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A life cycle assessment of destruction of ammunition

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ABSTRACT

The Swedish Armed Forces have large stocks of ammunition that were produced at a time when decommissioning was not considered. This ammunition will eventually become obsolete and must be destroyed, preferably with minimal impact on the environment and in a safe way for personnel. The aim of this paper is to make a comparison of the environmental impacts in a life cycle perspective of three different methods of decommissioning/destruction of ammunition, and to identify the environmental advantages and disadvantages of each of these destruction methods: open detonation; static kiln incineration with air pollution control combined with metal recycling, and a combination of incineration with air pollution control, open burning, recovery of some energetic material and metal recycling. Data used are for the specific processes and from established LCA databases. Recycling the materials in the ammunition and minimising the spread of airborne pollutants during incineration were found to be the most important factors affecting the life cycle environmental performance of the compared destruction methods. Open detonation with or without metal recycling proved to be the overall worst alternative from a life cycle perspective. The results for the static kiln and combination treatment indicate that the kind of ammunition and location of the destruction plant might determine the choice of method, since the environmental impacts from these methods are of little difference in the case of this specific grenade. Different methods for destruction of ammunition have previously been discussed from a risk and safety perspective. This is however to our knowledge the first study looking specifically on environmentally aspect in a life cycle perspective.

1. Introduction

Today there is growing understanding of the need to minimise the environmental impacts from all sectors, and the military sector cannot be an exception [1–4]. The Swedish Armed Forces have large amounts of ammunition in store, much of which was produced at a time when subsequent decommissioning was not considered. It was not until the 1980s that the purchaser actually began to ask for the possibility of decommissioning of the ammunition [5]. This is also the case in many other countries [5]. Sooner or later this ammunition will become obsolete and must therefore be destroyed. This problem has to be resolved, preferably with as little impact on the environment as possible and in a way that poses no threat to the health of personnel and general public [4,6].

There are several methods to use for explosive waste disposal [3,4,6–9]. Some, but far from all of the methods are also usable for disposal of explosive waste in the form of ammunition, depending on location of the destruction facility, kind of ammunition, amount of ammunition and quality of the ammunition (i.e. if is it safe to handle or not). Every method of destruction of energetic material, explosive waste or ammunition results in environmental impacts both in short terms and long terms [3,7,9,10].

The aim of this study is to assess the potential life cycle environmental impacts of different ways of decommissioning a grenade. The grenade chosen for this specific study is a 40 mm grenade of a type manufactured since the 1970s by Diehl BGT Defence GmbH & Co. KG and sold to Germany, Turkey and France. This type of grenade, which is a high explosive incendiary-tracer, is mainly used against air, sea and land targets and was chosen for this study because it is a rather typical example of common ammunition [11,12]. Our aim is to compare three different possible methods of destruction, two of which are modelled in two alternative ways:

- Open detonation, modelled both with and without recovery and recycling of metals.
- Incineration in a static kiln with air pollution control combined with recycling of metals, modelled with two different levels of air emissions.

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- A combination of incineration with air pollution control, open burning, recovery of some energetic material and recycling of metals.

The destruction alternatives are described in more detail in Section 2. These alternatives were chosen as three potentially interesting options currently available to a decision-maker and they were compared in order to answer the following specific questions:

- What are the environmental advantages and disadvantages of each of these destruction methods?
- Which part of the destruction process contributes most to the potential environmental impact?

To our knowledge there have been no assessments of this kind performed before except for the one by Hochschorner et al. [1,2]. The present study continues their work.

2. Background/destruction alternatives

Five destruction options were compared, as described in the introduction. For an overview of the alternatives, see Fig. 1. Since this study was only concerned with comparing different destruction procedures, the production of the grenade was not included within the system boundaries. Transport to the destruction plant was also omitted; since we assumed that all destruction plants were located in remote areas and that the difference in distances to these facilities was insignificant in terms of the overall comparison. In the following, the processes of each option are described. A complete overview of data and key assumptions are provided in Section 3.

2.1. Open detonation

In open detonation, the destruction plant must be located at a very remote area for safety reasons. In this alternative the ammunition is piled up in a detonation area. The maximum amount is about 20 tonnes of net energetic material (explosive substance), i.e. excluding for instance shells and packaging. This means that there is no limitation on the size of the objects. A helicopter inspects the area before the detonation to make sure that no-one unauthorized is present and afterwards to check for fires. A meteorologist has to check the weather conditions and a nurse has to be present. The detonation is initiated by several minor charges which have to be carefully arranged: the detonation has to start at the outside of the pile and move inwards at an even pace in order to destroy all ammunition and not throw away undetonated objects. The detonation creates a hole in the ground about 20 m in diameter and 5 m deep that has to be filled with a digger [11]. In the presentation of results, this alternative is called ‘open detonation’.

2.2. Open detonation combined with metal recycling

This option resembles open detonation, but the metals are recycled. Ideally the grenade can be disassembled and most of the metal can be recovered and recycled before detonation. This is how the destruction is usually carried out when conditions are suitable and when there is access to infrastructure for recycling metals. The metal parts are burned with air pollution control in order to remove all remaining energetic material before being sent to a metal recycling plant. In this study the recycled metals are assumed to replace virgin materials. The metal recycling rate was assumed to be 90%

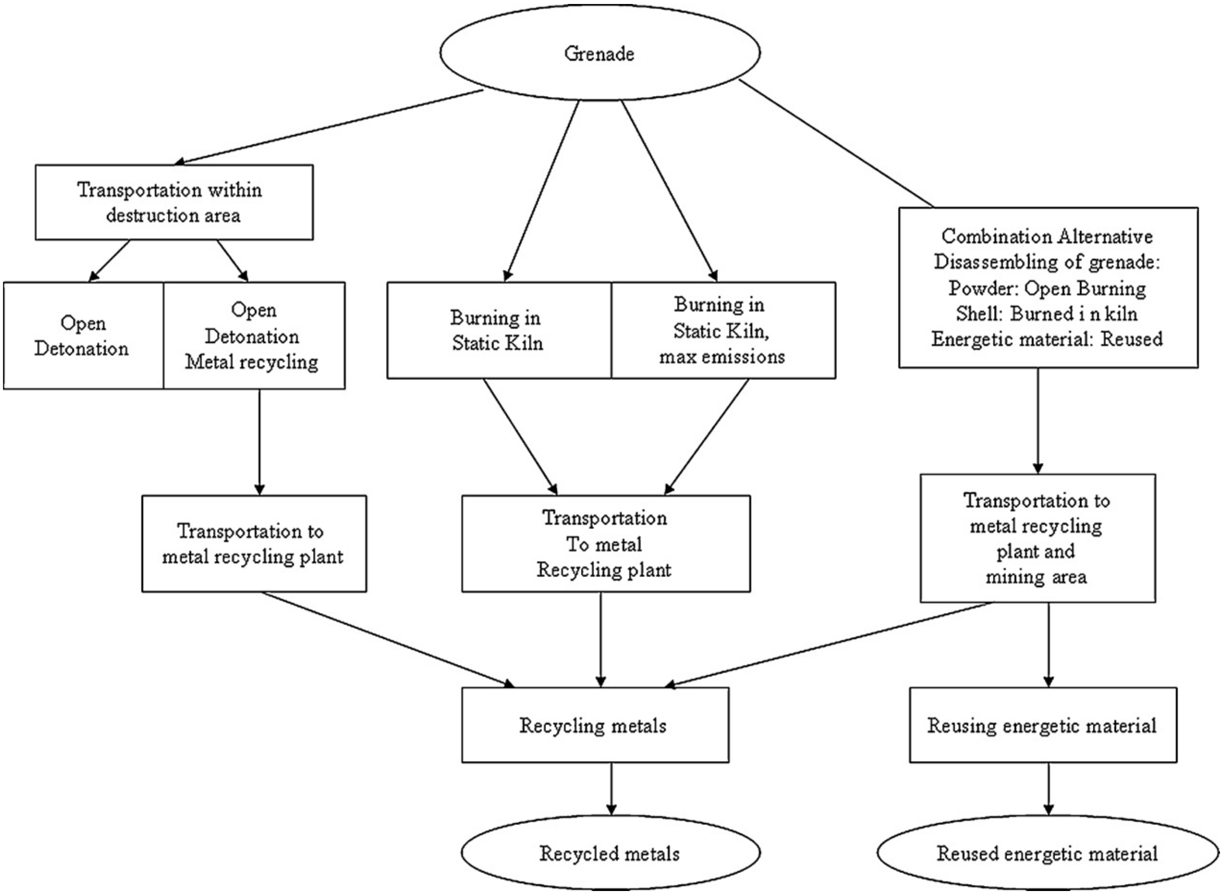

Fig. 1. Overview of the five destruction options compared in the study.

[12]. The remaining metals were assumed to be landfill, but emissions from these were not included. In the presentation of results, this alternative is called 'open detonation with metal recycling'.

2.3. *Incineration in a static kiln with air pollution control combined with metal recycling*

In this alternative, the grenades are fed into a static kiln by a conveyor and several lock chambers. In the detonation chamber the ammunition is heated to 450–550 °C, whereby all energetic material is burned or detonated and the metals are collected afterwards. The whole process is monitored by a control system and the operator works from a control room in safety. The gases produced are treated in several steps before being released. The metals are recycled at a metal recycling plant and assumed to replace virgin materials. In this study, the metal recycling rate was assumed to be 100% [13,14]. The detonation or burning of the energetic materials within the kiln produces sufficient heat to keep the destruction process going by itself and no extra energy is needed once the process has started. The data used to model this alternative represent current practice at destruction plants using equipment manufactured by Dynasafe AB [13,14]. The maximum amount of energetic material is rather limited; only about 10 kg can be fed at a time. This means that larger objects have to be disassembled if they are to be treated in the kiln. In the presentation of results, this alternative is called 'static kiln'.

2.4. *Incineration in a static kiln with air pollution control combined with recycling of metals, maximum allowed emissions*

This option resembles the Static Kiln alternative, but the emissions were set to the maximum permissible level according to European Directive 2000/76/EC, daily average limit. This is a worst-case scenario of incineration, and it means that the level of air pollution is 2–10 times that of the static kiln alternative. Some emissions regulated by the European Regulation 2000/76/EC, and hence included in this scenario, were not included (zero) in the static kiln scenario, since the company providing the equipment (Dynasafe AB) states that these substances are not emitted in the case of incineration of this specific grenade [13]. In the presentation of results, this alternative is called 'static kiln with max emissions'.

2.5. *A combination of incineration with air pollution control, open burning, recovery and recycling*

This is the main destruction method for this kind of ammunition in Sweden today. It is a combination of open burning, incineration in kiln with air pollution control, recycling and recovery of some of the material. At the destruction plant the grenades are disassembled. Open burning with no air pollution control destroys the powder. Some energetic material from the explosive charge can be recovered from the grenades. The metal parts are burned with air pollution control in order to remove all remaining energetic material before being sent to a metal recycling plant. If the grenade cannot be disassembled properly for some reason, it has to be destroyed by open detonation for safety reasons. In this scenario we assumed that all grenades could be disassembled safely and that metal recycling rate was 100% and energetic material recovery rate was 83% [12]. In the presentation of results, this alternative is called 'combination treatment'.

3. Methodology and data

Life cycle assessment (LCA) is a method for assessing the potential environmental impacts and resources used throughout a product's life from raw material acquisition, production, use and waste management [17]. The term 'product' can also include services such as waste management. This study was performed using LCA methods for waste management [15,16] and based on the ISO standard for LCA [17]. In line with methodology for waste management LCAs, the production of the grenade was not included in the study, because it would have been identical in all the options studied. In order to take into account the benefits of recycling, recovery and reuse of materials, it was assumed that these materials replace energy and materials of the same type produced from virgin sources.

Table 1
Materials for 100 grenades. Data provided by NAMMO Vingåkersverken AB [18,19].

Materials, 100 grenades	Amount (kg)	Comment or reference
Copper	3.7	[19]
Steel	80	Estimated
Felt	0.1	[19]
Hexal (explosive charge)	11.5	[18,19]
Brass	101.5	[18]
Lead	5	Estimated
Propelling charge, powder	47.5	[18,19]
Aluminium	1.8	Estimated
Nickel	0.2	[19]

3.1. *Inventory*

The functional unit was set to 100 grenades, i.e. this was the reference flow used for all calculations. The grenades were assumed to be decommissioned in Sweden in 2008. Grenade-specific data for this study were provided by NAMMO Vingåkersverken AB [11,12,18,19]. The composition of the grenade is given in Table 1.

The electricity used was assumed to be the average Nordic electricity mix, which includes large fractions of hydro and nuclear power.

Data and assumptions used when modelling the different alternatives are provided Table 2. These data were taken from Eriksson [11,12] and Weigel [13] unless otherwise specified. All data are calculated for the functional unit, 100 grenades.

The LCA calculations were done in the software Simapro 7. The major source of LCA process data, e.g. transports, recycling, and electricity, was the Ecoinvent 2 database, as implemented in SimaPro 7. Process emission data for the burning or detonation of energetic material are from Wilcox et al. [21] and are presented in Table A1 in the Appendix A. The energetic material of the explosive charge (hexal) was approximated to 'composition B surrogate with aluminium (HBX)' [21] due to accessibility of emission data. When recovered and reused, hexal was assumed to replace the use of the same amount of slurry; a mixture of mainly ammonium nitrate, other nitrates and some kind of fuel, at a mining site. The powder was estimated to be 'diesel fuel and dunnage' [21]. Wilcox et al. [21] report some emissions using parameters for which there were no corresponding data in the applied impact assessment methods. Hence, as noted in Table A2 in the Appendix A, these were replaced with other parameters in order to fit the impact assessment methods.

The shell is made of brass, which consists of 70% copper and 30% zinc. Because of lack of some specific metal recycling data, the brass is instead calculated as two separate fractions: copper and zinc and the amounts of recycled zinc, nickel and lead were added to the amount of recycled steel. Some packaging materials and manufacturing of capital goods for the destruction processes were excluded from the study. Since Ecoinvent data were developed for consumer scrap metal recycling, we omitted the scrap metal collection and treatment stages prior to recycling since these process stages were not considered to be applicable to our case.

Table 2
Data for the destruction alternatives. All data are per functional unit (100 grenades).

Data	Amount	Reference
Open detonation		
Transport within destruction area, lorry 16 t	12.4 tkm	[11]
Excavation, digger	2.51 m^3	[11]
Helicopter	0.003 h	[11]
Transport, car for blocking roads	0.236 pkm	[11]
Electricity for office space	0.113 kWh	[12,20]
Detonation	100 grenades	[21], Table A1 in Appendix A
Open detonation with metal recycling		
Transport within destruction area, Lorry 16 t	12.4 tkm	[11]
Excavation, digger	2.51 m^3	[11]
Helicopter	0.003 h	[11]
Transport, car for blocking roads:	0.236 pkm	[11]
Electricity for office space	0.113 kWh	[11,20]
Detonation	100 grenades	[21], Table A1 in Appendix A
Light fuel oil for burning the metals	329.8 kWh	[12]
Transport to metal recycling plant, Lorry 16 t	91 tkm	[12]
Recycling of copper	90.9 kg (90%)	[11,12]
Recycling of steel	94.95 kg (90%)	[11,12]
Recycling of aluminium	3.6 kg (90%)	[11,12]
Static kiln, static kiln with max emissions		
Natural gas	301 MJ	[13]
Lime	0.9 kg	[13]
Activated carbon	0.1 kg	[13]
Ammonia	1.5 kg	[13]
Electricity	100 kWh	[13]
Transport to metal recycling plant, lorry 16 t	96 tkm	[13]
Recycling of copper	101 kg (100%)	[13]
Recycling of steel and iron	105.5 kg (100%)	[13]
Recycling of aluminium	4.0 kg (100%)	[13]
Lignite ash, disposal	1.75 kg	[13]
Kiln air emissions	100 grenades	[13]
Combination treatment		
Light fuel oil for burning the metals	329.8 kWh	[12]
Electricity	60 kWh	[12]
Transport to metal recycling plant and mining site, lorry 16 t	110.03 tkm	[12]
Recycling of copper	101 kg (100%)	[11,12]
Recycling of steel and iron	105.5 kg (100%)	[11,12]
Recycling of aluminium	4.0 kg (100%)	[11,12]
Recovery of hexal	9.6 kg (83%)	[11,12]
Lignite ash, disposal	0.57 kg	[11,12]
Open burning of powder	47.5 kg	[11,12,18]
Kiln air emissions	100 grenades	[11,12]

In the static kiln, static kiln with max emissions and combination treatment alternatives, deposited ash was approximated to be lignite ash due to lack of data. Long-term emissions from landfilling were included.

3.2. Impact assessment and weighting methods

The life cycle impact assessment was performed using established methodologies [22]. We used the Centre for Environmental Studies (CML) baseline method of the Dutch guideline [23] as implemented in SimaPro 7. Some data that were not available in the CML baseline method were replaced with data from the EDIP method (EDIP/UMIP 97 V2.03) as applied in SimaPro 7.

The weighting step includes a value-based weighting of impact categories against each other. Because different weighting methods focus on different impact categories, it is often recommended that several weighting methods are used in parallel in order to get a more complete picture. Three different weighting methods were used in this study: Eco-indicator 99 [24], the Environment Priority Strategies (EPS 2000) [25] and Ecotax06 [26], as described below.

Eco-indicator 99 was developed by PRé consultants in the Netherlands. The methodology is described by Goedkoop and Spriensmaa [24] and three different versions have been developed to date. In this LCA we used the ‘hierarchist perspective’, which is the recommended default version where weighting is performed for three impact categories – human health, ecosystem quality and resources. It uses an end-point approach, which means that the impacts are calculated as damage. The weighting step is based on a panel of experts.

The Environment Priority Strategies (EPS 2000) method was developed within the Centre for the Environmental Assessment of Products and Material Systems (CPM) in Sweden. Weighting is made through valuation in five damage categories – human health, ecosystem production capacity, abiotic stock resource, biodiversity and cultural and recreational values. Each damage category consists of impact categories. Weighting factors represent the willingness to pay to avoid changes and are calculated in terms of environmental load units (ELU). For more information, see Steen [25]. This method is also an end-point method.

Ecotax06 is an upgraded version of Ecotax02 [26] described in Finnveden et al. [27]. This weighting method is based on environmental taxes and fees in Sweden in 2006 and links a tax or fee to a relevant impact category. Even if a tax or a fee is only expressed for one substance, it is possible to get a reference equivalent weight by making a characterisation factor conversion. The Ecotax method in this version is based on the CML baseline method except for the category abiotic resources, which is replaced by the exergy method [28]. Exergy can be regarded as a measure of available energy [28]. The Ecotax method is a monetary approach with the unit Swedish kronor (SEK). The method can be described as mid-point method

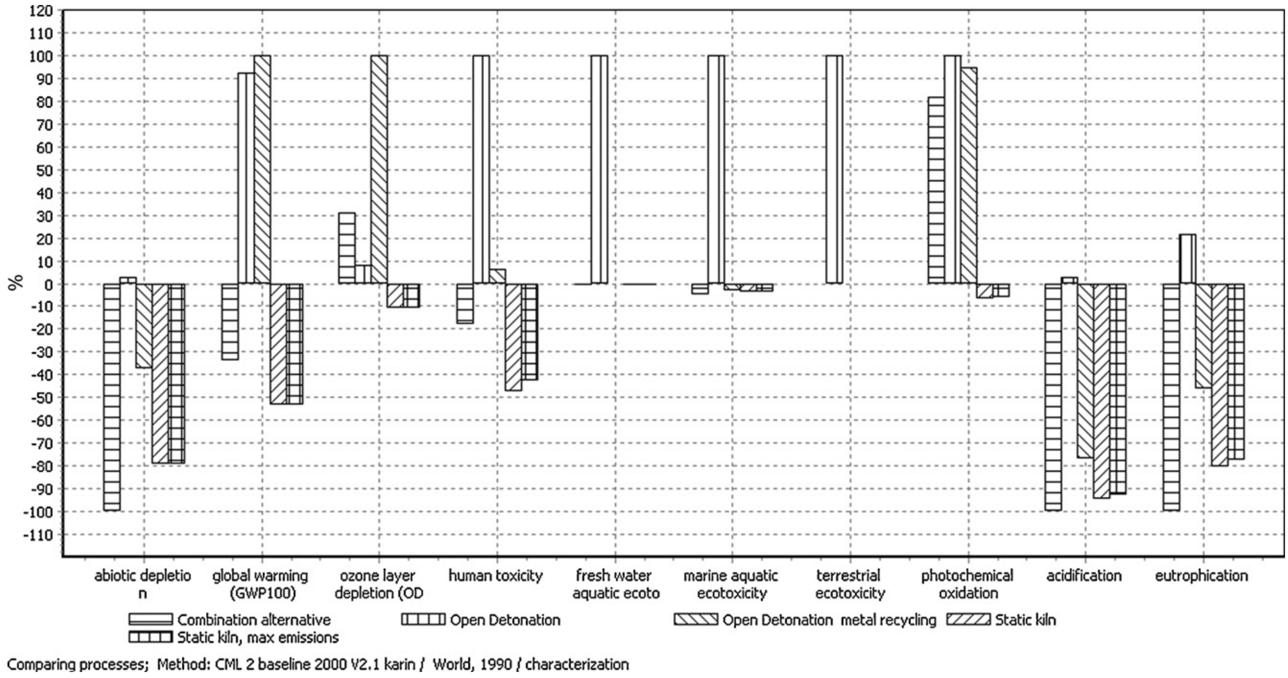

Fig. 2. Comparison using the CML impact assessment method of net potential environmental impact of the five destruction alternatives.

because the valuation is not done on end-points, i.e. damage, but instead on the level of environmental threats. There are two sets of weighting factors in which the minimum and maximum values are consistently chosen. More about the method can be found in Finnveden et al. [27].

4. Results

The relative comparison of potential environmental impact between the five alternatives is presented in Fig. 2. Net negative values in the figure arise when the avoided impacts due to recycling and replacement of virgin materials exceed those from other processes in the alternative.

The results in Fig. 2 indicate that open detonation, without recycling of metals, is the environmentally worst alternative for destruction of ammunition, for almost every of the assessed environmental impact categories. Adding metal recycling to the open detonation option however improves its environmental performance significantly for most impact categories, to a level comparable to that of the other modelled destruction options. The overall results for static kiln, static kiln with max emissions and combination treatment are quite similar. The results for some of the impact categories differ. The static kiln alternative had the best environmental performance for several impact categories, including global warming and human toxicity. On the other hand, the combination treatment proved to be the best alternative as regards acidification and eutrophication.

Apparently, the results do not unambiguously point at either of the methods as being the most environmentally friendly for this specific grenade. Weighting, with three different weighting methods, was applied to investigate whether either of the methods were preferable in an overall perspective. Table 3 shows the weighted results of the five destruction alternatives. It can be noted that the weighted total results for the alternatives that included metal recycling, i.e. all except the open detonation alternative, are in the same order of magnitude. Open detonation with metal recycling is however consistently somewhat worse than the other alternatives that include metal recycling.

In order to understand the underlying mechanisms of the life cycle environmental performance of the different alternatives, it is also important to identify what processes make the most significant contribution to the total results. This is done by making a process contribution analysis. Table A3 in the Appendix A shows the processes that contribute to the impact categories for the five destruction alternatives. The main conclusions that can be drawn from Table A3 are summarised in Table 4. For instance, it can be concluded that the detonation itself stands for the main contribution to the total potential impact of the open detonation alternative. The table also shows the importance of the avoided production of virgin metals, e.g. those in the shell of the grenade, in the combination treatment and both static kiln alternatives. The recycling of these metals makes it possible to avoid emissions for virgin metals production. The production of virgin metals uses a lot of fossil fuels, which also has a very large impact. However, the energy used (light fuel oil) for burning the metals prior to the recycling process makes a significant contribution to the potential global warming impact in the open detonation with metal recycling and the combination treatment alternatives. The results for the combination alternative also indicates that recycling of explosives (in this case hexal), can be environmentally relevant. Table A3 also

Table 3
Weighted results [Pt] of the destruction alternatives per weighting method.

	Eco-indicator 99 H	EPS2000	Ecotax06 max	Ecotax06 min
Open detonation	1.38E4	35.5	1.46E7	3.13E6
Open detonation with metal recycling	−111	−1.76E4	−3.16E5	−1.59E4
Static kiln	−140	−1.96E4	−3.97E5	−2.13E4
Static kiln with max emissions	−140	−1.96E4	−3.69E5	−2.09E4
Combination treatment	−142	−1.96E4	−4.97E5	−2.28E4

Table 4
Processes contributing most to the potential impacts and weighted results of the different alternatives.

Destruction alternative	Process contributing most to avoided potential impacts	Processes contributing most to negative potential impacts
Open detonation	None	Detonation
Open detonation with metal recycling	Recycling copper	Detonation, heat, produced by oil
Static kiln	Recycling copper	Transport between destruction plant and metal recycling plant, production of electricity
Static kiln with max emissions	Recycling copper	Emissions from burning process in kiln, transport between destruction plant and metal recycling plant
Combination treatment	Recycling copper	Heat, produced by oil, destruction part

indicates that the emissions from energy sources can be important.

In the open detonation scenario, the destruction process as a whole has a large impact on the environment. The transport between the destruction plant and the metal recycling plant and the consumption of electricity during the destruction phase contributed most to the impacts in the static kiln scenario. in the combination treatment, the energy use (oil) for burning the metals in order to remove all remaining explosives before transportation to a metal recycling plant seemed to be the process that contributed most to the negative impacts.

The differences in the results between the static kiln and combination treatment alternatives are due to several causes. For example, in the combination treatment alternative, part of the destruction process is performed with no air pollution control (burning of powder), whereas the whole of the destruction process in the static kiln scenario has air pollution control. The combination treatment recovers part of the explosives, but on the other hand extra energy (oil) has to be used to perform the destruction process, whereas the static kiln alternative uses the energy of the explosives instead. The static kiln adds chemicals (lime, carbon and ammonia), which the combination treatment does not. Transportation of the metals from the destruction plant to the metal recycling plant also gives potential impacts, but the avoided impacts of the recycling more than compensate for this.

5. Discussion

The risk associated with destruction of ammunition is commonly thought to be the risk of an explosion and thus harm for the personnel and the general public: the energetic materials are thought to be the risk one has to regard. However, this study shows that from an environmental perspective, the metals and the possibility of recycling these are an important issue as well.

Open detonation without metal recycling proved to be the environmentally worst alternative of those compared. Since there is no pollution control, the area will eventually be polluted by hazardous and/or toxic waste but not due to an accident [3]. However, it must be possible to use this destruction method on some occasions, e.g. when the ammunition cannot be handled in other ways because of safety regards for personnel. This issue is not considered in this paper.

Recycling of the metals is important for the results. The production of virgin metals has an environmental impact and consumes large amounts of resources that can be avoided by the recycling. Even if the recycling process consumes resources and produces emissions, the net result is better than producing virgin metals.

In the combination treatment today, the powder is destroyed by open burning and thus with no air pollution control. With a different technique it would perhaps be possible to perform air pollution control and recover the energy content of the powder and other energetic material if the materials cannot be reused. However, the authorities must approve the method and there is no such approved method at present.

The design of the grenade is crucial for how well and safely it can be disassembled. Disassembly is critical for the recycling, recovery and reuse of the different constituent materials. When conducting an LCA the design/development phase is usually excluded, since it is often assumed not to contribute significantly. However, one has to note that the decisions in the design/development phase greatly influence the environmental impacts in the other life cycle stages. The design of a product strongly predetermines its behaviour in the subsequent phases [29]. If the destruction part of the life cycle of the ammunition were given higher priority at acquisition, the design of the ammunition would probably enhance the possibilities of disassembling it in a safe way [1,2].

In short, the possibilities for recycling materials and pollution control lessen the impacts on the environment. By increasing the recycling of the materials in the grenade and better pollution control, the impacts could be mitigated.

The overall results for the static kiln-alternatives and the combination treatment are quite similar for this specific grenade. However, it is important to notice that if the ammunition had been for instance a chemical one, the results would probably be different. In the Combination Treatment, there is no pollution control for the destruction of the warhead with the chemicals, which means that all reaction products from the destruction are spread in the environment. In the static kiln-alternatives, these kinds of pollutants can be treated in several steps to reduce the emissions.

An LCA of this type does not take the safety of personnel into account, nor does it consider the issue of security, the economic costs or the use of the grenades in war. However, it is important that information on these issues is also integrated in the final decision-making [1,2].

6. Conclusion

Two things appear to be of importance for reducing the environmental impacts: Recycling the metals and air pollution control.

Open Detonation without metal recycling proved to be the environmentally worst alternative of those compared. The detonation in itself causes the largest environmental impacts. Impacts caused by the transport, electricity consumption, digger, etc, are altogether small compared to the detonation. There is no metal recycling or air pollution control. Open detonation with metal recycling is environmentally better due to the recycling, but it is still not as good as the other alternatives including metal recycling, see Fig. 2.

Static kiln and combination treatment are just about equal in merit regarding the environmental impacts in the case of this specific grenade. The results for these alternatives indicate that the kind of ammunition and possibly locations of the destruction plant might determine the choice of method since the environmental impacts from the methods are of little difference. Both methods have the possibility of recycling the metals and air pollution control.

Acknowledgements

We would like to thank our consultative group for valuable discussions, Åsa Moberg for valuable help with SimaPro Software, and the Swedish Rescue Services Agency for financing the project.

Appendix A.

See Tables A1–A3.

Table A1
Air emissions from the different destruction options alternatives.

Air emission	Amount	Reference
Open detonation, Open detonation with metal recycling		Explosive charge (hexal) emission [21] All values calculated on ‘composition B surrogate with aluminium (HBX)’
Emissions from hexal		
Carbon monoxide	0.054 kg	Tab 5.32 in [21]
Nitric oxide	0.113 kg	Tab 5.32 in [21]
Nitrogen dioxide	0.51 g	Tab 5.32 in [21]
Sulphur dioxide	0.012 kg	Tab 5.32 in [21], Tab 5.33 in [21]
Ethanol	0.16 g	i.e. Hydrocarbons, aliphatic, alkanes, unspecified tab 5.33 in [21]
Ethene	1.1 g	i.e. Hydrocarbons, aliphatic, alkenes, unspecified
Benzene	0.24 g	Tab 5.33 in [21] i.e. aromatics
Ethanol	0.903 g	Tab 5.33 in [21] i.e. TUHC
Ethanol	2.08 g	Tab 5.33 in [21] i.e. TNMHC
Ethanol	4.94 g	Tab 5.33 in [21] i.e. NMOC
Aluminium	0.107 kg	Tab 5.37 in [21]
Barium	2.31 g	Tab 5.37 in [21]
Cadmium	0.028 g	Tab 5.37 in [21]
Calcium	49.6 g	Tab 5.37 in [21]
Chromium VI	0.074 g	Tab 5.37 in [21]
Copper	42.2 g	Tab 5.37 in [21]
Lead	0.56 g	Tab 5.37 in [21]
Nickel	0.096 g	Tab 5.37 in [21]
Sodium	3.9 g	Tab 5.37 in [21]
Titanium	0.24 g	Tab 5.37 in [21]
Potassium	2.81 g	Tab 5.37 in [21]
Zinc	5.93 g	Tab 5.37 in [21]
Open detonation Open detonation with metal recycling		Gun powder emission [21] All values calculated on diesel fuel and dunnage burning
Emissions from powder		
Carbon dioxide	77.42 kg	Tab 5.70 in [21]
Carbon monoxide	7.48 kg	Tab 5.70 in [21]
Nitric oxide	0.2 kg	Tab 5.70 in [21]
Nitrogen dioxide	10.4 g	Tab 5.70 in [21]
Sulphur dioxide	47.2 g	Tab 5.70 in [21], Tab 5.71 in [21]
Ethanol	0.88 kg	i.e. Hydrocarbons, aliphatic, alkanes, unspecified tab 5.71 in [21]
Ethene	48.4 g	i.e. Hydrocarbons, aliphatic, alkenes, unspecified
Benzene	0.57 kg	Tab 5.71 in [21] i.e. aromatics
Ethanol	1.52 kg	Tab 5.71 in [21] i.e. TUHC
Ethanol	3.01 kg	Tab 5.71 in [21] i.e. TNMHC
Ethanol	1.97 kg	Tab 5.71 in [21] i.e. NMOC
Static Kiln		Air emissions from destruction process
Carbon monoxide	3.6 g	Calculated on a gas flue of 720 m^3/h during 1 h
Particulates, >2.5 um, and <10 um	0.72 g	Calculated on a gas flue of 720 m^3/h during 1 h
Nitrogen dioxide	72 g	Calculated on a gas flue of 720 m^3/h during 1 h
Carbon dioxide	43.64 kg	From hexal, powder and natural gas
Static kiln with max emissions		Air emissions from destruction process.
Carbon monoxide	36 g	Calculated on a gas flue of 720 m^3/h during 1 h, but maximum allowed emissions estimated
Particulates, >2.5 um, and <10 um	7.2 g	Calculated on a gas flue of 720 m^3/h during 1 h, but maximum allowed emission estimated unspecified particles, not in CML baseline
Nitrogen dioxide	144 g	Calculated on a gas flue of 720 m^3/h during 1 h, but maximum allowed emission estimated
Carbon dioxide	43.64 kg	From hexal, powder and natural gas
Hydrogen chloride	7.2 g	10 mg/m^3 × 720 m^3/h × 1 h
Hydrogen fluoride	0.72 g	1 mg/m^3 × 720 m^3/h × 1 h
Sulphur dioxide	36 g	50 mg/m^3 × 720 m^3/h × 1 h
Cadmium	36 mg	0.05 mg/m^3 × 720 m^3/h × 1 h
Mercury	36 mg	0.05 mg/m^3 × 720 m^3/h × 1 h
Antimony	36 mg	0.5 mg/m^3 × 720 m^3/h × 1 h
Arsenic	36 mg	0.5 mg/m^3 × 720 m^3/h × 1 h
Lead	36 mg	0.5 mg/m^3 × 720 m^3/h × 1 h
Chromium VI	36 mg	0.5 mg/m^3 × 720 m^3/h × 1 h
Cobalt	36 mg	0.5 mg/m^3 × 720 m^3/h × 1 h
Copper	36 mg	0.5 mg/m^3 × 720 m^3/h × 1 h
Manganese	36 mg	0.5 mg/m^3 × 720 m^3/h × 1 h
Nickel	36 mg	0.5 mg/m^3 × 720 m^3/h × 1 h
Vanadium	36 mg	0.5 mg/m^3 × 720 m^3/h × 1 h
Tin	36 mg	0.5 mg/m^3 × 720 m^3/h × 1 h
Polychlorinated biphenyls	72 mg	PCDD, PCDF, 0.1 ng/m^3 × 720 m^3 × 1 h
Combination Treatment		Gun powder emission [21]
Emissions from powder		All values calculated on diesel fuel and dunnage burning
Carbon dioxide	77.4 kg	Tab 5.70 in [21]
Carbon monoxide	7.48 kg	Tab 5.70 in [21]

Table A1 (*Continued*)

Air emission	Amount	Reference
Nitric oxide	0.2 kg	Tab 5.70 in [21]
Nitrogen dioxide	10.4 g	Tab 5.70 in [21]
Sulphur dioxide	47.2 g	Tab 5.70 in [21], Tab 5.71 in [21]
Ethanol	0.88 kg	i.e. Hydrocarbons, aliphatic, alkanes, unspecified, tab 5.71 in [21]
Ethene	48.4 g	i.e. Hydrocarbons, aliphatic, alkenes, unspecified, tab 5.71 in [21]
Benzene	0.57 kg	Tab 5.71 in [21] i.e. aromatics
Ethanol	1.52 kg	Tab 5.71 in [21] i.e. TUHC
Ethanol	3.01 kg	Tab 5.71 in [21] i.e. TNMHC
Ethanol	1.97 kg	Tab 5.71 in [21] i.e. NMOC

Table A2
Emission parameters used in Wilcox et al. [21] and the substances assumed to represent them.

Emission	Represented as
Hydrocarbons, aliphatic, alkanes, unspecified	Ethanol
Hydrocarbons, aliphatic, alkenes, unspecified	Ethene
Aromatics	Benzene
Total unidentified hydrocarbons (TUHC)	Ethanol
Total non-methane hydrocarbons (TNMHC)	Ethanol
Non-methane organic compounds (NMOC)	Ethanol

Table A3
Processes contributing to impact categories for the open detonation, open detonation with metal recycling, static kiln, static kiln with max emissions and combination treatment alternatives.

Processes, contribution	Resources exergy (MJ)	Global warming potential (kg CO_2 eq)	Ozone layer depletion (kg CFC-11 eq)	Human toxicity (kg 1,4-DP eq)	Fresh water aquatic ecotoxicity (kg 1.4-DP eq)	Marine aquatic ecotoxicity (kg 1.4-DP eq)	Terrestrial ecotoxicity (kg 1.4-DP eq)	Photochemical oxidation (kg C_2H_2)	Acidification (kg SO_2 eq)	Eutrophication (kg PO4—eq)
Open detonation, total	98.8	95.9	7.14E−7	3.12E3	4.55E4	9.41E6	1.79E3	3.2	0.107	0.07
Detonation	0	90.5	0	3.12E3	4.55E4	9.41E6	1.79E3	3.2	0.0765	0.064
Transport, lorry, within destruction area	73.4	4.52	6.08E−7	1.02	0.145	396	7.57E−3	0.00115	0.0246	0.00486
Digger	19.5	1.31	1.62E−7	0.798	0.0528	117	0.00191	2.73E−4	0.0101	0.00216
Helicopter	4.02	0.289	3.65E−8	0.024	0.00357	15.9	1.74E−4	5.85E−5	0.00125	4.81E−5
Transport, car	0.754	0.0444	5.23E−9	0.0293	0.00251	6.56	1.04E−4	5.17E−5	2E−4	3.03E−5
Electricity, office	1.06	0.0172	1.01E−9	0.0104	8.37E−4	10.9	0.00104	2.91E−6	6.59E−5	5.64E−6
Open detonation with metal recycling, total	−7.02E4	105	1.02E−5	200	−237	−3.07E5	−3.21	3.02	−3.06	−0.154
Detonation	0	90.5	0	1.53E3	9.56	4.02E4	0.623	3.2	0.0765	0.064
Transport, lorry, within destruction area	73.4	4.52	6.08E−7	1.02	0.145	396	0.00757	0.00115	0.0246	0.00486
Digger	9.76	1.31	1.62E−7	0.798	0.0528	117	0.00191	2.73E−4	0.0101	0.00216
Helicopter	2.01	0.289	3.65E−8	0.024	0.00357	15.9	1.74E−4	5.85E−5	0.00125	4.81E−5
Transport, car	0.754	0.0444	5.23E−9	0.0293	0.00251	6.56	1.04E−4	5.17E−5	2E−4	3.03E−5
Transport, lorry, to metal recycling plant	539	33.2	4.46E−6	7.48	1.07	2.9E3	0.0556	0.00841	0.18	0.0357
Electricity, office	1.06	0.0172	1.01E−9	0.0104	8.37E−4	10.9	0.00104	2.91E−6	6.59E−5	5.64E−6
Heat, light fuel oil	1.49E3	107	1.35E−5	11.5	1.38	6.28E3	0.109	0.0141	0.284	0.0259
Electricity, treating metals prior to sent to metal recycling plant	563	9.12	5.36E−7	5.53	0.445	5.8E3	0.555	0.00154	0.035	0.003
Recycling copper	−6.91E4	−5.6	−4.79E−6	−1.11E3	−206	−1.81E5	−4.07	−0.092	−2.97	−0.199
Recycling iron and steel	−3.06E3	−94.2	−1.91E−6	−43.1	−23	−5.79E4	−0.36	−0.0956	−0.5	−0.0734
Recycling aluminium	−760	−41.8	−2.36E−6	−201	−20.2	−1.23E5	−0.127	−0.017	−0.201	−0.0177
Static kiln, total	−7.91E4	−55.8	−1.1E−6	−1.48E3	−274	−3.84E5	−4.04	−0.21	−3.77	−0.267
Destruction part in kiln	0	43.6	0	0.087	0	0	0	0.00211	0.036	0.00936
Natural gas	370	4.2	2.85E−6	0.136	0.0796	146	0.0035	0.00185	0.014	0.00111
Lime	3.74	0.675	4.68E−8	0.0142	0.00233	8.69	1.79E−4	1.15E−4	5.87E−4	6.28E−5
Charcoal	6.94	−0.244	9.58E−10	0.00979	0.00118	5.71	4.05E−5	8.61E−4	7.24E−5	1.28E−5
Ammonia	63.2	3.1	4.6E−7	1.52	0.179	960	0.0364	5.19E−4	0.00972	6.8E−4
Transport, lorry	568	35	4.71E−6	7.89	1.13	3.06E3	0.0586	0.00887	0.19	0.0376
Electricity	939	15.2	8.94E−7	9.22	0.741	9.67E3	0.924	0.00257	0.0583	0.005
Lignite ash	0	0	0	1.54	1.42	4.72E3	1.25E−4	0	0	9.22E−4
Recycling copper	−7.68E4	−6.23	−5.32E−6	−1.23E3	−229	−2.01E5	−4.52	−0.102	−3.3	−0.221

Table A3 (*Continued*)

Processes, contribution	Resources exergy (MJ)	Global warming potential (kg CO_2 eq)	Ozone layer depletion (kg CFC-11 eq)	Human toxicity (kg 1,4-DP eq)	Fresh water aquatic ecotoxicity (kg 1.4-DP eq)	Marine aquatic ecotoxicity (kg 1.4-DP eq)	Terrestrial ecotoxicity (kg 1.4-DP eq)	Photochemical oxidation (kg C_2H_2)	Acidification (kg SO_2 eq)	Eutrophication (kg PO4—eq)
Recycling iron and steel	−3.4E3	−105	−2.12E−6	−47.9	−25.5	−6.43E4	−0.4	−0.106	−0.556	−0.0816
Recycling aluminium	−845	−46.5	−2.62E−6	−223	−22.4	−1.37E5	−0.141	−0.0189	−0.224	−0.0197
Static kiln with max emissions, total	−7.91E4	−55.8	−1.1E−6	−1.34E3	−274	−3.54E5	−2.83	−0.206	−3.69	−0.258
Destruction part in kiln	0	43.6	0	145	0.142	3.04E4	1.21	0.00673	0.115	0.0187
Natural gas	370	4.2	2.85E−6	0.136	0.0796	146	0.0035	0.00185	0.014	0.00111
Lime	3.74	0.675	4.68E−8	0.0142	0.00233	8.69	1.79E−4	1.15E−4	5.87E−4	6.28E−5
Charcoal	6.94	−0.244	9.58E−10	0.00979	0.00118	5.71	4.05E−5	8.61E−4	7.24E−5	1.28E−5
Ammonia	63.2	3.1	4.6E−7	1.52	0.179	960	0.0364	5.19E−4	0.00972	6.8E−4
Transport, lorry	568	35	4.71E−6	7.89	1.13	3.06E3	0.0586	0.00887	0.19	0.0376
Electricity	939	15.2	8.94E−7	9.22	0.741	9.67E3	0.924	0.00257	0.0583	0.005
Lignite ash	0	0	0	1.54	1.42	4.72E3	1.25E−4	0	0	9.22E−4
Recycling Copper	−7.68E4	−6.23	−5.32E−6	−1.23E3	−229	−2.01E5	−4.52	−0.102	−3.3	−0.221
Recycling iron and steel	−3.4E3	−105	−2.12E−6	−47.9	−25.5	−6.43E4	−0.4	−0.106	−0.556	−0.0816
Recycling aluminium	−845	−46.5	−2.62E−6	−223	−22.4	−1.37E5	−0.141	−0.0189	−0.224	−0.0197
Combination treatment, total	−8.05E4	−35.8	3.16E−6	−567	−292	−4.93E5	−4.66	2.61	−3.98	−0.333
Destruction part in kiln and open burning	0	77.4	0	1.08E3	4.79E−5	0.0016	9.12E−6	3.24	0.0618	0.0414
Transport, lorry, recycling metals and hexal	651	40.1	5.4E−6	9.04	1.29	3.51E3	0.0672	0.0102	0.218	0.0431
Electricity	563	9.12	5.36E−7	5.53	0.445	5.8E3	0.555	0.00154	0.035	0.003
Heat, light fuel oil	1.49E3	107	1.35E−5	11.5	1.38	6.28E3	0.109	0.0141	0.284	0.0259
Recycling copper	−7.68E4	−6.23	−5.32E−6	−1.23E3	−229	−2.01E5	−4.52	−0.102	−3.3	−0.221
Recycling iron and steel	−3.4E3	−105	−2.12E−6	−47.9	−25.5	−6.43E4	−0.4	−0.106	−0.556	−0.0816
Recycling aluminium	−845	−46.5	−2.62E−6	−223	−22.4	−1.37E5	−0.141	−0.0189	−0.224	−0.0197
Lignite ash	0	0	0	0.502	0.461	1.54E3	4.06E−5	0	0	3E−4
Recycling hexal	−2.16E3	−113	−6.17E−6	−174	−17.9	−1.08E5	−0.325	−0.423	−0.5	−0.125

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