Life Cycle Inventory of technologies for stone quarrying, cutting and finishing: Contribution to fill data gaps

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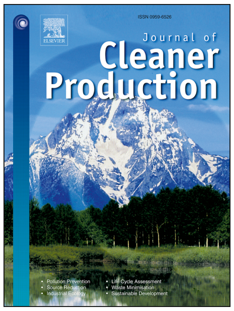

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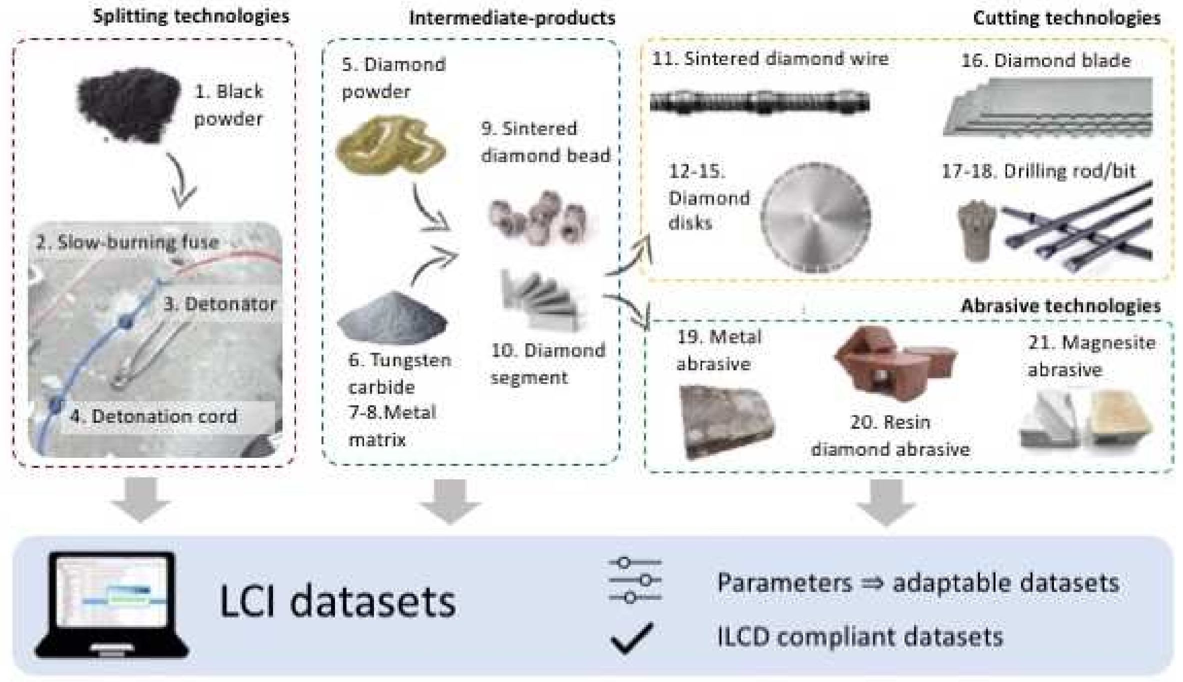
HIGHLIGHTS

- Life Cycle Inventory datasets on dimension stone technologies and tools
- LCI on explosives, abrasive technologies and intermediate products
- Inventory of technologies widely employed in stone and other sectors
- Parameters to adapt LCI datasets to specific technologies/tools

ABSTRACT

Italy is among the major producers of dimension stones and a world leader in terms of technologies for stone quarrying, cutting and finishing. In the current context of European Environmental and Raw Material policies, the stone sector is expected to enhance its overall sustainability and circularity. Previous studies have used Life Cycle Assessment (LCA) to evaluate the environmental performance of stone production, along the supply chain. Nevertheless, despite the fairly high level of maturity in terms of methodology, previous LCA studies have highlighted the scarce availability of Life Cycle Inventory (LCI) datasets related to stone sector technologies, which inevitably required the introduction of heavy simplifications. The present paper contributes to fill these gaps by providing detailed LCI datasets of the most common technologies and tools for stone quarrying, cutting and finishing. Datasets have been developed on the basis of primary data provided by three major Italian producers of cutting tools, complemented with secondary data from literature, where necessary. Moreover, modelling parameters have been set to enable the datasets update or their adaptation to specific production chains of the stone or other sectors. "Supplementary Material" provides details on the analysed technologies and on the related datasets (data sources, functional unit, system boundaries, Life Cycle models, parameters and uncertainty). Finally, LCI datasets are provided in file format as well.



KEYWORDS: dimension stone; Life Cycle Inventory; LCA; explosives; abrasive technologies; stone production chain

1. INTRODUCTION

The Italian territory features a significant lithological variety, which has been an important source of dimension stones all over the centuries. Italy is among the main stone producers and a world leader in terms of technologies for quarrying, cutting and finishing. The present paper specifically focuses on such technologies and provides datasets intended to facilitate the environmental profile measurement and to support a better sustainability of the stone sector. In fact, as declared in the Circular Economy Action Plan (European Commission, 2015), primary raw materials (which includes also dimension stones) *play an important role in production processes* and *attention must be paid to the environmental and social impacts of their production.* In this context, the European Union bases the Environmental and Raw Materials Policies on the consolidated Life Cycle Thinking (LCT) approach (European Commission, 2010), which consists in considering the entire life of products, services or projects to identify and reduce environmental, economic and social impacts all along the value production chain. To apply the concept of LCT to the stone sector, both techniques and technologies employed in the production chain should be investigated. In particular, techniques concern the operational way of carrying out quarrying, cutting and finishing processes, while technologies are basic tools and materials used to execute the techniques. For example, the main technique for marble quarrying consists in drilling intersecting holes along the edges of the bench, in order to create a close circuit where a wire is made rotating at high speed. This quarrying technique requires the use of different technologies, such as rods, bits and diamond wires.

In this context, to better understand and possibly improve the overall sustainability of the stone production chain, a fairly comprehensive and reliable inventory of energy, materials, emissions and waste involved during the technique execution and during the tools and machineries life cycle should be made available.

To turn the LCT approach into a quantitative assessment, different tools have been developed, the most known of which is Life Cycle Assessment (LCA). The Integrated Product Policy (European Commission, 2003) has identified LCA as the best framework to assess potential impacts of products and services and since that moment LCA has been more and more employed to boost the smart and sustainable growth of the European Union. LCA has been significantly implemented in some construction materials' sectors, such as in the ceramic, concrete and bricks sectors (Ibáñez-Forés and Bovea, 2016; Strazza et al., 2010; Torricelli et al., 2009), while in the dimension stone sector it has been relatively less employed. The limited number of LCA studies in this field could partially be ascribed to the high variability of the natural stone production chain (mainly related to the choice of techniques/technologies and to site-specific conditions) and, most probably, to the scarce availability of Life Cycle Inventory (LCI) datasets specific to the most common stone quarrying, cutting and finishing techniques and technologies. This lack of data is directly reflected in the LCA studies available for the stone sector, which have been necessarily simplified. Nicoletti et al. (2002) performed a LCA to compare ceramic and marble tiles, mainly based on energy and water consumption. Analogously, LCA studies have been developed by Traverso et al. (2010) who assessed the production of Perlato marble from Sicily, and by Torricelli and Palumbo (2016) who focused on the supply chain of Firenzuola stone from Tuscany. Nevertheless, also in these cases the assessments were mainly based on the input flows of energy and water resources, while impacts connected to the specific cutting technologies were not considered because of the unavailability of the related Life Cycle datasets. Similar studies have been developed in other stone production countries, such as Greece (Gazi et al., 2012), United Kingdom and Ireland (Crishna et al., 2011). Catarino et al. (2016) identified the main input/output flows of each unitary operation of the Portuguese marble production chain, but did not clearly disclosed the inventory. In 2012, a detailed LCI on the main techniques of the Brazilian stone production chain has been developed by the research centre CETEM of Rio de Janeiro (Castoldi Borlini Gadioli et al., 2012) and this same research group is currently updating the datasets. Nevertheless, since these datasets refer to the Brazilian average stone slab production, they are not necessarily representative of the Italian production. Mendoza et al. (2014) and Bai et al. (2016) disclosed LCIs and calculated the related potential environmental impact of the techniques employed respectively in the Spanish and Chinese granite production chains. However, in both cases, the LCA was developed including simplified datasets of the employed technologies, probably because of unavailability of more detailed data (e.g. the diamond wire was accounted as steel, while the diamond beads production was not considered).

The main novelty of this study is the development of detailed LCI datasets on the main quarrying, cutting and finishing technologies, which are produced and widely employed in Italy, as well as exported worldwide. This paper aims therefore at contributing to fill the gaps of representative LCI datasets in the stone sector by providing a set of data which are easily employable for the development of LCA studies tailored on specific production chains. A strength of this work is the introduction, in the provided LCI datasets, of editable parameters, which enable users to eventually update the datasets or to modify them according to specific production chains. Moreover, since analogous cutting technologies are employed also in other contexts (such as, for example, for building demolitions), these datasets could easily be adapted to other sectors. The inventory of each analysed technology is clearly quantified in this paper and is, as well, provided in file format in the Mendeley Data Repository, in order to allow its direct use in LCA software. Therefore, the availability of flexible and replicable datasets is expected to provide a practical support for the research on sustainability and circular economy and to increase the pool of publicly available data for specific applications in the stone and other sectors. Whereas technologies datasets are here presented, a companion paper (Bianco and Blengini, 2019) provides LCI data on the most common techniques used in the stone sector.

2. METHODOLOGY

The development of LCI datasets of technologies for stone quarrying, cutting and finishing has been carried out through the steps summarised in Fig. 1.

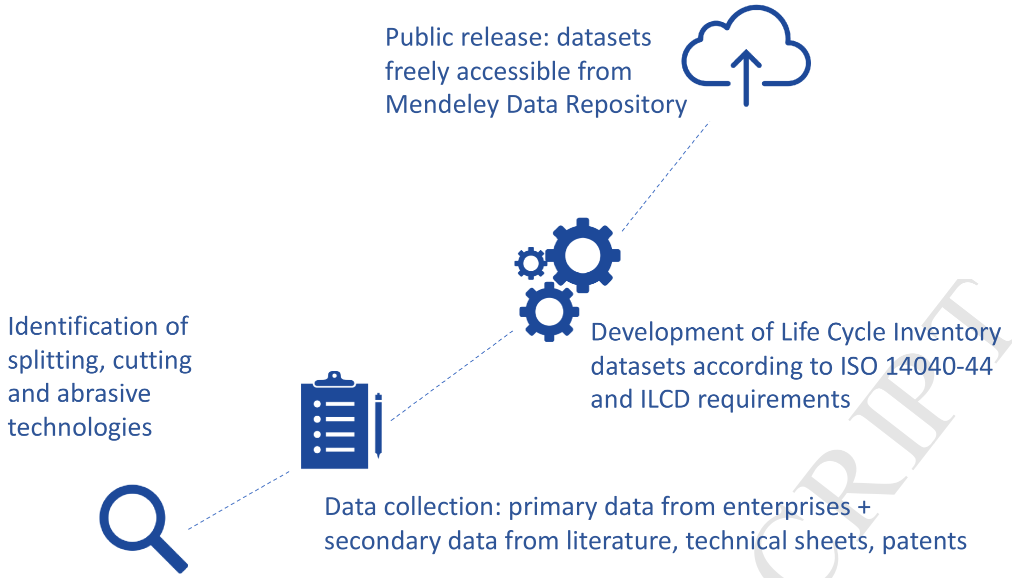


Figure 1: Scheme summarising the methodology followed for the development and share of the LCI datasets presented in this paper. The last step (in grey colour) will be accomplished in the next future.

Firstly, a preliminary investigation has been carried out in Italian quarries and transformation plants to identify the most widespread technologies employed in the ornamental stone sector. Since techniques and underlying technologies change mainly according to the hardness of the stone, the tools employed in both soft stones (such as marbles) and hard stones (such as granites) were investigated. In particular, on-site investigations took place in Piedmont and Tuscany regions and a literature review has been carried out to check if also in other Italian Regions the same technologies are used. The main literature sources have been Cardu (2013, 2012); Crivello (2012); Dadalto Sahao (2013); Giuffrida (2010); Gussoni (2016) Masciullo (2016); Primavori (2011, 1999).

Subsequently, it has been verified whether LCI datasets on the identified technologies or their components were already available in the main LCA databases. In particular, process datasets were searched in Gabi, Ecoinvent and ELCD databases. The production chain related to the unavailable LCI datasets has been further investigated through data collection with the aim of setting up good quality LCIs of the stone sector technologies.

To this aim, some enterprises producing stone quarrying, cutting and finishing technologies provided primary data. The enterprises that majorly collaborated to the project are Mega Diamant (Carrara, producing sintered diamond wire), Mimitalia (Vado Ligure, producing sintered tools) and Stein Varz (Crevoladossola, producing diamond cutting tools). Secondary data from scientific literature, patents and technical sheets were also employed for the datasets development.

Datasets were then developed according to ISO 14040-44 standards (The International Standards Organisation, 2006a, 2006b) and the requirements of format and quality defined in the International Reference Life Cycle Data System (ILCD) Handbook (European Commission, 2012). Therefore, the European Commission underlined the need and the importance of relying on uniform, consistent and good quality Life Cycle datasets (Recchioni et al., 2015) and, from 2014, developed the Life Cycle Data Network[1] (LCDN) to host compliant Life Cycle datasets. The developed datasets include input flows of materials, resources and energy and output flows of product, waste and emissions. As showed in Fig. 2, the processes of the waste treatment are included in the system boundaries only when, in the current practices, the waste is reintegrated in the same production chain. This is the case, for example, of diamond beads of cutting diamond wires: beads often have a lifetime longer than other components of the wire and are generally reused several times for the production of new diamond wires. On the contrary, waste that leave the stone

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[1] http://eplca.jrc.ec.europa.eu/LCDN/

production value chain is quantified, but no credits or debits are associated to it in the developed datasets. This choice is justified by the high variability of waste treatment, recycle, reuse or discard practices that would compromise the representativeness of the dataset.

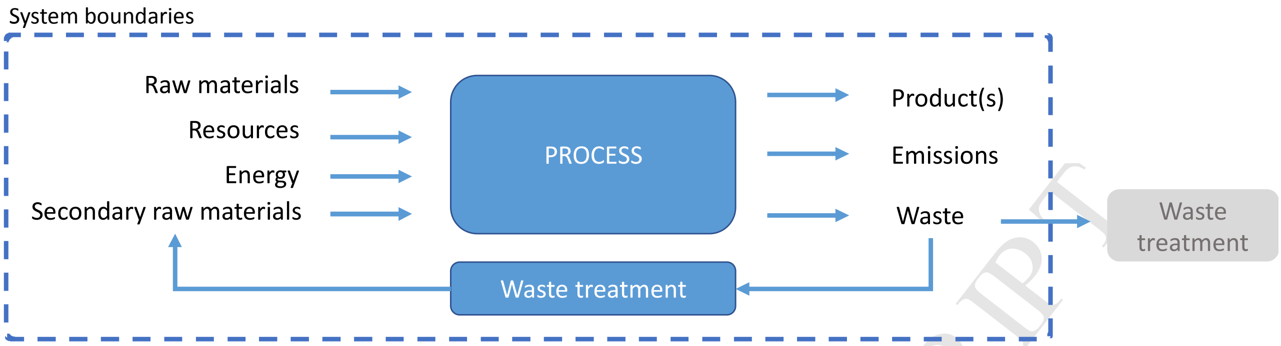

Figure 2: System boundaries of the developed LCI datasets.

The values of input/output flows are the average of the collected data. Primary data from Italian tools producers have been preferred when available; secondary data from literature, technical sheets and patents have also been used to both complete and cross check primary data. The specific source(s) of data are detailed in the Supplementary Material. In addition, for each input/output flow, data quality information is provided to easily identify the level of datasets reliability. To this aim, the well-established Ecoinvent pedigree matrix (Weidema et al., 2013) has been used for the assessment of data sources quality. As showed in Fig. 3, the pedigree matrix allows to evaluate the data sources according to five independent characteristics (reliability, completeness, temporal correlation, geographic correlation and further technological correlation) and each of them is rated with a score from 1 to 5 (where 1 corresponds to the highest quality and 5 to the worst one, as described in Fig. 3).

Reliability	Verified data based on measurements	Verified data partly based on assumptions or non-verified data based on measurements	Non-verified data partly based on qualified estimates	Qualified estimate (e.g. by industrial expert)	Non-qualified estimates
Completeness	Representative data from all sites relevant for the market considered, over and adequate period to even out normal fluctuations	Representative data from > 50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from only some sites (<< 50%) relevant for the market considered or > 50% of sites but from shorter periods	Representative data from only one site relevant for the market considered or some sites but from shorter periods	Representativeness unknown or data from a small number of sites and from shorter periods
Temporal correlation	Less than 3 years of difference to the time period of the data set	Less than 6 years of difference to the time period of the data set	Less than 10 years of difference to the time period of the data set	Less than 15 years of difference to the time period of the data set	Age of data unknown or more than 15 years of difference to the time period of the data set
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown or distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia)
Further technological correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study (i.e. identical technology) but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials	Data on related processes on laboratory scale or from different technology

Figure 3. Ecoinvent pedigree matrix. In the example showed in the Figure, the data quality can be summarized as (4,3,2,5,1).

With the support of Gabi software both Unit and System processes[2] have been developed. Specifically, Unit processes enable the user to transparently identify and quantify input/output flows involved in each technology. Moreover, Unit processes contain parameters that facilitate the eventual update of the dataset or its adaptation to specific production chains. For example, the dataset of diamond disks can be easily customized in function of the disk diameter, the thickness of the steel core, the number and dimensions of diamond segments, etc. Parameters could therefore enable the datasets to be used also in reference to analogous cutting technologies used in other sectors (such as the Construction and Demolition sector). On the other hand, system processes are provided for users that prefer to directly employ the datasets without modifications, avoid the connection with background datasets or limit the size of the file model.

The inventory of these datasets is quantified in detail in the next paragraph, while the file format of Unit and System datasets is available in the Mendeley Data Repository connected to this paper. Additional information on the tools production chain and on the datasets modelling are provided in the "Supplementary Material".

3. RESULTS: LCI DATASETS

Datasets presented in this paper are summarized in Fig. 4. The most common technologies for stone quarrying, cutting and finishing have been considered. Since some technologies are often employed in more

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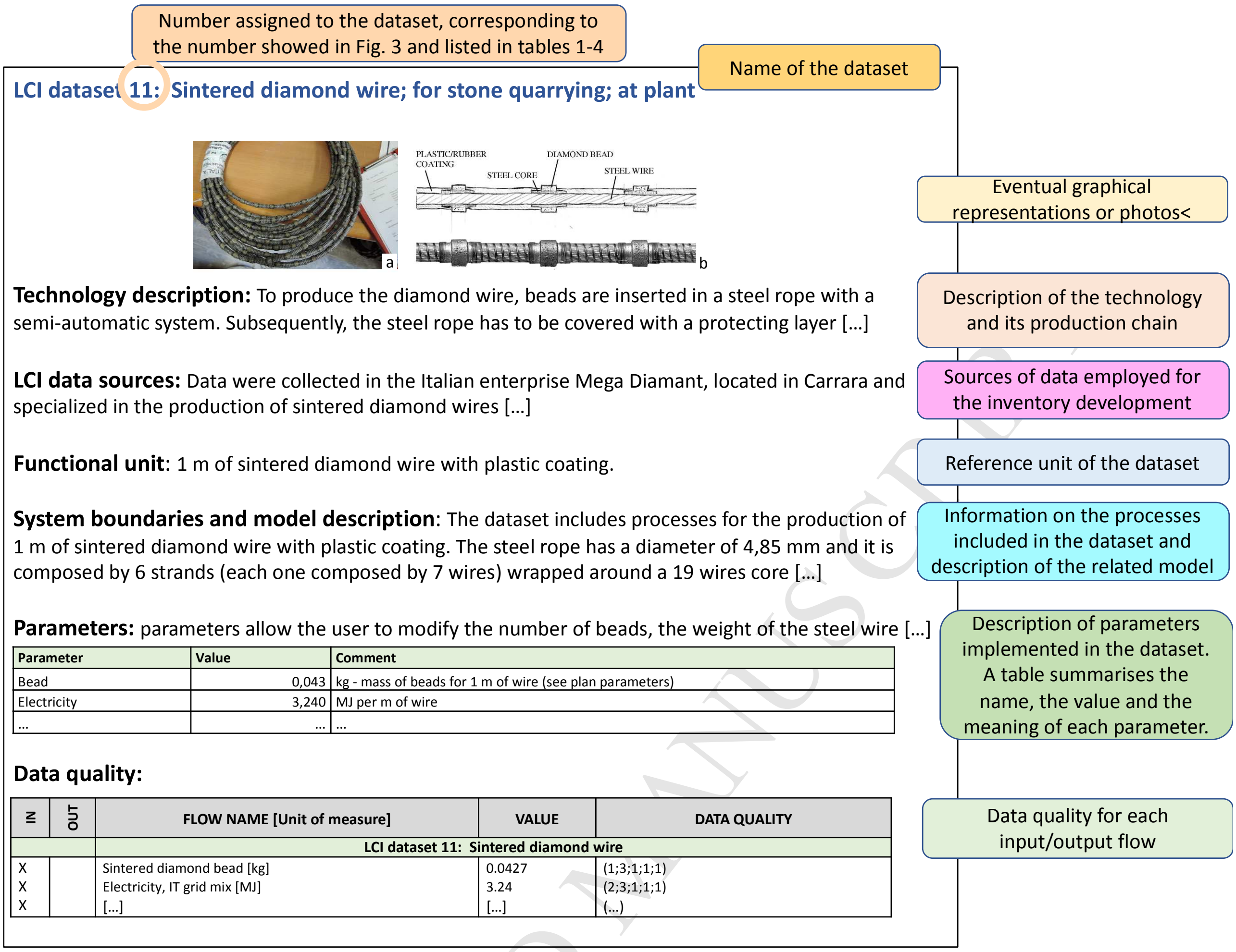
[2] A "unit process" is a gate-to-gate process, where input and output data are quantified with product flows and eventual elementary flows; a "system process" is an element with an aggregated inventory, where input and output data are all expressed as elementary flows.

than one phase of the stone production chain, technologies are here subdivided into: (i) explosives: tools used to create a controlled explosion and generally employed during the quarrying phase; (ii) abrasive technologies: tools providing mechanical abrasion, employed during all the three phases of stone production chain; (iii) intermediate products: semi-finished products necessary for the production of the before mentioned technologies. Fig. 4 indicates, as well, the stone production phase(s) during which the different explosive and abrasion technologies are used. Moreover, as it can be noticed, some intermediate products concur to the production of different tools, such is the case, for example, of the diamond powder. For each developed dataset, additional information is provided in the "Supplementary Material". Specifically, datasets sheets are organised as shown in Fig. 5 and contain details on the technologies production chains, data sources, functional unit, system boundaries, life cycle model, parameters and uncertainty.

Figure 4: Scheme summarizing the LCI datasets described in this paper. Technologies are divided into explosives, intermediate products and abrasive technologies. In brackets is indicated the phase of the stone supply chain during which the finished tools are usually employed (Q= quarrying; C = cutting; F = finishing).



Number assigned to the dataset, corresponding to the number showed in Fig. 3 and listed in tables 1-4

Name of the dataset

LCI dataset 11: Sintered diamond wire; for stone quarrying; at plant

Eventual graphical representations or photos<

Technology description: To produce the diamond wire, beads are inserted in a steel rope with a semi-automatic system. Subsequently, the steel rope has to be covered with a protecting layer […]

Description of the technology and its production chain

LCI data sources: Data were collected in the Italian enterprise Mega Diamant, located in Carrara and specialized in the production of sintered diamond wires […]

Sources of data employed for the inventory development

Functional unit: 1 m of sintered diamond wire with plastic coating.

Reference unit of the dataset

System boundaries and model description: The dataset includes processes for the production of 1 m of sintered diamond wire with plastic coating. The steel rope has a diameter of 4,85 mm and it is composed by 6 strands (each one composed by 7 wires) wrapped around a 19 wires core […]

Information on the processes included in the dataset and description of the related model

Parameters: parameters allow the user to modify the number of beads, the weight of the steel wire […]

Parameter	Value	Comment
Bead	0,043	kg - mass of beads for 1 m of wire (see plan parameters)
Electricity	3,240	MJ per m of wire
…	…	…

Description of parameters implemented in the dataset. A table summarises the name, the value and the meaning of each parameter.

Data quality:

IN	OUT	FLOW NAME [Unit of measure]	VALUE	DATA QUALITY
		LCI dataset 11: Sintered diamond wire		
X		Sintered diamond bead [kg]	0.0427	(1;3;1;1;1)
X		Electricity, IT grid mix [MJ]	3.24	(2;3;1;1;1)
X		[…]	[…]	(…)

Data quality for each input/output flow

Figure 5. Information provided in the Supplementary Material for each developed LCI dataset.

3.1 LCI of explosives in the dimension stone sector

Explosive tools are commonly employed in hard stone quarries to open benches and divide them into smaller commercial blocks. The most widespread technologies to perform a controlled splitting are black powder, detonating cords of penthrite, slow-burning fuses and detonators. These same tools are commonly employed also in other mining processes and in civil demolitions. Since Life Cycle databases do not currently include datasets on these tools, specific inventories have been developed, whose detailed input/output flows are gathered in Table 1 (LCI datasets 1-4). Reference processes from Gabi, Ecoinvent and ELCD databases are proposed.

INPUT	OUTPUT	FLOW NAME [Unit of measure]	VALUE	LCI DATASETS OF REFERENCE
		LCI dataset 1: Black powder		
X		Potassium nitrate [kg]	0.75	Ecoinvent: potassium nitrate, as N, at regional storehouse
X		Charcoal [kg]	0.14	Ecoinvent: charcoal, at plant
X		Sulphur [kg]	0.11	Gabi: Sulphur (elemental) at refinery
X		Electricity, IT grid mix [MJ]	0.152	Gabi: IT Electricity grid mix

X		Transport, lorry [kg*km]	1000	Gabi: Lorry transport
	X	Black powder [kg]	1	-
	X	Carbon dioxide [kg]	0.219	Elem. flow: Carbon dioxide, fossil [emission to air]
	X	Nitrogen [kg]	0.058	Elem. flow: Nitrogen, atmospheric [emission to air]
	X	Heat, waste [MJ]	3	Elem. flow: Heat, waste [emission to air]
	X	Potassium sulphate [kg]	0.434	Elem. flow: Sulfuric acid [emission to air]
		LCI dataset 2: Slow-burning fuse		
X		Black powder [kg]	0.011	Ecoinvent: potassium nitrate, as N, at regional storehouse
X		Cotton [kg]	0.001	Ecoinvent: charcoal, at plant
X		PVC [kg]	0.016	Gabi: Sulphur (elemental) at refinery
X		Transport [kg*km]	28	Gabi: Small lorry (7.5t) incl. fuel
X		Oil [kg]	0.002	Ecoinvent: lubricating oil, at plant
	X	Slow burning fuse [m]	1	-
		LCI dataset 3: Detonator		
X		Aluminium [kg]	0.001	Gabi: Aluminium extrusion profile mix
X		Transport [kg*km]	2	Gabi: Small lorry (7.5t) incl. fuel
	X	Detonator [pcs]	1	-
		LCI dataset 4: Detonation cord		
X		Pentaerythritol [kg]	0.0017	Ecoinvent: penta-erythritol, at plant
X		Nitric acid [kg]	0.0067	Gabi: Nitric acid (98%)
X		Toluene [kg]	0.0016	Gabi: Toluene
X		Polypropilene [kg]	0.018	Gabi: Polypropylene / Ethylene Propylene Diene Elastomer Granulate (PP/EPDM, TPE-O) Mix
X		Transport [kg*km]	14	Gabi: Small lorry (7.5t) incl. fuel
	X	Detonation cord; at quarry [m]	1	-

Table 1: Life Cycle Inventory of the main tools employed in hard stone quarries to perform the dynamic splitting technique. The data sources employed for the development of each dataset are the following. LCI datasets 1-2: Bacci, 2005; Davis, 1943; Evonik Industries, 2014; Reza et al., 2014; Selva and Nardin, 2013; von Maltitz, 2003. LCI dataset 3-4: Pravisani technical sheets; Palma Rojas et al., 2013.

3.2 LCI of intermediate products

The production of tools employed in the ornamental stone sector requires the use of different materials and intermediate products, some of them highly widespread also in other sectors. Since for some relevant components little or even no data are currently available in Life Cycle databases, the related production chains have been investigated as well and the resulting inventories are quantified in Table 2. In particular, LCI datasets have been developed on synthetic diamond powder (LCI dataset 5), a material largely employed for the production of abrasive tools, tungsten carbide (LCI dataset 6), employed in many different sectors for its hardness; two different composition of metal matrices (LCI datasets 7-8), widely used to produce cutting elements such as diamond segments (LCI dataset 10). Finally, the diamond powder is employed for the production of the diamond beads (LCI dataset 9), which are the cutting elements of diamond wires employed in stone quarries and transformation plants, but also for civil demolitions.

INPUT	OUTPUT	FLOW NAME [Unit of measure]	VALUE		LCI DATASETS OF REFERENCE
		LCI dataset 5: Diamond powder			
X		Electricity, IT grid mix [MJ]	3024		Ecoinvent: electricity, production mix CN
X		Graphite [kg]	1		Ecoinvent: graphite, at plant
X		Transport, transoceanic ship [kg*km]	170000		Ecoinvent: transport, transoceanic freight ship
X		Transport, lorry [kg*km]	0.063		Ecoinvent: transport, lorry 16-32t, EURO4
	X	Diamond powder [kg]	1		-
		LCI dataset 6: Tungsten carbide (WC)			
X		NaOH [kg]	0.91		Ecoinvent: Sodium hydroxide, 50% in H2O, production mix, at plant/RER
X		$Al_2(SO_4)_3$-18H_2O [kg]	0.071		Ecoinvent: Aluminium sulphate, powder, at plant/RER
X		Sodium sulfide [kg]	0.044		Ecoinvent: Sodium sulphide nanohydrate
X		$Mg(SO_4)$-7H_2O [kg]	0.027		Ecoinvent: Magnesium sulphate, at plant/RER
X		Ammonium hydroxide [kg]	0.106		Ecoinvent: Ammonia, liquid, at regional storehouse/CH
X		Soda ash [kg]	1.21		Ecoinvent: Soda, powder, at plant/RER
X		Sulphuric acid [kg]	1.24		Ecoinvent: Sulphuric acid, liquid, at plant/RER
X		Electricity [MJ]	159		Ecoinvent: Electricity, medium voltage, production RER, at grid/RER
X		H_2 compressed gas [kg]	0.0076		Ecoinvent: Hydrogen sulphide, H2S, at plant/RER
X		N_2 compressed gas [kg]	1.65		Ecoinvent: Nitrogen, liquid, at plant/RER
X		H_2S liquefied gas [kg]	0.32		Ecoinvent: Hydrogen, liquid, at plant/RER
X		Electricity [MJ]	77.2		Ecoinvent: Electricity, medium voltage, production UCTE, at grid
X		NaOH [kg]	0.58		Ecoinvent: Sodium hydroxide, 50% in H2O, production mix, at plant/RER
X		Water [kg]	2.84		Ecoinvent: cooling water
X		Carbon black [kg]	0.13		Ecoinvent: carbon black, at plant
X		Electricity [MJ]	164		Ecoinvent: Electricity, medium voltage, production UCTE, at grid
	X	Tungsten carbide [kg]	1		-
		LCI dataset 7-8: Metal matrix for cutting tools			
			49%Fe-18%Co	**57%Fe-25%Co**	
X		Iron [kg]	0.49	0.57	Ecoinvent: iron ore, 65% Fe, at beneficiation
X		Cobalt [kg]	0.18	0.25	Ecoinvent: cobalt, at plant
X		Nickel [kg]	0.06	0.12	Ecoinvent: nickel, 99.5%, at plant
X		Copper [kg]	0.20	0.05	Ecoinvent: copper oxide, at plant
X		Tungsten carbide [kg]	0.04	0.01	Created: Tungsten carbide
X		Tin [kg]	0.03	0	Ecoinvent: tin, at regional storage

	X	Metal matrix; for diamond cutting tools [kg]	1	1	-
		LCI dataset 9: Sintered diamond bead			
X		Electricity, IT grid mix [MJ]	0.36		Gabi: Electricity grid mix
X		Steel core [g]	3		Gabi: Steel billet (20MoCr4)
X		Cobalt [g]	7E-05		Ecoinvent: cobalt, at plant
X		Copper [g]	0.00021		Gabi: Copper mix (99,999% from electrolysis)
X		Iron [g]	3.5E-04		Ecoinvent: pig iron, at plant
X		Nickel [g]	2.1E-05		Ecoinvent: nickel, 99.5%, at plant
X		Tungsten [g]	3.5E-05		Created (cf. Par. 5.2.6): Tungsten (W)
X		Diamond powder [g]	2E-05		Created (cf. Par. 5.2.9): Diamond powder
X		Thickener [kg]	2E-05		Gabi: Polymethylmethacrylate granulate (PMMA)
X		Hardener [kg]	5E-05		Ecoinvent: cobalt, at plant
X		Silver weld [kg]	2.1E-04		Ecoinvent: silver, at regional storage
X		Nitrogen [kg]	0.0323		Gabi: Nitrogen
X		Hydrogen [kg]	9E-04		Gabi: Hydrogen
	X	Sintered diamond bead; for quarrying [g]	4		-
		LCI dataset 10: Diamond sector			
X		Electricity [MJ]	255		Gabi: IT Electricity grid mix
X		Graphite [kg]	0.0394		Ecoinvent: graphite, at plant
X		Diamond powder [kg]	0.02		Created: Diamond powder
X		Metal matrix; for diamond cutting tools [kg]	0.98		Created: Metal matrix; for diamond cutting tools; Mix 57%Fe-25%Co or Metal matrix; for diamond cutting tools; Mix 49%Fe-25%Co
	X	Diamond sector; for cutting tools [kg]	1		-

Table 1: Life Cycle Inventory of intermediate-products for the production of cutting and finishing tools. The data sources employed for the development of each dataset are the following. LCI dataset 5: Ali, 2011; Larsson et al., 2009; www.searates.com. LCI dataset 6: Archer et al., 2003; Bobba et al., 2016; Dahmus and Gutowski, 2004; Novak et al., 2004; Syrrakou et al., 2005. LCI datasets 7-8: primary data from enterprises Stein Varz (Crevoladossola) and MIMitalia (Vado Ligure); Umicore-Tungsten technical sheets. LCI dataset 9: primary data from enterprises Mega Diamant (Carrara) and MIMitalia (Vado Ligure); Umicore-Tungsten technical sheets; Bobrovnitchii et al., 2003; de Oliveira et al., 2007; Karagöz and Zeren, 2001; Konstanty, 2007; Tillmann et al., 2010; Zeren and Karagöz, 2007, 2006. LCI dataset 10: primary data from enterprise Stein Varz (Crevoladossola); technical sheets of the enterprises Diam Edil (Lumino), Cuts Diamant (Noceto), Unidiamant (Carpaneto Piacentino).

3.3 LCI of abrasive technologies

Table 3 gathers the inventories related to the production chain of the most common abrasive tools employed in the ornamental stone sector. In particular, LCI datasets have been developed for the technologies of: sintered diamond wire (LCI dataset 11), highly widespread to separate soft stone benches from the quarry bedrock, divide them into blocks and square shapeless blocks; giant diamond disks (LCI dataset 12), commonly used in hard stone transformation plants to square shapeless blocks or to cut thick slabs according to the requests of customers; diamond disks of 400 mm diameter (LCI dataset 13) and 600 mm diameter (LCI datasets 14-15), commonly employed for cutting stone slabs into smaller parts. As explained in detail in the “Supplementary Material”, two datasets have been created for the 600 mm diameter disk because its performance (and as a consequence the quantities of its input/output flows during its lifetime) significantly changes according to a prevalent use with soft or hard stones. Diamond blade (LCI dataset 16) is a technology used for cutting soft stone blocks into slabs; rods (LCI dataset 17) and bits (LCI dataset 18) are the most common tools employed to perform holes drilling in soft and hard stone quarries. In addition, since the most common surface treatments for stone slabs are the smoothing and polishing processes, the related technologies have been investigated. In particular, LCI datasets have been developed on three types of abrasives: metal abrasive (LCI dataset 19), generally used for the smoothing phase; resin diamond abrasive (LCI dataset 20), which is the most common tool for the polishing phase; magnesite abrasive (LCI dataset 21), another polishing abrasive, currently less widespread than the resin diamond one.

INPUT	OUTPUT	FLOW NAME [Unit of measure]	VALUE		LCI DATASETS OF REFERENCE
LCI dataset 11: Sintered diamond wire					
X		Sintered diamond bead [kg]	0.0427		Created: Sintered diamond bead; for quarry diamond wires
X		Electricity, IT grid mix [MJ]	3.24		Gabi: IT Electricity grid mix
X		Steel rope [kg]	0.095		Gabi: Steel wire rod
X		Plastic coating [kg]	0.15		Gabi- PlasticsEurope: Polyurethane flexible foam (PU)
X		Lorry transportation [kg*km]	3		Gabi: Lorry transport
	X	Sintered diamond wire; for stone quarrying [m]	1		-
	X	Plastic waste [kg]	0.045		-
LCI dataset 12: Giant diamond disk					
X		Steel [kg]	12.4		Created: Sintered diamond bead; for quarry diamond wires
X		Diamond segment [kg]	12.4		Gabi: IT Electricity grid mix
X		Electricity [MJ]	515		Gabi: Steel wire rod
X		Transport [kg*km]	248		Gabi- PlasticsEurope: Polyurethane flexible foam (PU)
	X	Giant diamond disk [pcs]	1		-
LCI dataset 13: Diamond disk; d=400 mm					
X		Steel [kg]	1.39		Gabi: Stainless steel Quarto plate (304)
X		Diamond segment [kg]	0.504		Created: Diamond segment; for cutting tools; Mix 49%Fe-18%Co (or Mix 57%Fe-25%Co)
X		Electricity [MJ]	107		Gabi: IT Electricity grid mix
X		Transport [kg*km]	18.9		Gabi: Lorry (22t) incl. fuel
	X	Diamond disk; d=400 mm [pcs]	1		-
LCI dataset 14-15: Diamond disk; d=600 mm					
			Soft stone	**Hard stone**	
X		Steel [kg]	2.49	1.07	Gabi: Stainless steel Quarto plate (304)
X		Diamond segment [kg]	0.546	0.897	Created: Diamond segment; for cutting tools; Mix 49%Fe-18%Co (or Mix 57%Fe-25%Co)
X		Electricity [MJ]	149		Gabi: IT Electricity grid mix
X		Transport [kg*km]	72.8	19.6	Gabi: Lorry (22t) incl. fuel
	X	Diamond disk; d=600 mm [pcs]	1		-
LCI dataset 16: Diamond blade					
X		Blade diamond insert (sintered) [kg]	0.2		Created: Diamond segment; for cutting tools; Mix 49%Fe-25%Co
X		Stainless steel [kg]	14.1		Gabi: Stainless steel quarto plate (304)
X		Electricity [MJ]	66.8		Gabi: IT Electricity grid mix

X		Transport [kg*km]	344	Gabi: Lorry transport
	X	Diamond blade [kg]	14.3	Created
	X	Stainless steel scrap	14.1	-
		LCI dataset 17: Drilling rod		
X		Steel rod [kg]	10.5	Gabi: Steel rebar
X		Tungsten carbide [kg]	0.086	Created: Tungsten carbide
X		Transport [kg*km]	525	Gabi: Lorry (22t) incl. fuel
	X	Drilling rod; at quarry [m]	3.20	-
	X	Iron scrap [kg]	10.5	-
		LCI dataset 18: Drilling bit		
X		Steel [kg]	2.2	Gabi: Steel rebar
X		Tungsten carbide [kg]	0.0058	Created: Tungsten carbide
X		Transport [kg*km]	110	Gabi: Lorry (22t) incl. fuel
	X	Drilling bit; at quarry [pcs]	1	-
	X	Iron scrap [kg]	2.2	-
		LCI dataset 19: Metal abrasive		
X		Electricity [MJ]	12.6	PE: IT Electricity grid mix
X		Diamond segment [kg]	0.144	Created: Diamond segment; for cutting tools; Mix 49%Fe-18%Co
X		Steel [kg]	2.22	PE: Steel hot rolled section
X		Transportation [kg*km]	450	PE: Lorry (22t) incl. fuel
	X	Metal abrasive; for stone surface treatment [pcs]	1	-
		LCI dataset 20: Resin diamond abrasive		
X		Epoxy resin [kg]	0.145	Gabi: Epoxy resin
X		Diamond powder [kg]	0.034	Created: Diamond powder
X		Silica sand [kg]	0.121	Gabi: Silica sand (Excavation and processing)
X		Ethanol [kg]	0.043	Gabi: Ethanol
X		Methylene [kg]	0.145	Gabi: Methylene diisocyanate (MDI)
X		Silicon carbide [kg]	0.087	Ecoinvemt: silicon carbide, at plant
X		Graphite [kg]	0.034	Ecoinvent: graphite, at plant
X		Plastic [kg]	0.1	Gabi: Plastic injection moulding part (unspecific)
X		Electricity [MJ]	10.8	Gabi: IT Electricity grid mix
X		Transportation [kg*km]	127	Gabi: Lorry (22t) incl. fuel
	X	Resin diamond abrasive; for stone polishing [kg]	1	-
		LCI dataset 21: Magnesite abrasive		
X		Phenolic resin [kg]	0.067	Ecoinvent: phenolic resin, at plant
X		Magnesium oxide [kg]	0.248	Ecoinvent: magnesium oxide, at plant
X		Magnesium chloride [kg]	0.161	Gabi: Magnesium
X		Water [kg]	0.063	Gabi: Tap water
X		Silicon carbide [kg]	0.080	Ecoinvemt: silicon carbide, at plant
X		Aluminium oxide	0.040	Ecoinvemt: aluminium oxide, at plant
X		Quartz sand [kg]	0.013	Gabi: Silica sand (Excavation and processing)
X		Plastic [kg]	0.1	Gabi: Plastic injection moulding part (unspecific)
X		Electricity [MJ]	10.8	Gabi: IT Electricity grid mix
X		Transportation [kg*km]	127	Gabi: Lorry (22t) incl. fuel
	X	Magnesite abrasive; for stone polishing [kg]	1	-

Table 3: Life Cycle Inventory of the main dimension stone cutting technologies. The data sources employed for the development of each dataset are the following. LCI dataset 11: primary data from enterprise Mega Diamant (Carrara); technical sheets of the enterprises Metalfuni and CO.FI.PLAST. LCI dataset 12-15: primary data from

enterprise Stein Varz (Crevoladossola) and from three stone transformation plants located in Piedmont and Carrara. LCI dataset 16: primary data from enterprise Stein Varz (Crevoladossola); technical sheets from enterprises BM and Dellas. LCI dataset 17-18: direct measurements on drilling rods/bits; technical sheets of enterprises Geocom and Tenir. LCI dataset 19: primary data from enterprise Stein Varz (Crevoladossola) and a transformation plants located in Carrara. LCI dataset 20: Scalari, 2007; Thimmappaiah et al., 1999; Wiand, 1995; Yuhang and Zheng, 2006; Zhou et al., 2012. LCI dataset 21: Liu et al., 2012.

4. CONCLUSIONS

As several European Environmental policies are based on Life Cycle Thinking (LCT) to a large extent, the availability of good quality Life Cycle Inventory (LCI) data is recognized as an important step to turn the approach into a true enhancement of sustainability. In this context, the present paper provides detailed Inventories on the most widespread technologies currently employed in the ornamental stone sector. Datasets are mainly based on primary data from Italian producers, while secondary data from literature, technical sheets and patents were used to complete and cross-check primary data. Moreover, since some technologies and/or their components are used in many different sectors (such as the mining and civil engineering ones), the developed LCI datasets could result representative also in different contexts from the ornamental stone one. The LCI datasets are provided both as Unit and System processes to enhance their versatility. Furthermore, a significant added value is given by the parametrization of the Unit process datasets: parameters allow users to easily modify, adapt or update the datasets. The developed LCI is therefore a flexible and replicable tool able to practically support researchers, enterprises and LCA practitioners/developers working in the field of sustainability and Circular Economy.

Datasets here described are freely available also in the ILCD file format in the Mendeley Data Repository for their direct use into LCA software.

Further research should be carried out to enrich Life Cycle databases with datasets related to other common technologies employed in the ornamental stone sector, such as, for example, the tools used for the quite high variety of surface treatments (resins, materials employed for the techniques of flaming, waterjet, sand blasting).

Finally, the Life Cycle dataset of some intermediate products such as diamond powder and tungsten carbide should be further investigated through the collection of industrial primary data, in order to replace the literature data used in this paper.

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