Does the Production of an Airbag Injure more People than the Airbag Saves in Traffic?

Opting for an Empirically Based Approach to Social Life Cycle Assessment

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Summary

Social life cycle assessment (S-LCA) has been discussed for some years in the LCA community. We raise two points of criticism against current S-LCA approaches. First, the development of S-LCA methodology has not, to date, been based on experience with actual case studies. Second, for social impacts to be meaningfully assessed in a life cycle perspective, social indicators need to be unambiguously interpreted in all social contexts along the life cycle. We here discuss an empirically based approach to S-LCA, illustrated by a case study of an automobile airbag system. The aim of the case study is to compare the injuries and lives lost during the product life cycle of the airbag system (excluding waste handling impacts) with the injuries prevented and lives saved during its use. The indicator used for assessing social impacts in this study is disability-adjusted life years (DALY). The results from this study indicate that the purpose of an airbag system, which is to save lives and prevent injuries, is justified also in a life cycle perspective.

Introduction

Social life cycle assessment (S-LCA) has been discussed for some years in the LCA community. The discussion of social impacts in a life cycle perspective has a long history and can be said to have begun with attempts to include health impacts on workers and other groups in LCA (see, for instance, Antonsson and Carlsson 1995; Schmidt et al. 1992). The term S-LCA was coined by O'Brien and colleagues (1996). Their article was followed by a number of different S-LCA frameworks. Dreyer and colleagues (2006) suggested that the S-LCA methodology should be less focused than classical LCA (E-LCA) on industrial processes and more focused on organizations' and companies' conduct. Hunkeler (2006) proposed a geographically specific midpoint-based S-LCA methodology using hours of labor as the midpoint indicator of social impacts. Weidema (2006) proposed quality-adjusted life years (QALY) as a possible single-score indicator of human well-being for use in S-LCA studies. These suggested frameworks were reviewed by Jørgensen and colleagues (2008), who concluded that there was considerable variation in the approaches to, and perceptions of, social impacts and S-LCA methodology. In order to amend this, the task force on the integration of social criteria into LCA, formed by the United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) life cycle initiative, delivered guidelines for S-LCA in 2009. These guidelines are referred to below as the UNEP/SETAC guidelines, but are cited as Benoît and colleagues (2009) in the reference list in order to acknowledge the work of these authors. The UNEP/SETAC guidelines, along with the frameworks of

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Hunkeler (2006) and Weidema (2006) were reviewed by Parent and colleagues (2010), who concluded again that there was considerable variation in the approach and indicators for social impacts in the reviewed methods, and that these fundamentally different approaches led naturally to different outcomes. Recently a few S-LCA case studies have been conducted, such as the study on roses by Franze and Ciroth (2011) and the study on laptops by Ekener-Petersen and Finnveden (2013).

The work presented here has emerged out of curiosity about this obviously still divided field, as well as out of skepticism about the previous frameworks on S-LCA, in particular the UNEP/SETAC guidelines. There are primarily two reasons for our skepticism.

Our first reason for skepticism is that the development of S-LCA methodology and theory has not, to date, been based on experience from actual case studies, but rather on common sense-derived frameworks. We have only found one S-LCA case study published before the UNEP/SETAC guidelines, namely the work of Hunkeler (2006). The development of the more established E-LCA methodology was to a large extent driven by case studies on, for example, packaging and waste treatment (see Baumann and Tillman 2004). When the first guidelines on E-LCA were published in the early 1990s, they were based on the extensive empirical work on E-LCA already conducted (Consoli et al. 1993). Basing method development on actual case studies is a fundamental feature of systems analysis—generalizations such as method rules are drawn from many case studies, not the other way around (Arbnor and Bjerke 1977; Miser and Quade 1985). For S-LCA, in contrast, there is a risk of developing methodology that is neither practical nor relevant to users in real-life situations.

Our second reason for skepticism is that a coherent discussion about the social values and ethical and ideological positions that underlie the indicators of social impacts is missing in the current reviewed literature. Many of the indicators of social impacts discussed in the context of S-LCA, in particular in the UNEP/SETAC guidelines, are highly ideological and may be interpreted differently depending on political and ethical views and on cultural background. Consider the social impact of child labor. Many people, including the authors of the UNEP/SETAC guidelines, would argue that child labor is unwanted, and indeed child labor is prohibited in most developed countries. However, others would argue that even the worst forms of child labor may increase the general human well-being in developing countries and that a reduction in child labor would be undesirable (Dessy and Pallage 2005). Others argue that the view of children working in developing countries as victims that should be excluded from the production of value is highly ideological and denies the children their agency (Nieuwenhuys 1996). Other social indicators included in the UNEP/SETAC guideline face similar problems of being ambiguous and ideological, such as working hours, the presence of labor unions, policies to protect cultural heritage, freedom of expression, a locally hired workforce, and intellectual property rights.

The opportunity to explore methods for S-LCA in a case study presented itself in the context of a collaboration with the company Autoliv. Autoliv is a producer of safety devices for cars, such as airbags. An airbag is a cushion that inflates rapidly in case of a car accident in order to protect the driver of the car from death or severe injuries. Autoliv has explored the use of the E-LCA methodology, reported in two LCA studies, one on airbags (Mujiyanto and Priyojati 2010) and one on the electronic control unit for airbags (Suyang and Jingjing 2010). After this, Autoliv expressed a wish for us to investigate social impacts along the life cycle of their products since this relates closely to the core business mission of Autoliv, which is to prevent injuries and the loss of lives through automotive safety equipment. The production of airbags requires the production of explosives that inflate the airbag as well as the mining of various metals used for the electronic control unit (ECU) that controls inflation. This motivated us to analyze the social impacts of airbags over the whole life cycle of the product, excluding waste handling, and compare those social impacts with the social benefits that occur during the use stage of an airbag. We decided to compare the injuries and lives lost during the product life cycle of the airbag system with the injuries prevented and lives saved during its use. By reporting this case study, we hope to bring these issues to discussion, following up on a presentation of the study and of preliminary results at the 6th International Conference on Industrial Ecology in 2011 (Baumann et al. 2011).

Methods

Studied System and Goal of the Study

The airbag system considered in this study consists of the airbag and its ECU. The airbag consists of a textile cushion that can be deployed rapidly in case of an automobile collision to protect the driver or other occupants of the automobile. There are two types of airbags: frontal airbags and side airbags. In this study, a typical frontal driver airbag system is considered. The airbag system was designed as a safety device supplementary to seat belts. The driver airbag consists of six components: label, nut, cushion, can, cover, and inflator. The ECU is the "brain" of the airbag system that determines when the airbag will deploy, and is typically installed in the middle of the vehicle or beneath the front seat, with sensors in various locations throughout the car. The ECU has five components: label, cover, housing, screw, and printed circuit board. The life cycles of the airbag and the ECU were studied by Mujiyanto and Priyojati (2010) and Suyang and Jingjing (2010), respectively, and their system descriptions provide the basis for the calculations here (see figure 1). The system boundaries of the S-LCA are the same as those of the corresponding E-LCA by Mujiyanto and Priyojati (2010) and Suyang and Jingjing (2010), and are also suggested by Hunkeler (2006) and the UNEP/SETAC guidelines.

The goal of this S-LCA was to investigate whether the purpose of an Autoliv driver airbag system, which is to save lives and prevent severe injuries, is justified from a life cycle perspective. The functional unit of the S-LCA is one Autoliv driver airbag system, including the airbag and the ECU. Since

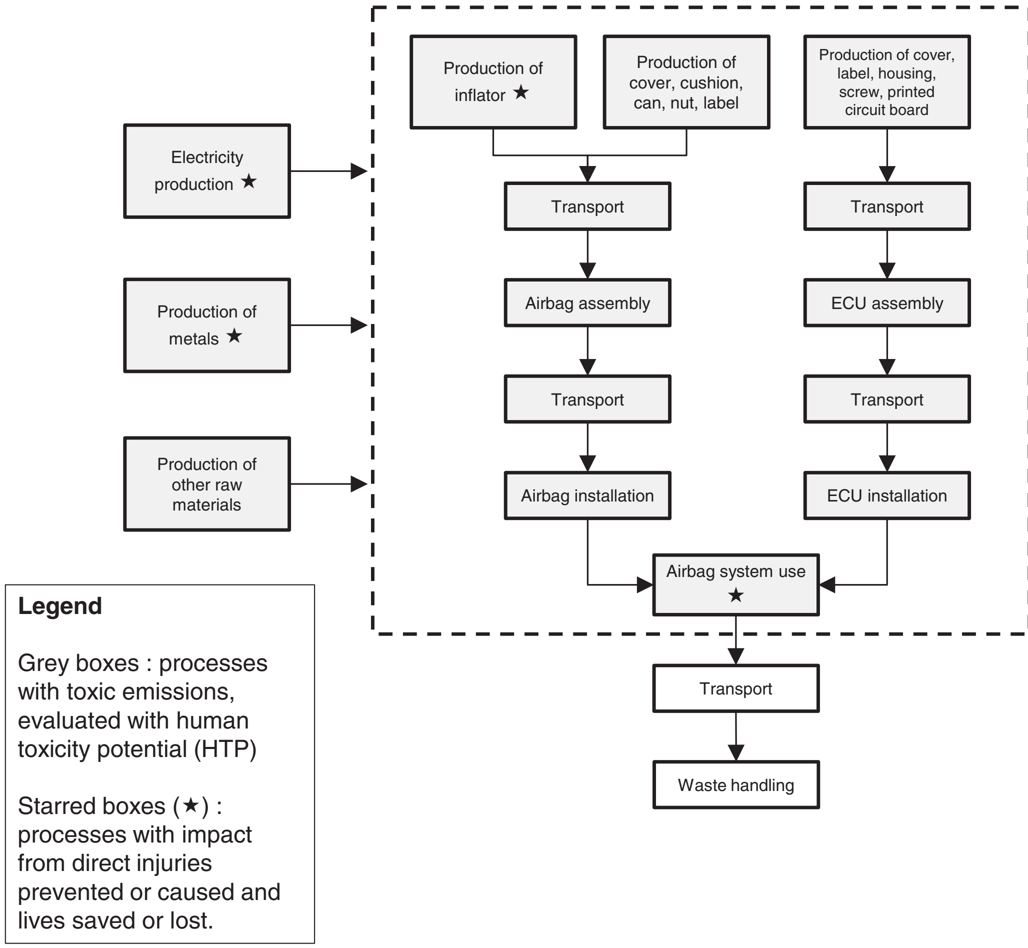

Figure 1 Life cycle model of an automobile airbag system. Technical processes where impact has been assessed are marked in the flow chart. The dashed line encloses the part of the system that constitutes the actual airbag production system. Included processes for production of electricity, metals and other raw materials feed into the enclosed part of the system at many different points. ECU = electronic control unit.

LCA is a flow modeling method, the reference flow defines the functional unit. Here the reference flow is the annual production of airbag systems and the lives and injuries that are saved and lost annually. A more detailed technical account of the completed S-LCA study is found in the report by Tong and Wang (2011).

Impact Assessment Method

It was essential to find an indicator that could express both the functionality of the product system as well as its negative social impacts. After an extensive literature review of S-LCA methods and studies and subsequent discussions with representatives of Autoliv, a suitable indicator of social impacts was found in the E-LCA literature: the disability-adjusted life years (DALY) indicator, which is an element of the life cycle impact assessment methods of Eco-indicator '99. The DALY indicator is suitable because it describes the same impacts that airbags aim to prevent, namely mortality and severe health impacts to humans. Prior to our research, DALY has not been used in S-LCA, but Weidema (2006) discusses it in the context of proposing QALY.

Since DALY indicators can be used for both assessing negative impacts of the production of the airbag system and the benefits from its use, a comprehensive and consistent analysis of central social aspects for an airbag system could be analyzed. It is therefore possible to say that this study constitutes a variation of cost–benefit analysis of the airbag system, using DALY instead of money as in traditional cost–benefit analysis. Although additional indicators besides DALY may be relevant for assessing the social impacts of the airbag system, no other interesting and unambiguous indicator was identified from our review and during the discussions with representatives from Autoliv. In particular, none of the other indicators found could capture the positive social impact of the airbag during its use phase.

The ethical basis for the impact assessment is that all lives of people living now and in the future are of equal value and that a year lost is of the same value regardless of the age of the person. Based on these ethical considerations, DALY can be calculated as the sum of years of life lost (YLL) and years of life disabled (YLD):

$$DALY = YLL + YLD. \quad (1)$$

The YLD can be estimated as

$$YLD = w \times D, \quad (2)$$

where w is a severity factor between 0 (complete health) and 1 (complete disability) and D is the duration of the disability measured in years.

Inventory of Disability-Adjusted Life Years

Based on the E-LCA studies of the airbag system conducted by Mujiyanto and Priyojati (2010) and Suyang and Jingjing (2010), certain production steps were considered to have little negative social impact with regard to DALY, while four process areas were deemed in need of scrutiny. DALY lost for these four important processes are quantified in this article. The processes are (1) the emissions of toxic substances along the whole life cycle, excluding waste handling, (2) accidents during the mining of metals, (3) accidents during the production of electricity, and (4) accidents during the production of pyrotechnic material for the inflator. Toxic emissions and pyrotechnic materials are obvious hazards. Metals account for a large part of the Autoliv airbag system by weight (Mujiyanto and Priyojati 2010; Suyang and Jingjing 2010), and since mining is quite a dangerous industry as compared with most others (Coleman and Kerkering 2007), it is of interest to investigate deaths and serious injuries related to the mining of metals required for an airbag system. Electricity production is also known to be an industry with considerable casualties (Starfelt and Wikdahl 2011; Wilson et al. 1999). The use phase of the airbag system was also assessed in terms of DALY saved, which is a process with positive impacts. See figure 1 for an overview of the system studied, including the processes whose impacts are quantified in this article. A summary of the types of inventory data that were obtained can be found in table 1. The methods for quantifying DALY lost or saved for each of the five processes are presented below.

Disability-Adjusted Life Years Lost from the Mining of Metals

The number of DALY lost from the mining of metals was obtained from the Western Australian Department of Mines and Petroleum, since these statistics represent the only known source of transparent data on mining accidents available. Data on deaths and injuries per number of employees was obtained from the Department of Mines and Petroleum (2010) and data on the number of employees and metal production was obtained from the Department of Mines and Petroleum (2009).

Data on lives lost were then converted into YLL by applying the average global life expectancy (WHO 2011) and the average age of workers killed in mining accidents. The average age of workers killed and injured in mining accidents was estimated based on data from Western Australia (see Appendix 11B in the report by Tong and Wang [2011]).

According to the Department of Mines and Petroleum (2010), the most common type of accident in the mining industry that causes serious injuries are overexertion or strenuous movements, which can lead to sprains or strains. Polinder and colleagues (2007) present values for the duration ($w_{sprain/strain}$) and severity ($D_{sprain/strain}$) of sprains/strains, which are used to calculate the YLD from the mining of metals. These are approximations, which probably leads to underestimation of the YLD, since the duration of sprain or strain injuries is low as compared with other potential injuries from mining accidents.

Disability-Adjusted Life Years Lost from Electricity Production

Data on casualties per kilowatt-hour (kWh) for different kinds of electricity production were obtained from the work of Wilson and colleagues (1999) and Starfelt and Wikdahl (2011). The number of deaths per airbag system could be calculated using knowledge about electricity use and sources in the airbag system's life cycle. Again, in order to turn these data into YLLs, the average global life expectancy was applied. Unfortunately the average age of death in electricity production accidents is not known to the authors of this article, but the average age of death for all kinds of accidents in industries in the United States is known (U.S. Bureau of Labor Statistics 2010) and was applied as an approximate value for the age at the time of death in electricity production accidents for lack of a better estimate. Whether or not this approximation leads to over- or underestimation of the YLL is difficult to say.

Disability-Adjusted Life Years Lost from Pyrotechnic Materials Production

The pyrotechnic materials used by Autoliv are produced in house. We were therefore able to obtain information about this from them. According to this information, there were 227 occupational injury claims in 2010 in the factory in the United States where the pyrotechnic materials and inflators are produced, but no fatal or serious injuries recorded, according to Occupational Safety and Health Administration standards (Andersson 2012). In recent years some minor injuries have occurred, such as people falling off roofs, but none related to the pyrotechnic materials. In fact, no severe injuries related to the production of pyrotechnic materials had occurred for many years. Hence the production of pyrotechnic materials does not contribute to any DALY lost (Andersson 2012).

Disability-Adjusted Life Years Lost from Toxic Emissions

An impact assessment model must be applied when assessing the DALY lost due to toxic emissions along the life cycle of the airbag system (excluding waste handling). In this case, the

Table 1 Inventory data and their symbols, values, units, and references.[a]

Parameter	*Symbol*	*Value*	*Unit*	*Reference*
Lives lost during metal mining	—	Different for different metals	lives/kg	Department of Mines and Petroleum (2009, 2010)
Duration of sprain/strain	$D_{\text{sprain/strain}}$	0.140	years	Polinder et al. (2007)
Severity of sprain/strain	$w_{\text{sprain/strain}}$	0.2666	dimensionless	Polinder et al. (2007)
Average age of worker killed in mining accidents	—	36	years	Tong and Wang (2011)
Lives lost in accidents during electricity production	—	Different for different electricity sources	lives/kWh	Wilson et al. (1999), Starfelt and Wikdahl (2011)
Approximate age of workers killed in electricity production	—	46	years	U.S. Bureau of Labor Statistics (2010)
Casualties and fatal injuries from production of pyrotechnic materials	—	0	lives	Andersson (2012)
Human toxicity potential characterization factor *s*	$HTP_{x,e}$	Different for different toxicants	kg/kg 1,4-DCB	Huijbregts et al. (2000)
Amounts of toxic emissions	—	Different for different toxicants	kg	Mujiyanto and Priyojati (2010), Suyang and Jingjing (2010)
Characterization factor for turning HTP into DALY	Q_{em}	7.0×10^{-7}	years/kg 1,4-DCB eq.	Goedkoop et al. (2008)
Number of lives saved by airbag and seatbelt	S	25,000	lives/year	Autoliv (2011)
Life-saving effectiveness of airbag	e_{airbag}	14	%	Glassbrenner (2003)
Life-saving effectiveness of seatbelt	e_{seatbelt}	48	%	Glassbrenner (2003)
Number of injuries prevented by airbag and seatbelt	P	250 000	injuries/year	Autoliv (2011)
Injury-preventing effectiveness of airbag	f_{airbag}	7	%	NHTSA (1996)
Injury-preventing effectiveness of seatbelt	f_{seatbelt}	60	%	NHTSA (1996)
Average global life expectancy	—	68	years	WHO (2011)
Average age of driver involved in fatal accident	—	43	years	Tong and Wang (2011)
Duration of spinal cord injury	$D_{\text{spinal cord}}$	35	years	Based on Murray and Lopez (1996)
Severity factor of spinal cord injury	$w_{\text{spinal cord}}$	0.725	dimensionless	Murray and Lopez (1996)
Annual number of produced airbag systems	—	87×10^6	airbag systems/year	Andersson (2012)

Notes: [a]In addition to this, basic data about the life cycle of the airbag system were obtained from the reports by Mujiyanto and Priyojati (2010) and Suyang and Jingjing (2010).
kg = kilograms; kWh = kilowatt-hours; DCB = dichlorobenzene; eq. = equivalents; NHTSA = National Highway Traffic Safety Administration; HTP = human toxicity potential; DALY = disability-adjusted life years. "—" means that no algebraic symbol has been assigned to the parameter.

Uniform System for the Evaluation of Substances Adapted for LCA Purposes (USES-LCA) model used in the Eco-indicator '99 impact assessment method was applied (Huijbregts et al. 2000). The model includes direct impacts to human health from toxic substances such as metals (e.g., mercury and arsenic), organic pollutants (e.g., benzene and atrazine), and air pollutants (e.g., nitrogen dioxide and particulate matter). USES-LCA is a global, nested multimedia fate, exposure, and effects model that can be used to obtain characterization factors for toxic chemicals in LCA. First, the human risk characterization ratio (RCR) is calculated:

$$\text{RCR}_{\text{human,x,s,e}} = \sum_{r=1}^{n} \frac{\text{PDI}_{\text{r,x,s,e}}}{\text{HLV}_{\text{r,x}}}, \tag{3}$$

where $\text{RCR}_{\text{human},x,s,e}$ is the human risk characterization ratio, x is the substance of interest, s is the geographical scale of interest (local, regional, continental, or global), e is the compartment of interest, r is the exposure route of interest, $PDI_{r,x,s,e}$ is the predicted daily intake measured in kilograms of substance taken in per day per kilogram of body mass and $HLV_{r,x}$ is the human limit value, which is also measured in kilograms of substance taken in per day per kilogram of body mass. Based on an RCR that has been weighted population-wise at a global spatial scale (s), the human toxicity potential (HTP) is calculated according to

$$HTP_{x,e} = \frac{\text{weighted } RCR_{human,x,e}}{\text{weighted } RCR_{ref}}, \quad (4)$$

where $HTP_{x,e}$ is the human toxicity potential characterization factor measured in kilograms of substance x per kilograms of 1,4-dichlorobenzene (DCB) equivalents and the RCR_{ref} is a reference value for the substance of interest, in this case the organochlorinated substance 1,4-DCB. The HTP of all substances emitted during the life cycle (excluding waste handling) of the airbag system (Mujiyanto and Priyojati 2010; Suyang and Jingjing 2010) and present among the 181 substances for which reference values exist (Huijbregts et al. 2000) was calculated and summed. The HTP values can then be used to calculate DALY values with the following general equation (Goedkoop et al. 2008):

$$I_e = \sum Q_{em} \times I_m \quad (5)$$

where I_e is the endpoint indicator (in this case DALY), I_m is the midpoint indicator (in this case HTP), and Q_{em} is a characterization factor that links the midpoint indicator to the endpoint indicator. This characterization factor has a common value for all the substances that were included in this study, since humans are the endpoint for all substances.

Disability-Adjusted Life Years Saved During the Use Phase

According to Autoliv, their products save 25,000 lives and prevent 250,000 severe injuries annually (Autoliv 2011). It is necessary to apportion lives saved to the airbag and to the seatbelt, respectively, since they serve automotive safety in combination and since our study only focuses on the airbag system. Glassbrenner (2003) describes three attribution methods regarding lives saved: the belt-maximizing method, the bag-maximizing method, and the restraint-neutral method. The belt-maximizing method attributes the maximum benefit to the seatbelt and residual benefit to the airbag, while the bag-maximizing method inverts this—the maximum benefit possible is attributed to the airbag and residual benefit to the seatbelt. The third method—the restraint-neutral attribution—does not give any preference to either safety product. The choice is partly an ethical one. In this case, the restraint-neutral method is preferred since the method makes it easier to assess and use available data. Glassbrenner (2003) describes the restraint-neutral attribution to airbags mathematically as

$$S_{airbag} = \frac{S \times e_{airbag}}{e_{airbag} + e_{seatbelt}}, \quad (6)$$

where S_{airbag} is the number of lives saved by airbags alone, S is the total number of lives saved by the airbag and seatbelt systems together, e_{airbag} is the effectiveness of airbags alone in preventing deaths, and $e_{seatbelt}$ is the effectiveness of seatbelts alone in preventing deaths. In order to arrive at the YLL saved by the airbag system, S_{airbag} is then divided by the total number of airbag systems produced by Autoliv annually and multiplied by the average number of life years saved per incident. The average number of life years saved per incident was calculated as the average life expectancy minus the average age of drivers involved in fatal accidents. The average age of a person involved in a fatal car accident was estimated to be 43 years (see Appendix 11B in the report by Tong and Wang [2011]. This resulted in 25 life years saved for each prevented death considering the average global average life expectancy of 68 years (WHO 2011).

In order to calculate the YLD saved by the airbag system, the same attribution method (restraint-neutral) was used, but using P to denote injuries prevented and f to denote efficiencies, analogous to S and e in equation (6), respectively. This was because no specific attribution methods have been found that attribute severe injuries between airbag and seatbelt systems and since there are no major differences between how seatbelt and airbag systems work when preventing death and when preventing severe injuries. In order to arrive at the YLD saved by the airbag system, P_{airbag} was divided by the total number of airbag systems sold by Autoliv and multiplied by the duration of the nonfatal injuries prevented and the severity factor for spinal cord injuries ($w_{spinal\ cord}$) prevented in order to obtain the YLD saved per airbag system according to equation (2). Spinal cord injury is one of the most common severe injuries in car accidents. The duration and severity of the nonfatal injury prevented was estimated as equivalent to that of spinal cord injuries. A spinal cord injury often lasts for the person's entire remaining lifetime (Murray and Lopez 1996). Thus we estimate the average duration of a spinal cord injury that was prevented as 35 years (WHO 2011).

Results

The calculations show that the DALY lost for the life cycle, excluding waste handling, of one airbag system are considerably lower than the DALY saved from its use in traffic (see table 2). The lost DALY are 4.6×10^{-5} years per airbag system, whereas the DALY saved are 1.2×10^{-2} years per airbag system. The DALY lost/saved is thus 1/260. The largest contribution to lost DALY is from the electricity production, followed by the toxic emissions. The mining of metals constitutes the lowest contribution to the lost DALY. Since the DALY saved are about 300 times higher than the lost DALY, the results indicate that the purpose of an airbag system, which is to save lives and prevent injuries, may be justified. However, additional and alternative data, for example, on toxic emissions during waste handling, may change the result.

Table 2 Results for a social life cycle assessment of automobile air bags

Processes	*Years of life saved or lost*	*Years of life disabled or years of fit life saved*	*Disability-adjusted life years saved or lost*
Mining of metals	-3.1×10^{-7}	-1.3×10^{-8}	-3.2×10^{-7}
Electricity production	-4.2×10^{-5}	NA	-4.2×10^{-5}
Production of pyrotechnical materials	0	0	0
Toxic emissions*	NA	NA	-3.9×10^{-5}
Use in traffic	2.2×10^{-3}	9.8×10^{-3}	1.2×10^{-2}

Notes: Years of life lost, years of life disabled, and disability-adjusted life years lost are indicated with a minus sign while years of life saved, years of fit life saved, and disability-adjusted life years saved are represented as positive values. All values are per airbag system.
*For this impact category, the model used provides results in terms of disability-adjusted life years directly, hence no values are presented for years of life lost or years of life disabled from toxic emissions.
NA = not available.

Discussion

The results are discussed below. The robustness of the results was tested by analyzing the significance of certain data gaps, in particular those related to waste management, and data choices.

Toxic Emissions and Waste Handling

The results of this study indicate that the airbag system saves more DALY than are lost during its life cycle. However, as can be seen in figure 1, the waste handling phase was not included in these calculations. It has been reported that landfilling of electronic waste, such as the ECU, may cause leakage of metals such as lead, copper, nickel, zinc, and cadmium and organic compounds such as brominated flame retardants and plasticizers (SEPA 2011). Incineration of electronic waste may cause emissions of toxic substances, such as dioxins, brominated flame retardants, polycyclic aromatic hydrocarbons (PAHs), copper, and lead (SEPA 2011). In order to test the significance of their omission from the study, the amount of emissions to the air from incineration of the ECU that would cause the DALY lost to exceed the DALY saved were calculated for three substances: dioxin, lead, and PAHs. For dioxins, emissions of about 10 milligrams (mg) per airbag system during waste handling would cause the DALY lost to exceed the DALY saved. For lead, however, about 100 kilograms (kg) emitted per airbag system is required for the DALY lost to exceed the DALY saved. Considering that the total weight of an ECU is about 400 grams (g), it seems unlikely that emissions of 100 kg of lead would occur during incineration of the ECU. For PAHs, emissions of about 100 g would cause the DALY lost to exceed the DALY saved. The large differences are due to the fact that in the USES-LCA model, emissions of dioxin to the air are considered about seven orders of magnitude more severe than emissions of lead to the air, and emissions of PAHs are somewhere in between. In fact, dioxin has the highest HTP of all substances listed in the work of Huijbregts and colleagues (2000). Considering the long-term effects of dioxin exposure (WHO 2010), and the suggested tolerable daily intake of only 1–4 picograms per kilogram (pg/kg) of bodyweight (Van Leeuwen et al. 2000), this may not be unreasonable. Since it appears that a small increase in dioxin emissions can cause a large increase in DALY lost, the main recommendation to Autoliv is therefore to avoid emissions of dioxins at the milligram scale, not just during waste handling, but throughout the entire life cycle of the airbag system. After the results of this study were presented to representatives from Autoliv, an investigation of dioxin emissions along the life cycle of the airbag system was initiated to ensure that the dioxin emissions are as low as reported and that no additional sources of dioxin emissions exist (Andersson 2012). Had the results shown less favorable results for the airbag system, Autoliv representatives were prepared to further check on upstream suppliers and their dioxin emissions.

Estimating the DALY lost for toxic emissions is a relatively intricate task in comparison to doing so for mining of metals. The USES-LCA model as well as the conversion of HTP to DALY builds on a number of assumptions and is thus affected by considerable model uncertainty. Including the health and environmental effects from chemicals has been a significant problem in LCA (Baumann and Tillman 2004; Finnveden et al. 2009), and some have argued that LCA studies including impacts on human health from chemical substances make use of several simplifying assumptions that result in unrealistic worst-case estimations (Owens 1997). In addition, there are a number of parameters in the USES-LCA model and in the conversion of HTP to DALY that are probably affected by considerable parameter uncertainty, such as PDI, HVL, RCR_{ref}, and Q_{em}. The calculations of health impacts from chemicals in this article should therefore be seen as indications only. The calculations of DALY lost due to emissions of chemicals from electricity generation conducted by Starfelt and Wikdahl (2011) are based on the same type of method, and thus those results should also be seen as indications.

Effects of Data Approximations

The data presented in table 1 have been collected on the basis of our best efforts and intentions. Still, obtaining better input data would refine the results. For instance, data on deaths and injuries during the mining of metals was obtained for Western Australia, as it was difficult to obtain data from other geographical areas. The high availability of data for that region is probably thanks to its considerable mineral resources. However, it is not certain that those numbers are representative for all countries where raw materials for the Autoliv airbag system are extracted. For instance, it is possible that some mining in developing countries has considerably fewer safety measures and therefore higher death tolls. In addition, the data obtained for casualties and injuries from electricity production are highly aggregated and there may be major local variations that are not reflected in this study. Obtaining data on injuries, and not just on lives lost, from electricity production may also have increased the DALY lost. In all, these approximations due to the limited availability of data give an advantage to the airbag system. However, it should be noted that the effect of the data approximations on the main result of this article is only minor. Consider a scenario for which mining of metals takes place under less safe conditions. If it is assumed that all accidents during mining of metals lead to death, and that the number of accidents would double, and that the age of the dying worker is as low as 15 years old, the DALY lost due to mining would still only about triple to 10^{-6} years. As can be seen from Table 2, mining of metals would then still be the lowest contribution to the total DALY lost (except for production of pyrotechnic materials), and the DALY saved by the airbag system would still be much higher. The same applies for the assumptions regarding the number of accidents and average age of the stricken for production of electricity: even considerable changes of these numbers do not change the main outcome of the study.

Risk Compensation

Numbers such as the 25,000 lives saved per year are calculated by Autoliv based on the standards of the U.S. National Highway Traffic Safety Administration, and some people consider such claims dubious. For instance, Adams's (1995) theory of risk compensation suggests that once people are exposed to certain risks, they change their behavior to reduce the risk. Similarly, if a risk is reduced, behavior may change in a way that leads to higher risk taking. According to Adams (1995), the use of seatbelts is a risk-reducing measure that induces such risk-taking behavior. He argues that although seatbelts obviously may save a person's life during a car accident, they also make drivers feel more secure and they therefore become less careful. This leads to less careful driving, which increases the probability of car accidents. According to Adams, the reduced risk from seatbelts and the increased risk from less careful driving are about equally large, and thus cancel each other out. Although Adams (1995) does not discuss airbag systems explicitly, there is a possibility that the numbers of 25,000 lives saved and 250,000 injuries prevented (see table 1) are overestimated due to risk compensation. However, more recent studies show no evidence of risk compensation for both seatbelts (Houston and Richardson 2007; Nakahara et al. 2003) and airbags (Harless and Hoffer 2003; Sagberg et al. 1997). In general, the literature indicates that risk compensation is larger for accident-reducing measures such as antilock braking systems than for injury-reducing measures such as seatbelts and airbags (Sagberg et al. 1997).

Risk in Industrial Ecology

The terms "risk" and "potential impacts" occur in two different contexts in this work: first, in calculations of DALY from toxic emissions and second, in the work on risk compensation. It is clear that risk is a broad concept with strong elements of human perception and behavior. For this reason risks to human health are difficult to model in a comprehensive and straightforward way. Applications of concepts of risk (such as HTP) exist in LCA and industrial ecology, but a more thorough scrutiny of the risk literature may clarify the situation. This, however, remains for future research.

Development of the Social Life Cycle Assessment Methodology

Our methodological experience during this study illuminates some of our skepticism about the UNEP/SETAC guideline mentioned earlier. Our first skepticism concerned the value of common sense-derived frameworks relative to empirically based systematizations. By conducting this case study, we have shown that DALY can be a relevant indicator for assessing social impacts from a life cycle perspective, and we hope that additional interesting S-LCA case studies will follow so that, eventually, practical guidelines can be developed. In our study, DALY is an indicator that is interesting since the aim of the airbag system is to save lives and prevent injuries, whereas the production of the airbag system may cause deaths and injuries. Accordingly, DALY may also be a relevant indicator of social impacts in the life cycle of other products with the explicit aim of saving lives and preventing injuries, such as the above-mentioned seatbelts, as well as medicines, exercise equipment, and catalytic converters for cars. In addition, using DALY to assess social impact may also be relevant for comparison of products for which injuries and lives lost constitute important social impacts. An example may be to compare gold mined in conflict areas using mercury, which clearly contributes to many lost lives (Dimčevska et al. 2007; Granatstein and Young 2009), to gold produced in other areas without the use of mercury. There are surely also cases when DALY is not a relevant indicator of social impacts, and then other indicators relevant for the specific product and the goal of the study should be used.

Our second source of skepticism was the underlying ethical values of the indicators of social impacts in the S-LCA literature, in particular in the UNEP/SETAC framework. DALY, however, can be viewed as an established indicator for social impacts. For example, Norris (2006) also used DALY for evaluating the social impact of products, although he did not use the term S-LCA. For our study, the DALY indicator was particularly appropriate since both impacts from the airbag system's life cycle and benefits from its use in traffic could be evaluated together. The indicators of social impacts suggested in the UNEP/SETAC guidelines had to be rejected owing to this requirement in this case study. Some authors have argued that human health is already included in E-LCA and should therefore not be included in S-LCA (Dreyer et al. 2006). However, humans are both social and biological creatures, and a boundary is not obviously evident. We rather agree with those who suggest that health is the most intrinsic social value of all and should therefore be in focus in S-LCA (Norris 2006).

The terminology in the UNEP/SETAC guidelines contains many different concepts related to the term "indicator of social impact," such as social impact (consequences of positive and negative pressures on social endpoints), stakeholder category (cluster of stakeholders expected to have shared interests owing to their similar relationship to the investigated product systems), impact categories (groupings of S-LCA results related to social issues of interest to stakeholders and decision makers), subcategories (socially significant themes or attributes), and subcategory indicators (indicators for measuring impacts on subcategories, which are grouped into impact categories). Although this typology is extensive, we found little use for these concepts considering the nature of our study. This is due to the ethical standpoint of our study in that the lives and health of all stakeholders have equal value, and thus there are no reasons to divide the stakeholders into categories. It is also due to the straightforwardness of the DALY as an indicator of social impacts—the social impact of years lost is measured in terms of years lost—which gives no reason to divide the social impact into subcategories and subcategory indicators.

Conclusions

We have here presented an S-LCA case study of an airbag system, using DALY as indicator of social impacts. The results from this study indicate that the purpose of an airbag system, which is to save lives and prevent injuries, is justified in this case. A number of issues related to uncertainty in the data are discussed and it is concluded that most of the input data are in need of further refinements. Our recommendation to the company Autoliv is that, although the results indicate that currently the number of DALY saved are nearly 300 times higher than the number of DALY lost for the airbag system, toxic emissions during waste handling should be further investigated, in particular emissions of dioxins.

We believe that method development within the field of LCA is more efficient and effective when it is based on case studies, as history has shown and the systems theory literature suggests. Unfortunately most methods for S-LCA proposed in the literature so far were not useful for our study, and we even had to revert back to E-LCA to find an appropriate method for impact assessment. Moreover, for social impacts to be meaningfully assessed in a life cycle perspective, indicators need to be unambiguously interpreted and meaningful in all social contexts along the life cycle. Otherwise the calculations make little sense for product evaluations. We hope that this contribution can open the way to more case studies that do not strictly follow the UNEP/SETAC guidelines, but rather choose the method that is most relevant for the specific case in question, eventually leading to a more empirically based S-LCA methodology.

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