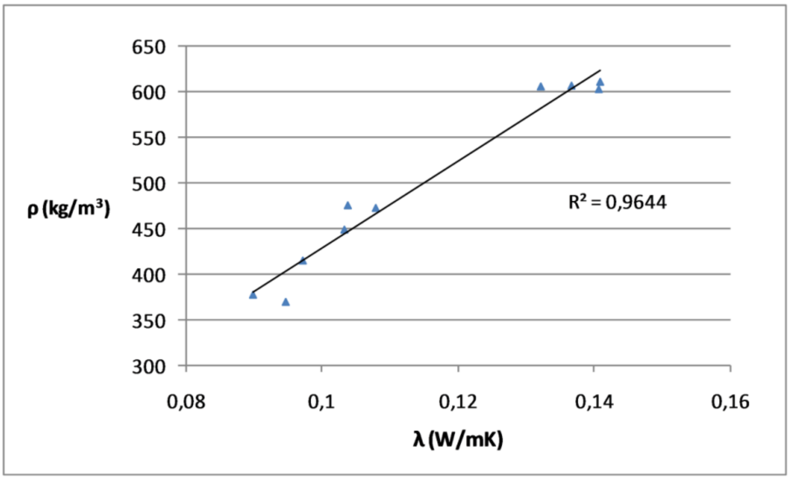


Fig. 6. Dependence of the thermal conductivity on the density.

5.4 Mechanical test results

Compressive test results

In order to compare the results obtained from the samples with reference values of density, ultimate strength and strain, a reference sample has been realized with only the bindings (hydrate and hydraulic lime in a ratio 4/1).

The physical characteristics of the samples and the results of the compressive test are reported in Table 5, where sample ID refers to Table 2.

Table 5. Physical characteristics of the samples and results of compressive tests.

Sample ID	Dimensions (Height/Diameter) (mm/mm)	Density (kg/m^3)	Young Modulus (N/mm^2)	Ultimate strength (N/mm^2)	Strain (%)
4-20-C	97/97	607	40.0	0.462	2.34
4-20-D	97/97	614	49.3	0.419	2.75
4-30-C	100/99	435	16.5	0.088	-*
4-30-D	100/99	442	19.7	0.187	-*
2-20-C	99/99	604	64.1	0.259	1.01
2-20-D	98/99	610	34.9	0.194	1.09
2-30-C	99/98	462	20.0	0.097	-*
2-30-D	98/98	480	16.3	0.210	-*
2-40-C	97/98	328	8.4	0.086	-*
2-40-D	97/98	328	7.1	0.044	-*
Reference sample	99/95	955		0.219	0.28

* Not measurable

In the performed tests, the upper crossbar speed has been set equal to 0.2 mm/min in order to have a very slow increase of the stress because of the poor expected mechanical properties and in order to obtain a reliable constitutive information of the tested material. From the tests, several couples of values describing the force-displacement curve are obtained. Such values have been processed to obtain the stress-strain curve reported in Figs. 7, 8 and 9.

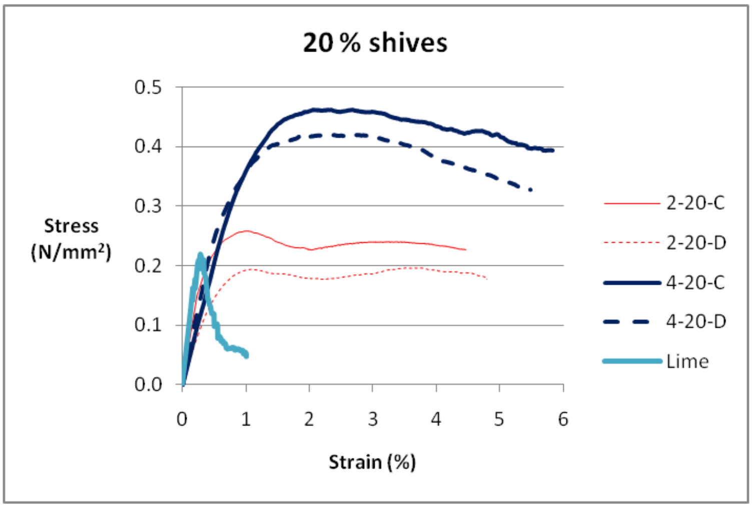


Fig. 7. Stress-strain curve of samples with 20% of shives.

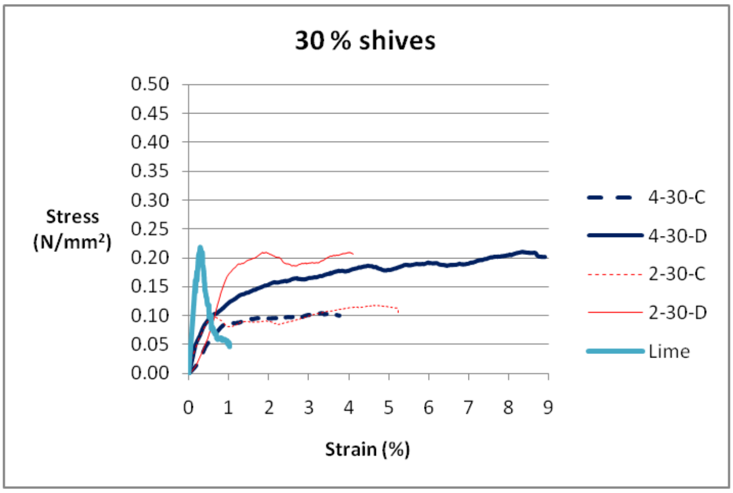


Fig. 8. Stress-strain curve of samples with 30% of shives.

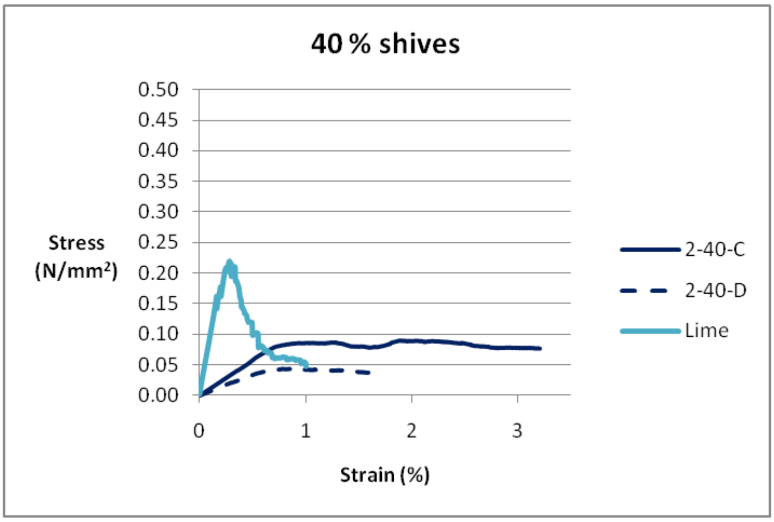


Fig. 9. Stress-strain curve of samples with 40% of shives.

In all graphs, a high strain capacity after the initial elastic phase can be pointed out. The ultimate strength is clearly influenced by the amount of shives in the mixture, generally increasing when it decreases. In all graphs, and especially for the mixtures with higher amount of shives, some instability phenomenon and atypical shape of the stress-strain curves can be observed, probably due to localized yieldings as well as to internal reorganization of the interaction between hemp and lime. Another remark is that a high variability of the results has been obtained, suggesting both a better standardization of the sampling composition and preparation and the use of a greater number of samples. The Young modulus of the mixture, measured as the slope of the initial part of the curve (elastic phase) is maximum in samples with 20% of shives and tends to decrease when the amount of shives increases as it is shown in Table 6.

Flexural test results

The flexural tests have been performed on the same panels used for thermal tests, in particular on stripes obtained from the panels identified by letter A in the sample ID. Only mixtures with 20% of shives have been tested because of the already mentioned poor mechanical properties of the composite materials.

As for the compressive tests, the universal testing machine used in flexural tests provides, as output, couples of values describing the force-displacement curve. From these data, the ultimate stress can be obtained by means of the Navier equation where the ultimate force is used as input.

In Table 6 the physical and mechanical characteristics of samples, obtained by means of the flexural tests, are reported. Sample ID refers to Table 2.

Table 6. Physical characteristics of the samples and pertinent results of the flexural tests

Sample ID	Density (kg/m^3)	Ultimate strength (N)	Ultimate stress (N/mm^2)
4-20-A.1	571	147.4	0.141
4-20-A.2	595	138.6	0.133
4-20-A.3	592	113.9	0.107
2-20-A.1	591	98.4	0.080
2-20-A.2	600	90.9	0.090
2-20-A.3	592	110.5	0.101

In Figs.10 and 11, the force-displacement curves respectively for 2 and 4 mm shives granulometry are reported.

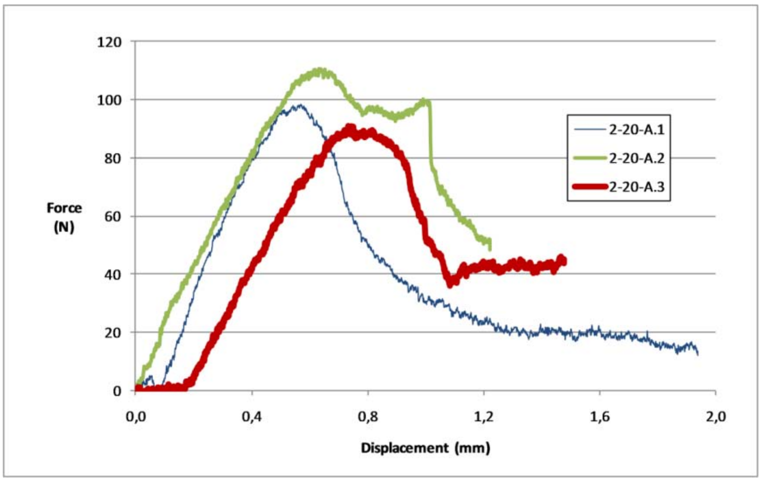


Fig. 10. Force-displacement curve for 2-20-A samples.

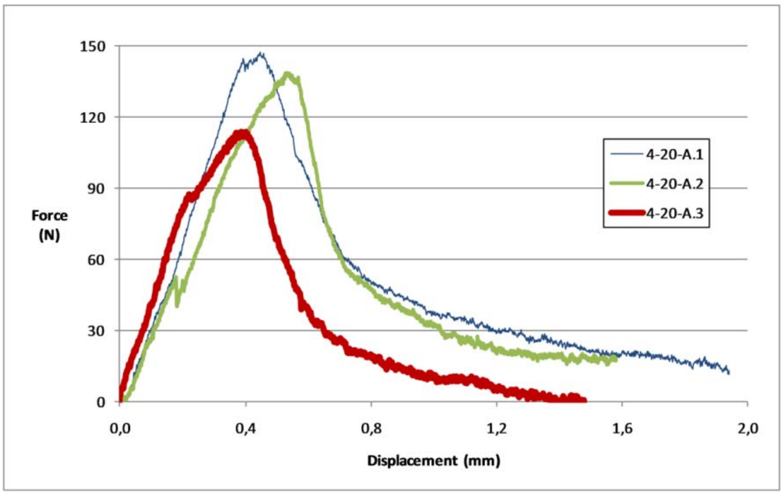


Fig. 11. Force-displacement curve for 4-20-A samples.

In all graphs, a peculiar behaviour of the material under investigation is evidenced. As it can be evidenced from an examination of Figures 10 and 11, the material does not show a brittle behaviour once the ultimate force has been reached, which is a characteristic of materials such lime or concrete. This particular behaviour has to be clearly ascribed to the presence of shives confirming their influence on the mechanical behaviour. It is to emphasize that in Fig. 11 the specimen 4-20-A.2 shows a jump during the initial phase which has to be ascribed to some defects of the specimen which do not influence the overall behaviour of the material since after the jump the slope of the curve is the same as that before the jump.

6 Discussion of results

In this Paragraph, the results of our analysis are compared with the published results dealing with a biocomposite of lime and hemp. The mix used greatly changes from author to author, both in the percentage of hemp used and the type of binders. Furthermore, the process for the realization of the samples has a great influence on both mechanical and thermal results, especially the compaction procedure and the drying process. For these reasons, the results varies in a rather wide range.

The thermal conductivity values λ obtained from the thermal tests performed on the hemp-lime biocomposite are nearly the same as the ones reported in literature. In fact, the measured values range between 0.0899 and 0.1408 W/mK, while the values present in literature are reported between 0.06 and 0.19 W/mK [42-47]. Anyway, values reported in literature do not always specify the amount of shives of the mixture. On the other hand, it is clear that the thermal properties of the mixture depend on the amount of shives present (Fig. 12).

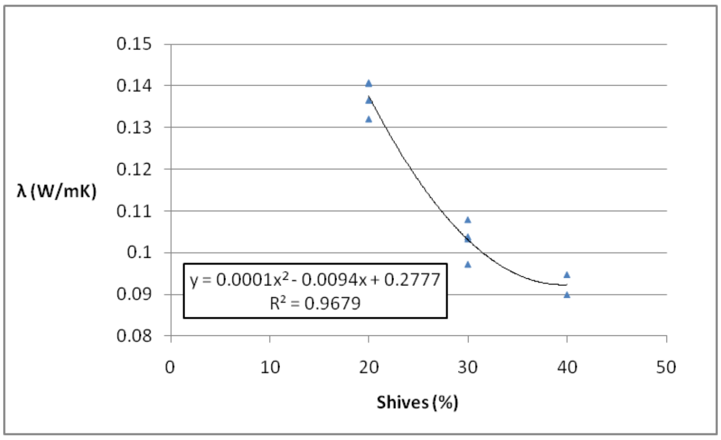


Fig. 12. Thermal conductivity as a function of the percentage in weight of shives in the mixture.

From the analysis of Fig. 12, it can be pointed out that the decrease of thermal conductivity is not linearly proportional to the increase of shives of the mixture. Moreover, with the increasing of shives content, the thermal conductivity of the composite material shows a decreasing of the slope, therefore, it could probably exist a maximum value beyond which it is no more convenient to increase such amount of shives.

From another point of view, there is also a physical limit to the amount of shives that can be added to the mixture due to the impossibility to make it homogenous with the increasing of the shives content.
The influence of the shive granulometry on the thermal conductivity instead is very low if compared to its amount in the mixture. In fact, in samples with 20% of shives the highest values have been obtained for 4 mm granulometry, while with 30% of shives content, the highest value of the thermal conductivity has been reached for a granulometry of 2 mm. Anyway, differences of thermal conductivity with a fixed amount of shives have always been founded within 4-5%.
The other very relevant aspect taken into account has been the analysis of the structural characteristics of the biocomposite.
From the compressive tests it emerges that shives give a high ductility to the biocomposite and, therefore, a high capacity of plastic deformation. As it could be expected, the constitutive behaviour of the material under investigation clearly does not show a well-defined ultimate stress and strain as, for example, in traditional concrete. The presence of hemp drastically changes the constitutive curve which, in some reported cases, shows a non decreasing stress-strain relationship when the test has been stopped. It is worth noting that in these cases, however, the samples showed an overall aspect such that the samples can be absolutely regarded as destroyed. The above reported behaviour is not new and it can be ascribed to the material internal reorganization during the test as well as to the interaction between hemp and binding. However, by increasing the amount of shives in the mixture the ultimate strength decreases consequently. The ultimate strength values of the samples tested fall within the literature range [42, 45-50] except for samples with 40% of shives, that is nearly the maximum amount of shives that can be added to the mix: anyway, it has to be pointed out that the drying process used greatly influences the mechanical properties. An interesting phenomenon, observed on the outer surfaces of the cylindrical samples, is the formation of a layer, 5-10 mm thick, that has been "baked" in the thermostatic chamber and that is structurally separated from the heart of the sample; it shows low cohesion and tends to exfoliate (Fig. 13). Due to this characteristic of the samples, the flexural tests of all the samples show very poor results. Likely, the drying process should be carried out at a lower temperature, controlling the moisture level in the thermostatic chamber.

Fig. 13. Outer (left) and inner (right) layer of cylindrical samples.

7 The comparison with hay fiber

In the same laboratory, described before, further investigations were carried out for another natural fiber which can be used for the same purpose, that is hay. The realization of tests and the way in which they were performed on the biocomposite hay-lime are the same of those previously described for hemp.

The aim of this work was to verify if the replacement of hay fibers with the shives ones in biocomposite is possible, in order to obtain a material having the same thermic properties and, at the same time, to test its mechanical properties; this choice is motivated by the lower cost of hay compared to hemp and the easier availability of this fiber in our country.

Hay is a mixture of cut and dried grass which is often used as forage. When the grass is collected, its water content ranges between 75-85 % and in hay it is reduced to 15-18%. Generally drying, with good weather conditions, lasts for 3-4 days. This material could be used in building in different ways: insulation panel for external walls or flat roofs, or rigid material to be mixed directly on-site and in-situ. Just a complete characterization of the material according to various parameters could show the most adapted use.

The results of tests performed on specimens of biocomposite and the experience gained during the experimental activity allow to draw some conclusions about the thermic and mechanic features.

First, it should be noted that the material complies fully with the principles of environmental sustainability, thanks to high ecological profile of its main components: hay and lime.

As regards lightness, lime-hay biocomposite is quite similar to lime-shives biocomposite. It has very low density values in comparison with those of products with similar purposes in building. Obviously this is related to the presence of hay and also to lower density of the hydrated lime compared to other mineral binders. Comparing values of thermal conductivity of lime–hay biocomposite with those of the biocomposite lime-shives it is noted that: as regard hay-lime biocomposite values range from 0.07176 to 0.1534 W/mK, while as regard lime-shives biocomposite values ranged between 0.0899 and 0.1408 W/mK (see Paragraph 5.3).

It is easy to point out that from a thermal point of view the two biocomposites have the same behaviour. So choocing one or the other material will depend on other factors, such as for example: local availability, transport costs, easy workability of raw material, etc. These conditions are typical characteristics of fiber hay. Indeed hay, unlike shives, is available in all the Italian territory and thereforeit is easy to available, its transport is low cost and it is easy to work. For these reasons, lime-hay biocomposite is preferred to lime–shives biocomposite.

However, if good thermal properties have been discharged, mechanical characteristics must be analyzed in more detail. In fact, the specimens, results are very weak (N/mm^2 0.075 - 0.252 N/mm^2). In this case lime-shives biocomposite has a better resistance (N/mm^2 0.252 - 0.462 N/mm^2). Moreover, as regard bending test, the highest values measured by a mechanical instrument were relatively low, 1.7-1.8 Kg/cm^2 this cannot allow lowering calculation of specimens .

In order to validate these results, other specimens following other experimental protocols were carried out, varying fiber and lime percentage used. But specimens obtained were very fragile, which easily broke, on some of these it was not possible to perform mechanical tests, and on those on which it was possible to perform mechanical tests values of mechanical resistance obtained were the same of the tests carried out before.

In the end, it was decided to analyze another solution: the use of only vegetable fiber of hay as insulation to fill gap (as it had happened with straw). This would also improve the appearance of an acoustic absorbent environment.

By experimental tests to prove whether this theory is valid or not, and by measures implemented in the single fiber (ρ = 240 Kg/m^3, l= 0,05414; ρ = 188 Kg/m^3, l = 0.05196) you could deduce that the best thermic conductivity values are recorded in case of lower density values and therefore in presence of a greater amount of air, this condition should be avoided since it may lead to a worsening of the sound-absorbing characteristics.

However, a very important aspect to keep in mind in case you want to use the simple “hay bale” as a fill insulation cavity is that hay, unlike straw, is essentially constituted by green grass containing pollen which may cause allergic reactions to certain subjects.

The results obtained in this trial represent only a first step towards a thermophysical knowledge of this material, in fact, it could be better to have further tests with the use of natural resins or glues that can generate an increase in mechanical strength. Unfortunately, by the results of these initial analyzes we are almost sure that it is not advisable to use hay for these purposes.

8 Conclusions

In this first attempt of thermo-physical characterization, the biocomposite of hemp and lime has shown potentially very good properties that could allow its exploitation in many applications to the building sector, such as an additional layer in load bearing wall or, combined with a wooden framework, as load bearing wall itself. Furthermore, due to its low density, it could be conveniently used in some applications where a structure cannot be overloaded such as in the realization of a green covering on top of a preexisting building. Other important aspects of this type of material are a less impacting ecological profile during its whole life cycle and lower costs with respect to traditional materials.

From the tests done, it is possible to argue that the addition of a certain amount of hemp to any mortar implies an improvement of the thermal performances of the material and a consistent lightening.

Anyway, further tests should be done in order to improve the mechanical properties of the biocomposite. In particular, a in-depth study of the influence of the amount and granulometry of shives in the mixture and the effects of the duration and modality of the drying process on the mechanical properties of the biocomposite should be carried out.

The relatively high spread of results concerning mechanical characteristics suggests a better standardization of the sample composition and preparation.

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