Life Cycle Assessment and System Dynamics: an integrated approach for the dimension stone sector

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Abstract

The Italian traditional sector of dimension stones (mostly marbles and granites) has begun to recognize the importance of improving its sustainability. Nevertheless, a lot of different variables, sometimes in conflict, influence the production system from the economical, environmental and social point of view. As a consequence, a global and holistic approach is required. The on-going study aims to provide some tools facilitating the analysis of this complex system through the integration of the Life Cycle Thinking and the System Dynamic (SD) Approach. On-site data were collected in order to perform a more accurate Life Cycle Assessment (LCA) with boundaries from-cradle-to-gate. An SD model was then developed to interlink the obtained values of environmental potential impacts with economical aspects and to dynamically simulate the behaviour of the system.Introduction

1. Introduction

Dimension stones (such as granites and marbles) represent a sector of the Italian market with a long tradition. During the last decades, however, this sector deeply changed mainly because of the mechanisation and of the introduction of new working techniques (Fig. 1). Consequently, this transformed the relationships between the stone sector, the territory and the society and made the ornamental stone responsible of impacts of different nature. Issues of concern are, for example, the depletion of ornamental stone, which is a non-renewable resource, the modification of natural equilibrium and the pollution related to the stone activity. As stated by Bellini (1992) and Doveri (2008), some problems of turbid water occurred when slurry wastes reach the aquifer. Moreover, as described by Cuccia et al. (2011), dry processes and stone lorry transportation lead to problems of atmospheric aerosols in the near inhabited areas. The issue of pollution is then related also to the processes themselves (use of energy, fuel, explosives, etc.) and to the wastes they produce. On this topic, many researchers are currently investigating how stone slurry muds can potentially be recycled (e.g. Marras et al., 2010; Dino & Fornaro, 2005, Vola et al., 2011). It is so clear that, as most of the industrial processes, the stone sector has important implications on the Italian market and is source of occupational opportunities, but at the same time it involves also costs for the society and the environment. Since the variables that influence the sector are deeply interconnected, the management needs to follow an approach as much holistic and comprehensive as possible.

Figure 1: At the left, marble quarry in the Colonnata basin (Carrara); at the right, cutting of granite slabs (Crodo, Verbania)

In such systems, indeed, the whole is much more than the sum of its parts, because it has to be added also the contribution of the trans/cross-boundary interrelationships between and among the parts (Halog and Manik, 2011).
For this reason, in order to make the sector sustainable and resilient over time, it is necessary to analyse the system in its global complexity. The study presented in this paper is part of an on-going PhD study, which aims to give to the stone sector some tools in order to assess its sustainability. From the environmental point of view, it is followed a Life Cycle approach, which allows to analyse the stone production in its entirety and to avoid the shifting of impacts from one stage of the process to another one. This means that the study evaluates the potential environmental effects all along the life cycle of the stone process, with boundaries from-cradle-to-gate (from the extraction of raw materials to the finished stone product). The Life Cycle Assessment (LCA) is therefore the tool employed to calculate the potential impacts of the stone production. This kind of evaluation is usually run on voluntary basis, but they are currently largely diffused in many different fields and reported in literature as efficient tools for investigating the impact of processes (e.g. Durucan et al., 2006), for evaluating different alternatives (e.g. Bribián et al., 2011) or for comparing different products (e.g. Pargana et al., 2014). In the dimension stone field, previous LCA analyses were carried out (e.g. Traverso et al., 2009; Capitano et al., 2011), but, since just scarce data on specific stone processes are available in LCA databases, they often presented a high percentage of assumptions. Moreover, as stated before, other interlinked aspects influence the sustainability of the system. In order to define the interconnections among the different kind of variables, the study has been integrated with the System Dynamic approach, which allows to simulate the dynamicity and non-linearity of the variables over time (Reichel and Runger, 2013; Stasinopoulos et al., 2011, Trappey et al., 2011). Aim of this paper is therefore to suggest to stone industry managers an integrated methodology as tool to help them facing multi-criteria issues.

2. Methodology

The current investigation involved analysing Italian stone quarries and transformation plants to study the sustainability of the stone sector. To this aim, the methodology followed in the study is the systematic approach of the life cycle thinking, aiming at analysing a product or process over its entire life cycle. For the environmental aspects, the Life Cycle Assessment is a worldwide accepted objective tool for analyzing and quantifying the environmental consequences of products. Guidelines for assessing an LCA are standardised by the International Organization of Standardisation's (ISO) 14040-44 and by the International Reference Life Cycle Data System (ILCD) Handbook released by the European Commission Joint Research Centre (JRC). To perform an LCA, four iterative stages have to be followed: goal and scope definitions, life-cycle inventory (LCI) analysis, life-cycle impact assessment (LCIA), and interpretation. Available databases (such as Ecoinvent, Thinkstep, ELCD) gather LCA datasets about a wide range of processes. Nevertheless, there still lack information about many processes and products. The field investigated in the current study, for example, is not supported, at the moment, with datasets of the specific stone processes. In order to analyse the impacts with a more accurate detail, the study examined the processes by collecting data directly on site and through the dialog with owners of quarries and transformation plants, with firms connected to the sector and with public administrations. This inventory phase is usually the most complex and time consuming stage of the LCA. It is often difficult to gather all the data required because of the secrecy of some industrial processes or because of the unavailability of some data. In these cases the current research attempted to make estimations based on analogous processes and to evaluate the influence of the assumptions on the results. The collection of data was combined with the realization of a parameterised model developed with the LCA software application Gabi, which, with databases and methods, help the calculation of the potential impacts. Aim of the project is to provide companies and researcher with a flexible tool, which contains the most significant processes of the stone sector, but that is, at the meantime, able to be adapted to specific productions. The phase of Impact Assessment was carried out with average data of the Italian production. Nevertheless, as previously stated, other aspects of different nature influence the sustainability of the stone sector. In order to have a more global comprehension of the system and to estimate the interactions between different variables, existing hybrid models were reviewed (Onat et al., 2016; Bilec et al., 2006). As a result, the integration between LCA analysis and System Dynamics (SD) approach was chosen. The SD is a tool firstly applied to business managerial problems, but then broadened to many other fields since long (Forrester, 1969). In particular, SD allows modelling the dynamic non-linearity of systems through variables linked by connectors defined by mathematical functions. The current research developed a model to gather and interlink environmental and economic variables.

3. Case study

Aim of the research project is to provide professionals of the stone sector with tools able to support the sustainability of specific stone productions. As stated before, the followed approach is the combination of LCA and SD. Because of the lack, in LCA databases, of datasets about stone processes, on field investigations occurred. Two representative Italian contexts were analysed: the marble stone industry of Carrara basin (Tuscany) and the granite production of Verbano Cusio Ossola province (Piedmont). This choice was made because of the significant differences in physical properties between marbles and granites, which led to the development of two different process technologies. The study is currently investigating the processes and materials involved in the life cycle of hard and soft stones, with boundaries *form-cradle-to-gate* (from the extraction of the stone to the finished product). This paper focuses in particular on the extraction of soft stones (such as marble), because of the larger availability of data. The described methodology is applied on a type bench cut, with dimensions of 17m x 8m x 3m. The total volume extracted in this case is therefore of 408 m^3, which is then split into 5 blocks in order to allow the lorry transportation. This process is composed by: the basal cutting with a chain saw machine, the drilling of holes for the diamond wire passage, the bench cut with diamond wire machine, the cut into smaller blocks with diamond wire, the consequent production of slurry mud, which can be destined, in different percentages, to disposal, recycle or be dispersed into the environment.

The investigation involved both direct and indirect impacts. For example, as far as concern the marble cutting with diamond wire techniques, the direct impacts include the consumption of wires and other materials (vulcanised rubber for the pulleys, protection ribbons) and the electricity spent for cutting (water was not considered because it is reused through a closed loop); while indirect impacts are the production of the diamond wire as well as the other involved tools (Table 1).

Table 1: Direct and indirect impacts that were taken into account for the Life Cycle Assessment of the marble extraction phase

	Direct impacts	**Indirect impacts**
Drilling	Consumption of widia inserts	Production of widia inserts (primary data, on-going investigation)
Chain cutting	Electricity	(secondary data)
	Consumption of widia inserts	Production of widia inserts (primary data, on-going investigation)
	Consumption of biologic grease	Production of lubricant grease (secondary data)
	Electricity	(secondary data)
DW cutting	Consumption of diamond wire	Production of diamond wire: steel wire (secondary data), plastic coating (secondary data), diamond bead (primary data), electricity (secondary data)
	Consumption of vulcanised rubber	Production of vulcanised rubber (secondary data)
	Consumption of protection ribbon	Production of teflon ribbon (secondary data)
	Electricity	(secondary data)

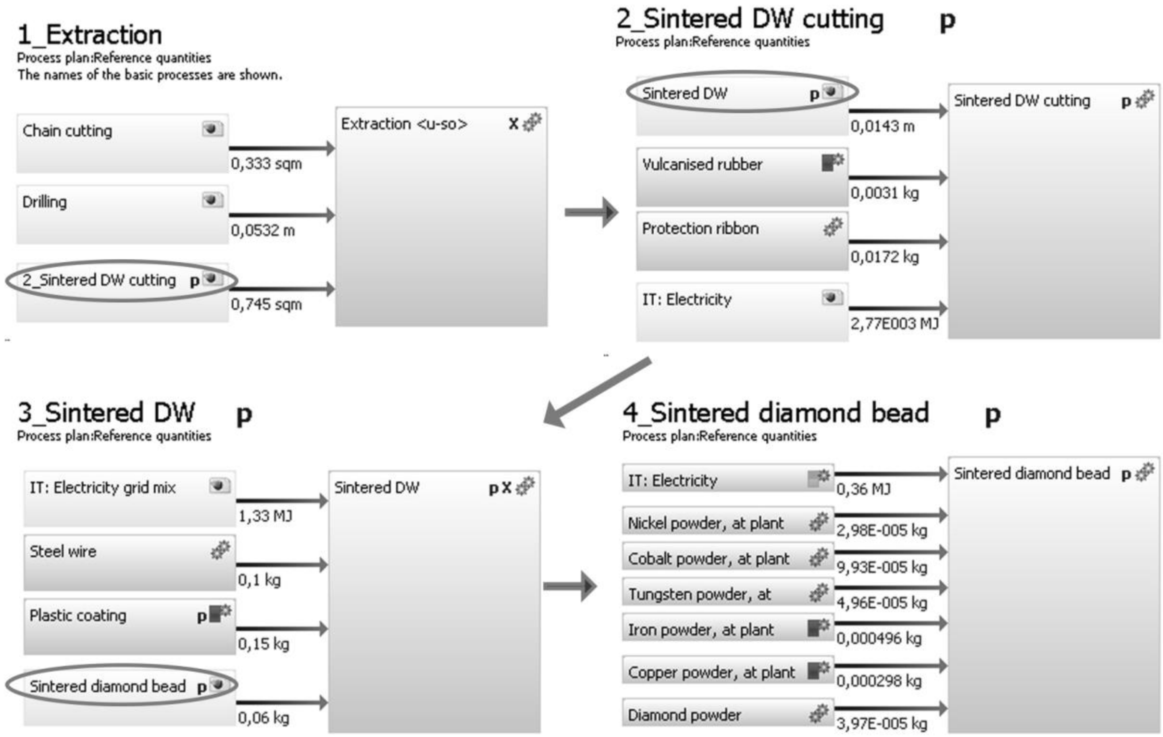

Figure 2: Part of the LCA model showing the diamond wire (DW) cutting of marble. As it can be noticed, every plan progressively contains the impacts related to the different inputs. (Developed with Gabi software)

These processes were used to create an LCA model built with a vertical structure, where the plans of the direct process incorporate the indirect ones.

This kind of structure was chosen to facilitate both the separate identification of impacts related to the different processes of the system and following phase of SD modelling. The structure of the model for the process of the marble extraction with diamond wire (DW) technique is showed in Fig. 2.

A lot of variables can differ from quarry to quarry, firstly because of the natural variability of stone deposits, but also because of the use of different machineries, which can influence the consumption of materials and energy. A good flexibility of the model is reached through the setting of parameters which facilitate the customisation of the model according to specific cases or scenarios (Fig. 3). With the average values' setting, impact assessments related to 1 m^3 of quarried marble were performed.

The methods used for the assessment are Recipe 1.08 at Midpoint and ILCD, focusing on climate change, freshwater ecotoxicity and resource depletion. The climate change impact category has been chosen because it is well understood also by non LCA practitioner, such as, for example the owners of stone companies; the freshwater ecotoxicity was chosen because of the potential impact that slurry waste have on aquifers; the resource depletion is significant of the fact that a non-renewable resource is extracted.

Free parameters

Object	Parameter	Formula	Value	MiM Stan	Comment, units, defaults
2_Sintered DW cutting	MassTOT_rubber		347	0 %	Mass of the protective rubber pulley-diamond w
2_Sintered DW cutting	Power_DWmachine		55	0 %	Electric motor power [KWh]
2_Sintered DW cutting	Speed_DWcut		14	0 %	m2 of stone cutting in 1 hour
2_Sintered DW cutting	TimeTOT_DWmach		8E003	0 %	TOT hours of working of the DW machines [h/ye
Sintered DW	Bead_mass		26,6	0 %	g per bead
Sintered DW	Bead_n		30	0 %	n° of beads per m of wire
Sintered DW cutting	Electr_DWcut	Power_DWmachine*Speed_DWcut	770		Electric energy per m2 of stone cutting [kwh]
Sintered DW cutting	Rubber	MassTOT_rubber/(TimeTOT_DWmach*Speed_DWcut)	0,0031		Mass of rubber per m2 of stone cutting [kg]

Figure 3: Some parameters of the DW cutting. They allow the customization of the model according to specific productions

Table 2 shows the contribution of each process for the type cut (408 m^3) and for 1 m^3 of extracted stone. This data are preliminary results and are still under development. As it can be noticed, the major contribute for the global warming is the cutting with diamond wires, mainly due to the production of synthetic diamond powder (secondary data from literature). Data on the production of widia inserts for chain cutters and drilling tools are currently not available; consequently it was assumed that, for the similarity of the process (sinterisation of carbides with metals), the impacts of widia is similar to the impact given by the sinterisation of diamond beads.

Finally, it is significant to notice the quite high potential impact on freshwater ecotoxicity in case the slurry waste is dispersed into the aquifer (the composition of the slurry waste comes from chemical analysis on marble quarry muds). In order to perform a more complete analysis of the stone sector, LCA results were integrated with economic variables in a System Dynamic model.

Table 2: Phases of the marble extraction with the relative impact contributions referred to the extraction of 1 m^3 of stone

<table>
<tr><td colspan="2"></td><td>Type bench (408 m³)</td><td colspan="4">1m³ cutting</td></tr>
<tr><td colspan="2">Process</td><td>Input quantity</td><td>Input quantity</td><td>Climate change [kg CO2-Eq]</td><td>Freshwater ecotoxicity [kg 1,4-DB eq]</td><td>Resource Depletion, fossil and mineral [kg Sb-Eq]</td></tr>
<tr><td colspan="2">Chain cutting</td><td>51 sqm</td><td>0.125 sqm</td><td>0.45</td><td>1.91E-04</td><td rowspan="3">0.00057</td></tr>
<tr><td colspan="2">Drilling</td><td>222 m</td><td>0.053 m</td><td>0.03</td><td>3.49E-07</td></tr>
<tr><td colspan="2">DW cutting_tot</td><td>304 sqm</td><td>0.745 sqm</td><td>7.9</td><td>8.61E-04</td></tr>
<tr><td rowspan="2">Slurry waste</td><td>to water</td><td rowspan="2">155 kg</td><td rowspan="2">0.38 kg</td><td>0.0003</td><td>7.98</td><td>6.91802E-11</td></tr>
<tr><td>to landfill</td><td>0.0027</td><td>2.28E-08</td><td>5.36E-09</td></tr>
<tr><td colspan="2">Machineries (fuel)</td><td>2195 l</td><td>5.38 l</td><td>15.74</td><td>1.100E-04</td><td>1.06157E-08</td></tr>
</table>

Thus, they were investigated characteristics (e.g. production, speed, horsepower of machineries, etc.) and costs of the most common materials employed for the stone extraction.

Cost of labour and number of workers are other variables of the model. Costs that do not depend on the management of the quarry (such as concessions taxes) are not taken into account. As it can be seen in Fig. 4, starting from the input data, a simulation is made run; the operator can dynamically change some variables directly on the model and evaluate, through trend graphs, how changes influence environmental and economical aspects. For example, a major speed of the cutting tools causes a faster cutting and consequently a reduction of energy consumption (lower economic and environmental costs).

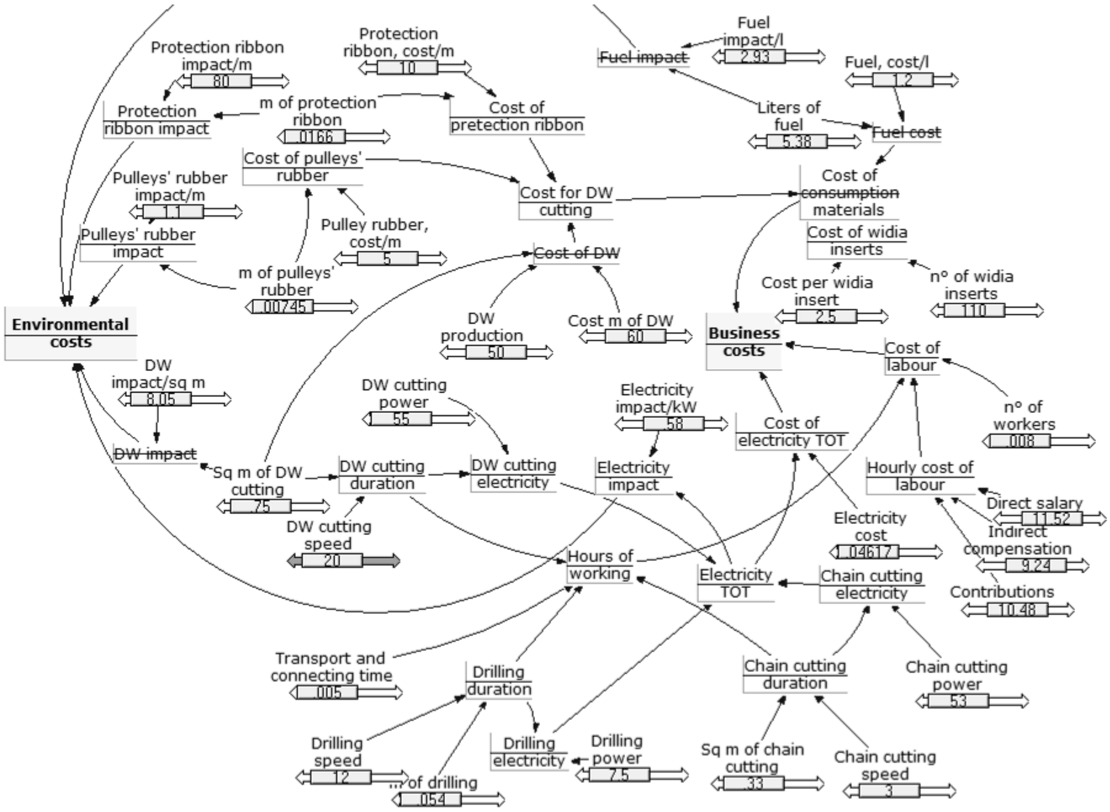

Figure 4:Model connecting environmental and economical costs of marble extraction. As it can be seen, the value of variables represented with a double arrow can be dynamically changed directly on the simulation (developed with Vensim PLE software)

Nevertheless, the increase in speed entails also a lower performance of the tools, which leads to increase the quantity of necessary items, with consequent added economic and environmental costs. At the moment the model does not contain social variables because of the unavailability of accurate data and because of the difficulty of weighting the social aspects with a quantitative value.

4. Conclusion

The decisions that industry managers have to make are usually dependent on complex systems where variables of different nature interact and influence each other in a dynamic and non-linear way. The current study is focused on the Italian dimension stone sector, which has begun to recognize the importance of increasing its sustainability. Goal of the on-going study is not to indicate the best techniques in absolute terms, but to give to enterprises some tools to support evaluations and decisions with a holistic and dynamic approach. The standardised LCA has been chosen as first tool to evaluate the potential environmental impacts. A flexible model has been realised to allow evaluations on specific productions. Moreover, the research integrated the LCA with the approach of the system dynamics. Variables related to characteristics of tools and to their costs have been interlinked to perform economical and environmental analyses. There is however need to integrate also social aspects. Currently, the study mostly focused on the quarrying processes of marbles, but further research is under development to examine also the transformation phase and the variables influencing the production of hard stones. This study and the complete models will be shared with interested companies to encourage the enhancement of sustainability of the stone sector.

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