

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

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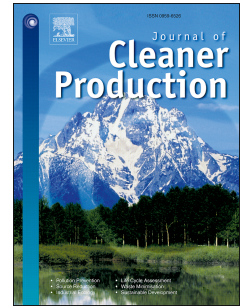
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3 **Life Cycle Inventory of technologies for stone quarrying, cutting and**
4 **finishing: Contribution to fill data gaps.**

5

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11 **HIGHLIGHTS**

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- 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
- 16

17 **ABSTRACT**

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

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

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1. INTRODUCTION

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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.

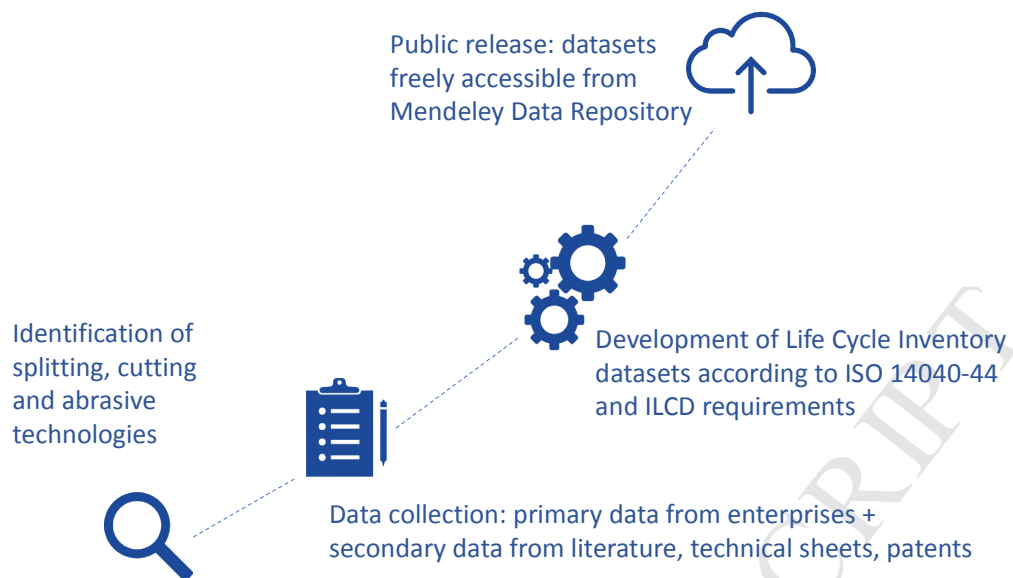
To turn the LCT approach into a quantitative assessment, different tools have been developed, the most known of which is Life Cycle Assessment (LCA). The Integrated Product Policy (European Commission, 2003) has identified LCA as the best framework to assess potential impacts of products and services 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

63 in the ceramic, concrete and bricks sectors (Ibáñez-Forés and Bovea, 2016; Strazza et al., 2010; Torricelli et
64 al., 2009), while in the dimension stone sector it has been relatively less employed. The limited number of
65 LCA studies in this field could partially be ascribed to the high variability of the natural stone production
66 chain (mainly related to the choice of techniques/technologies and to site-specific conditions) and, most
67 probably, to the scarce availability of Life Cycle Inventory (LCI) datasets specific to the most common stone
68 quarrying, cutting and finishing techniques and technologies. This lack of data is directly reflected in the
69 LCA studies available for the stone sector, which have been necessarily simplified. Nicoletti et al. (2002)
70 performed a LCA to compare ceramic and marble tiles, mainly based on energy and water consumption.
71 Analogously, LCA studies have been developed by Traverso et al. (2010) who assessed the production of
72 Perlato marble from Sicily, and by Torricelli and Palumbo (2016) who focused on the supply chain of
73 Firenzuola stone from Tuscany. Nevertheless, also in these cases the assessments were mainly based on the
74 input flows of energy and water resources, while impacts connected to the specific cutting technologies were
75 not considered because of the unavailability of the related Life Cycle datasets. Similar studies have been
76 developed in other stone production countries, such as Greece (Gazi et al., 2012), United Kingdom and
77 Ireland (Crishna et al., 2011). Catarino et al. (2016) identified the main input/output flows of each unitary
78 operation of the Portuguese marble production chain, but did not clearly disclosed the inventory. In 2012, a
79 detailed LCI on the main techniques of the Brazilian stone production chain has been developed by the
80 research centre CETEM of Rio de Janeiro (Castoldi Borlini Gadioli et al., 2012) and this same research
81 group is currently updating the datasets. Nevertheless, since these datasets refer to the Brazilian average
82 stone slab production, they are not necessarily representative of the Italian production. Mendoza et al. (2014)
83 and Bai et al. (2016) disclosed LCIs and calculated the related potential environmental impact of the
84 techniques employed respectively in the Spanish and Chinese granite production chains. However, in both
85 cases, the LCA was developed including simplified datasets of the employed technologies, probably because
86 of unavailability of more detailed data (e.g. the diamond wire was accounted as steel, while the diamond
87 beads production was not considered).

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

103 104 **2. METHODOLOGY**

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



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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.

111 Firstly, a preliminary investigation has been carried out in Italian quarries and transformation plants to
112 identify the most widespread technologies employed in the ornamental stone sector. Since techniques and
113 underlying technologies change mainly according to the hardness of the stone, the tools employed in both
114 soft stones (such as marbles) and hard stones (such as granites) were investigated. In particular, on-site
115 investigations took place in Piedmont and Tuscany regions and a literature review has been carried out to
116 check if also in other Italian Regions the same technologies are used. The main literature sources have been
117 Cardu (2013, 2012); Crivello (2012); Dadalto Sahao (2013); Giuffrida (2010); Gussoni (2016) Masciullo
118 (2016); Primavori (2011, 1999).

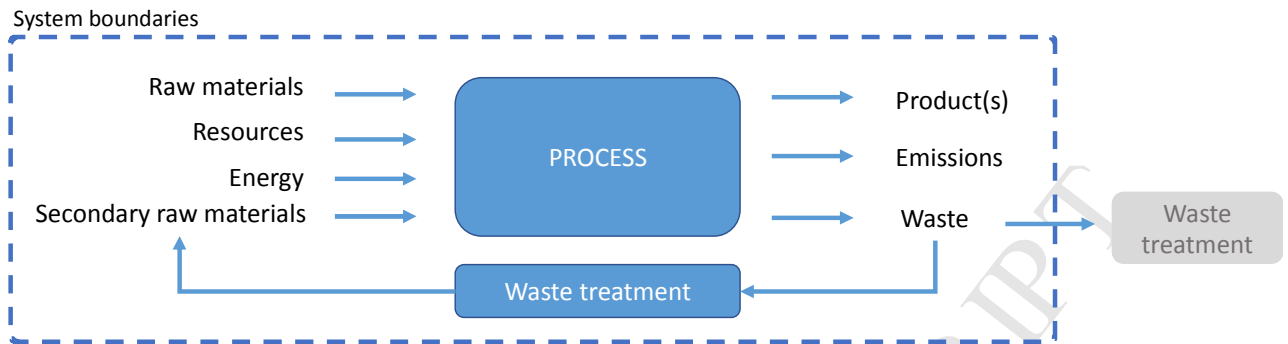
119 Subsequently, it has been verified whether LCI datasets on the identified technologies or their
120 components were already available in the main LCA databases. In particular, process datasets were searched
121 in Gabi, Ecoinvent and ELCD databases. The production chain related to the unavailable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

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

129 Datasets were then developed according to ISO 14040-44 standards (The International Standards
130 Organisation, 2006a, 2006b) and the requirements of format and quality defined in the International
131 Reference Life Cycle Data System (ILCD) Handbook (European Commission, 2012). Therefore, the
132 European Commission underlined the need and the importance of relying on uniform, consistent and good
133 quality Life Cycle datasets (Recchioni et al., 2015) and, from 2014, developed the Life Cycle Data Network¹
134 (LCDN) to host compliant Life Cycle datasets. The developed datasets include input flows of materials,
135 resources and energy and output flows of product, waste and emissions. As showed in Fig. 2, the processes
136 of the waste treatment are included in the system boundaries only when, in the current practices, the waste is
137 reintegrated in the same production chain. This is the case, for example, of diamond beads of cutting
138 diamond wires: beads often have a lifetime longer than other components of the wire and are generally
139 reused several times for the production of new diamond wires. On the contrary, waste that leave the stone

¹ <http://eplca.jrc.ec.europa.eu/LCDN/>

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



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Figure 2: System boundaries of the developed LCI datasets.

145 The values of input/output flows are the average of the collected data. Primary data from Italian tools
 146 producers have been preferred when available; secondary data from literature, technical sheets and patents
 147 have also been used to both complete and cross check primary data. The specific source(s) of data are
 148 detailed in the Supplementary Material. In addition, for each input/output flow, data quality information is
 149 provided to easily identify the level of datasets reliability. To this aim, the well-established Ecoinvent
 150 pedigree matrix (Weidema et al., 2013) has been used for the assessment of data sources quality. As showed
 151 in Fig. 3, the pedigree matrix allows to evaluate the data sources according to five independent
 152 characteristics (reliability, completeness, temporal correlation, geographic correlation and further
 153 technological correlation) and each of them is rated with a score from 1 to 5 (where 1 corresponds to the
 154 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

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

158 With the support of Gabi software both Unit and System processes² have been developed. Specifically,
 159 Unit processes enable the user to transparently identify and quantify input/output flows involved in each
 160 technology. Moreover, Unit processes contain parameters that facilitate the eventual update of the dataset or
 161 its adaptation to specific production chains. For example, the dataset of diamond disks can be easily
 162 customized in function of the disk diameter, the thickness of the steel core, the number and dimensions of
 163 diamond segments, etc. Parameters could therefore enable the datasets to be used also in reference to
 164 analogous cutting technologies used in other sectors (such as the Construction and Demolition sector). On
 165 the other hand, system processes are provided for users that prefer to directly employ the datasets without
 166 modifications, avoid the connection with background datasets or limit the size of the file model.

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

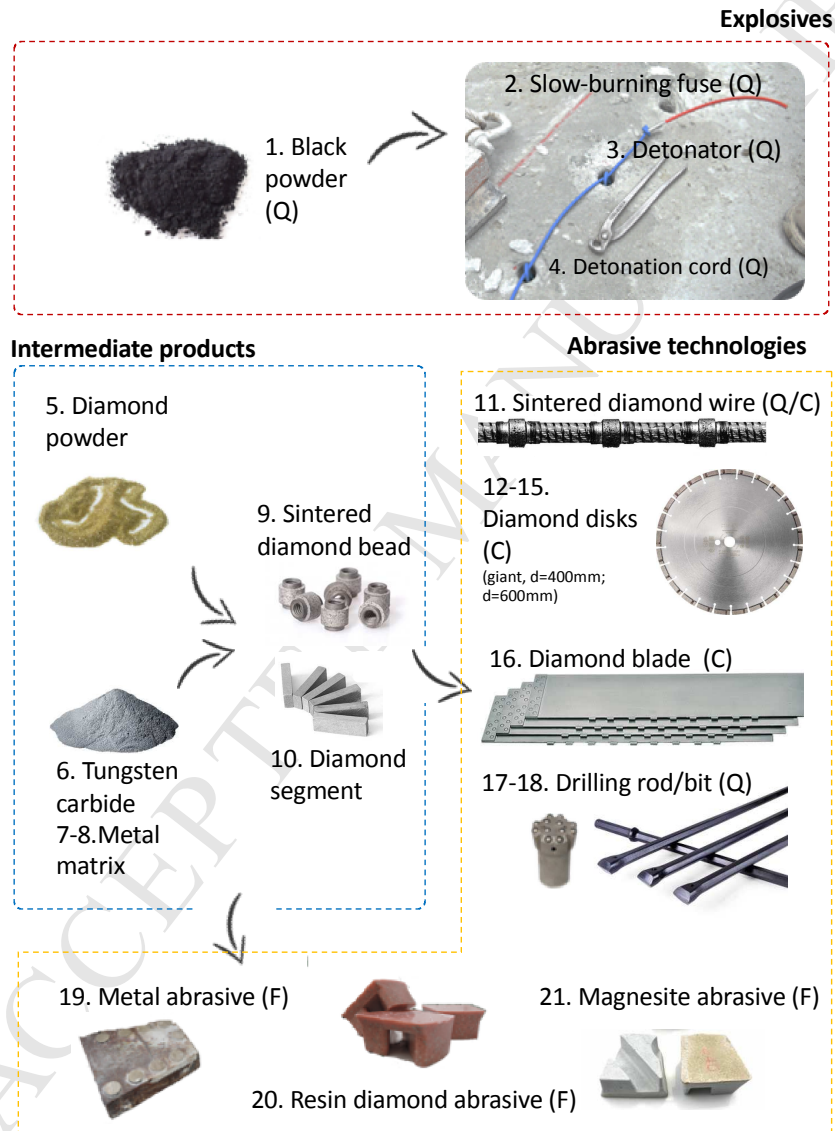
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172 3. RESULTS: LCI DATASETS

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

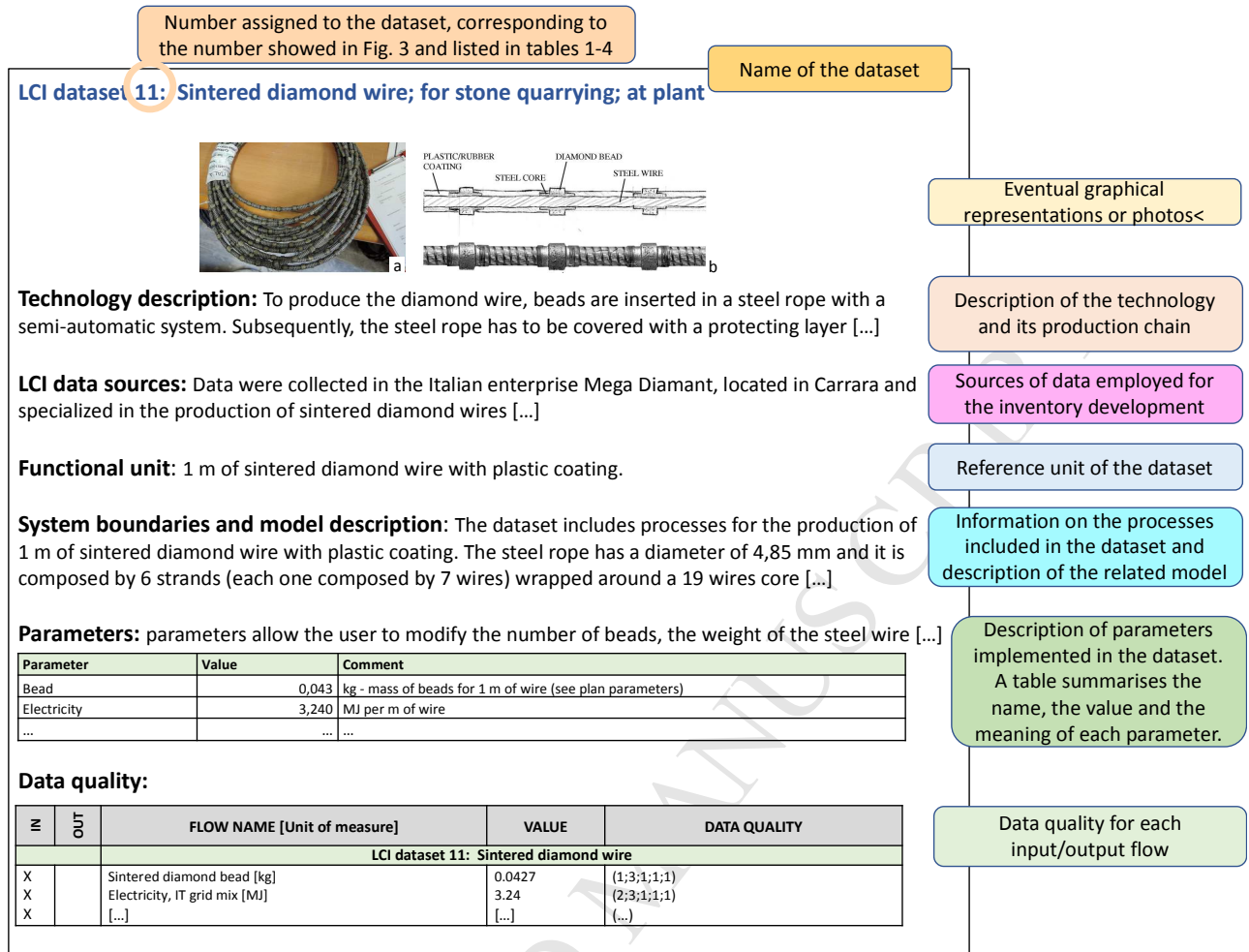
² A “unit process” is a gate-to-gate process, where input and output data are quantified with product flows and eventual elementary flows; a “system process” is an element with an aggregated inventory, where input and output data are all expressed as elementary flows.

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



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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).



190
191 **Figure 5.** Information provided in the Supplementary Material for each developed LCI dataset.

192 **3.1 LCI of explosives in the dimension stone sector**

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

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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	-

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

206

207 3.2 LCI of intermediate products

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

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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 H ₂ O, production mix, at plant/RER	
X	Al ₂ (SO ₄) ₃ -18H ₂ O [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 ₂ O [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, H ₂ S, at plant/RER	
X	N ₂ compressed gas [kg]	1.65	Ecoinvent: Nitrogen, liquid, at plant/RER	
X	H ₂ S 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 H ₂ O, 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	-

219 **Table 1:** Life Cycle Inventory of intermediate-products for the production of cutting and finishing tools. The data
220 sources employed for the development of each dataset are the following. LCI dataset 5: Ali, 2011; Larsson et al.,
221 2009; www.searates.com. LCI dataset 6: Archer et al., 2003; Bobba et al., 2016; Dahmus and Gutowski, 2004;
222 Novak et al., 2004; Syrakou et al., 2005. LCI datasets 7-8: primary data from enterprises Stein Varz
223 (Crevoladossola) and MIMitalia (Vado Ligure); Umicore-Tungsten technical sheets. LCI dataset 9: primary data
224 from enterprises Mega Diamant (Carrara) and MIMitalia (Vado Ligure); Umicore-Tungsten technical sheets;
225 Bobrovnichii et al., 2003; de Oliveira et al., 2007; Karagöz and Zeren, 2001; Konstanty, 2007; Tillmann et al.,
226 2010; Zeren and Karagöz, 2007, 2006. LCI dataset 10: primary data from enterprise Stein Varz (Crevoladossola);
227 technical sheets of the enterprises Diam Edil (Lumino), Cuts Diamant (Noceto), Unidiamant (Carpaneto
228 Piacentino).

229

230 3.3 LCI of abrasive technologies

231 Table 3 gathers the inventories related to the production chain of the most common abrasive tools
232 employed in the ornamental stone sector. In particular, LCI datasets have been developed for the
233 technologies of: sintered diamond wire (LCI dataset 11), highly widespread to separate soft stone benches
234 from the quarry bedrock, divide them into blocks and square shapeless blocks; giant diamond disks (LCI
235 dataset 12), commonly used in hard stone transformation plants to square shapeless blocks or to cut thick
236 slabs according to the requests of customers; diamond disks of 400 mm diameter (LCI dataset 13) and 600
237 mm diameter (LCI datasets 14-15), commonly employed for cutting stone slabs into smaller parts. As
238 explained in detail in the “Supplementary Material”, two datasets have been created for the 600 mm diameter
239 disk because its performance (and as a consequence the quantities of its input/output flows during its
240 lifetime) significantly changes according to a prevalent use with soft or hard stones. Diamond blade (LCI
241 dataset 16) is a technology used for cutting soft stone blocks into slabs; rods (LCI dataset 17) and bits (LCI

242 dataset 18) are the most common tools employed to perform holes drilling in soft and hard stone quarries. In
 243 addition, since the most common surface treatments for stone slabs are the smoothing and polishing
 244 processes, the related technologies have been investigated. In particular, LCI datasets have been developed
 245 on three types of abrasives: metal abrasive (LCI dataset 19), generally used for the smoothing phase; resin
 246 diamond abrasive (LCI dataset 20), which is the most common tool for the polishing phase; magnesite
 247 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	Ecoinvent: 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	Ecoinvent: silicon carbide, at plant
X	Aluminium oxide	0.040	Ecoinvent: 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	-

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

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

257

258 4. CONCLUSIONS

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

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

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

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

281

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289

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