24th ABCM International Congress of Mechanical Engineering
December 3-8, 2017, Curitiba, PR, Brazil

COBEM-2017-2109
ASSESSING THE ENVIRONMENTAL IMPACTS OF MILLING PROCESSES

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Abstract. *There is an increasing pressure to the industry sector to manage the environmental impacts of its products and process. However, we can manage just what we can measure, and this is the recent challenge for the process industry, the development of methodologies which enable the measurement of the environmental impacts to help decision making. So, this work proposes the use a commercial life cycle assessment tool to access and compare several milling processes in terms of environmental impacts, also identifying process inputs hotspots.*

Keywords: *Impact indicator, life cycle assessment, process, sustainability*

1. INTRODUCTION

Each day, the sustainability issue gains more importance in all the fields of the society due to various phenomena occurring such as global warming, pollution of the environment, and the disappearance of many species of wildlife. Data shows that 42,5% of the world energy consumption in 2015 (International Energy Agency, 2016) and 32% of the greenhouse gases emission in 2010 (Pachauri and Meyer, 2015) were attributed to the industrial sector, making manufacturing companies receives increased pressure from many fields of the society to think beyond merely the economics benefits of their processes and products but also consider their environmental and social impacts (JOUNG *et al*., 2012), contemplating the three bottle line of sustainability (economic, environmental and social aspects).

The most widely accepted methodology being used to analyze the environmental impacts of a product is the Life Cycle Assessment (LCA) (Garcia *et al.*, 2014). Despite mostly applied to product, recent literature suggest that it has also the potential as a tool for analysis and design of processes, and stresses that one of the biggest challenges of this decade in the field of process systems engineering is the development of tools for environmental considerations, notably to produce more detailed analysis on the influence of process operating conditions on environmental impacts (Jacquemin *et al*., 2012).

So, due to the acceptability of the LCA method to evaluate environmental impacts at the product level, its highlighted potential to be applied at process level and the need for development of tools to access environmental impacts of them, the goal of this study is to evaluate the use of a commercial LCA tool (GABi 6) to assess the environmental impact of a unit milling operation, comparing different milling scenarios in terms of environmental impacts, identifying potential opportunities and gaps in its application at the process level, intending to help decision making for a cleaner production.

2. LIFE CYCLE ASSESSMENT

LCA is a technique for assessing the environmental aspects and potential impacts associated with a product (manufactured and consumed), throughout its life, from raw material acquisition through production, use and disposal, and has been standardized by ISO 14040 (Principles and Framework) and ISO 14044 (Requirements and Guidelines).

2.1 Life cycle assessment history

According to Guinée (2011), who provided a review about LCA history, the first studies that are now recognized as (partial) LCA date from the late 1960s and early 1970s, in a period called "decades of conception" (1970-1990), with widely diverge approaches, terminologies and results.

The second period (1990-2000), called "decade of standardization", LCA became part of policy documents and legislation, getting the international organization for standardization (ISO) involved and many methods started to be developed, such as CML 1992, endpoint or damage approach.

The third period (2000-2010), called decade of elaboration, European and American agencies began to put LCA into practice and improve the supporting tools, characterizing a decade of divergence in the method again, as ISO never aimed to standardized the method in detail. So, for the present decade, the author proposes the challenge of structure, select and make the plethora of models available for the different questions.

In the field of process applications, Azapagic and Clift (1999) wrote a review on the application of LCA in process selection, design and optimization, showing several works dating from 1995, pointing that the main problem lies in finding the optimum improvement strategies and choosing the best alternative in a decision environment with multiple, and often conflicting objectives.

Since then, the number of works linking LCA and the process industries has just raised, as can be seen in the review papers of Jacquemin *et al.* (2012) and Fazeni et al. (2014) and currently is being used mainly in three ways: as multi-objective optimization where LCA is used for inventory data and the result of the assessment is the input of an optimization model; coupling LCA with other assessment tools to complete the studies and improve the limitations of the LCA and analyzing environmental impact of processes by using the LCA methodology alone in order to compare different scenarios or for identifying the hotspots (JACQUEMIN *et al*., 2012).

Despite recognizing significant accomplishment, LCA is still considered a promising approach at an early phase for process applications (FAZENI et al. 2014), with many challenges for the future in fields of process design, control, operations, modeling, integration and supporting methods and tools (JACQUEMIN et al., 2012). Even if not widespread to the industrial process analysis, is becoming more and more attractive and important these days for developing a new enhanced integrated method and tool, in order to include more environmental consideration and support to develop a more sustainable processes and industry (GILLANI, 2013).

2.2 Life cycle assessment methodology

According to ISO 14040:2006 and ISO 14044:2006, a life cycle assessment shall include the definition of goal and scope, inventory analysis, impact assessment and interpretation of results. Figure 1 shows the LCA framework and its main applications.

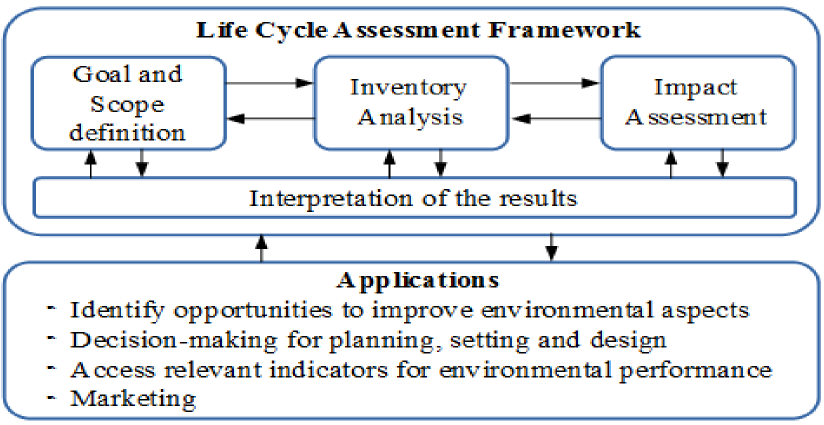

Figure 1. Life Cycle Assessment conduction framework and its main applications (adapted from ISO 14040, 2006)

In defining the scope of an LCA, the function of the system, the functional unit and the system boundary shall be considered and clearly described, ensuring that the breadth, depth and detail of the study are compatible and sufficient to address the stated goal. The life cycle inventory analysis phase involves the compilation and quantification of inputs and outputs for a product, throughout its life cycle and the impact assessment phase aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a system throughout the life cycle of the product (ISO 14044, 2006), or process.

Regarding the interpretation phase, it may involve the iterative process of reviewing and revising the scope and the nature and quality of the data, and Though subsequent decisions and actions may incorporate environmental implications identified in the findings of the interpretation, they lie beyond the scope of the LCA study, since other factors such as technical performance, economic and social aspects are also considered (ISO 14040:2006).

3. EXPERIMENTAL PROCEDURE

Intending to evaluate the environmental impact of milling processes, this work proposes the use of a commercial Life Cycle Assessment tool, the GaBi 6 (GaBi, 2010), to access the environmental impacts generated from them. Four different milling processes was selected: milling of a low alloyed steel of average parts, milling of a low alloyed steel of small parts, milling of a chromium steel of average parts and milling of a chromium steel of small parts.

The considered functional unit was one kilogram of machined material and the system boundary was the unit milling process and all the resources necessaries to do the process and generated from the process.

To access those resources, it was used the Ecoinvent database (Weidema *et al*., 2013) contained in the program, considering all the inputs amount suggested in the database.

The resources amount was converted into several environmental impacts categories, according to the CML2001 – April 2013 characterization method, also contained in the software. All the available impact categories contained in the method were considered.

To enable a visual comparison among the strategies, a multi-objective impact indicator radar chart was created. For that, the value of 1.0 was attributed to the most impactful indicator of the process, for each category, and a percentage impact indicator calculated to the others less impactful processes, according to Eq. (1).

$$Percentage\ Impact\ Indicator = \frac{Input\ Impact\ Amount}{Total\ Standard\ Impact\ Amount} \tag{1}$$

The average impact indicator was also calculated for each process, summing up the percentage impact indicator of all the categories and dividing for the number of impacts categories, according to eq. (2). Note that was considered the same weight for all the indicators.

$$Average\ Impact\ Indicator = \frac{\sum_{i}^{n} Percentage\ Impact\ Indicator}{Number\ of\ Indicators} \tag{2}$$

This analysis was made comparing the four different selected processes and also comparing the several inputs of one single process, in order to identify the most pollutant input of the process.

4. RESULTS AND DISCUSSION

The first assessment enabled with the use of the program was the resources inputs and amount accounted to the total process impact. Table 1 shows the inputs considered for the milling processes according to the Ecoinvent database.

Table 1. Resources inputs amount to the four milling processes.

Input	Quantity	Unit	Standard Deviation	Milling, low-alloyed steel, Avg. part	Milling, low-alloyed steel, Small part	Milling, 18/8 chromium steel, avg. part	Milling, 18/8 chromium steel, small part
Disposal, used mineral oil, 10% water, to hazardous waste incineration	Mass	kg	163%	3,82E-003	3,82E-003	3,82E-003	3,82E-003
Compressed air, average installation, >30kW, 7 bar gauge, at supply network	Volume	m3	163%	1,28E+000	1,28E+000	1,28E+000	1,28E+000
Lubricating oil, at plant (organics)	Mass	kg	163%	3,82E-003	3,82E-003	3,82E-003	3,82E-003
Metal working factory (General Manufacturing)	Number of piece	pcs.	332%	2,02E-009	2,02E-009	2,02E-009	2.02E-009
Metal working factory operation,	Mass	kg	163%	4,41E+000	4,41E+000	4,41E+000	4,41E+000

average heat energy (General Manufacturing)							
Metal working machine, unspecified, at plant (General Manufacturing)	Mass	kg	332%	1,74E-004	1,74E-004	1,74E-004	1,74E-004
Workpiece material, at plant (Benefication)	Mass	kg	105%	1,00E+000	1,00E+000	1,00E+000	1,00E+000
Electricity, low voltage, production UCTE, at grid	Energy	MJ	124%	1,71E+000	8,16E+000	2,41E+000	1,15E+001

According to table 1, it is possible to conclud that all the inputs amount for all the process are kept standard, with exception for the electricity consumption, higher for small parts, since small parts usually requires slower and short cutting parameters, providing shorter material removal rate and consequently higher specific energy to cut, as explained in the work of Yoon et al, 2014, and for the 18/8 chromium steel, due the worse machinability, as discussed by Paro et al., 2001. It is also important highlight that instead heaving the same workpiece material amount (removed material in the form of chip) for all the situations, they will provide different impacts, since have different composition.

Another point to be highlighted is the high standard deviation, up to 332% for some indicators, showing up that the core characteristic of the LCA, its 'holistic' nature, is both its major strength and, at the same time, its limitation. The broad scope of analyzing the complete life cycle of a product can only be achieved at the expense of simplifying other aspects, not providing the framework for a full-fledged local risk assessment study (TUKKER, 2004), information known and advised by the software LCI report documentation itself, since “due the large variation from factory to factory, in case this dataset becomes important in the results, it has to be investigated further if the rough estimations made are applicable or not”.

For an easier visualization and interpretation of the results, the resource inputs amount was converted into a multi-objective radar chart, showed in Figure 2, comparing the four processes: the milling of a low alloyed steel (small and average parts) and the milling of a 18/8 chrome steel (small and average parts). The average impact indicator was also added to the chart.

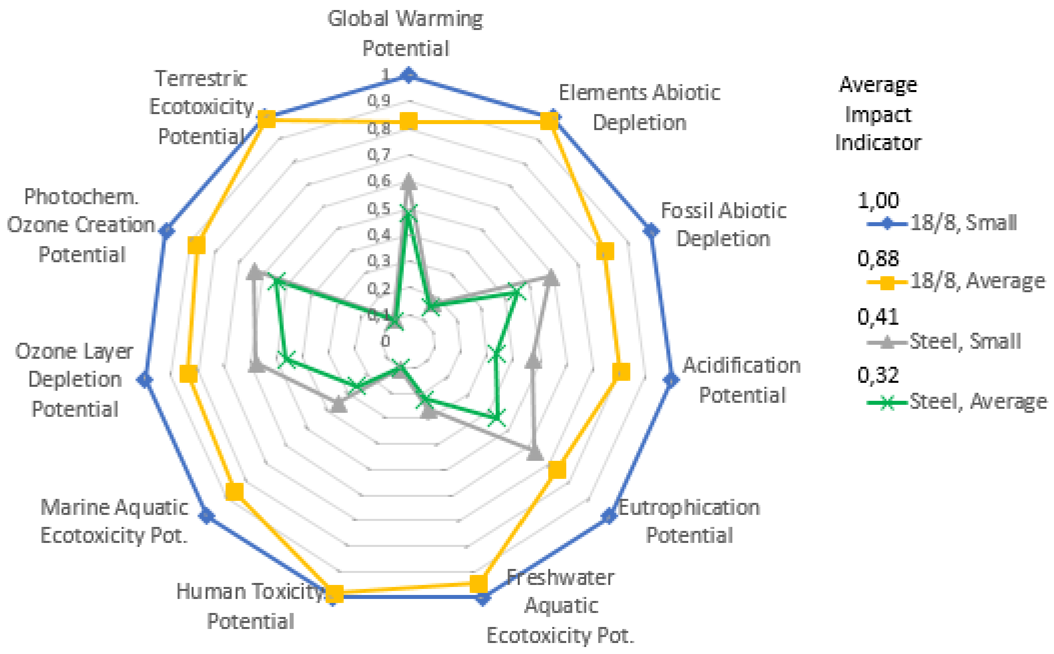

Figure 2. Multi-objective environmental impact radar chart and average impact indicator for each process

Analyzing this pollutant chart, it is possible observe that the most pollutant process is the milling of 18/8 steel of small parts, since all the indicators for this process are higher than for the others, followed by the milling of 18/8 steel of average parts, milling of low alloyed steel of small parts and milling of low alloyed steel of average parts. So, first of all, the 18/8 steel is variable which makes the process more pollutant, mainly influencing categories such as Human Toxicity, Terrestric Ecotoxicity and elements abiotic depletion, and then, the size of the piece, most influencing categories such as Global Warming and Eutrophication.

Intending to evaluate which resource input most cotribute to the total inpact, one single process, the milling of a low alloyed steel of small parts, was also exploded, and the environmental impact percentage of each input calculated. Figure 3 shows the multi-objective radar chart and the average impact indicator of them.

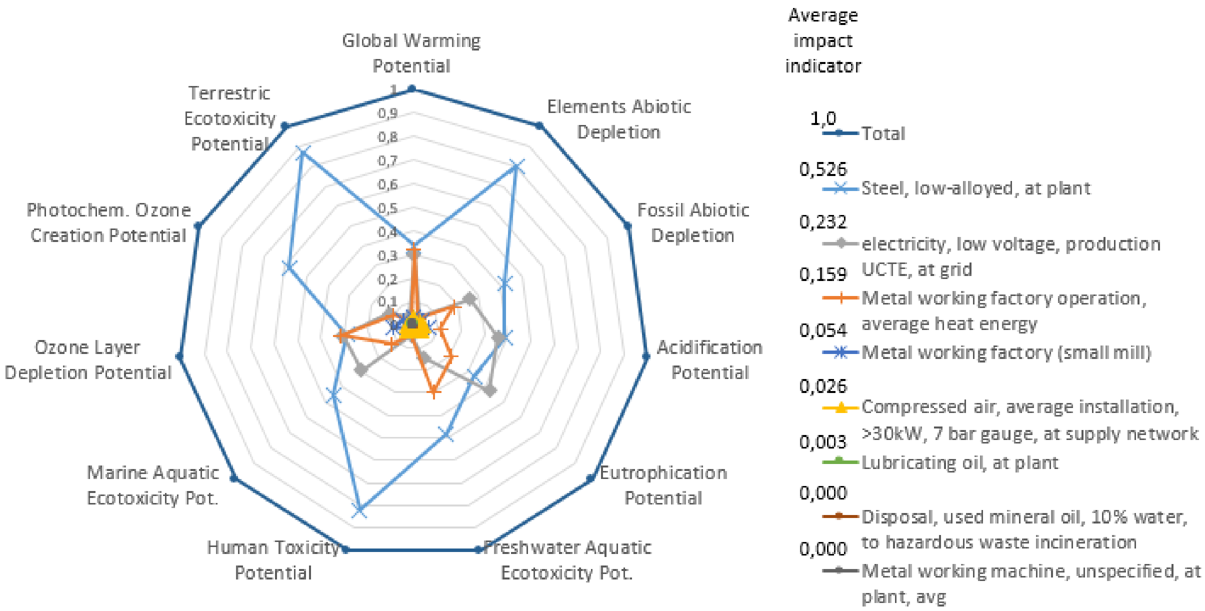

Figure 3. Multi-objective environmental impact net chart and average impact indicator for each input

Analyzing the chart of Figure 3, it is possible to suggest that the most impactful input is the steel, due its bigger impact area and percentage of impact (impact factor percentage of 0,526), contributing with more than a half of the total impact of the process. It is noticed that the steel is recorded as removed material in the form of chips, a waste inherent of the machining processes, not allowing many options for its reduction at the process level but showing the importance for material recycling and stock reduction plans at the system and product level.

Considering the impact factor percentage, the second most impactful input for this process is the electricity (impact factor percentage of 0,232), followed by the metal working factory operation electricity (impact factor percentage of 0,159), metal working factory (impact factor percentage of 0,054), compressed air (impact factor percentage of 0,026), the lubricating oil (0,003), disposal of used mineral oil and the machine (with impact factor percentage less than 0,000).

It is also noticed here that different from what happened with the processes LCA where all the indicators for one process were higher than for another, making the comparison easy, for the inputs analysis happened some interchange of indicators, highlighting the importance for a more judicious weighting process and impact categories selection.

5. CONCLUSION

The presented methodology showed to be a powerful tool to access the environmental impacts of processes, with some gaps that still need to be worked on as the high standard deviation for some relevant resources inputs.

Through the software provided, it was possible conclude that the removed material (in form of chips) is the most pollutant resource. The electricity, the factory operation, the factory and the compressed air also have relevant impact. By the other hand, lubricating oil, disposal of oil and the machine have low impact contribution to the process.

It was also concluded that the machining of the 18/8 Chrome steel is more pollutant than the machining of the low alloyed steel, and the machining of small parts is also more pollutant than the machining of average parts.

6. ACKNOWLEDGEMENTS

This work was carried out with CNPq support, National Council for Scientific and Technological Development - Brazil and the experiments conducted at LMAS, the Laboratory *for Manufacturing and Sustainability – Berkeley.*

To São Paulo Research Foundation (FAPESP), grant # 2013/00551-7.

In memory of David Alan Dornfeld, who passed away before we had written this report but was fundamental for the development of this work, opening his Laboratory for all the experiments conduction.

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