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Strategic Life Cycle Assessment, SLCA, applied on the comparison between an electric vehicle and a vehicle with an internal combustion engine

Hélder Alves de Almeida Júnior, helder.alves.eng@gmail.com[1]
Daniel Enrique Castro, Daniel@plusengenharia.com.br[2]

[1]CEFET-MG, Technical Federal Center of Minas Gerais, Av. Amazonas 7675- Nova Gameleira - Belo Horizonte - MG – Brazil
[2]CEFET-MG, Technical Federal Center of Minas Gerais, Av. Amazonas 7675- Nova Gameleira - Belo Horizonte - MG – Brazil

Abstract*. It is increasingly urgent to define a technology that allows the replacement current vehicles powered by internal combustion engines by a more sustainable vehicle. There are several technological options such as electric vehicles, hybrids and vehicles powered by biofuels. So far there is no clear methodology for comparing the strengths and weaknesses of these alternative technologies. This paper presents a methodology that aims to compare from a strategic point of view technological alternatives comprehensively prioritizing their impacts throughout the lifecycle thus providing a clearer basis for decision making.*

Keywords*: Life Cycle Assessment, Strategic Life Cycle Assessment, FMEA, Sustainability*

1. INTRODUCTION

The current model of economic development adopted by most countries in the world requires efficient transport of goods and people between cities and different regions of a country. This led to a rapid increase in the number of vehicles in most countries in recent decades. Most vehicles currently use nonrenewable fossil fuels, which cause serious environmental impacts, among which stands out the so-called greenhouse, considered the main responsible for global warming. There are several proposals to replace the traditional vehicle with internal combustion engine as vehicles with electric motors, with engines fueled by biofuels or by hydrogen, as well as hybrid vehicles. The problem seems to be very complex due to the diversity of materials to consider as well as the scope of the study, since it is necessary to extend the analysis to the entire vehicle lifecycle from extraction of raw materials, manufacturing, use and final disposal including recycling of materials. One of the most currently techniques used for this type of study is the Life Cycle Assessment (LCA), which allows a comprehensive assessment of the impacts of products throughout their lifecycle. This technique requires the collection of data from all environmental impacts generated by all materials throughout the lifecycle of a product. This phase of LCA called inventory is very time consuming and, often, there are insufficient data to determine all these impacts. For this reason, this type of analysis is restricted to very small components or simple products and can´t be applied to complex products such as vehicles. A new method is presented that combines LCA with the FMEA technique (Failure Mode end Effect Analysis) to make a comparative analysis of the environmental and energy impacts of new products throughout their life cycle. FMEA is a known tool used widely in various fields of engineering, such as design, manufacturing processes and analysis of system failures. FMEA prioritize effectively the impacts generated by the different components of a vehicle. Two types of vehicle were analyzed, one with electric motor and other with internal combustion engine. The result let compare the main impacts of these vehicles and gives insight about the need for additional research to determine which of these vehicles is actually more sustainable throughout the life cycle.

2. LIFE CYCLE ASSESSMENT (LCA)

Life cycle assessment LCA is a tool used to assess the global impact of goods and services. It´s a systematic assessment that quantifies the flows of energy and materials in the life cycle of a product or service. The Environmental Protection Agency, EPA defines LCA as "a tool to evaluate holistically, a product or activity throughout its life cycle" (Vigon et al., 1993). The beginning of the LCA is by creating a flowchart of the process specifying all material and energy flows entering and leaving the system considering all stages of the life cycle: acquisition of raw materials, processing the raw materials to obtain the product, use of the product and final disposal and recycling. LCA is a complex approach with several variables. Therefore, there is a formal structure to conduct a Life Cycle Assessment of a product as illustrated in the next figure.

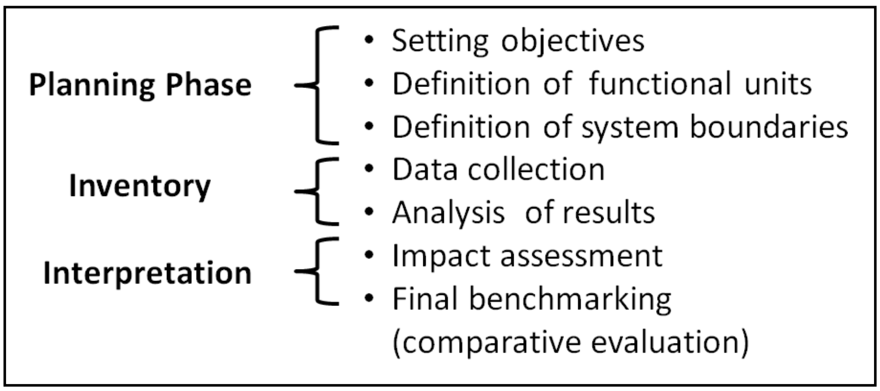

Figure 1. Necessary steps for a LCA

Planning Phase

According to Almeida, 2006, the systems evaluated by LCA are open, so it is important to establish a plan for the LCA procedure. During the planning phase the reasons to perform LCA should be established. It is also at this stage that the boundaries of the system should be set, defining the purpose of the assessment and a strategy for data collection and the methods used to collect. Defined the limits of the system and the purpose of the evaluation, a functional unit should be chosen for the calculation of the inputs and outputs of the system. The adequate choice of the functional unit for the LCA is a very important task, considering that it may lead to ambiguous results, especially comparing different products. Almeida, 2006 defines functional unit as the reference for the inventory. It is a measurement of the function performed by the system, for example, a system may produce 1 kg of polymer, a paper bag or a vehicle. This unit refers to a unit of product and a unit of function.

Inventory

According to ISO 14040 the inventory is the second step to perform LCA. This step determines the emissions that occur throughout the life cycle of the product and the amount of energy and raw materials used. The inventory provides detailed understanding of the production process. Thus, several important information are indicated in the inventory like explicit points of waste and its disposal, amounts of material circulating in the system and leaving the system. It is also possible to determine the pollution associated to a unit of the system and to identify waste of raw material. The results of an inventory are tables showing the impacts of materials and energy involved in each stage of the life cycle of a product.

Interpretation

The last step of LCA is the interpretation of the impacts collected in the inventory. Each impact needs to be characterized and evaluated. This phase should determine the severity of the impacts. Three stages are necessary to achieve this goal: classification, characterization and valuation of the impacts:
Classification: Inventory impacts are classified into categories like depletion of natural resources, human health or ecological injures.
Characterization: Potential impacts in each category are quantified using physical, chemical, biological and toxicological relevant data.
Valuation: discusses the importance of the impact assessment. This step may involve interpretation, weighting and ordering the data collected in the inventory.

3. THE MAIN FEATURES OF FMEA (FAILURE MODE AND EFFECT ANALYSIS)

Failure Mode and Effect Analysis-FMEA is a technical document in spreadsheet format, which allows to identify and to prioritize potential failures in projects, processes or products considering the effects of each failure mode on the performance of the product or process. This tool allows the definition of preventive and detective controls in order to prevent the occurrence of failure modes or to reduce their rate of occurrence. The essence of FMEA is to identify, prevent and prioritize failure modes using the following scheme of indexes:

Detection Index: indicates the probability that the proposed control system will detect the root cause of a failure mode before the product reaches the customer.

Occurrence Index: indicates the estimated number of failures that can occur considering a normal working period.

Severity Index: indicates the severity of the effect of potential failure modes in the product or service.

The product of these three indexes will generate the Risk Priority Number, RPN, or overall risk index that measures the overall impact of the failure mode in the context of the analysis (design, system or process). The following figure shows the typical format of a FMEA spreadsheet,

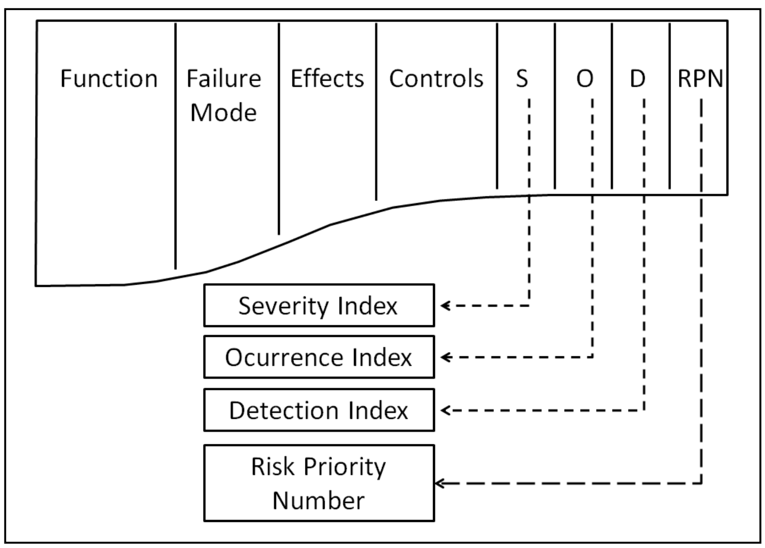

Figure 2. – Main fields of a FMEA spreadsheet

The FMEA indexes are measured on a scale from 1 to 10. The higher the index, ie, closer to 10 most critical are the dimensions linked to it (Severity, Occurrence and Detection). The RPN index is the product of the three previous indexes. Thus, RPN may range between 1 and 1000. The higher the RPN value most critical is the analyzed failure mode.

4. APPLICATION OF THE STRATEGIC LIFE CYCLE ASSESSMENT (SLCA)

PLANNING PHASE

The aim of this paper is to perform a Life Cycle Assessment comparing two vehicular technologies: electric vehicles (EV) and internal combustion engine vehicles (ICEV). In the planning phase of LCA is necessary to define the objectives of the assessment and the functional units considered. Table 1 shows the main components of the functional units corresponding to the two vehicular technologies considered in this paper.

Table 1. – Description of the functional units of the two analyzed vehicle technologies

Functional Unit	Electric Vehicle (EV)	Internal combustion engine Vehicle (ICEV)
Brakes	Drum and disk brake	Drum and disk brake
Driving System (engine)	Electric motor	Internal combustion engine
Fuel Supply System	Battery and electric power	Fuel tank and fossil fuel
Suspension System	Spring and damper	Spring and damper
Structure	Bodywork	Bodywork
Transmission	Shaft, gimbal system	Shaft, gearbox, gimbal system
Electric System	Electrical wiring	Electrical wiring, starter motor, alternator
Cooling system Engine	(without)	pipes, radiator valves

As showed in table 1 there are eight functional units to consider in the analysis. For the comparative LCA of the two vehicular technologies considered (EV and ICEV) there are four functional units virtually identical: brakes, suspension system, structure and transmission. For this reason, these four units will produce similar impacts during the vehicle life cycle and don´t contribute for a comparative LCA. There are two functional units with minor differences between technologies: electric system and engine cooling system. For an initial analysis, these two units can also be disregarded.

There are actually two functional units that must be analyzed in detail with respect to their impact on the life cycle of the vehicle: driving system (engine) and fuel supply system. To perform a more detailed analysis of these two units is necessary to evaluate the processes linked to them throughout the life cycle of the vehicles considered here. The next table summarizes the main processes of each stage of the life cycle for each considered functional unit for the two types of vehicle compared here.

Table 2. – Main processes for all stages of the life cycle corresponding to the functional units Driving System (engine) and Fuel Supply System

Stages of the life cycle	Electric Vehicle (EV)		Internal combustion engine vehicle (ICEV)	
	Engine	Fuel supply system	Engine	Fuel supply system
Raw material	extraction of copper and other metals	(without impact)	extraction of iron and other metals	petroleum extraction
Manufacture	casting and machining	power generation (hydro)	casting and machining	oil distillation
Use	maintenance, lubrication and replacement of components	distribution and transmission of electricity and battery use	maintenance, lubrication and replacement of components	distribution of fuel and fuel combustion
End Disposal	recycling of raw materials (copper and other metals)	battery recycling	recycling of raw materials (iron and other metals)	metal recycling (fuel tank)

The driving systems (engines) for the two considered vehicles (EV and ICEV) are different but their processes during the life cycle of the vehicle are not so different because they are made from similar materials (mainly metals) and are produced by similar manufacture processes (machining, casting, cutting, etc.). For this reason, this unit will not be considered in the present comparative LCA. The fuel supply system is the functional unit showing more differences between the two technologies analyzed. For this reason, a comparative LCA between these two vehicle technologies should focus on this functional unit.

INVENTORY

As shown in the previous section, the generation of electricity (power generation) is the first process of the fuel supply system for an electric vehicle. For this reason, this process will be used in order to demonstrate the method developed in this study.

Because the main source of electricity in Brazil is hydroelectric, the initial study to assess the impact of the life cycle of an electric vehicle will base on this type of power generation. The inventory considered in this work (Ribeiro, 2003) corresponds to the Itaipu hydroelectric plant, the largest in Brazil and one of the largest in the world. The inventory considers the impacts in the following categories:

- Consumption of material resources
- Consumption of energy resources
- Atmospheric emissions
- Fluid waste
- Solid waste
- Losses

For each category, the inventory identifies the different types of impact quantified in a standard physical unit in order to compare the results with other types of power generation systems. In this case, all impacts of the inventory are measured per unit of generated energy (MWh).

Table 3. Inventory for the Hydroelectric plant of Itaipú - Brazil (data impacts are related to 1MWh), Ribeiro (2003)

Consump. of mat. Resources		
Water	Kg	8,90E+00
Air	Kg	1,24E-05
Sand	Kg	4,12E-01
Clay	Kg	8,34E-02
Basalt	Kg	1,08E+01
Bauxite	Kg	4,00E-05
Calcite	Kg	4,86E-01
Coal	Kg	5,40E-02
Dolomite	Kg	9,69E-04
Fluorite	Kg	6,63E-04
Oil	Kg	1,19E-01
Natual Gas	Kg	8,84E-04
Gipsite	Kg	8,33E-03
Wood	Kg	1,44E-01
Cu-mineral	Kg	2,01E-03
Iron-mineral	Kg	1,66E-01
Mn-Mineral	Kg	1,27E-03
Quarzit	Kg	2,54E-03
Rock salt	Kg	1,90E-05
steel scrap	Kg	6,53E-02
Cu-scrap	Kg	2,93E-04
earth	Kg	3,98E+00

Consumprtion of energy resources		
Energy	MJ	4,33E-02
Energy from coal	MJ	9,50E-04
Energy from nat. Gas	MJ	2,52E-01
Energy from oil	MJ	6,08E-02
Energy from uran	MJ	9,50E-04
Hidropower	MJ	1,46E+00

Atmospheric emissions		
1,3 Butadien	kg	1,40E-07
aldehydes	kg	3,40E-05
ammonia	kg	2,16E-07
Benzen	kg	1,64E-05
Benzopyrene	kg	2,42E-09
CaO	kg	1,21E-03
CH4	kg	1,32E-01
Lead	kg	1,65E-11
CO	kg	1,12E-01
CO2	kg	1,56E+00
COV	kg	2,64E-04
COV exc. Metan	kg	1,10E-04
Etan	kg	3,70E-05
F2	kg	7,65E-08
FeO	kg	8,18E-04
Fluoreteno	kg	2,42E-08
Fluoride	kg	1,72E-06
soot	kg	5,84E-05
H2	kg	1,83E-04
H2S	kg	1,10E-05
HCl	kg	4,97E-08
Hidrocarbons	kg	3,86E-04
Hidroc. Halifatic	kg	3,43E-05
Hidroc. Aromatic.	kg	3,26E-07
unpecified	kg	1,03E-05
particulated	kg	1,37E-02
Hg	kg	8,27E-15
Heavy metals	kg	9,50E-08
Metil- mercaptan	kg	1,35E-09
N2O	kg	5,89E-07
NO2	kg	1,49E-05
NOx	kg	2,97E-03
Oil	kg	1,79E-05
PM10	kg	4,01E-04
dust	kg	1,07E-02
SO2	kg	3,49E-03
SOx	kg	2,70E-04
Toluen	kg	1,05E-07
Xilen	kg	1,13E-07

Fluid waste		
acetic acid	kg	5,80E-03
acetaldheyde	kg	8,09E-05
acetone	kg	1,50E-04
Acid (H+)	kg	2,85E-06
tar	kg	1,39E-02
ammonia	kg	5,19E-08
lead	kg	4,03E-09
cyanide	kg	3,18E-07
Cl-	kg	3,75E-06
Cu	kg	1,21E-09
Chrom 3+	kg	1,47E-09
DQO	kg	2,46E-07
phenol	kg	5,37E-07
iron	kg	5,38E-06
fluoride	kg	2,23E-06
H2	kg	1,54E-07
Hexan	kg	5,36E-08
Hydrocarbons	kg	2,10E-06
Inorganic - general	kg	6,36E-03
Metalic ions	kg	5,00E-07
Mn	kg	1,15E-07
Hg	kg	2,42E-10
Mthanol	kg	2,10E-03
methyl acetate	kg	1,85E-04
N total	kg	4,03E-08
NH3	kg	4,76E-06
nitrate	kg	4,75E-06
oil	kg	1,34E-05
dissolved organics	kg	1,90E-06
PAH	kg	4,03E-10
Oil	kg	2,22E-06
sodium	kg	1,88E-06
dissolved solids	kg	6,30E-06
suspended solids	kg	1,92E-05
dissolved substances	kg	9,50E-07
suspended substances	kg	6,65E-06
sulfite	kg	3,56E-07
Zn	kg	1,78E-05

Solid waste		
slag	kg	4,97E-08
sludge	kg	2,12E-03
steelplant-waste	kg	5,65E-03
inorganic waste	kg	3,02E-01
mineral waste	kg	5,46E-06
not inert waste	kg	1,43E-04
solid waste	kg	5,99E-05

Losses		
Heat loss (air)	MJ	1,24E-02
Heat loss (water)	MJ	6,35E-02
land use	m²	1,52E-01

As observed in table 3 the results of the inventory are quantitative and do not allow a relative assessment of all impacts. To assess the real impact of new technologies is necessary to be able to prioritize impacts in order to check which are the most important. As indicated in table 2, power generation represents in electric vehicles only the first process in the manufacture stage of the life cycle of the fuel supply system. Only for this stage, the inventory has indicated 113 impacts (see table 4) divided as follows:

Table 4- Ranking of impacts of a hydroelectric plant

Inventory Category	Number of impacts
Consumption of material resources	22
Consumption of energy resources	6
Atmospheric emissions	38
Fluid waste	37
Solid waste	7
Losses	3
Total	**113**

INTERPRETATION

Prioritization of inventory impacts using FMEA

The proposed method combines the results obtained in the inventory of a conventional LCA with FMEA to perform the prioritization of impacts. Inventory impacts can be considered as failure modes of a process since they can lead to potential failures in the process, depending on its severity. FMEA is one of the best engineering tools to analyze the influence of potential failures modes in new projects or processes. As mentioned in section 3, FMEA uses three indexes to prioritize failure modes: Severity Index (S), Occurrence Index (O) and Detection Index (D). These indexes range between 1 and 10 depending on the overall severity of the impact. In the next section the methodology used in this study to calculate the indexes of FMEA to prioritize inventory impacts will be presented.

Severity Index (S)

This index was calculated considering the relative weight of each impact in each category (Weight Factor) multiplied by a severity factor, which depends on the most characteristic types of impact for each category considered in the inventory. To the result of this multiplication was added the value 1, which is the minimum value expected for this index. Table 5 summarizes the severity indexes for the inventory categories Energy Consumption and Energy Losses.

Table 5 – Severity Index (S) for the categories Energy Consumption and Energy Losses

ENERGY CONSUMPTION AND ENERGY LOSSES

			Severity Factor		
	MJ	Weight Factor	Renewable energy	Not renewable energy	**S**
Hidropower	1,46E+00	0,77	5	10	**5**
Natural gas energy	2,52E-01	0,13	5	10	**2**
Heat losses (water)	6,35E-02	0,03	5	10	**1**
Energy from oil	6,08E-02	0,03	5	10	**1**
Energy (unspecified)	4,33E-02	0,02	5	10	**1**
Heat losses (air)	1,24E-02	0,01	5	10	**1**
Energy from coal	9,50E-04	0,00	5	10	**1**
Energy from uran	9,50E-04	0,00	5	10	**1**
Total	1,89E+00				

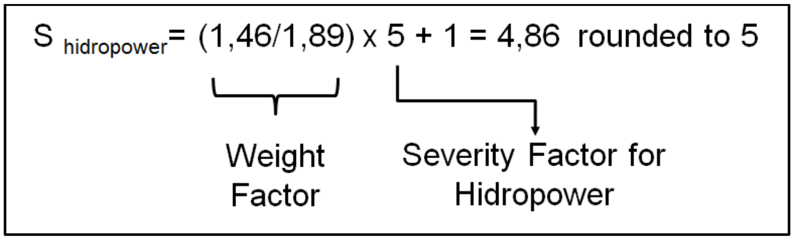

Figure 3. – Example of calculating the severity index for the inventory impact: "energy consumption of hydropower"

Figure 3 shows the calculation model used to calculate the severity index. In the figure was used the example of the severity index for the inventory impact "energy consumption of hydropower". As observed in this figure the weight factor is the rate between the intensity of impact of each item of each category and the total intensity of all items together. For the case of energy impacts (consumption and losses) the intensity is measured in MJ. Table 6 summarizes the Severity Factors considered in the present analysis for all impact categories of the inventory. It must be pointed out, that the value of the severity factor can be altered in order to simulate other severity conditions.

Table 6 – Table with the Severity Factors considered for each category of the inventory

SEVERITY FACTORS

CONSUMPTION OF NATURAL RESOURCES	
Renewable	Nonrenewable
5	10

ENERGY CONSUMPTION AND ENERGY LOSSES	
Renewable	Nonrenewable
5	10

ATMOSPHERIC EMISSIONS	
Without greenhouse effect	With greenhouse effect
5	10

FLUID WASTE	
Low pollutant	High Pollutant
5	10

SOLID WASTE	
Low pollutant	High Pollutant
5	10

In order to consider low pollutant or high pollutant levels for solid and fluid wastes the COPAM/CERH-MG norm (2008) was consulted.

Occurrence Index (O)

This index assesses the frequency of occurrence for each impact analyzed. In the case of power sources, which is the case analyzed in this inventory, the occurrence of impacts depends on the expected mean life of the energy source. Table 7 shows many renewable and nonrenewable energy sources with their expected mean life. The maximal life corresponds to hydropower plants, more than 100 years. For this reason, this source was the reference to calculate the corresponding occurrence indexes for the other energy sources.

Table 7 – Occurrence Index (O) for different energy sources

Energy Source	Expected Life [Years]	O
Hydropower	100	1
Thermal	30	8
Nuclear	30	8
Solar	25	9
Windpower	20	9

Detection Index (D)

The detection index must assess the ability to detect the impacts considered in inventory. The detection of impacts depends mainly on the category of impact. For instance, energy consumption impacts are relatively easy to detect, since this kind of impact is already measured in almost all processes. Energy losses are more difficult to measure, but normally it is possible to develop technical solutions to measure this type of impact. Thermal losses for instance, that are the most common energy losses in industrial plants and energy generation systems can be monitored using thermography. Wastes of materials are much more difficult to detect, since this type of wastes spread on plant and machinery. Generally, the detection capability of waste materials directly depends on its density. Solid wastes are easier to detect than liquid wastes and these in turn are easier to detect than the gaseous wastes. Based on these concepts the detection index scale showed in table 8 was develop.

Table 8 – Adopted scale of Detection Index (D)

Level of Detection	Examples of impacts	D
Detection of impact is guaranteed	Consumption of energy	1
		2
Good chance to detect the impact	Losses of energy (heat, air, etc.)	3
		4
Is possible to detect the impact	Solid waste impact	5
		6
Is difficult to detect the impact	Fluid waste impact	7
		8
Very difficult to detect the impact	Atmospheric emmisions	9
Impact is impossible to detect		10

5. RESULTS OBTAINED WITH THE PROPOSED METHOD

The results obtained with the proposed LCA method indicate CO_2-atmospheric emission as the major environmental impact of the stage of energy generation with a risk priority number of 81. In the second position of impacts is tar as fluid waste with a risk priority number of 42. Water is the third global impact of this stage as consumption of material resources with a risk priority number of 35.

Table 9 – Results of the Strategic Life Cycle Assessment (SLCA) for the stage "energy generation" (first process of the fuel supply system of electric vehicles)

CONSUMPTION OF MATERIAL RESOURCES		Severity Factor					
	weight factor	Renewable	Nonrenewable	S	O	D	RPN
Basalt	0,43	5	10	5	1	5	**25**
Water	0,35	5	10	3	1	7	**21**
Earth	0,16	5	10	2	1	5	**10**

ENERGY CONSUMPTION AND ENERGY LOSSES		Severity Factor					
	weight factor	Renewable	Nonrenewable	IG	IO	ID	RPN
Hydropower	0,77	5	10	5	1	1	**5**
Energy natural gas	0,13	5	10	2	1	1	**2**

ATMOSPHERIC EMISSIONS		Severity Factor					
	weight factor	Without Greenhouse	With Greenhouse	IG	IO	ID	RPN
CO2	0,85	5	10	10	1	9	**81**
CH4	0,07	5	10	2	1	9	**18**

FLUID WASTE		Severity Factor					
	weight factor	Low Pollutant	High Pollutant	IG	IO	ID	RPN
Tar	0,48	5	10	6	1	7	**42**
General Inorganic	0,22	5	10	3	1	7	**21**
Acetic Acid	0,20	5	10	2	1	7	**14**
Methanol	0,07	5	10	1	1	7	**7**

SOLID WASTE		Severity Factor					
	weight factor	Low Pollutant	High Pollutant	IG	IO	ID	RPN
Inorganic Residue	0,97	5	10	10	1	5	**50**

The results obtained with the proposed LCA method indicate CO2 atmospheric emission as the major environmental impact of the stage "energy generation" with a risk priority number (RPN) of 81. In the second position of impacts are general inorganic solid wastes with a risk priority number of 50. Tar is the third global impact of this stage in the inventory as fluid waste with a risk priority number of 42. It must be pointed out, that for the case of general inorganic wastes (fluid or solid) it was considered the highest severity factor 10 because it is not clear the presence or not of heavy metals in such wastes. All the other impacts of the inventory presented very low RPN levels, lower than 2. They don´t need to be considered as a high potential risk for the process.

6. CONCLUSIONS

The development of new products with more advanced technologies requires a careful analysis of all impacts throughout their life cycle before they are released to the market. Due to the large number of variables involved in this type of analysis is necessary to develop methodologies oriented to verify more quickly and strategic the impacts throughout the life cycle of a product. Currently the Life Cycle Assessment (LCA) is one of the most important tools developed for this type of analysis. Unfortunately most of these analyzes realized with this tool are limited to only to carry out the inventory of some types of processes and do not allow a more comprehensive and strategic view of the impacts throughout the life cycle of a product. The methodology proposed in this paper achieves fast and effective this goal by applying the results of inventories using FMEA to prioritize the impacts of a product and thus be able to decide more clearly about how to proceed with a particular project or the development of a new technology. This new methodology can be denominated as Strategic Life Cycle Assessment (SLCA), since it allows a more comprehensive and strategic view of all impacts related to new technologies, even for complex processes with a large number of variables to be weighted.

The methodology SLCA was applied to assess the impacts for the process energy generation of hydroelectric power, which is one of five processes involved in the life cycle of fuel supply system for electric vehicles. The results obtained clearly distinguish the three major environmental impacts (CO2 as atmospheric emission, Tar as fluid waste and Water consumption) from a total universe of 113 impacts raised in the inventory.

In future works the tool SLCA will be applied throughout the functional units of the fuel supply system of electric vehicles and internal combustion engines in order to obtain a strategic map of the impacts for these two technologies. The goal of this research activity is to determine which measures are necessaries to enable a vehicle that minimizes overall impacts to the environment and thus be more sustainable than current vehicles using nonrenewable fossil fuels.

7. ACKNOWLEDGEMENTS

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