Life-Cycle Assessment methodology: a tool for the evaluation of environmental and toxicological impacts of ammunitions

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1. Introduction

Over the last ten years the environmental concerns associated with the military activities have increased due to legislation pressure and an increasing awareness to the environmental issues. Such situation has leaded the defence industry and the Armed Forces to seek for a tool to evaluate the environmental burdens associated with ammunitions. Some methodologies have been applied to evaluate the environmental impacts and rank the different alternatives from an environmental point of view. Examples of those methodologies are the POEMS methodology (UK) and the MIDAS (USA), although the results delivered by these methodologies are very broad and the assessment of eventual environmental benefits from different production, use or disposal alternatives are difficult to evaluate.

One of the suitable solutions to overcome this problem is the implantation of a life-cycle approach, based in the Life-Cycle Assessment (LCA) methodology, to assess the environmental and toxicological impacts of ammunitions. The Life-Cycle Assessment (LCA) is a methodology for assessing the potential environmental and toxicological impacts of a product system throughout its life-cycle (ISO 14040, 2006). The application of the LCA methodology to military system can assist in i) which are the hotspots and how do they contribute to the impacts associated with the production of ammunitions; ii) the comparison of the impacts from different formulations and production solutions to assess which one presents lower impact and why; iii) the assessment of impacts resulting from the use of ammunitions and the consequences for human health and ecosystems; iv) in the comparison and analysis of the

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advantages and disadvantages of different pathways of demilitarization techniques.

To show the field of possibilities just described the results of two LCA studies will be presented. Those studies are: i) the comparative assessment for production and use of four different 9 mm ammunitions with two types of projectiles (steel-lead versus composite) and two types of primers (lead versus non-lead) and ii) and a quantitative assessment of the environmental and toxicological impacts associated with two different demilitarisation paths - open detonation and incineration with gas treatment.

2. Life-Cycle Assessment Methodology

Life-Cycle Assessment (LCA) methodology assesses the potential environmental impacts of a product system throughout its Life-Cycle (LC). LCA is based on system analysis and handles the process as a chain of subsystems which exchange inputs and outputs (Malça and Freire, 2006). The Life-Cycle includes the extraction of materials, production, use and disposal (cradle-to-grave). The results obtained by an LCA study can be used to identify environmentally preferable solutions and opportunities to improve products or processes.

According to the ISO standards (ISO 14040, 2006), an LCA has four interrelated phases: goal and scope definition, Life-Cycle Inventory (LCI), Life-Cycle Impact Assessment (LCIA) and interpretation. The first phase of the LCA includes the definition of the goal and scope of the study, including the product system boundaries and a functional unit. The functional unit is a reference that relates the system inputs and outputs and is required to ensure comparability of results between different LCA studies. In the inventory analysis, the inputs and outputs of the system are collected and compiled. In the LCIA, inventory data is characterized into specific environmental impact categories according to selected LCIA methods. It should be noted that different LCIA methods will lead to distinct results (values, impact categories and units). Interpretation is the final phase of the LCA procedure, in which the results are summarized and discussed as a basis for conclusions, recommendations and decision making in accordance with the goal and scope definition phase (ISO 14040).

3. Case studies

This section presents the life-cycle model and inventory developed and respective results for two case studies to demonstrate the capabilities of LCA studies.

3.1 Comparative assessment of four small calibre ammunitions

A detailed Life-Cycle Inventory (LCI) was implemented, in which primary data referent to the ammunition production was collected from a Romanian company and may be considered as representative of the production process of this type of ammunitions. The 9 mm ammunitions assessed were:

#1) Ammunition with steel-lead bullet (projectile) and with leaded primer (TNR-Pb - Lead trinitroresorcinate);

#2) Ammunition with steel-lead bullet (projectile) and with non-leaded primer (DDNP – Diazodinitrophenol);

#3) Ammunition with composite (nylon-copper) bullet (projectile) and with leaded primer (TNR-Pb - Lead trinitroresorcinate);

#4) Ammunition with composite (nylon-copper) bullet (projectile) and with non-leaded primer (DDNP – Diazodinitrophenol).

Table 1 presents the energy and water requirements associated with 9 mm ammunitions production. Table 2 presents the emissions associated with the firing of the four types of ammunitions. The gaseous emissions (CO2, CO, HCN, NO, NO2, NH3 and CH4) and metal quantity in solid residues (Pb, Cu, Zn and Sb) were quantified by an experimental set-up and techniques described in Rotariu and Petre (2014).

Table 1. Data for energy and water requirement for production of 9 mm ammunitions

Electricity	0.046 kWh/bullet
Natural gas	0.240 MJ/bullet
Water	2.042 kg/bullet

Table 2. Emissions associated with use of 9 mm ammunitions in study

Substance	Emissions (mg/bullet)

	#1	#2	#3	#4
CO	198.65	184.75	119.21	118.76
CO_2	**101.79**	**96.79**	58.56	57.93
NO	3.80	3.22	3.85	4.41
NO_2	0.64	0.62	0.49	0.52
NH_3	**3.10**	**2.46**	1.67	1.84
HCN	**1.77**	**1.22**	0.18	0.13
CH_4	**1.10**	**0.96**	0.61	0.59
Pb	**3.14**	**1.04**	0.81	0.04
Cu	0.55	0.41	**4.85**	**5.21**
Zn	**0.12**	**0.11**	**0.19**	0.03
Sb	**0.37**	**0.20**	0.15	-

3.1.2 Results

Figure 1 presents the life-cycle environmental impact comparison referent to the production and use for the four 9 mm ammunitions. It is observed that the production phase have a higher contribution to the environmental impact categories, whilst the use phase shows a higher contribution to the toxicity categories (due to the emissions associated with the ammunition firing). Ammunition #1 is the one presenting the highest impact for seven out of nine impact categories, but mainly for the Human Toxicity categories due to the emissions of lead in the use phase. The composite ammunitions (#3 and #4) present higher impacts for the categories Eutrophication (due to the copper and nylon production) and Ecotoxicity (associated with the emissions of cooper). For the Human Toxicity categories the presence of lead, either in the projectile or in the primer, is relevant and its substitution leads to unequivocal toxicological benefits.

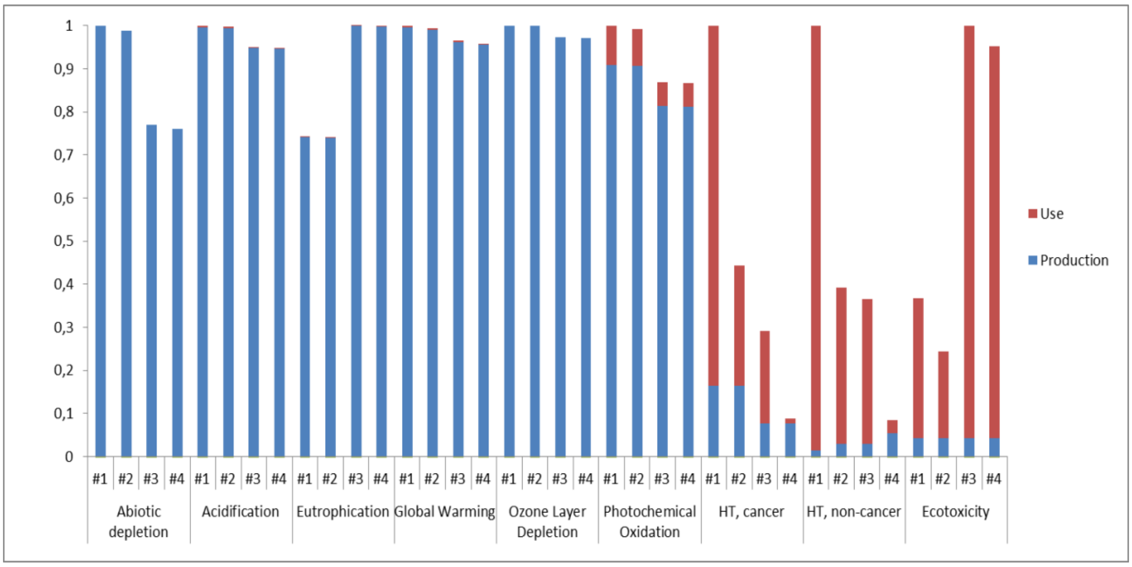

Figure 1. Life-Cycle impact comparison between the four 9 mm ammunitions: #1 – steel-lead projectile with lead primer; #2 – steel-lead projectile with non-lead primer; #3 – composite projectile with lead primer; #4 – composite projectile with non-lead primer

Since the production phase presents the higher significance to the environmental impact categories it is shown in detail the contribution to each one of the impact associated with 9 mm ammunition production (Figure 2). For ammunitions #1 and #2, it is observed that energy requirement presents the highest impact contribution for Abiotic Depletion (46%), Global Warming (55%) and Ozone Layer Depletion (65%), whilst brass (used for the cartridge) have the highest contribution for the categories Acidification (43%), Eutrophication (76%), Photochemical Oxidation (39%) and non-cancer Human Toxicity (76%). Projectile of ammunitions #1 and #2 also presents a significant impact for categories Abiotic Depletion (37%), Photochemical Oxidation (30%) and, in fact being the highest impact contributor, to cancer Human Toxicity (58%), mainly due to the emissions associated with the production of steel and lead.

For ammunitions #3 and #4 the contribution to the impacts arising from energy requirement and cartridge production, when compared with ammunitions #1 and #2, are higher once the composite projectile presents a lower influence. Therefore, it is observed that brass becomes a higher contributor to cancer Human Toxicity (increasing to 54%), in which the projectile contributes with only 5% (decreasing 53% compared with the steel-lead projectile). However, the composite projectile presents an increase of 20% for the non-cancer Human Toxicity, mainly due to the emissions associated with production of copper. Regarding the Ecotoxicity, the highest contribution to the impacts for all the four ammunitions is associated with the propellant, mainly due to the cultivation phase of cotton that is used for production of the single base powder.

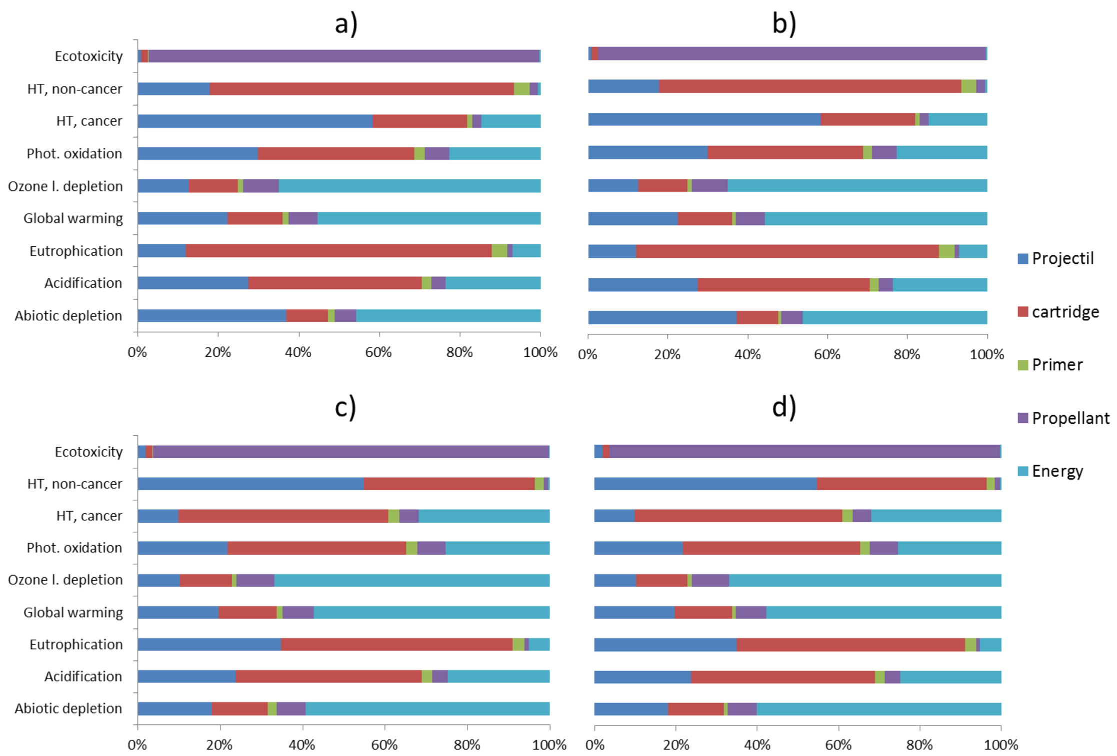

Figure 2. Representation of the main contribution to the total impacts associated with the four 9 mm ammunitions production: a) #1 - steel and lead projectile with lead primer; b) #2 - steel and lead projectile with non-lead primer; c) #3 - composite projectile with lead primer; d) #4 - composite projectile with non-lead primer

3.2 Comparative assessment of two demilitarisation techniques

This subsection presents the comparison between two ways to disposal a large calibre munition (Open Detonation vs Incineration with Gas Treatment) in an environmental perspective. For both demilitarisation techniques was considered a 155 mm generic large calibre ammunition with a charge of 4.5 kg of composition B in the projectile, which corresponds to around 10 kg TNT equivalent of energetic material.

The Incineration with Gas Treatment process is based on data from Ferreira et al. (2013), in which the model and inventory was developed based on the idD operations covering the following processes: dismantling of ammunition, unloading of energetic material, incineration in static kiln and consequent gas treatment. Life-Cycle Inventory included the consumption of energy (electricity and propane), consumables for the gas treatment, transport of materials, equipment and emissions from combustion. For Open Detonation it was compiled data from literature regarding the materials used for detonation (Bellow et al., 2008) and air emissions associated with detonation (US army Environmental command, 2009). Table 3 and 4 presents the energy and materials associated with the Incineration and Gas Treatment process, while Table 5 and 6 shows the emissions from Open Detonation and the materials used in the detonation.

Table 3. Energy and water consumption associate with the dismantling process

Electricity	1.369 kWh
Propane	0.479 kg
Water	6.161 kg

Table 4. Energy, consumables and emissions associated with the incineration and gas treatment process

		Energy			
Inputs	Electricity			7.860	*kWh*
	Propane			1.320	*kg*
		Materials			
	Water			15.31	kg
	Urea			0.280	kg
	Hydrochloric acid			0.078	kg
	Sodium Hydroxide			0.060	kg
	Hydrogen Peroxide			0.004	kg
	Zeolite			0.050	kg
		Materials			
	Sludge			0.008	kg
	Fly ashes			0.032	kg
	Ash and Slag			0.040	kg
		Emissions to air			
Outputs	2,3,7,8 TCDD*	8.65E-13 kg	NO_x	4.06E-03	kg
	1,2,3,4,7,8 HxCDD*	1.73E-12 kg	SO_2	3.98E-04	kg
	1,2,3,7,8,9 HxCDD*	8.65E-13 kg	Hg	1.71E-06	kg
	1,2,3,4,6,7,8 HpCDD*	8.65E-13 kg	Cd	1.54E-06	kg
	OCDD	8.65E-15 kg	As	3.33E-06	kg
	Furan	9.52E-12 kg	Ni	2.47E-06	kg
	HF	8.36E-05 kg	Pb	2.05E-06	kg
	HCl	8.36E-05 kg	Cu	2.05E-06	kg
	VOC	6.55E-04 kg	Cr	2.05E-06	kg
	CO	1.28E-03 kg	CO_2	6.24E+00	kg

H_2S	2.81E-04 kg	PM	4.20E-04 kg

Table 5. Emissions associated with the open detonation of a generic 155 mm ammunition (US army Environmental command, 2009)

Emissions (g/ammunition)					
carbon dioxide	9.35E+02	chromium	3.91E-02	acetylene	1.45E+01
carbon monoxide	2.21E+01	cobalt	1.36E-02	benzaldehyde	4.08E-02
lead	1.62E-02	copper	3.15E-02	2-butenal	1.19E-02
oxides of nitrogen	6.55E+01	total dioxin	3.40E-08	1-butene	1.87E-02
PM2.5	57E+02	ethylbenzene	1.19E-02	cis-2-butene	5.44E-03
PM10	7.99E+02	ethylene	4.85E-01	trans-2-butene	6.12E-03
sulphur dioxide	1.70E+00	formaldehyde	7.06E-02	diethylphthalate	4.76E-03
acetaldehyde	1.53E-01	manganese	3.06E-01	dodecane	9.35E-03
acetonitrile	1.36E-02	methylene chloride	8.16E-02	ethane	1.53E-01
acetophenone	5.36E-03	2-methylnaphthalene	1.53E-03	hexaldehyde	2.81E-02
ammonia	7.31E-02	naphthalene	1.36E-02	magnesium	5.53E+02
antimony	7.40E-02	nitroglycerin	2.64E-02	methyl ethyl ketone	2.38E-02
arsenic	1.70E-03	phenol	2.04E-03	1-propyne	7.48E-02
barium	6.38E-02	phosphorus	1.87E-01	valeraldehyde	3.91E-02
benzene	1.70E-01	propinaldehyde	7.31E-02	furan	3.57E-02
beryllium	4.68E-04	propylene	9.35E-02		
cadmium	1.11E+00	toluene	5.19E-02		
carbon disulphide	1.79E-02	xylene	4.51E-03		
chloromethane	1.11E-02	zinc	5.78E-01		

Table 6. Donor and gravel used for detonation of a generic large calibre ammunition (Bellow *et al.*, 2008)

Materials for detonation	Amount (kg/ammunition)
C4 donor	0.6
Gravel	1138.5

3.2.2 Results

Picture 3 presents the environmental and toxicological comparison between Open Detonation and Incineration with Gas Treatment. It can be seen that Incineration presents high impact for the six environmental categories. The reason for this impact is associated with the high energy requirements for the kiln and the gas treatment process, which represents more than 80% of the total impact. For Global Warming, the emissions, mainly resulting from the propane combustion, also represents a significant impact (46%). On the other hand, Open Detonation dominates the impacts for Human Health and Ecosystems due to emissions resulting from the detonation. The detonation emissions represent 35% of the total impacts for cancer Human Toxicity; 98% for non-cancer Human Toxicity; and 72% for Ecotoxicity.

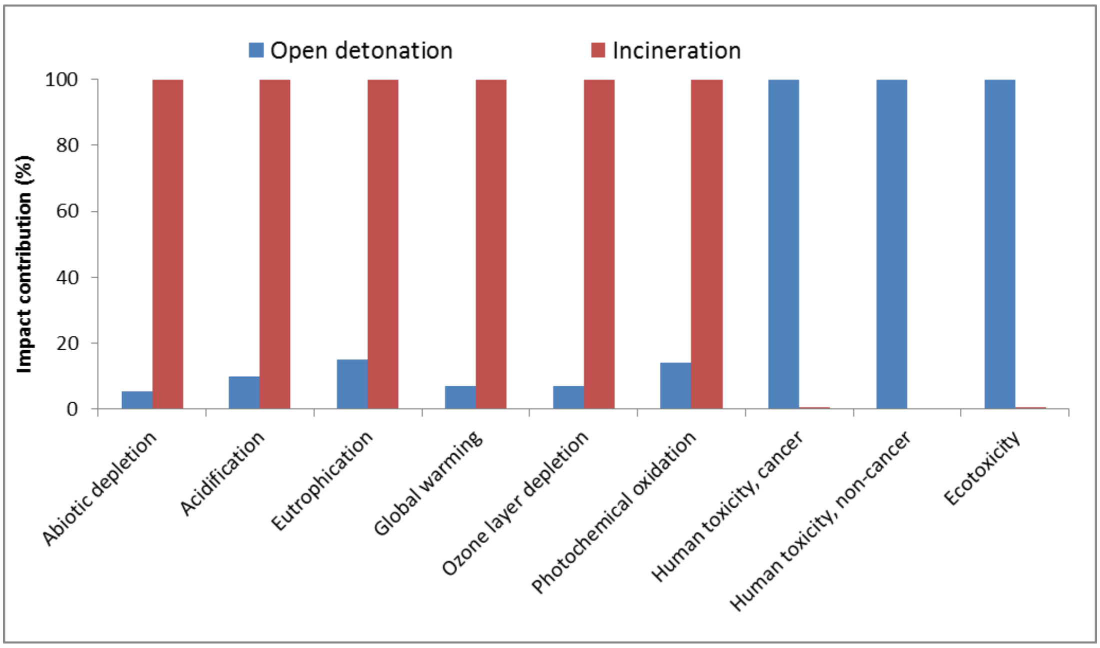

Figure 3. Environmental and toxicological impact comparison between Open Detonation and Incineration with Gas Treatment

4. Conclusion

This article presented the application of the Life-Cycle assessment methodology to assess the environmental and toxicological impacts associated with military products or systems. It was presented two case studies to demonstrate the feasibility of the LCA. The first case study applied a eco-design approach in which was carried out a comparative assessment for production and use of four different 9 mm ammunitions with two types of projectiles (steel-lead versus composite) and two types of primers (lead versus non-lead). It was concluded that the substitution of lead in the primer decreased the toxicity impacts for human health, and the production of a projectile with a lighter material (composite) also decreased the total environmental impact. However, the composite projectile increased the impact for Ecosystems due to emissions of copper. Therefore, it is needed to continue to search of different alternatives to decrease the environmental and toxicological impacts of bullets.

For the second case study was carried out a comparative assessment of the environmental and toxicological impacts associated with two different demilitarisation paths - open detonation and incineration with gas treatment. It was observed that the incineration in static kiln presented higher impacts for the six environmental impact categories mainly due to the high energy requirements; while Open Detonation dominates completely the toxicological impacts due to emissions resulting from the detonation.

Summary

Over the last ten years the environmental concerns associated with the military activities have increased due to legislation pressure and an increasing awareness to the environmental issues. Such situation has leaded the defence industry and the Armed Forces to seek for a tool to evaluate the environmental burdens associated with ammunitions. Some methodologies have been applied to evaluate the environmental impacts and rank the different alternatives from an environmental point of view. Examples of those methodologies are the POEMS methodology (UK) and the MIDAS (USA), although the results delivered by these methodologies are very broad and the assessment of eventual environmental benefits from different production, use or disposal alternatives are difficult to evaluate.

One of the suitable solutions to overcome this problem is the implantation of a life-cycle approach, based in the Life-Cycle Assessment (LCA) methodology, to assess the environmental and toxicological impacts of ammunitions. The Life-Cycle Assessment (LCA) is a methodology for assessing the potential environmental and toxicological impacts of a product system throughout its life-cycle (ISO 14040, 2006; ISO 14044, 2006). The application of the LCA methodology to military system can assist in i) which are the hotspots and how do they contribute to the impacts associated with the production of ammunitions; ii) the comparison of the impacts from different formulations and production solutions to assess which one presents lower impact and why; iii) the assessment of impacts resulting from the use of ammunitions and the consequences for human health and ecosystems; iv) in the comparison and analysis of the advantages and disadvantages of different pathways of demilitarization techniques.

To show the field of possibilities just described the results of two LCA studies will be presented. Those studies are: i) the comparative assessment for production and use of four different 9 mm ammunitions with two types of projectiles (steel-lead versus composite) and two types of primers (lead versus non-lead) and ii) and a quantitative assessment of the environmental and toxicological impacts associated with two different demil paths - open detonation and incineration with gas treatment.

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