A simplified method for the indirect evaluation of the "embodied pollution" of natural stones (marble) working chain to be applied for achieving the Ecolabel brand of the product

Cinzia Capitano[1], Laura Cirrincione[1], Giorgia Peri[1,*], Gianfranco Rizzo[1], Gianluca Scaccianoce[1]

[1]*Department of Engineering, University of Palermo, Viale delle Scienze, Building 9, 90128, Palermo, Italy*

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[*] Corresponding author. Mail: peri@dream.unipa.it

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Abstract

The constant push toward higher energy and environmental quality buildings makes the acquisition of excellence marks for products and materials, of which the building envelope is constituted, increasingly urgent. The recent European (EU) Commission Decision 2021/476 is applicable to marble used in construction. It sets out criteria that companies producing marble have to accomplish to obtain the EU Ecolabel brand. Unfortunately, some criteria such as, for example, those that refer to the application of the Environmental Management System, ISO 14001 and EMAS certifications, or those that concern the ISO 14067 as well as the Product Environment Footprint procedure, are difficult to apply for companies in the marble extraction and processing sector. These companies, in fact, are usually family-run and find it difficult to adhere to such complex schemes. This difficulty obviously limits the number of companies and products that can aspire to an environmental excellence label.

On the other hand, the new Decision seems inadequate to identify the environmental impact of the transport of material between the different workstations of the same company; aspect that would be important to consider to evaluate in a broader and more detailed way this impact in the framework of the attribution of an environmental excellence label.

To provide a contribution to overcome these difficulties for the companies and to open a debate on the criteria that lead to the assignment of the EU Ecolabel brand, here an alternative simplified method for the indirect assessment of pollutant emissions from the work chain of marble companies, which also includes the contribution of the transport phase of the semi-finished material between the different workstations of the company, is proposed. The method simply starts with an evaluation of the type and quantity of energy sources used in the work cycle and the emission factors of the main pollutants emitted. In this way, a sort of material impact sheet is obtained that contains not only the embodied energy of the marble but also the “embodied pollution” associated to it. The method, besides being easy to use, could be adopted in the criteria that lead to the attribution of the EU Ecolabel brand to companies that work marble.

Keywords: air pollutant emissions; embodied pollution; emission factors; EU Eco-label; marble; transportation.

Nomenclature

i-th	Pollutant
k-th	Energy source (or energy vector)
PE_i	Amount of the i-th pollutant emitted in the marble manufacturing process [kg]
EV_k	Amount of the k-th energy source used in the marble manufacturing process [GJ]
$EF_k\|_i$	Emission factor related to the k-th energy source for the i-th pollutant [kg/GJ]

1. Introduction

Buildings are responsible for almost 40% of total final energy consumption and 36% of CO_2 emissions throughout Europe (European Commission, 2022). Therefore, the building sector is considered one of the most important EU sectors both in terms of energy efficiency and environmental policies for a sustainable development in the Member States (Cirrincione et al., 2019). To this end, several directives on the energy performance of buildings have been developed. Among these, the 2002/91/EC (European Parliament and Council, 2002), its recast, *i.e.* 2010/31/EU (European Parliament and Council, 2010), and the recent 884/2018/EU (European Parliament and Council, 2018) are the most important to mention. In addition to the promotion of the use of energy from renewable sources in the buildings sector (Hoang et al., 2021a; Nguyen et al., 2021a), two main measures have been introduced, i.e. the establishment of an energy certification system and the introduction of the concept of nearly zero energy buildings (nZEB) (Giama et al., 2021; Cirrincione et al., 2020a). In this context, the attempt to singling out criteria to attribute the EU Ecolabel also to buildings is another important initiative to cite (Peri and Rizzo, 2012). Buildings can also play a significant role in the construction of smart cities (Di Dio et al., 2018).

Within this general effort, the quality of building materials has been increasingly gaining great interest, since the energy demanded for the air conditioning of buildings and the related environmental impacts depend significantly on the envelopes' characteristics and their constituent materials (Cirrincione et al., 2020b). Thus, appropriate criteria have been developed to evaluate and certify the environmental quality and even the environmental excellence of single building components. Among the building stone materials, there is marble that, thanks to its aesthetic properties and durability, has always been appreciated by the construction industry and is finding a new growing interest as a valuable material for high quality buildings.

Certainly, while the current Covid-19 pandemic with its blocking actions has led to positive effects such as, for instance, an improvement of air quality in some countries (Balasubramaniam et al., 2020), a significant decline in global CO_2 emissions (Nguyen et al., 2021b), and a fall in global energy demand (Hoang et al., 2021b), on the other hand it has put a strain on the Italian stone sector (Intesa San Paolo, 2021). However, a gradual recovery of this sector has been noted for the year 2021 in Italy thanks to the strengthening of demand in the construction sector, positively supported by the "Superbonus" action and investments in infrastructure planned in the National Recovery and Resilience Plan (NRRP) (Italian Ministry of Economy and Finance, 2022).

Among the environmental certifications currently available for marble - whose life cycle is described in (Capitano et al., 2017) and (Hanieh et al., 2014) -, it is worth mentioning the EU Ecolabel. This label is an ISO Type I label that is based on a multi-criteria assessment, in which each criterion constitutes precise benchmarks that must be met to obtain the label from an impartial third party. This label thus attests the environmental excellence of products/services throughout their lifetime, compared to others in the same category.

The scheme of criteria to attribute the EU Ecolabel to natural stones (including marble), contained in the Decision 2021/476 (European Commission, 2021), certainly represents a progress towards an increasingly accurate assessment of the environmental impact of the marble production process. Compared to the scheme contained in the previous Decision 2009/607, the updated version considers some aspects of the impact of the natural stone production process of non-negligible importance, such as the consumption of primary and electrical energy in the various processing stages (extraction, cutting and finishing/polishing and transport). Indeed, the use of these primary energy sources translates into significant environmental impacts of the marble production chain.

Nevertheless, the analysis of the Decision raises the following two questions:

1) What is the actual level of feasibility of implementing this new scheme based on the required data and proposed analysis methods?

2) How to correctly attribute the impact of the transport phase, since different companies may be subject to moving the intermediate products through their processing sites along different distances, due to the particular location on the territory of these sites?

Regarding the first question, it must be said that the new scheme, requiring complex evaluation methods (EMAS or ISO14001), does not adequately fit in with the practical possibility of intervention by marble companies which are generally (and in Italy and in the Custonaci district, in particular), family-run, as opposed to more consolidated and industrialized companies dealing with other hard covering materials. Likewise, marble companies would find it difficult to apply the sophisticated analysis methods proposed by the Decision (in case of request for additional optional points) to assess the greenhouse gases released, i.e. the "Carbon Footprint" or the "Product Environmental Footprint" methods.

In this paper, we suggest a possible solution to this operational difficulty, namely the use of an easier to apply indirect method for the determination of pollutant emissions based on the energy used in the processing cycle. This method would essentially be based on the evaluation of the quantities of energy used in the various phases of the marble production chain and on the use of the corresponding emission factors for the main emitted pollutants. In this regard, the precise identification of these quantities of energy is already required for attributing the Ecolabel according to the new scheme. Thanks to this indirect method, it would be easy to obtain not only the "embodied energy" of the marble, but also its "embodied emissions", thus outlining a sort of environmental profile, declined by means of a specific data sheet which, beyond its intrinsic usefulness, could also be included among the criteria to be meet to assign the Ecolabel.

As for the second question, the energy consumption of the transport phase should also be evaluated. This aspect can be problematic when comparing different companies, considering that they may show an inhomogeneous performance as their products may cover different distances depending on the company location. With respect to this question, the new scheme of the Decision does not seem to provide an answer. In fact, for the transportation phase impact assessment it merely indicates to use the distance (which is, in any case, optional) between the quarry and the cutting and polishing plants. Clearly this, when comparatively evaluating the performance of companies that move the intermediate product along different distances, would tend to penalize those whose processing sites are located in a more dispersed manner in the territory. The hypothesis suggested here to overcome this difficulty is that of using another indicator, represented simply by the energy consumption per unit of product transported (m^3) per unit of distance (km). These energy uses (where not directly declared by the company) should also be appropriately calculated based on the type and age of vehicles used.

Figure 1 shows graphically the logical flow through which this work develops, from the reporting of difficulties in the new Directive, to the proposal of their resolution, ending with the drafting of an impact card of the marble produced in a given company.

Figure 1

All these considerations may represent a first basis of discussion for a future revision of the Decision, which could therefore include among its criteria not only the proposed environmental data sheet - obtained with the introduced indirect method -, but also an equalization of the impacts of the transport phase. This sheet would have the advantage of including both energy and emissions incorporated in the product functional unit. We believe that the uniqueness of this study lies precisely in the reasons above.

The practicability of this method has been tested on a type of marble produced in the Custonaci basin, in Sicily.

To better highlight the limits of the recent EU Decision, from which the proposal presented stems, below we propose a critical analysis of the energy and environmental criteria that appear in that European document.

2. Energy and environmental criteria in the 2021/476 Decision

The EU Ecolabel criteria contained in the recent Commission Decision for hard coverings aim "… at promoting products that have a lower environmental impact along their life cycle, are produced using material efficient and energy efficient processes, with reduced emissions to air, and reduced water consumption. Considering efforts towards climate neutrality and the decarbonization of Union industry, limits have been set on process CO_2 emissions for combustion processes, and the use of renewable electricity and the calculation of the carbon footprint are incentivized by the award of points" (European Commission, 2021).

The criteria specifically seek to: (a) encourage energy-efficient production practices; (b) decrease emissions that cause relevant environmental issues such as, for instance, global warming, acidification and eutrophication, and that constitute a potential damage for human health; (c) foster water-efficient production methods; and (d) facilitate materials-efficient products. To this end, the criteria are specifically aimed at:

- establishing max thresholds for specific energy consumption where benchmarks may be developed, and asks for plans to decrease energy consumption where benchmarks cannot be derived;
- recognizing and recompense the employment of renewable energy sources;
- establishing specific targets for CO_2, SO_x, NO_x and dust emissions from processes in which fuel is burned. These objectives are verified by means of dedicated criteria, depending on the types of materials to be treated (Table 1).

2.1 *Some limitations of the criteria*

As it can be seen from Table 1, only the control of VOC emissions is common to all hard coating materials. These emission limits (including formaldehyde, after 28 days) are verified according to EN 16516. Air emissions of dust, HF, NO_x, and SO_x are included in the criteria only for ceramic and fired clay materials and for precast concrete or compressed earth blocks. For these materials the emissions are verified by test methods referring to international standards: in particular, EN 13284 for dust, ISO 15713 for HF, EN 14792 for NO_x and EN 14791 for SO_x. Specific mandatory emission limits and environmental excellence thresholds are also given in the Decision. It is worth noting that similar criteria are not covered for natural stone materials that are the focus of the present paper.

Table 1. Energy and pollutant emission criteria for hard-coating products established by Commission Decision (EU) 2021/476 (indicating the specific paragraph at which they are treated).

Materials	**Criteria for energy consumption and pollutant emissions**				
	VOC	**Energy and fuel**	**CO_2**	**Air emissions**	**Dust**
Natural stone	(1.3)	Energy consumption at the quarry (2.1) and the transformation plant (2.7)			Dust control at the quarry (2.4) and at the transformation plant (2.9)
Agglomerated stone based on resin binders	(1.3)	Energy consumption (3.1)			Dust control and air quality (3.2)
Ceramic and fired clay	(1.3)	Fuel consumption for drying and firing (4.1)	(4.2)	Emissions of HF, NO_x and SO_x (4.4)	(4.4)
Precast concrete or compressed earth blocks based on hydraulic binders or alternative cements	(1.3)	Energy consumption (5.5)	(5.2)	Emissions of NO_x and SO_x to air (5.3)	(5.3)

In terms of energy consumption, limits are given for agglomerated stone products (based on resin binders) in terms of specific electricity use not to exceed, set at 1.1 MJ/kg. Additional points are also attributable for improved performance. For ceramic and fired clay products, energy consumption is calculated in terms of relevant mandatory limits on fuel use for drying and firing. For precast concrete or compressed earth blocks, energy consumption must be claimed through the establishment of a program to monitor, record and (possibly) reduce it. Additional points could be claimed by companies that use renewable energy sources for a portion of the energy consumed (including electricity), or depending on how the renewable electricity is purchased, or if a carbon footprint analysis is performed for the product according to ISO 14067. CO_2 emissions for ceramics and fired clay are subject to mandatory limits or environmental excellence thresholds, per unit of product, based on the carbon intensity of the fuels used. For precast concrete or compressed earth blocks, CO_2 emissions must not exceed proper mandatory limits (or environmental excellence thresholds), calculated through Regulations (EU) 2019/331 or (EU) No. 601/2012 for cement clinker and lime, or through ISO 14067 Carbon Footprint for alternative cements.

In other words, for materials belonging to processed hard coating products, well-established limits and calculation methods are given for some important components of the environmental impact. On the other hand, for natural stone products (including marble), no particular limits are suggested either for energy consumption or for CO_2 emissions. In fact, for these materials only criteria not having specific limits for energy consumption in the quarry and in the transformation plant are contemplated. Moreover, these criteria simply require that a program be in place to monitor, record, and decrease specific energy consumption and specific CO_2 emissions, without indicating numerical values for limits or thresholds to be met. Should the company claim additional points, a carbon footprint analysis must be produced, in compliance with ISO 14067, or a Product Environment Footprint procedure. Moreover, while for some products benchmarks for pollutant emissions are expressly identified, for natural stone products - apart from VOCs - it is only indicated the possession, by the applying companies, of ISO 14001 and/or EMAS certifications (art. 1.7 of the Decision) related to the Environmental Management System, thus leaving to the companies the application of the analysis of the product life cycle. However, this criterion is optional.

2.2 A proposal for overcoming the limitations of the criteria

The new Decision has certainly improved the assessment of the environmental and energy performance of hard covering products. However, some aspects need to be further analyzed, with particular regard to natural stones, including marble. The processing chain of this product, in fact, is characterized by an energy consumption and an emission of pollutants that cannot be neglected, and that should be properly specified, although limits are not expressly indicated among the criteria of the Decision. Despite the fact that for natural stones values for polluting emissions (whose determination would imply the application of laborious investigation methods using sophisticated equipment) are not explicitly indicated, fortunately, such emissions could be reported and calculated indirectly in relation to the energy sources involved in the process, thus allowing the definition of appropriate figures for these air releases. As for marble production, its extraction in the quarry generally requires the use of explosives, which, in turn, are responsible for the emission of a certain amount of air pollutants. Additionally, to better define the real impact of the natural stone processing chain, the role of transporting materials through companies' sites along their processing chains should also be defined.

To this end, an operational scheme can be set up to determine the pollutant emissions of the marble production phases (including the transport phases of the semi-finished product between the different sites of the same company), as shown in Figure 2. It is important to note that this scheme is in line with the criteria of the Decision. In fact, it starts with determining the types and quantities of energy sources involved in the working processes in the quarry and at the processing points. The energy consumption dependent on the movement of materials between sites of the marble working chain is given special attention. Thanks to the application of the indirect method proposed here, the polluting emissions connected with the energy sources used are determined. Referring to the energy related to the transformation points, we have not considered the use of on-site buildings and lighting systems: these energy consumptions, in fact, although relevant in a complete analysis of the company's efficiency, are strongly dependent on the number and characteristics of the owned houses and their lighting policies. Therefore, they are weakly correlated with the marble transformation operations. Consequently, in the application of this method aimed at defining the (sometimes hidden) polluting emissions of marble processing steps, they can be omitted without affecting its generality. Regarding the transportation of marble during the production process, we have not considered the amount of energy required to deliver the finished product to the transportation hubs. Similarly to the energy needed for administrative or lighting purposes, in fact, these consumptions do not depend on the internal layout of the site and, therefore, can be preliminarily omitted in the description of this simplified method.

Figure 2

The indirect method relies on information that can be obtained relatively easily from company managers or appointed technicians, based on the machinery operating in the supply chain and the means of transport that move the product along the processing stages.

Based on the operational scheme introduced above, a field analysis of a marble production site is presented here.

3. Field analysis of a marble productive site and its simplified environmental evaluation

The study refers to a company operating in the municipality of Custonaci and producing one of the most important Sicilian marbles on the market, the so-called "Perlato di Sicilia". The choice of the site stems from the circumstance that it is broadly representative of the various production companies in the district considered.

The analysis consisted of a preliminary cognitive investigation, also through direct interviews with the personnel in charge of the company (Raimondi, 2004), in order of singling out the production process phases and each island in which the marble is transformed from natural stone and dimensional stone to the finished product. Subsequently, a direct survey was conducted to both identify the machinery involved in the different phases and collect the power and energy data associated with them, along with their operating times. The transport phase of the marble along the production line was also analysed.

3.1 Description of energy sources involved in the work phases

The work chain of the company (whose average annual quantity of processed material is about 14,500 m^3) essentially consists of five operation phases: quarrying, cutting, finishing, plus two loading and transport sections, from quarry to cutting and from cutting to finishing, respectively (Figure 3).

Figure 3

The main equipment used in the quarry are drillers, to make vertical and horizontal holes in the mountain marble blocks (Figure 4), and diamond wire saws to slice them, both powered by electricity. There are also bulldozers and excavators powered by fossil fuels, particularly diesel oil, aimed at tipping the marble slices (Figure 5) and moving blocks within the quarry area (Figure 6).

Figure 4

Figure 5

Figure 6

Among the energy sources used in the quarry, explosives (black powder in this case) used to expand the cuts made by the diamond wire saw in the rock and to detach the slices from should also be mentioned.

As for the equipment used in the cutting phase, these are: marble block cutters (Figure 7) to obtain slabs and tiles; a splitter to produce tiles of reduced thickness; and equipment to move the semi-finished marble products within the processing plant area.

Figure 7

In the finishing phase, mainly electric machines are used for polishing slabs and tiles, (Figure 8) and equipment (mostly diesel oil-powered) whose purpose is to handle semi-finished marble products.

Figure 8

The amount of energy involved in the marble processing cycle in this company was essentially divided into two main categories: that required by the machinery operating in the processing islands and that used to handle the semi-finished and finished product through the different sections of the chain. The examined production process requires a total amount of energy of almost 14,565 GJ (*i.e.* 347 toe) annually, to produce 3,869 m^3 of tiles and 2,493 m^3 of slabs, resulting in specific values of primary energy of 3.20 GJ/m^3 for tiles and 0.91 GJ/m^3 for slabs (finished product), respectively (Table 2).

These figures, compared with the few literature data, show the considerable variability of the energy required to transform natural stone into finished marble products. In fact, referring to tiles, Gazi et al. (2012) report a value of 1.70 GJ/m^3, while Nicoletti et al. (2002) indicate a considerably higher value of 6.78 GJ/m^3. As for slabs, Gazi et al. (2012) report a value of 0.468 GJ/m^3, while the Carrara marble production district reports a value of 1.056 GJ/m^3. Many reasons could be adduced to explain these differences - although such comparisons are beyond the scope of this work - but essentially, they are due to the different impact of the transport phases and to the role of the operating machines in the quarry, which are sometimes very high, as in the case of the figure reported by Nicoletti et al. (2002).

Table 2. Overview of the use of energy for the production of "Perlato di Sicilia" of the considered enterprise.

	Amount of electric energy used [GJ_e/year]	**Amount of primary energy used (diesel oil)** [GJ_t/year]	**Amount of primary energy used (explosive)** [GJ_t/year]	**Total amount of energy consumed*** [GJ_t/year]

Quarrying	161	468	3.2	820
Cutting actvities	4,290	567	-	9,877
Polishing actvities	1,275	567	-	3,333
Transportation	-	535	-	535
Total	**5,726**	**2,137**	**3.2**	**14,565**

*Values were obtained by appropriately converting the electricity data in the second column into primary energy values through a coefficient that expresses the current conversion efficiency of the Italian national electricity production system (ARERA, 2008), i.e., 1 GJ_e=2.17 GJ_t.

As emerged from the field analysis, all the activities involved in the production process spend a certain amount of primary energy and/or electricity (together with a little amount of explosive) and, therefore, are responsible for a certain release of air pollutants. Consequently, neglecting the emissions associated with this energy consumption would underestimate the actual environmental impact of marble and, consequently, omit important components of the overall environmental performance of this product, in an excellence label such as the Ecolabel. Typically, these estimates are performed using expensive and complex field instrumentation capable of detecting the pollutants from the processing steps. Alternatively, these assessments can be obtained through the use of methods typical of LCA procedures, using some emission databases available in the literature. As said, both these procedures are however very laborious and badly adapted to the operational capabilities of companies with a very simple structure, as often are marble extraction ones. Consequently, such difficulties tend to exclude these companies from the possibility of obtaining important marks of environmental excellence, such as the Ecolabel, for their products. Likely, the singling out of the air pollutants deriving from each working island of the enterprise could be usefully realized through the amount and type of the involved energy consumption (as described in Figure 1). This simplified approach can allow the marble quarrying companies to evaluate with relative ease the environmental impact of their product. Below we propose a simplified method that, starting from the type and quantity of energy sources involved in the production of marble, allows to estimate the polluting emissions related to the processing chain of this product.

3.2 Pollution related to the energy sources involved: an indirect assessment

It should be noted that the emissions related to the electricity consumption represent indirect releases, in the sense that air pollutants are not directly emitted near the production sites but in the power plant that generates the electricity. Despite not being directly ascribable to the companies (and are reliant on the national fuel mix with which the electricity is produced), these emissions certainly contribute to define the overall environmental profile of the material/product. Consequently, they should be carefully evaluated together with direct emissions, *i.e.* those associated with fossil fuel consumption (diesel oil and explosive, in the present case) involved in the working chain of the marble in a given company, especially in view of the evaluation of the environmental excellence of a product, as the EU Ecolabel is supposed to do.

To this end, we propose an indirect evaluation method, able to take into account pollutant emissions related to both primary energy and electricity. The method is essentially based on the assessment of the amount of air pollutants, PE_i (for the i-th pollutant of the N total pollutants considered), emitted by the energy source involved, EV_k (for the k-th energy source of the M total energy sources considered), employed in the marble manufacturing process, and related to their emission factors, EF_k.

This logical nested structure is expressed by the algorithms of equations (1) to (N) that have been applied for computing the air pollutants related to the involved energy sources that, in turn, allow to fill out the marble impact sheet. In other words, the total emissions of each pollutant are given by summing those related to all the energy sources involved in the working process.

$$PE_{i=1} = \sum_{k=1}^{M} (EV_k|_{i=1} \;\; EF_k|_{i=1}) \tag{1}$$

$$PE_{i=2} = \sum_{k=1}^{M} (EV_k|_{i=2} \;\; EF_k|_{i=2}) \tag{2}$$

…..

$$PE_{i=N} = \sum_{k=1}^{M} (EV_M|_{i=N} \;\; EF_k|_{i=N}) \tag{N}$$

By using this simply indirect approach, which has a deterministic structure unlike that of heuristic methods (Abualigah et al., 2021; Abualigah et al., 2022; Oyelade et al., 2022), the environmental performance of the functional unit (1 m^3) of marble can be appraised. On purpose, three different sets of emission factors have been used (Table 3), one for each energy source involved in the process. As for the electric energy source, emission factors associated to the national Italian electric energy production were considered. In detail, reference was made to emission factors for electricity production and consumption in Italy (updated to 2019 and estimated for 2020) provided by ISPRA and TERNA S.p.A., which is the source of data on electricity production, heat production, and energy consumption of the country power plants (ISPRA-SINA, 2022a).

As for diesel oil, the database of average emission factors for road transport in Italy (ISPRA-SINA, 2022b) was used, based on the "EMEP/EEA Air pollutant emission inventory guidebook 2019" (EEA, 2019), and consistent with the 2006 IPCC Guidelines for greenhouse gas (IPCC, 2006), whose estimates were revised according to the update of the COPERT version 5.2.2 estimation model

(EMISIA, 2022). Finally, for emission factors related to the use of explosives, the fifth edition of AP-42, "Compilation of Air Pollutant Emissions Factors" (US EPA, 2022), was taken as a reference.

By using this simple indirect approach, it is possible to assess the environmental impact of all activities involved in the marble production that are associated with their energy use and, therefore, to get a more realistic view of the marble environmental impact.

Table 3 Emission factors related to electricity production, diesel oil, and explosive consumption used in this work, expressed in g/MJ.

	Pollutant (index *i*)									
Energy source (index *k*)	**CO_2** i=1	**NO_x** i=2	**SO_2** i = 3	**CO** i=4	**VOC** i=5	**NMVOC** i=6	**PM_{10}** i = 7	**$PM_{2,5}$** i= 8	**H_2S** i= 9	**CH_4** i =10
k = 1 Electric energy (ISPRA-SINA, 2022a)	73.98	0.06	0.01	0.03	-	0.02	$7\cdot10^{-4}$	-	-	0.18
k = 2 Diesel oil (ISPRA-SINA, 2022b)	74.31	0.93	$3\cdot10^{-4}$	0.18	0.05	0.04	0.04	0.04	-	$7.5\cdot10^{-4}$
k = 3 Black powder (explosive) (US EPA, 2022)	-	-	-	28.33	-	-	-	-	4.00	$7\cdot10^{-4}$

3.3 Energy and embedded pollution of marble: impact scorecard of the results

Following the operational scheme of Figure 2, it is possible to compile the marble impact sheets, both in terms of the quantity of energy involved in the process (embodied energy) and of polluting emissions released during the processing phase (embodied emissions), including the phase of the internal handling of the material. Table 4 shows the embodied energy and the embodied emissions of the two main types of products processed in the company in question, i.e. tiles and slabs.

Table 4 Overall marble impact sheet of the company considered.

		Tiles	**Slabs**
Embodied energy			
Amount of energy involved in the process	*index*		
Electric energy [GJ_e/year]	*k=1*	4938.86	852.72
Primary energy (diesel oil) [GJ_t/year]	*k=2*	1708.38	428.62
Primary energy explosive [GJ_t/year]	*k=3*	2.88	0.32

Total *[GJ$_t$/year]*		12428.59	2279.34
Specific *[GJt/year/m^3 of product]*		3.21	0.91
Embodied emissions			
Pollutant emissions (kg/year except for CO_2: tonn/year)	*index*		
CO_2	*i=1*	492.33	94.94
NO_x	*i=2*	1885.99	450.56
SO_2	*i=3*	66.55	11.54
CO	*i=4*	528.07	110.91
VOC	*i=5*	83.91	21.05
NMVOC	*i=6*	195.53	39.33
PM_{10}	*i=7*	74.09	18.30
$PM_{2,5}$	*i=8*	64.22	16.11
H_2S	*i=9*	11.52	1.28
CH_4	*i=10*	892.79	155.02

The level of detail of the data obtained through the method also allows to draw up even more detailed sheets that can identify the energy used and the emissions released by the individual processing phases for the two finished products (Table 4, in fact, contains such data for both tiles and slabs).

Furthermore, the method enables to monitor the environmental impact and energy consumption of each single processing phase, also with a view to intervening punctually on the cycle to improve its performance. On purpose, Table 5 shows the detailed values referred to tiles. Such analyses can more easily allow companies to identify (and correct) the most energy-consuming and polluting phases of the production chain.

As observed, at least in the field survey presented here, cutting and polishing activities turned out to be, for most pollutants, those responsible for the highest releases into the atmosphere. Particulalry, cutting activities are those characterized by the highest emissions, followed by polishing activities.

Table 5. Impact card of the marble products (tiles) of the company considered.

		Quarrying	**Cutting**	**Polishing**	**Transportation**	**Total**
Embodied energy	*index*					

Amount of energy involved in the process						
Electric energy [GJ_e/year]	*k=1*	144.90	3755.44	1038.52	0.00	4938.86
Primary energy (diesel oil) [GJ_t/year]	*k=2*	421.20	460.87	344.82	481.50	1708.38
Primary energy explosive [GJ_t/year]	*k=3*	2.88	0.00	0.00	0.00	2.88
Total *[GJ_t/year]*						12428.59
Specific *[GJ_t/year m^3 produced]*						3.21
Embodied emissions						
Pollutant emissions (kg/year except for CO_2: tonn/year)	*index*					
CO_2	*i=1*	42.02	312.08	102.45	35.78	492.33
NO_x	*i=2*	402.20	650.60	383.10	450.08	1885.99
SO_2	*i=3*	2.08	50.31	13.99	0.17	66.55
CO	*i=4*	163.44	184.21	91.21	89.20	528.07
VOC	*i=5*	20.69	22.64	16.94	23.65	83.91
NMVOC	*i=6*	21.19	113.76	40.51	20.06	195.53
PM_{10}	*i=7*	17.47	21.78	14.98	19.85	74.09
$PM_{2,5}$	*i=8*	15.83	17.32	12,96	18.10	64.22
H_2S	*i=9*	11.52	0.00	0.00	0.00	11.52
CH_4	*i=10*	30.92	671.07	187.20	3.59	892.79

Regarding the transportation, with reference to NO_x, VOC, PM_{10} and $PM_{2.5}$, this phase was responsible for higher emissions than extraction. This is essentially because the emission factors relating to electricity (used in the quarry) for these pollutants are lower than those relating to diesel oil (used for transport). However, an estimate of the error that could be made if the contribution of the transport to the total release of pollutants was not considered has been computed. It resulted that neglecting this segment would lead to important underestimates of the pollutant emissions, as reported in Table 6, separately for tiles and slabs. Errors referring to the SO_2 and CH_4 releases are not indicated since their amounts involved in this phase are negligible compared to the other ones, while error values referring to H_2S are not reported since this pollutant only applies to the quarrying.

Table 6 Percentage errors in the evaluation of the emissions of the main pollutants when neglecting the contribution of the transport phase.

	Percentage errors neglecting the transport phase	
	Tiles	*Slabs*
Pollutants		
CO_2	7 %	4%
NO_x	24 %	11%
CO	17 %	9%
VOC	28 %	12%
NMVOC	10 %	6%
PM_{10}	27 %	12%
$PM_{2.5}$	28 %	12%

Datasheets like those in Tables 4 and 5 could usefully be included among the criteria that marble companies must meet to apply for the Ecolabel awarding. Clearly, other impacts could be added to the sheets - such as water consumption, waste produced, noise pollution - to embody in them the criteria already provided for in the EU Decision 2021/476.

4. Discussion

As a general consideration, it must be noted that in this study - which is a sort of simplified LCA conducted from cradle to gate – mainly related to the effects of the types of energy employed in the process - the marble use and disposal phases are excluded: this is consistent with the Decision’s approach that for the "fitness for use" does not indicate specific criteria for the energy use and pollutant emissions. Therefore, energy consumption and polluting emissions connected with product maintenance such as polishing and buffing, and waxing are not calculated here.

Concerning the limits of the proposed approach, two main criticalities emerge, which depend on the limitations of the actual state of the research. These limitations refer to the actual knowledge of the emission factors, on which the method strongly depend. That is:

a) the current scarce availability of the emission factors of fuels;

b) the lack of specific attention to the type of explosives used in the quarry, along with their emission factors.

As for point a), it is necessary to reflect on the availability in literature of emission factors of pollutants of the energy sources used in the marble working process; such factors should be officially released and widely recognized by users. As mentioned earlier, in the present application we have used databases very popular in the scientific literature but, despite their wide diffusion, a careful attention on their direct applicability to the marble production chain must certainly be posited. For instance, the emission factors of the fuels used for transport are typical of engines of the European automotive scenario: their uncritical extension to other regional situations is therefore problematic. It should also be noted that, regarding the calculation of emission factors related to the unit of electrical energy, the mix of the composition of its kWh must be carefully considered, to accurately identify the energy mix that generates it from year to year. At this regard, the definition of the rate of imported electricity and not produced in the country where the marble company is located has to be included: this, in fact, would lead to emission factors of this form of energy different from those of the country where the companies operate. Moreover, the possible contribution of renewable sources in generating the mix of electric energy should also be considered, since the pertinent emission factors would change consequently.

As for point b), it would be necessary to know more precisely the type of explosives used by the companies to separate the marble slabs from the mountain, to identify more accurately the related polluting emissions: this information, in fact, is not easily achievable from the companies. Moreover, it is important to conduct an in-depth study of the emission factors of these explosives. In this study, the factors proposed by the "Compilation of Air Pollutant Emissions Factors", particularly the Fifth Edition of AP-42, were tentatively used. However, these databases report explosives emission factors only for some substances (CO, NO_x, CH_4, H_2S): the possible availability of emission factors referring to other pollutants should be further investigated.

Apart from what has already been observed above on the phase of transport of the semi-finished material, it should be highlighted another position of the Decision about this phase of the working process that can lead to unbalanced evaluations of the product environmental impact. In fact, the Decision (point 2.11) in its optional manner of considering the role of transport, introduces the possibility of assigning up to five additional points to companies that transport products from the quarry to the processing plant for less than 260 km. Anyway, this criterion puts at the same level all companies that handle materials below this distance: from this point of view, the criterion does not seem sufficiently fair. In order not to harm companies because of the distances over which they are obliged to move products, but to consider anyway the efficiency and impact of the means of transport they use, it could be proposed to adopt a specific indicator of the fuel consumption per unit of distance ($MJ/m^3/km$). By means of such modification, within the indirect method here introduced, it would be feasible to get an assessment of the polluting emissions from transport for homogenously comparing the performance of different sites that are obliged to handle the intermediate product over different distances.

It should also be noted that, in perspective, another problem emerges that requires a revision of marble quality marks, to which the method introduced here may provide a solution. In fact, increasingly, products (and marble among them) are processed in districts that group together different companies producing the same product. Therefore, a mark of excellence for products should be attributed to the whole cluster of companies instead to a single one. But companies belonging to a given district can achieve different scores among them within the Decision scheme; one of the reasons could depend on the fact that each company could be obliged to cover different distances in the transport phase, in this way possibly achieving different scores. This problem could be solved by using the new indicator here introduced that evaluates the specific pollutant emissions (emissions per km) related to the transportation segment: this would make comparable the emissions of the cluster of companies of a given district, at least for the transportation phase. As for the attribution of an excellence brand to a whole district, its scoring could be tentatively represented by the average of the scores obtained by each individual company, weighted on the amount of marble produced. Obviously, this is only a proposal that certainly needs further checks on the field: anyway, the structure of the simple method here proposed seems to be able to comply also with these incoming problems.

5 Conclusions

This work arose from the consideration that, in the context of the criteria for assigning the EU Ecolabel to marble, the phase of transporting the material between the different workstations of a company was not taken into due consideration. Moreover, some of the criteria proposed in the Decision 2021/476 require the accomplishment of the ISO 14001 and the EMAS certifications, as well as of the ISO 14067 and the Product Environment Footprint procedure, the full application of which, due to their complexity, is beyond the operational capacity of companies, often managed at family level.

To overcome these difficulties, a simplified assessment method has been proposed that allows to determine the pollutant emissions related to the marble processing cycle simply starting from the types and quantities of energy related to it. The method, among other things, makes it possible to consider the indirect emissions of the production cycle, such as those related to the employed electricity that is usually generated far from the working sites.

The practicability and the effectiveness of the method have been verified through a field application, concerning a natural stones extraction and processing company operating in the

Custonaci marble basin, in Sicily, which produces marble slabs and tiles. As demonstrated by the application, the transport phase is not negligible in the evaluation of both the energy used in the whole working cycle and all the related polluting emissions. In the case of tiles, the energy used in the transport phase accounts for 28.2% of the total energy used. This value has repercussions on the evaluation of emissions of individual pollutants: in fact, it implies a release of 28.3% of NO_x, 28,2% of $PM_{2.5}$, 28,1 % of VOC, 26,8 of PM_{10}, 16,8% of CO, 10,2% of NMVOC, 7,2% of CO_2. Similar differences have been found for the case of slabs. Clearly, disregarding these contributions would lead to a considerable underestimation of the overall environmental impact of the marble production chain that a mark of environmental excellence, such as the Ecolabel, cannot neglect.

In addition, among the main results of this study, and thanks to the structure of the proposed method, it should be noticed the possibility to draw up an overall evaluation sheet of the material. In this way, it is possible to obtain a complete card of the energy and environmental performance of the material that provides indications useful to likely enhance the performances of its working cycle.

The structure of the method itself (which allows to reveal some "hidden" components of the pollutant emission properties of marble) has led to the introduction of the concept of embodied pollutant emissions in a given material (here marble), to be added to that of embedded energy already widely used by researchers. In other words, with this simple procedure, companies can take advantage of an approach that is very close to the typical LCA one, avoiding at the same time its intrinsic complexity.

Moreover, the proposed approach represents an enhancement of the Decision 2021/476 which, currently, does not include - except optionally - the assessment of pollutant emissions from the manufacturing process (other than the release of some limited substances, such as VOC and CO).

Further research is certainly needed in this field, particularly in relation to the more precise definition of emission factors of energy sources and explosives used in the marble working process. In addition, the issue of the attribution of emissions associated to transport must be particularly investigated, in order not to excessively penalize companies which, due to the dislocation of their work stations, are obliged to move their intermediate products over longer distances than other companies whose work stations are closer.

However, already at present, this method could be included among the criteria for the attribution of the EU Ecolabel to natural stones. Its adoption, in fact, while safeguarding the importance of the environmental assessment of the "marble" product, would facilitate and encourage companies to apply for the Ecolabel, which would provide them with significant commercial advantages.

The authors therefore believe that this indirect method of evaluation of polluting emissions, based on the type and quantity of energy sources used in the production cycle (together with the evaluation of the impacts produced by the transport phase of semi-finished products), could be a useful starting point for a future revision of the criteria for the attribution of the Ecolabel to marble.

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FIGURES’ CAPTIONS

Figure 1. Logical flow of the proposal introduced in this work.

Figure 2 Proposal of a methodological scheme for the evaluation of air pollutants from marble production.

Figure 3 Main activities of the analyzed site, from quarrying to the final product.

Figure 4. Enlarged cut of the marble vain in the quarry.

Figure 5. Marble slice tipping operation.

Figure 6. Handling and loading blocks onto transport vehicles.

Figure 7. Block cutting machine.

Figure 8. Polishing machine.

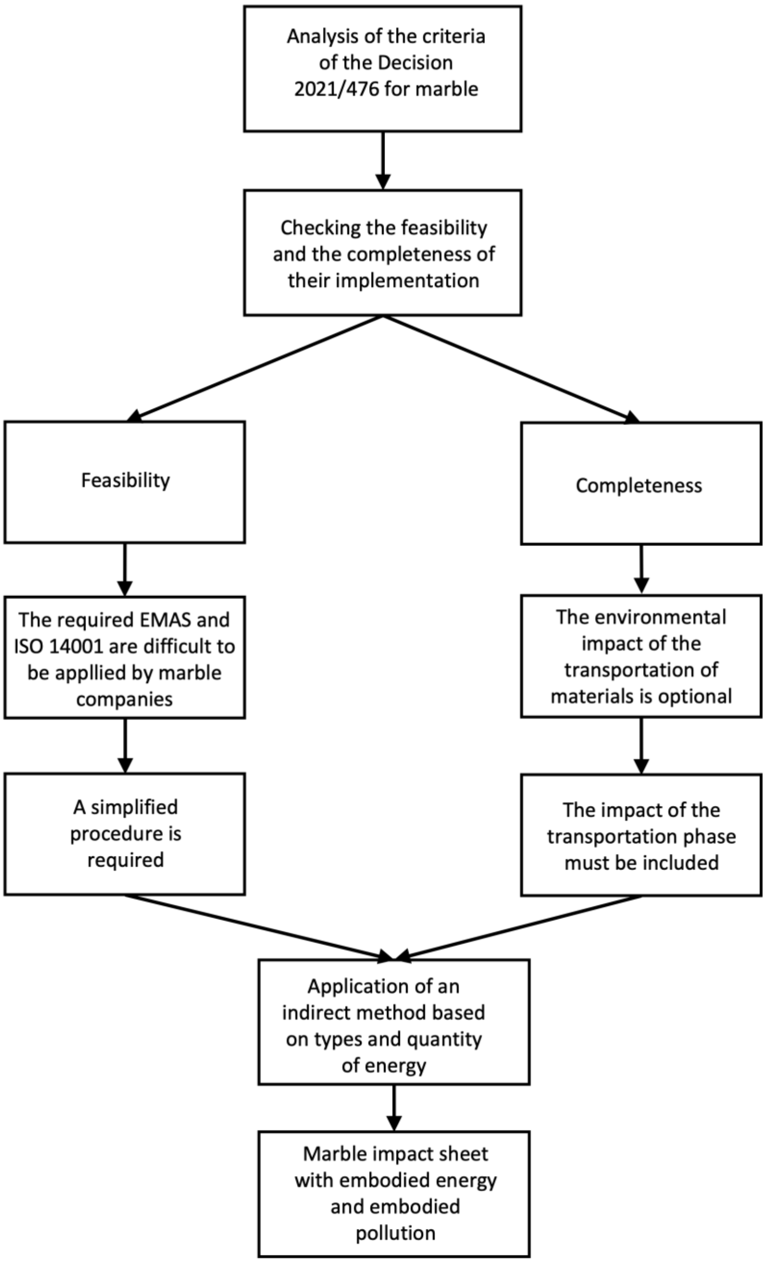
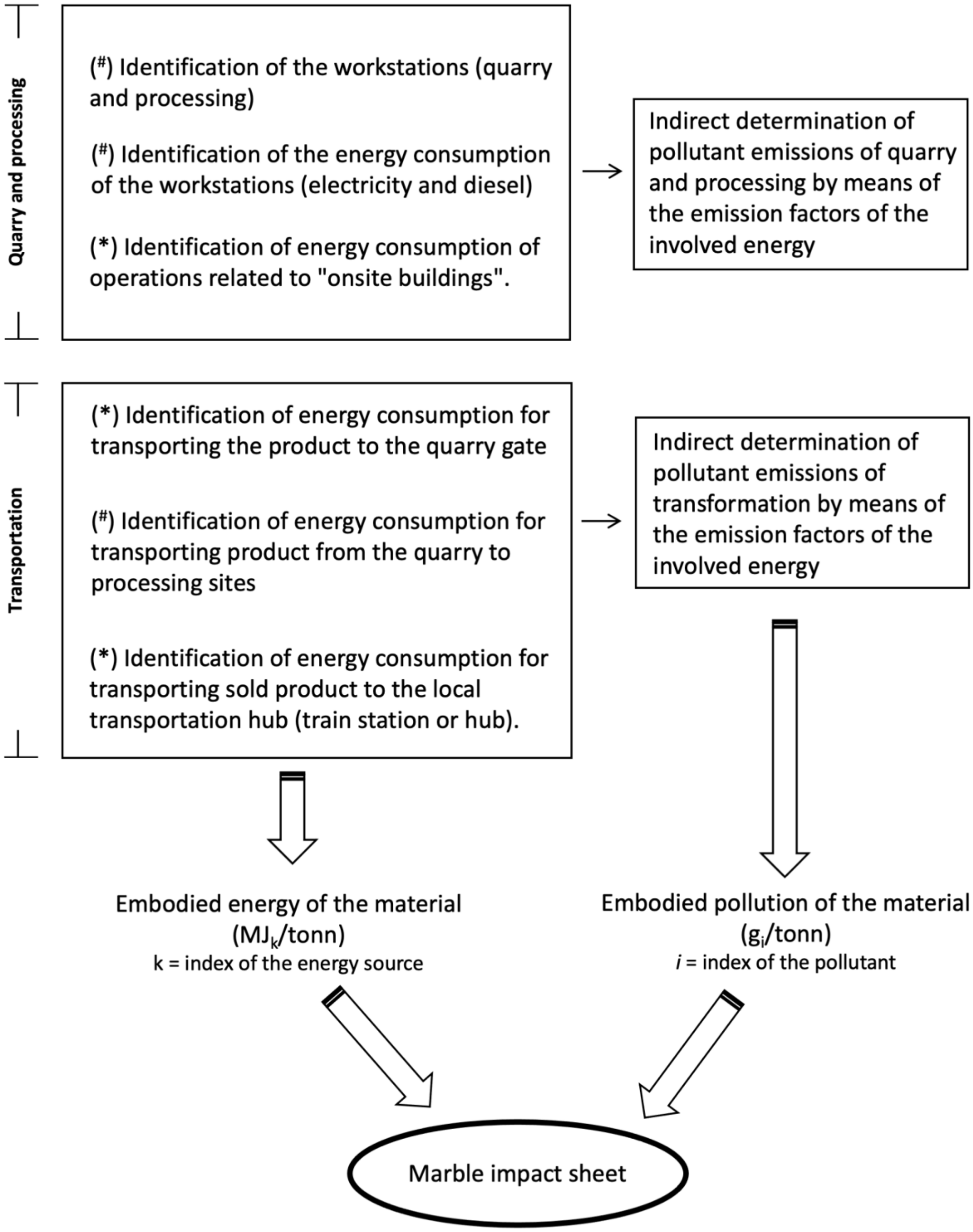

Analysis of the criteria of the Decision 2021/476 for marble
Checking the feasibility and the completeness of their implementation
Feasibility
Completeness
The required EMAS and ISO 14001 are difficult to be appllied by marble companies
The environmental impact of the transportation of materials is optional
A simplified procedure is required
The impact of the transportation phase must be included
Application of an indirect method based on types and quantity of energy
Marble impact sheet with embodied energy and embodied pollution

Figure 1



(*) Step contemplated in the Decision and not applied in the proposed simplified procedure

(#) Step contemplated in the Decision and applied in the present scheme

Figure 2

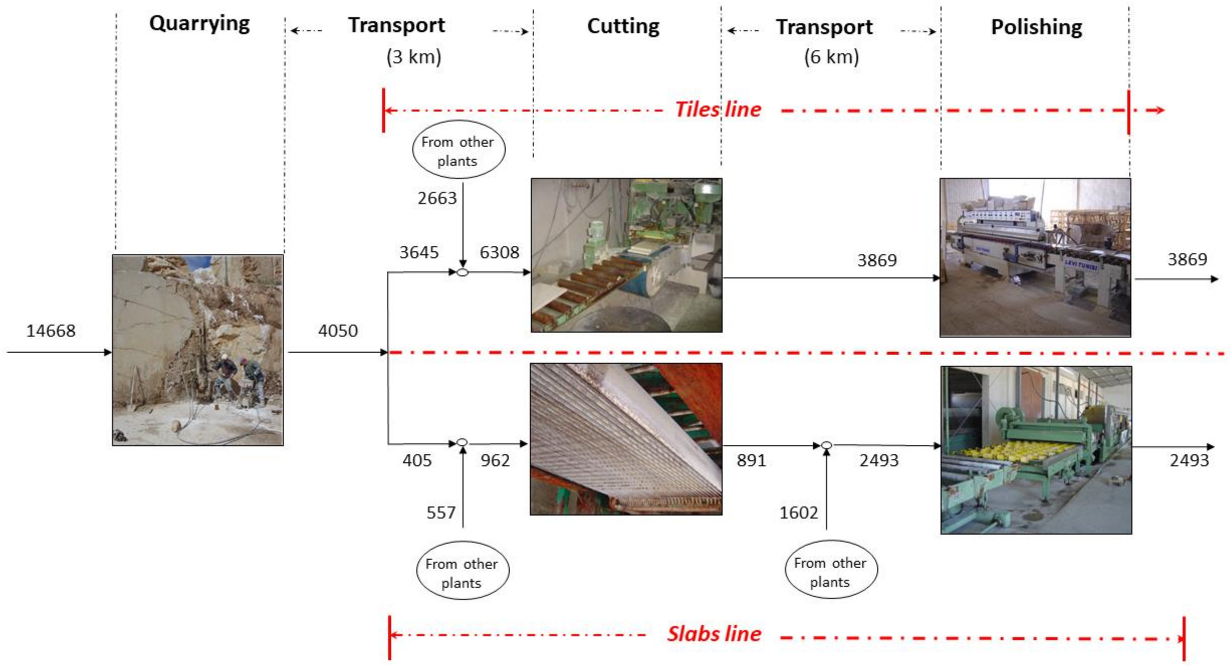

Quarrying
Transport
(3 km)
Cutting
Transport
(6 km)
Polishing
Tiles line
From other plants
2663
3645
6308
3869
3869
14668
4050
405
962
891
2493
2493
557
1602
From other plants
From other plants
Slabs line

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8