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LCA OF BUILDINGS AND BUILDING MATERIALS

Environmental performance of building materials: life cycle assessment of a typical Sicilian marble

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Abstract

Background, aim, and scope The building sector is strategically important for achieving sustainability. Therefore, the improvement of energy and environmental performances are relevant targets because precious building materials such as marble have a significant impact on the environment. The aim of this paper is an analysis of a typical Sicilian marble (Perlato di Sicilia) to evaluate its energy and environmental performance. Marble plays an important role in the economy of Italy and has a global market share of 58% in terms of exports. For the main production areas of marble, relevant environmental performance data are missing except for one region (Tuscany—Massa e Carrara province). Perlato di Sicilia, the main marble of Custonaci (Sicily), has never been analyzed previously.

Materials and methods Life cycle assessment (LCA) according to ISO 14040/44 is applied to marble tiles and slabs. For the life cycle inventory, data were collected from a representative plant in the Custonaci basin. In this small area of 69 km^2, about 54 quarries and related cutting plants are concentrated. The impact assessment includes the following categories: global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), and photochemical oxidation (POCP), following the CML-IA baseline 2007.

Results The results of the impact assessment for 1 m³ of marble tiles are 314.8 kg CO_{2eq} of GWP, 1.19 kg SO_{2eq} of AP, 0.073 g $PO_{4\text{—}eq}$ of EP, and 0.046 kg ethylene$_{eq}$ of POCP. For slabs, the corresponding results were 200.1 kg CO_{2eq} of GWP, 0.77 kg SO_{2eq} of AP, 0.053 kg $PO_{4\text{—}eq}$ of EP, and 0.029 kg ethylene$_{eq}$ of POCP. The total embodied energy values of tiles and slabs are, respectively, 1,772 MJ/m^3 and 1,168 MJ/m^3. This comparison shows that tiles manufacturing has higher values of embodied energy and environmental performance indicators. The value of the Custonaci slabs is reasonable compared to the Carrara marble (mainly slabs), and the embodied energy value of which is between 698 MJ/m^3 and 1,414 MJ/m^3. The main contribution to the energy consumption is due to electricity demand: 80% for tiles and 75% for slabs. Moreover, a comparison with the European type I Ecolabel criteria for natural hard floor coverings has been carried out to understand the range of the environmental impacts of Perlato di Sicilia compared to the thresholds reported in European Decision 272/2002.

Conclusions, recommendations, and perspectives This study is the first LCA of a typical Sicilian marble. The environmental interventions of the Custonaci marble appear to be slightly higher than Carrara marble. The nature of Custonaci marble and the technology involved in its production have reached the same performance level as in Carrara. Nevertheless, Custonaci marble is on the way to being an environmentally friendly product, as is shown by the comparison with Ecolabel criteria. The hot spots determined in this study are: the amount of spoils produced

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during the extraction step, the disposal of sludge resulting from cutting and finishing directly in the sawmill, the lack of the water recycling treatment in the quarry itself (as outlined in the European Ecolabel criteria), and the high electricity consumption.

Keywords Environmental performance · Floor tiles · LCA · LCI · Marble

1 Background, aim, and scope

The building sector is a relevant contributor to global energy consumption and environmental impacts. This sector is often referred to as the "40% sector" (CAN Europe 2005) because it is responsible of 30–40 percent of total energy use worldwide (UNEP 2007, WBCSD 2007, De T'Serclaes 2007). For this reason, it is important to implement policies and procedures for reducing the environmental impact of this particular sector. In this field, life cycle assessment (LCA) established a strategic role for evaluating both energy and environmental performances (Kotaji et al. 2003) and provided an adequate instrument for environmental decision support (Vince et al. 2008).

The LCA methodology has been widely adopted by the building sector and is recognized as a valuable tool in support of sustainable building (SETAC 2001). There are several applications (Bovea et al. 2007; RMIT 2002; Potting and Blok 1995) based on LCA in the building sector today, and several databases (BRE 2000; Boustead Consulting 1993) have been implemented to support them.

Moreover, the Kyoto protocol, adopted by the United Nations in Italy on the 16 of February 2005 (United Nations 1998), further calls for the availability of evaluation methods able to provide an assessment of the pressures exerted by anthropogenic activities on the natural environment.

In this direction, the application of the LCA to this sector does not only focus on individual building sector materials and products but has been extended to buildings overall. This is currently further developed into a proposal on EU Ecolabel criteria for the product group "buildings" (Neri 2007).

Several building materials and products have already been assessed by LCA (Woolley and Kimmins 2000) such as: wood, concrete (Björklund and Tillman 1997), clay bricks (Koroneos and Dompros 2006), insulating stone wool (Schmidt et al. 2004), hard floor coverings (Günther and Langowski 1997), and so on. However, there are still some materials for which life cycle inventory (LCI) data are missing or not well established. An example is marble. In fact, an analysis for different kinds of hard floor coverings from tiles to marble (Nicoletti et al. 2002) has already been carried out, but the Sicilian marble production cycle has not previously been evaluated. Moreover, the present available data are few and not homogenously related to the same functional unit.

Marble is an important building material for the Italian economy. Its production is concentrated in a limited number of countries (primarily China, Turkey, Italy, Germany, Spain, and Portugal), and the entire European Union supplies about 17% of the marble extracted globally (CCIAA Massa-Carrara 2004). Italy, the main European producer of raw and decorated marble, plays a primary role in this sector with 58% of the world exportation of marble products (Santoprete 1993; Monsignori et al. 2007). Specifically, the Italian region of Sicily plays an important role in this sector. Combined with Tuscany and Lazio, the three regions have the highest value of production.

The Custonaci basin in Sicily is the site of about 54 marble quarries in an area of 69 km^2 (La Gennusa et al. 2006). Presently, the Custonaci industrial area accounts for about 85% of the marble produced in Sicily, 15.7% in Italy, and 2.7% in the world (Fonte 2004).

The Italian standard UNI EN 12670/2003 (UNI EN 12670/2003) defines marble as "a crystalline rock, dense, ornamental, suitable for building and it can be polished, it is mainly consisting of ores that have a Mohs hardness scale value of 3 to 4 (like calcite, dolomite)." Moreover, it defines "calcite marble" as a marble including "more than 90% of calcite." These definitions do apply to the material extracted from Custonaci. This work is particularly focused on Perlato di Sicilia, which appeared on the market around the year 1950, mainly to meet the local demand as an alternative for the most costly Bianco Carrara marble.

This paper focuses on the application of LCA (ISO 14040 2006) to Perlato di Sicilia. The analysis of the whole production process of Perlato di Sicilia illustrates the environmental performance and the hot spots of the entire production cycle of marble. In addition to this case study, a comparison with existing European Ecolabel criteria for hard floor coverings (Baldo et al. 2002) has been made for completing the environmental analysis (European Commission 2002a).

2 Materials and methods

2.1 Scope, system boundaries, and assumptions

The goal of this paper is the compilation of an LCA of Perlato di Sicilia, in order to quantify its environmental performance. All production steps have been investigated, and the system boundary is shown in Fig. 1.

The production of the marble is consisting of three main process units: quarry, manufacturing sawmill (sawmill 1), and finishing sawmill (sawmill 2). For carrying out the LCA of marble products, the considered system involves

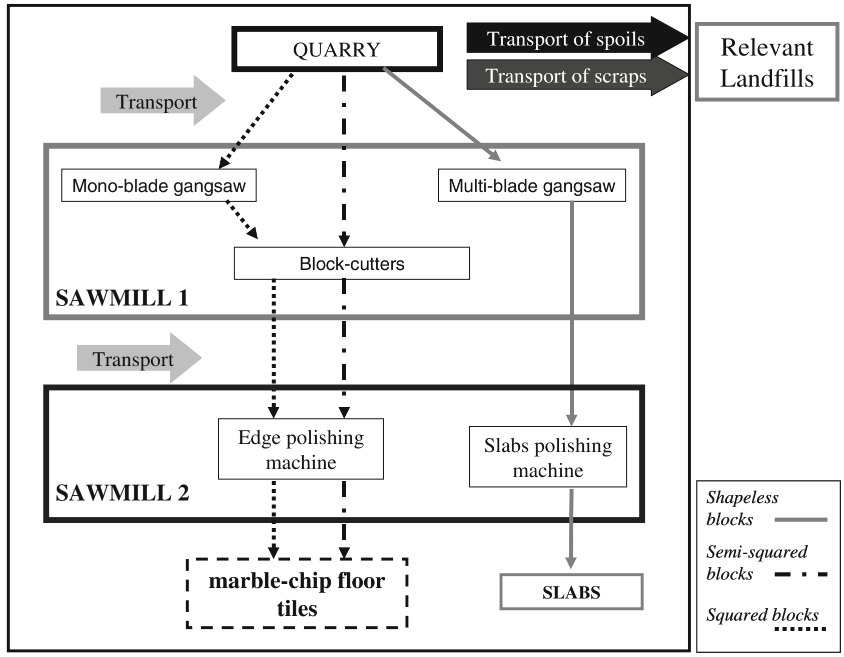


Fig. 1 Scope and system boundaries of Perlato di Sicilia slabs and floor tiles

the following phases of production: extraction and cutting in the quarry, cutting and resin finishing in sawmill 1, polishing and buffing in sawmill 2, the transportation of products along the routes from quarry to sawmills 1 and 2, and the transportation of spoils and scraps to specific landfills.

With regard to marble, no relevant environmental exchanges occur during the use of the products. The disposal phase of these products has been ignored in this analysis because it is temporally and physically separated from the production cycle. Because of the material durability, marble products frequently last as long as the buildings in which they are used.

The following assumptions have to be made:

1. The pollutant emissions related to the electric energy production are those referring to the Italian energy system (Ministero delle Attività Produttive 2002; Table 1);
2. The value of the energy input of the explosive refers to the energy realized during the explosion (Mancini and Cardu 1997);
3. The energy consumption and the environmental impact of all transport steps (such as the transport of the main product from quarry to sawmill 1 and the scraps to the landfill) are calculated starting from the known values of fuel consumption;
4. Data of water consumption in the sawmills are not available because the water source is owned by the plant owner and it is not monitored. Nevertheless, the used water is totally recycled in both plants;
5. The distance for the transportation of the products from sawmill 1 to sawmill 2 is about 6.5 km;
6. The production, use, and disposal of diamond wire has not been considered because data on such are not available;
7. The raw material extraction, production, and transportation have been assessed using the LCA as established in ISO 14040/44 (ISO 14044 2006);
8. The unitary volume (1 m^3) of marble has been chosen as the functional unit.

The industrial process considered here is an example of the multifunctional process in which different kinds of marble products are manufactured in the same plant, making an allocation procedure necessary. For each processed unit, the values of all inputs and outputs are known, including the mass of all products; on the contrary, the costs that depend on the market and other parameters are not included in the analysis. Hence, we have preferred to allocate all consumptions and emissions by mass.

Table 1 Emission factors of used fuel: electricity and diesel

Emission factors (g/MJ)	CO_2	NO_x	SO_2	CO	HC	Particulate	VOC
Electricity	200.5	0.2	0.52	0.19	0.002	0.38	NA
Diesel	74	0.79	0.02	0.20	0.002	0.06	0.210

NA not available

2.2 LCI

In preparing the LCI of the examined type of marble, primary data were collected every 4 months for the duration of the year 2004. The data reported in the tables and figures are an example of the values obtained in 4 months. For all three big plants, all inputs and outputs involved in the productive processes and all equipments for different manufacturing stages are considered. A summary of the equipment used in the productive cycle was compiled for each considered plant.

Quarry Marble is extracted from the quarries using different techniques depending on the characteristics of the rock and deposits. First of all, a big marble step is cutting from the mountain. The main cutting technique, in particular in the Custonaci site, utilizes diamond wire and diamond saw-cutting machines. The diamond wire, which is used in conjunction with a suspension of water and sand that is poured into channels in the stone, makes a linear cut in the rocks.

The removal of the block from the rock face is performed using straddle bearings, or explosives and excavators, as it occurs in this case. After the rocks have been cut and moved from the mountains, the quarry operations end with the sectioning and the cutting of the blocks, into commercially sized blocks of standard dimensions ($3\times1.8\times1.5$ m).

The raw product is dispatched to local manufacturing units, where the blocks are classified and selected on the basis of the frequency of veins they show. At this stage, there are three different types of block: shapeless (block without regular shape), semisquared (block with a roughly parallelepiped shape), and squared (block with a more uniform square shape).

Concerning the quarry operations, we considered all different types of energy consumption (energy, diesel oil, and explosive) for each step of the marble manufacturing (extraction and squaring phases) and transportation (from the quarry to sawmill 1). The values of the inputs and outputs are reported in Table 2.

Two different kinds of solid waste can be singled out in the quarry: the “spoils” come from the extraction of the marble and are produced when a big block of marble is removed from the mountain. In fact, since it is not possible to precisely control the explosions used to remove the big blocks from the mountain, a remarkable amount of spoils is produced in this step. Other “scraps,” produced from the squaring phase, consist of small pieces of marble and dust. The water used for cooling the diamond wire and saws in the quarry is not recycled. The column called total quarry reports data of the inputs and outputs of the entire quarry considering it as a single process unit; i.e., we know the entire consume of water in the quarry and not each allocated value for the single process unit (extraction, cutting, and so on).

Sawmill 1 Depending on the shape of the blocks, they are sent either to the multibladed gangsaw for the production of slabs or to block cutters for obtaining sheets. Tiles and slabs, characterized by their respective thicknesses, are cut at this phase. Slabs could be further cut into steps or risers. The shapeless blocks are cut into semisquared blocks by a single-bladed saw before going to block cutters.

Water used for cooling the saws and polishing wheels contributes to the production of large amounts of mud. This is sent to the sedimentator where the water is recycled by a flocculating process. In this step of the production, the involved solid waste consists of sawing sludge and stony fragments.

All spoils and scraps from the quarry and sawmills are discarded in a specific landfill, instead of being reused either for environmental requalification of the quarry site

Table 2 Inputs and outputs of quarry (data related to 4 months)

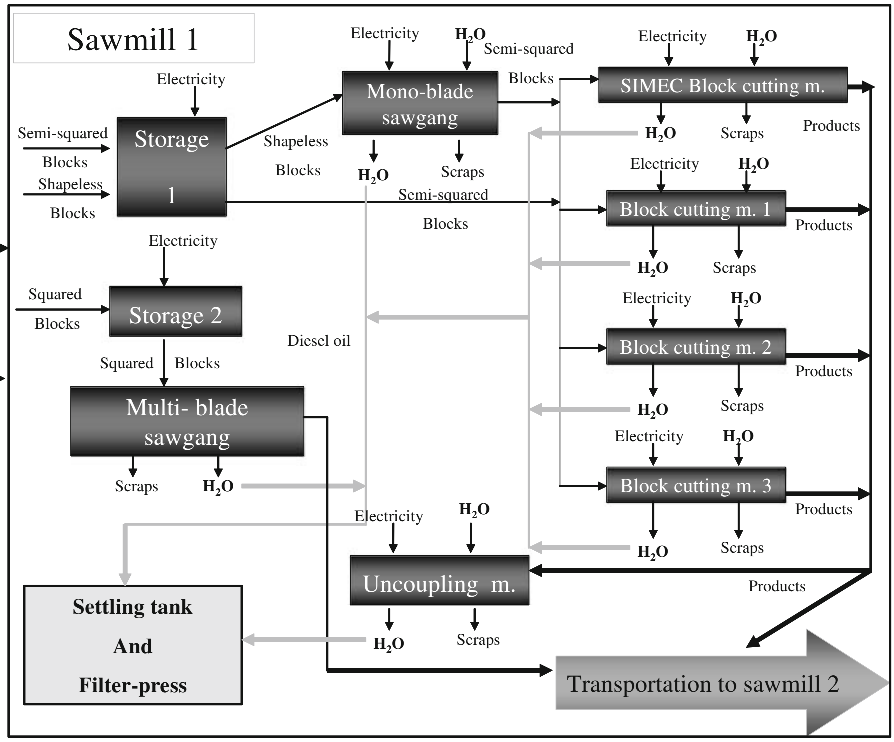
	Extraction		Squaring		Transportation of product		Transportation of spoils		Transportation of scraps		Total quarry[a]	
	Input	Output	Input	Output	Input	Output	Input	Output	Input	Output	Input	Output
Electricity (MJ)	27,376	–	26,193	–	–	–	–	–	–	–	53,569	–
Explosive (MJ)[b]	1,073	–	–	–	–	–	–	–	–	–	1,073	–
Diesel oil (MJ)	–	–	156,004	–	27,053	–	23,882	–	45,911	–	252,850	–
Water (m^3)	NA	–	NA	–	–	–	–	–	–	–	1,018	–
Product (m^3)	4,896	3,683	3,683	1,350	1,350	1,350	–	–		–	4,896	1,350
Solid waste (m^3)		1,213		2,333			1,213	1,213	2,333	2,333	–	3,546

NA not available

[a] Since we consider the quarry as a single unit process, its inputs and outputs are reported

[b] The input of explosive refers to energy realized during the explosion

Fig. 2 Flow chart of the manufacturing step of Perlato di Sicilia production (sawmill 1)



after the deposit is expired, or for producing other kinds of material. The sawing sludge disposal could also be used for environmental recovery of worn-out quarries (L.D. 152 2006, D'Agostino et al. 2006), however, this is beyond the scope of this study, and the material in question is, in any event, deposited in a suitable landfill.

The flowchart in this productive island is the most complicated of productive cycle, because it features different kinds of marble products (slabs, floor tiles, steps, etc.), and moreover, there are four block-cutting machines that run in the same time. All inputs and outputs of sawmill 1 reported in Fig. 2 refer to slabs and tiles production cycles.

From a production framework, it is possible to single out two different productive lines: the production line of shapeless and semisquared blocks and the production line of squared blocks (see Fig. 2). Values of inputs and outputs of the process units of tiles are reported in Table 3.

In the row called "stone material inputs," the quantity of the manufacturing products of the relative machine is inserted. The same consideration have to be made for the row "products" that represents the amount of the manufactured and treated marble products from every machine, for example tiles from the block-cutting machine 1. The energy consumption of the Simec cutting machine is the highest because its power is the highest but, in the same time, its production is the most efficient.

The energy consumption for moving material (belt elevators belonging to "Storage 1") and transporting it to the sawmill 2 are also considered here. The column "others" includes the consumptions due to activities such as lighting and air conditioning in the administration offices.

Table 4 shows the data on the input materials involved in slabs production. After cutting treatments, marble products show some cracks and holes that have to be filled in with

Table 3 Inputs (*I*) and outputs (*O*) of tiles in sawmill 1 (data related to 4 months)

	Storage 1	Monoblade gangsaw	Block-cutting machine 1	Block-cutting machine 2	Block-cutting machine 3	Simec block cutting machine	Uncoupling machine	Setting tank and filter-press	Others
I: Electricity (MJ)	19,388	35,640	201,834	208,135	232,355	271,135	283,324	76,032	39,731
I: stone material inputs (m^3)	3,046	416	354	319	547	862	1,117	–	–
O: Product (m^3)	2,082	396	262	236	405	638	865	–	–
O: Scraps (m^3)	–	21	92	83	142	223	252	–	–
Ö: Sludge (m^3)	–	–	–	–	–	–	–	498	–

Table 4 Inputs (*I*) and outputs (*O*) of slabs production in sawmill 1 (data related to 4 months)

	Storage 2	Multiblade gangsaw
I: Electricity (MJ)	2,424	197,683
I: Material Inputs (m^3)	321	321
O: Product (m^3)	321	297
O: Scraps (m^3)	–	24

polyester resin. Since this material could produce a serious negative environmental impact, monitoring the related consumption is crucial. The amount of polyester resin used is about 4.38 Kg/m^3 of finished product. The used resin for Perlato di Sicilia is about half of the usual amount used for other kinds of stones and marbles (Borgioli and Cremonesi 2005).

Sawmill 2 The last part of the marble production cycle involves polishing treatments of the products in preparation for the commercial phase. Table 5 shows energy and material inputs and outputs and the involved quantities related to each machine. Also in this production phase, the water used for cooling the blades of the polishing equipment is recycled and sent to the treatment plant located in sawmill 1.

The last part of the LCI was the calculation of all liquid, solid, and gaseous emissions. The obtained results are about 72% of scraps in quarry per functional unit for both tiles and slabs, and 39% of waste stone for the tiles and about 8% of waste for slabs in sawmill 1. The other solid waste is the sludge from the filter press, which amounts to 0.31 m^3/m^3 in sawmill 1 and 0.13 m^3/m^3 in sawmill 2. These values concern the whole production in each plant.

Air pollutant emissions mainly consisted of carbon dioxide and sulfur dioxide. The total carbon dioxide emissions, for both products, tiles and slabs, are, respectively, about 314.8 kg/m^3 and 200.11 kg/m^3. The K_2O and K_2S pollutants are emitted by the use of explosive and are produced only in the quarry, and consequently, their values are really low.

In general, the air emissions can affect the ecosystem around the considered plant, and this depends on the typology of the source. The most affecting to the local ecosystem are those produced in the same site, and these are produced by the combustion processes in the plant. A comparison between local and total emissions is shown in Fig. 3. The local emissions are monitored by local environmental agency, and therefore, it is not allowed to exceed prescribed limits.

2.3 Data quality and sensitivity analysis

All data have been collected by deriving the values directly from bills and by checking the performance of the process units. The latter procedure was used to verify the consumption data gathered from the bills by collecting data on the nominal power of each process unit and then monitoring it in different running conditions to calculate the resulting energy consumption. This procedure has been applied to each operational unit of the marble production cycle, and at the end, an energy balance was carried out to verify the consumption data reported on the bills.

A sensitivity analysis has been made, and the results indicate that the explosive input can be neglected because its value is around 0.01–0.02% of the total amount of the energy used in the entirely production cycle. It affects 100% K_2O and K_2S emissions that are only produced by explosive use, and about 1% the results of the SO_2 and CO emissions in both tiles and slabs. The other two components of energy are more meaningful; in fact, the electricity is about 80% of the total consumptions and the diesel 19% of it. Hence, the relating data can affect more the result of the total emissions.

The energy inputs of the quarry are not very significant; halving the electricity consumptions causes a reduction of the emissions of 0.4%. Instead, the sawmill energy inputs affect the entire production of both products significantly. In the sawmill 1, the most affecting block-cutting machine of the tiles production is the Simec one, because it produces more products. For example, cutting its present consump-

Table 5 Inputs (*I*) and outputs (*O*) of production in sawmill 2 (data related to 4 months)

	Polishing machine SIMEC LM 2000 for slabs	Polishing machine SIMEC LM 92 for tiles	Polishing machine SIMEC LM 600 for tiles	Pumps	Other services	Belt elevator	Crane truck	Total sawmill 2
I: Electricity (MJ)	78,756	167,575	178,599	50,688	1,977	–	–	477,596
I: Diesel oil (MJ)	–	–	–	–	–	94,470	94,470	188,940
I: Material inputs (m^3)	831	532	643	2,005	2,005	1,175	830	2,006
O: Product (m^3)	830	532	643	2,005	2,005	1,175	830	2,005
O: Scraps (m^3)	1	–	–	–	–	–	–	1
O: Sludge (m^3)	–	–	–	–	–	–	–	265

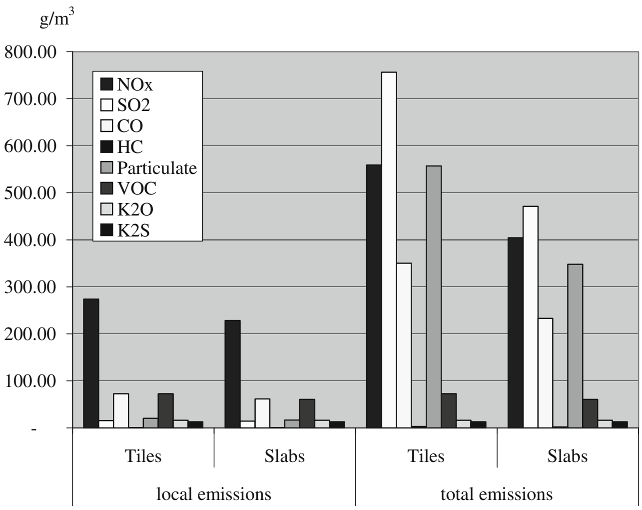


Fig. 3 A comparison of the local and total emissions

tion to the half value, without decreasing the present products production, means reducing about 6% of CO_2 and SO_2 emissions. The most relevant input of the environmental performance of slab products is the multi-blade sawgang electricity because of halving its present affects respectively about 37% of the SO_2 emissions, 33% CO_2, and so on. In the sawmill 2, the energy consumptions of the each polishing machine affects the environmental performance about 4–5% to both slabs and tiles.

3 Results

3.1 Life cycle impact assessment

The impact assessment methodology applied here is a “problem-oriented” approach (Heijungs et al. 1992) where the inventory data are associated with specific environmental impact categories.

The environmental impacts that have been taken into account in this study are global warming potential (GWP; Houghton et al. 2001), acidification (AP; Huijbregts 1999), eutrophication (EP; Heijungs et al. 1992), and photochemical oxidation (POCP; Jenkin and Hayman 1999). All results are related to the functional unit (cubic meter) of product. The characterization factors used for the midpoint categories (Stanners and Bourdeau 1996) are those stated in the database CML-IA Aug 2007 (De Bruijn et al. 2007).

Embodied energy (Cole and Rousseau 1992), which is based directly on the inventory assessment, is the indicator used for calculating energy consumption by functional unit (Venkatarama Reddy and Jagadish 2002). The embodied energy values of slabs and floor tiles are summarized in Fig. 4.

As it is shown, the marble tiles production requires more energy. The tile values represent the average results of embodied energy for different kinds of tiles manufactured in the considered plant. There are eight different values based on the different block-cutting machines used, and the respective embodied energy values are between 1,168 and 1,772 MJ/m^3. The most important contributor to embodied energy is electricity. More in details making a comparison among the different block-cutting machines, the Simec one that has the highest consumption has the lowest value of the embodied energy, 424.7 MJ/m^3, against the cutting machine 2 that has the highest value 880.5 MJ/m^3.

The next step, in evaluating the whole environmental impact of this activity, is to transfer the results of life inventory in terms of contributions to the studied impact categories. The obtained results of Perlato di Sicilia are summarized in Fig. 5.

This environmental assessment does not examine the impact generated by solid waste, since the study does not consider the amount of land covered by the quarry or marble mud and spoils. A recent research project has analyzed the opportunity of delivering marble mud to marble quarries for purposes of environmental recovery (D’Agostino et al. 2006).

Evaluation of the marble production cycle, undertaken in accordance with the criteria of European Ecolabel type I (European 2002b; ISO 14024 1999), supports these results. This label is assigned to products that meet product or service group-specific environmental performance standards and thresholds. These standards and thresholds are singled out for each specific products or services group by using the LCA. In this case, the analyzed specific group is hard floor coverings. The product group in Ecolabel scheme is subdivided in two major subgroups: natural

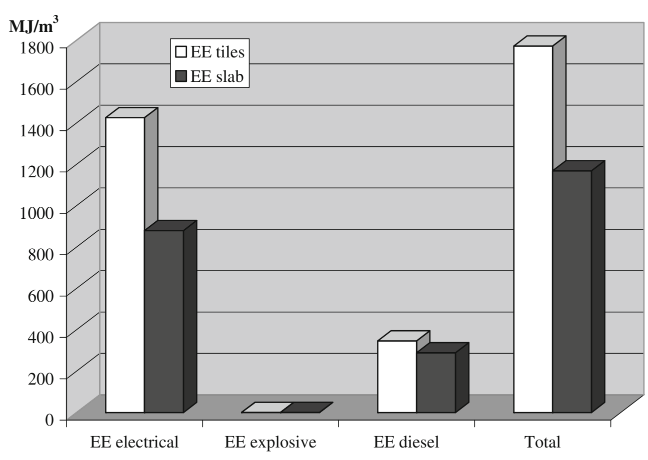


Fig. 4 Embodied energy for energy sources used in floor tile and slab production

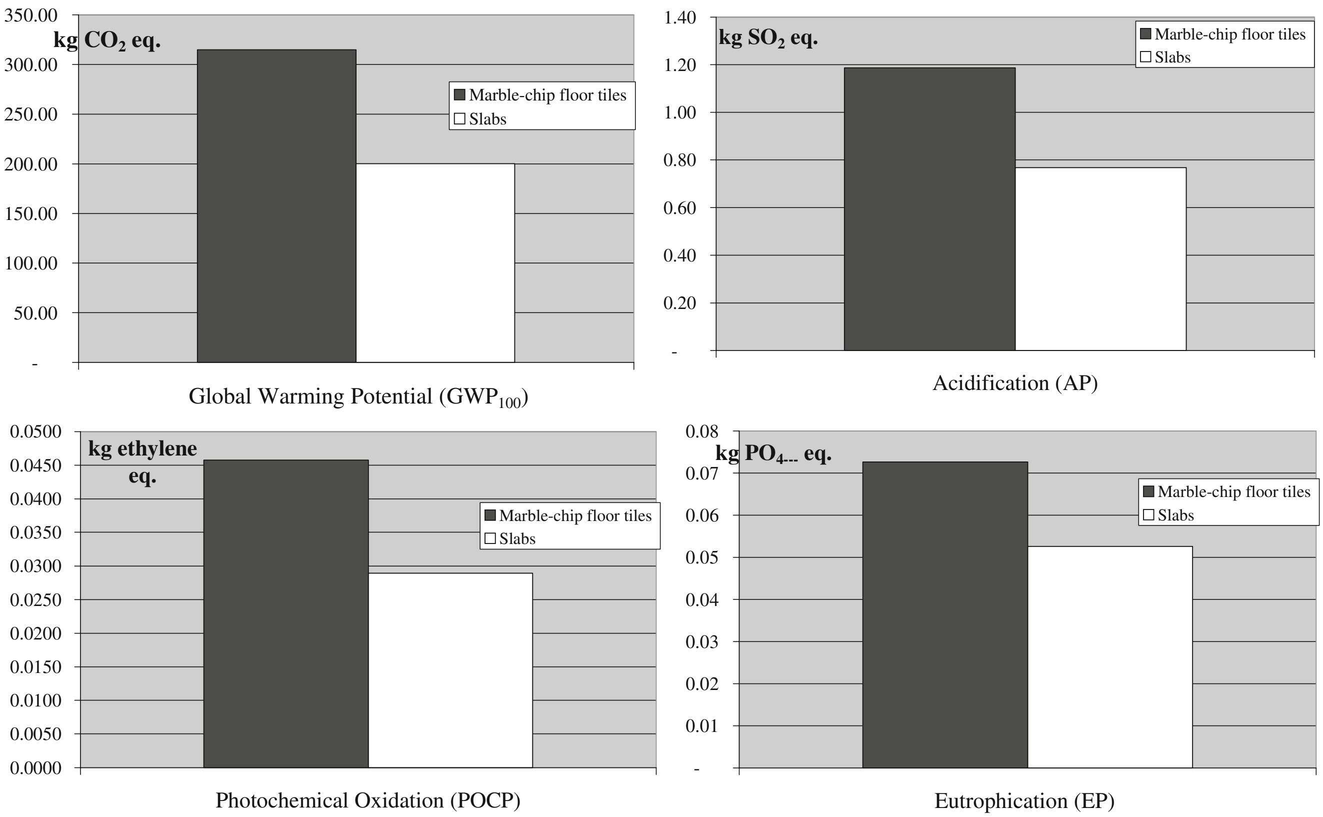


Fig. 5 The results of main midpoint categories for cubic meter of Sicilian marble

products and processed products. Hence, we consider the criteria related to the natural products (Table 6).

The Sicilian marble meets most criteria related to the extraction and selection of raw materials. In fact, for example, the block recovery of Perlato di Sicilia is about 27% more than the limits 20%, and the natural resource appreciation is about 75% more than 35%. Another example is the use of the substances harmful for the

Table 6 Ecolabel criteria of hard floor coverings: natural products (European Commission 2002b)

Extraction and selection of raw materials		Production and finishing		Use and end of life	
Reduction of the impact on the natural environment:	No interference with deep confined waterbeds, surface water-bodies with civil catching or springs, with average flow > 5 m^3/s, or protected areas according to Directive 2000/60/EC	Reduction of water pollution	■ Water recycling ratio ≥ 90% ■ Reduction of emissions to water (in mg/l): Suspended solids < 40; Cd < 0.015; Cr (VI) < 0.15; Fe<1.5; Pb < 0.15.	Consumer information for environmental use	Product packaging or documentation shall bear information ■ On the environmental benefits for the eco-label and on green behaviour to protect further the environment. ■ Recommendations on the use and maintenance, especially outdoor floorings. ■ Indication of the route of recycling or disposal. ■ Information on the Ecolabel and its related product groups.
	Waste water recovery closed system in place. Water shall be recycled Technical report on extraction and recovery showing compliance with Directives 92/43/EEC and 79/409/EEC. (Applicants outside EU: Compliance with UN 1992 Convention of Biological Biodiversity).	Reduction of air pollution	Particulates < 150 μg/Nm^3 Styrene < 210 mg/ Nm^3-		
	Score system based on matrix of 9 indicators: • Water recycling ratio ≥ 80% • Rehabilitation simultaneity ≤ 50% • Block recovery: Marbles ≥ 20% • Natural resource appreciation (usable material/extracted material): marbles and granites ≥ 35% • Working conditions of operating equipment • Air quality: PM 10 suspended particles ≤ 150 μg/Nm^3 • Water quality: suspended solids: ≤ 40 mg/l. • Noise: ≤ 60 dB(A) • Visual impact ≤ 30%	Reduction of the impacts of solid waste	Implementation of a waste management system including the following procedures: • Separation and use of recyclable materials. • Recovering of materials for other uses. • Handling hazardous waste.		

environment and health that is limited to the polyester resin, and its amount is about 0.16% of the total weight of considered raw material (marble) that is definitively less of 10%, the Ecolabel threshold. The exception is, for example, the water used in the quarry that should be recycled more than 80% to avoid polluting ground waters but it is not recycled at all. The second part related to production and finishing steps has good environmental performance related to the water emissions; in fact, the water is 100% recycled, and there are no emissions in the surrounding groundwater sources. About the waste management, the criteria are met only because in the plant the procedures for separating the different solid wastes are applied but then all kinds of them are transferred to the specific landfills and not recovered or reused. Moreover, there are not available data on the concentrations of particulate and styrene but we have only the emissions of particulate for cubic meter of product that is 557 g/m^3 of tiles and 348 g/m^3 of slabs. Last part of the criteria related to the use of the product is out of the system considered in this study.

4 Conclusions, recommendations, and perspectives

The marble production plant studied here is representative of the average production technology in the Custonaci basin, particularly in terms of equipment and processes. This study is the first application of LCA to Perlato di Sicilia for which data were not available.

A summary of the embodied energy of building materials is shown in Fig. 6. It shows that the Perlato di Sicilia value is not so far from the value of stone 2,030 MJ/m^3, but it is slightly higher than the Carrara marbles (Liguori et al. 2008). An explanation is that the Carrara marble is a metamorphic stone, and the extraction phase produces fewer scraps. It produces more undamaged blocks and accordingly uses less energy to produce the same amount of marble slabs and tiles.

Figure 6 presents some data of embodied energy of building sector (Alcorn 2001) and the range where their values are included but it does not want to compare the materials that have evidently different functions and production cycles. Of course, all these data are necessary for the entirely environmental evaluation of a building in according to the European project to carry out the Ecolabel criteria for the buildings.

As mentioned above, there are only two edited studies on Italian marble but only one is a complete LCA (Nicoletti et al. 2002). It considers the square meter of product as a functional unit making a comparison between marble and ceramic tiles but this study neglects other marble products such as slabs. Anyway, the marble analyzed is extracted in Massa Carrara, so an analysis of Perlato di Sicilia completes the marble productions scenario in Italy and more in general, in Europe.

The comparison with present European Ecolabel criteria further illustrates our finding that marble is competitive in terms of environmental aspects if applied properly. Of course, the management of the entire production cycle, including elements such as the recycling of all water in extraction phase and the solid waste management in all plants, should respect the threshold established by these criteria. This study can lead the analyzed company to improve the present conditions in according to the result obtained here.

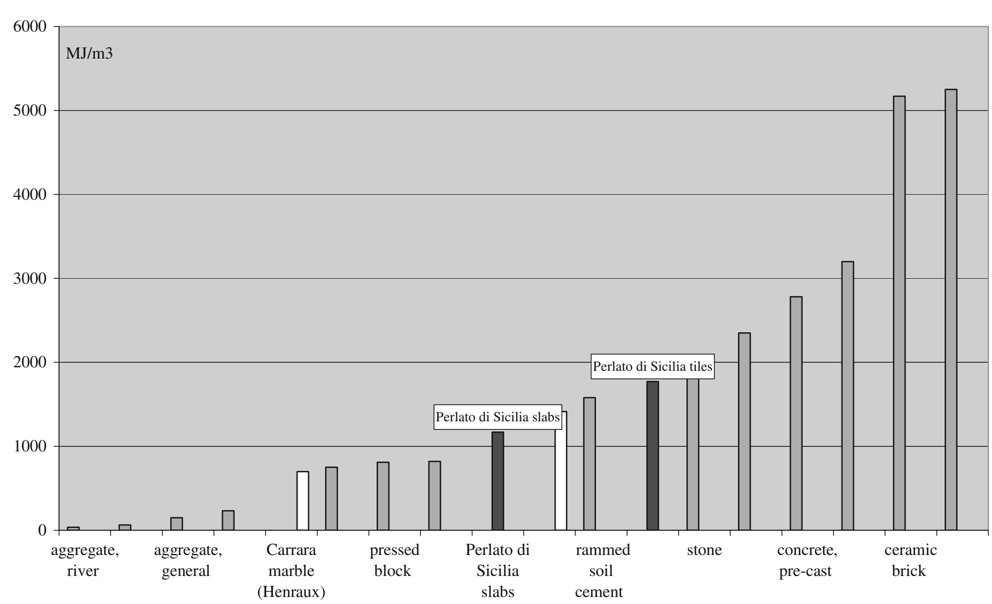


Fig. 6 Range of embodied energy of building materials (Alcorn 2001)

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