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SOCIAL LCA IN PROGRESS

A method for human health impact assessment in social LCA: lessons from three case studies

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Abstract
Purpose Improving human health is a long-lasting endeavour of mankind. In the field of social life cycle assessment (SLCA), the importance of human health is often highlighted, and further development of impact assessment methods has been recommended. The purpose of this article is to present a method for assessing human health impacts within SLCA.
Methods By using a systematic combining approach, knowledge and experience about assessing human health impacts were obtained from three previously conducted case studies. The first case study was about an airbag system, the second about a catalytic converter and the third about gold jewellery. The disability-adjusted life years (DALY) indicator was used for impact assessment in all three case studies.
Results and discussion Both positive and negative human health impacts associated with the products were identified and assessed in the three case studies. For the airbag system, avoided health impacts in the use phase outweighed health impacts during production. For the catalytic converter, whether health impacts avoided exceeded health impacts caused or not depended on which time perspective regarding impacts was employed. Gold jewellery does not help avoiding any health impacts but caused considerable health impacts when produced at a certain location. Based on experience from these case studies, a generic human health impact assessment method was developed, and a life cycle human health typology for products was developed based on the method. The method provides a basis for analysis and interpretation of health impacts along product life cycles, and it is therefore important to report both positive and negative health impacts separately for different actors.
Conclusions The developed human health impact assessment method involves the assessment and comparison of both positive and negative human health impacts along product life cycles. In addition to the products assessed in the three case studies, we suggest additional products that could be particularly interesting to assess with the developed method, including medicines, seat belts, other conflict minerals, alcoholic beverages and products with a high chemical impact.

Keywords Airbag · Catalytic converter · Gold · Human health · Jewellery · Social life cycle assessment (SLCA)

1 Introduction

Improving human health is a long-lasting endeavour of mankind, and scientific research is fundamental for achieving this goal (World Health Organization 2013). Human health is considered in many different scientific disciplines, including of course medical science. It is also frequently mentioned as an important aspect in the field of social life cycle assessment (SLCA). For example, Norris (2006) discussed socio-economic impacts and used human health in terms of mortality and morbidity as endpoint. As illustrated, he calculated the disability-adjusted life years (DALY) for electricity production at three geographical locations with different grid

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mixes. Weidema (2006) described human health as an aspect of human life with intrinsic value. The life cycle initiative, a joint organisation of the United Nations Environment Programme (UNEP) and the Society for Environmental Toxicology and Chemistry (SETAC), developed guidelines for SLCA which included a list of six impact categories (Benoît et al. 2009). One of these six impact categories was health and safety. Jørgensen et al. (2010) discussed physical and mental health as a main social impact. A handbook on product social impact assessment referred to health and safety as a social topic—the only social topic relevant for all three stakeholder groups considered there (Fontes et al. 2014). Simas et al. (2014) used DALY to assess occupational health damage as part of their "bad labour" footprint.

Regarding impact assessment, two human health impact pathways based on socio-economic relationships have been formally proposed in the SLCA literature. The first is the Preston pathway, which describes how health in terms of life expectancy can increase with increased income, and how decreased income can reduce life expectancy (Feschet et al. 2013). The second is the Wilkinson pathway, which describes how increases in economic equity improve human health in terms of child mortality, and how reduced economic equity results in reduced human health (Bocoum et al. 2015).

The discussion on and assessment of work environment health impacts have been on-going since the early days of life cycle assessment (LCA) development (Schmidt et al. 1992), and this discussion has become intertwined with the discussion on social impacts. In the first published article where SLCA is mentioned, work environment health impacts are referred to as social impacts (O'Brien et al. 1996). In the guidelines for SLCA, health and safety of workers is an included subcategory (Benoît et al. 2009). Consequently, work environment health impacts can be seen as one type of social impacts, and thus work environment LCA (WELCA) can be seen as a subpart of SLCA. In the article by Scanlon et al. (2015), WELCA and SLCA are mentioned as two parallel efforts of incorporating social and socio-economic aspects of products into LCA.

Human health is not only discussed in the context of SLCA and WELCA. In environmental LCA (ELCA), human health is an area of protection, together with the environment and natural resources (ISO 2006). For example, the DALY indicator has been used to quantify impacts from emissions to this area of protection (Kobayashi et al. 2015). It is, however, also obvious that emissions to the environment as considered in ELCA are not the only potential impact to human health from products. Dreyer et al. (2006) discussed the overlap between SLCA and ELCA when it comes to human health and suggested that a future integration of areas of protection may be relevant. In a recent article, Dewulf et al. (2015) illustrated human health as being in the cross-section of society and the environment. Since the ultimate aim of SLCA is to improve human wellbeing (Benoît et al. 2009), we consider human health impacts to be social impacts in this article, even if some health impacts discussed occur via exposure to substances that were first emitted to the environment.

In the SLCA guidelines, Benoît et al. (2009) recommended further development of impact assessment methods, which they described as an "open field for future research." The aim of this article is to present a method for assessing human health impacts within SLCA. The method is developed based on empirical experience from three case studies and entails identification of health impacts along the life cycle and their subsequent assessment using the DALY indicator. This method also constitutes a complement to already-developed impact assessment methods based on more socio-economic factors (Feschet et al. 2013; Bocoum et al. 2015).

2 Methods and materials

2.1 Systematic combining

LCA is a systems analysis method (Baumann and Tillman 2004), and the development of new methods based on experience from conducted case studies is a common and valuable approach in systems analysis (Miser and Quade 1985). This approach is of particular relevance for systems analysis methods that are difficult to validate (Miser and Quade 1988), which includes LCA. Dubois and Gadde (2002) referred to this use of case studies to develop methods and theory as *systematic combining*, and write:

> Case studies provide unique means of developing theory by utilizing in-depth insights of empirical phenomena and their contexts. […] [A] preliminary analytical framework consists of articulated 'preconceptions'. Over time, it is developed according to what is discovered through the empirical fieldwork, as well as through analysis and interpretation. This stems from the fact that theory cannot be understood without empirical observation and vice versa.

Case studies thus provide valuable proofs of concept (or calls for adjustments) when developing method and theory. Such systematic combining is the method of this article. This is thus a synthesis article that draws upon knowledge and experience gained from three conducted case studies in order to develop a method for human health impact assessment in SLCA.

2.2 Calculation of DALY

Different indicators have been used to quantify human health impacts in SLCA. Norris (2006) used DALY for assessing health impacts from electricity production, Feschet et al. (2013) used life expectancy at birth (LEX) as human health indicator for the Preston pathway, and Bocoum et al. (2015) used infant mortality as human health indicator for the Wilkinson pathway. In all three case studies described in this article, the DALY indicator has been used. DALY is measured in the unit years and was originally developed by the World Health Organization and the World Bank in order to measure aggregated health impacts (Gold et al. 2002). The World Health Organization proposes the calculation of DALY for most diseases and health conditions. Although there are some differences in the exact calculation of DALY in the three case studies, the general method remains the same. Equal weighting is given to the significance of 1 year of life lost at any age, and DALY is calculated as the sum of years of life lost (YLL) and years of life disabled (YLD) (Goedkoop et al. 2013; Scanlon et al. 2013):

$$\mathrm{DALY} = \mathrm{YLL} + \mathrm{YLD} \tag{1}$$

The YLL is calculated as the difference between the actual age at death (t_{death}) and the life expectancy at that age in the population (t_{exp}):

$$\mathrm{YLL} = t_{\mathrm{exp}} - t_{\mathrm{death}} \tag{2}$$

The YLD is calculated as:

$$\mathrm{YLD} = w \times D \tag{3}$$

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

2.3 Case study selection

The method was developed continuously during the work on three case studies. The first study is an assessment of an airbag system, which is a product designed to save lives by reducing casualties and injuries to drivers and passengers in car crashes. The second study is an assessment of a catalytic converter, which is a product designed to save lives and reduce injuries due to reductions of exhaust gas emissions. The third study is an assessment of gold jewellery, with gold mined at three different locations. At one of these locations, the gold is used to finance opposing parties in a conflict, which is estimated to have caused millions of casualties. The three case studies are summarized in Table 1 and presented in more detail in Sect. 3. Note that the case studies have been published previously. All the detailed calculations and data are therefore not repeated here. Rather, we give a brief description of the three case studies and highlight common features that lead to the development of the generic human health impact assessment method. For a more detailed description, we direct interested readers to the specific studies, of which two are openly available on the web (Islam 2015; Parsmo 2015).

3 Case studies

3.1 Health impacts from an airbag system

An airbag is a cushion that inflates rapidly in the case of a car accident in order to protect the driver of the car and passengers from death and severe injuries. The inflation of the airbag is controlled by an electronic control unit, which together with the airbag constitutes the airbag system. The company Autoliv is a producer of safety devices for cars, including airbag systems, and had explored environmental impacts of their products in a number of ELCA studies (Iwanek and Samiee 2010; Mujiyanto and Priyojati 2010; Suyang and Jingjing 2010; Munnwer et al. 2012). The company then expressed an interest in investigating social impacts along the life cycle of their airbag system as well. It was decided that the aim of the study should be to compare the injuries and lives lost during the product life cycle of an airbag system with the injuries prevented and lives saved during its use (Baumann et al. 2013). The driver airbag consists of six components (label, nut, cushion, can, cover and inflator) and the electronic control unit consists of five components (label, cover, housing, screw and printed circuit board), which in turn both consist of different materials, such as metals and petrochemicals (Mujiyanto and Priyojati 2010; Suyang and Jingjing 2010). All these components, including their supply chains, were considered in the study, and the functional unit was one frontal airbag system. However, waste treatment of the airbag system was not included in the study.

The social indicator employed to fulfil the aim of the study was DALY, as described in Sect. 2.1. DALY was chosen since it can be used to quantify both impacts that an airbag system aims at avoiding during its use phase and health impacts from the rest of the airbag system's life cycle. Parts of the airbag system's production system were deemed to probably not have notable health impacts, while four areas were deemed in need of scrutiny: (1) emissions of toxic substances along the life cycle, (2) work environment impacts during mining of metals, (3) work environment impacts during electricity generation, and (4) work environment impacts during production of pyrotechnical material for the inflator.

Toxic emissions and pyrotechnical materials are obvious health hazards. Metals account for a large part of the airbag system by weight, and mining activities cause higher health impacts than many other industries (Coleman and Kerkering 2007). Electricity generation is also known to be an industry with considerable casualties, particularly for some energy

Table 1 Description of the three included case studies

	Baumann et al. (2013)	Islam (2015)	Parsmo (2015)
Product studied	Airbag system	Catalytic converter	Gold jewellery
Functional unit	One airbag system	One converter	One golden ring
Impacts included	Emissions[a] Work environment[b]	Emissions Work environment	Emissions Work environment Conflict
Health saver, taker or neutral?	Health saver	Depends on value perspective	Health taker

[a] Only emissions contributing to human toxicity potential were included

[b] Only work environment impacts related to electricity generation and mining were included

sources (Wilson et al. 1999). The use phase of the airbag system was also assessed in terms of DALY avoided. The equation used to calculate the net DALY of the airbag system in this case study was thus:

$$\begin{aligned}\mathrm{DALY}_{\text{airbag system}} = {} & \mathrm{DALY}_{\text{toxic}} + \mathrm{DALY}_{\text{mining}} \\ & + \mathrm{DALY}_{\text{electricity}} + \mathrm{DALY}_{\text{pyrotechnical}} \\ & + \mathrm{DALY}_{\text{use phase}} \end{aligned} \quad (4)$$

Data on metal amounts, electricity use and toxic emissions were obtained from previously conducted ELCA studies of Autoliv's airbag and electronic control unit (Mujiyanto and Priyojati 2010; Suyang and Jingjing 2010). The ReCiPe impact assessment method was applied for assessing the DALY from toxic emissions along the life cycle of the airbag system (Goedkoop et al. 2013). Only health impacts due to human toxicity were included. Furthermore, the ReCiPe method includes three different value perspectives that represent different views on environmental issues. The individualist perspective is based on short-term interests and technological optimism. The hierarchist perspective is based on the most common policy principles regarding time frame and other assumptions and is recommended as a default. The egalitarian perspective is more precautionary and takes a long-term perspective. In the assessment of the airbag system, the hierarchist perspective was employed.

Data on number of lives lost from mining of metals were obtained from accident statistics in an Australian mining fatalities database (Department of Mines and Petroleum 2010). Data on casualties per kilowatt-hour for different kinds of electricity generation were obtained from two published sources (Wilson et al. 1999; Starfelt and Wikdahl 2011). Some of this electricity casualty data were global averages, some were specific for different countries (such as China and the USA), and some for regions (such as Europe). The data obtained on accidents and casualties in mining and electricity generation were calculated into DALY by application of the average global life expectancy (World Health Organization 2011) as well as durations and severity factors for relevant injuries (Polinder et al. 2007).

The pyrotechnical materials used by Autoliv are produced in-house, and we obtained information about their production from the producer. According to this information, there were no fatal or serious injuries recorded for many years. Thus, after this investigation, the production of pyrotechnical materials was deemed to have a negligible contribution to the net DALY.

The DALY avoided in the use phase were obtained based on annual lives saved and injuries prevented by Autoliv's seatbelts and airbag systems. By application of the attribution method described by Glassbrenner (2003), the lives saved and injuries prevented were divided between seatbelts and airbag systems. This attribution method is called restraint-neutral attribution, which does not give any preference to either of the two safety products. In order to convert to functional unit, lives saved and injuries prevented were divided by the annual number of sold airbag systems by Autoliv. Again, assumptions about life expectancy, injury duration, and injury severity factor had to be made.

The results of the study showed that the DALY caused during the product life cycle of the airbag system were considerably lower than the DALY avoided from its use in traffic. The DALY caused were approximately 8×10^{-5} years per airbag system, whereas the DALY avoided were approximately 1×10^{-2} years. The largest contribution to DALY caused was accidents during electricity generation and toxic emissions during the whole life cycle, which contributed by approximately equal shares. Since the DALY avoided were more than 100 times higher than the DALY caused, the result indicates that the purpose of an airbag system, which is to save lives and prevent injuries, seems to be justified.

The sensitivity analysis showed that the results were robust. However, Autoliv does not perform the waste treatment themself, and the end of life process for airbag systems is thus uncertain. Incineration of electronic waste may cause emissions of hazardous substances. In order to test the importance of the omission of waste treatment, the amount of emissions to air from incineration of the electronic control unit that would result in the DALY caused exceeding the DALY avoided was calculated. This was done for three typical electronic waste incineration contaminants, namely dioxins, lead and polycyclic aromatic hydrocarbons (PAH) (Swedish Environmental Protection 2011). For dioxins, emissions of about 10 mg per airbag system during waste treatment would result in the DALY caused exceeding the DALY avoided. For lead and PAH, the corresponding numbers were much higher. The main recommendation to Autoliv was therefore to try to avoid emissions of dioxins at the milligram level or higher during waste treatment through life cycle management initiatives.

3.2 Health impacts from a catalytic converter

Catalytic converters convert the toxic exhaust gas emissions of carbon monoxide (CO), uncombusted hydrocarbons (HC) and nitrogen oxides (NO_x) into the non-toxic gases water (H_2O), carbon dioxide (CO_2) and nitrogen (N_2). As a follow-up study to the assessment of the airbag system, we wanted to know if a catalytic converter used to reduce exhaust gases in cars avoids more DALY than it causes (Islam 2015). Amatayakul and Ramnäs (2001) had already shown that a catalytic converter caused more environmental impact throughout its life cycle than it avoided in the use phase. Their results showed that environmental impacts from mining of platinum group metals (PGM) in South Africa outweighed the environmental gains from the converter's use phase. The question was whether a catalytic converter also causes more health impacts throughout its life cycle than it avoids in the use phase, and whether the PGM mining would once again turn out to dominate the impact.

A catalytic converter consists of six main components: ceramic honeycomb (19 % of weight), insulating material (2 %), wash coat (4 %), PGM catalyst (<1 %), steel housing (68 %), and heat shield (7 %). The production of these was included in the study, along with the use phase of the converter in a passenger car. Different recycling rates were also tested in the study.

The health impacts included were expanded compared to the airbag system study. Instead of merely considering emissions contributing to human toxicity, also emissions contributing to global warming, ozone depletion, photochemical smog, ionizing radiation and particulate matter were considered. These are all impact categories that contribute to human health impacts according to the ReCiPe method (Goedkoop et al. 2013). DALY avoided in the catalytic converter's use phase were similarly quantified by assessing avoided health impacts from the reduced emissions with the ReCiPe method.

Work environment impacts for all processes were included this time, and not only for mining and electricity generation as in the airbag system study. Scanlon et al. (2015) had developed characterization factors for work environment impacts for a large number of industrial activities. These include both injuries (such as bruises, wounds and traumatic injuries) and workplace exposure to chemicals. They are calculated as the ratio between the work environment-related DALY for a specific industry and the amount of physical output from that industry:

$$CF_{\mathrm{WE},n} = \frac{\mathrm{DALY}_n}{m_n} \tag{5}$$

where $CF_{\mathrm{WE},n}$ is the work environment characterization factor for the industry n and m_n is the physical output of the industry n. An example of an industry n is iron ore mining, and the DALY_n then quantifies the annual years of disability caused in the iron ore mining industry. The output m_n is given as kilograms of iron ore in that case, and the $CF_{\mathrm{WE},n}$ then takes the unit of years of disability per kilograms iron ore. The characterization factors by Scanlon et al. (2015) apply for working conditions in the USA, but they were doubled for South Africa, Russia and other countries outside Europe in order to account for presumed higher work environment impacts.

The net DALY of the catalytic converter was calculated as:

$$\begin{aligned}\mathrm{DALY}_{\text{catalytic converter}} = {} & \mathrm{DALY}_{\text{emissions}} \\ & + \mathrm{DALY}_{\text{workplace accidents}} \\ & + \mathrm{DALY}_{\text{use phase}}\end{aligned} \tag{6}$$

Overall, the net DALY varied between approximately −5 and 7 days, meaning that the converter could cause more health impacts than are avoided. Impacts from emissions to the environment—affecting the general population—turned out to be considerably larger than health impacts in the workplace environment. The results showed that whether a catalytic converter avoids more DALY than it causes depends mainly on the time perspective in the ReCiPe method. For the individualist and hierarchist perspectives, which consider time frames up to 100 years, the catalytic converter is a net provider of health regardless of other assumptions. For the egalitarian perspective, for which an infinite time frame is considered, the catalytic converter is generally a net depriver of health. However, increased recycling rate and functional lifetime of the converter could make it a net provider of health also for the egalitarian perspective. Regardless of value perspective and other assumptions, the main contributor to DALY caused was indeed the PGM mining (ca 80 %).

3.3 Health impacts from gold jewellery

Gold was suggested as a potentially interesting product to study from a health perspective in the article by Baumann et al. (2013), mainly due to two reasons: The use of mercury in small-scale gold mining, and the role of gold in conflicts. In this case study, human health impacts of gold jewellery production were assessed in order to investigate whether the mercury and conflicts, or other processes, resulted in high health impacts (Parsmo 2015). Gold jewellery was chosen over other uses of gold in order to avoid difficult-to-assess avoided health impacts in the use phase. For example, gold is used in electronic medical instruments, which could have positive health impacts. Such assessments would require data on the health impacts of such instruments and allocation of those impacts to the gold components. Gold production in the Democratic Republic of the Congo (DRC), South Africa and Sweden was considered. Besides the gold production system, the production of mercury was also included in the DRC case.

Health impacts from emissions, including those of mercury, were assessed with the ReCiPe method. Similarly to the catalytic converter study, all six impact categories contributing to human health were included (human toxicity, global warming, ozone depletion, photochemical smog, ionizing radiation and particulate matter). Work environment impacts were also assessed in the same way as in the catalytic converter study, using the characterization factors provided by Scanlon et al. (2015). The influence of increasing the value of these characterization factors to account for more severe working conditions was investigated in the sensitivity analysis. Violence related to robbery during the retailing and use phases of gold jewellery was not included due to lack of data, although jewellers' shops are typical targets of armed robberies that sometimes result in injuries (O'Donnell and Morrison 1997).

What makes this study different from the other two, apart from that there is no avoided DALY in the use phase, is the influence of the product to the continuation of a conflict. The conflict that the gold contributes to is (mainly) the Second Congo War and its aftermath in the DRC. This conflict started in 1998 when President Laurent Kabila ordered Rwandan military to leave the country. Although the war was first fought mainly between the newly installed government of Kabila and foreign powers such as Rwanda, Uganda and Burundi, additional military groups soon joined the fighting. The conflict has been described as the bloodiest since World War II, and 5.4 million people are estimated to have lost their lives as a result of the conflict (Coghlan et al. 2007). This death toll not only is partly due to combat actions but also includes casualties due to diseases such as AIDS and severe contagion among refugees with limited access to food and clean water.

The role of gold and other minerals in the conflict is not trivial to assess. The long-lasting conflict in the DRC arguably has various other causes, including ethnic tension, poor economy, colonial power and its withdrawal, conflict over land, absence of security and non-functional governmental institutions (Thom 1999; Ndikumana and Emizet 2003; Turner 2007). However, there are several reasons to believe that the conflict may not have taken place were it not for the presence of minerals in the region or at least would not have been as bloody and long lasting. First, there are witness observations of overtaking of mines by various military groups, promises of gold to people joining military forces and direct killings of people to get access to areas rich in minerals (Human Rights 2005; Global 2009; Amnesty 2013). Second, economic analyses show that the revenue from minerals serves as an economic basis for providing weapons. An evaluation of eight conflicts in the DRC between 1960 and 2000 concluded that seven out of eight conflicts were partly our fully financed by natural resources (Ndikumana and Emizet 2003). The revenues can come directly from the minerals or from enforcing road taxes on transporting minerals. Third, many neighbouring countries, most notably Rwanda, Burundi and Uganda, have an economic interest in the mineral extraction, and people living in these countries are benefiting economically from the trade (Ndikumana and Emizet 2003; Mullins and Rothe 2008). For example, Uganda produced 500 US dollars worth of gold in 2007 but exported 27 million US dollars worth of gold the same year (Granatstein and Young 2009). The difference between these two numbers is likely unofficial imports from the DRC. Fourth, an economic study evaluating parameter increasing the probability of civil war concluded that the geographical concentration of natural resources significantly increased the probability of civil war in regions, especially during the 1990s (Ndikumana and Emizet 2003). Although other factors certainly play an important role in the conflict, it was assumed in the gold jewellery study that the minerals are accountable for all deaths in the conflict.

The conflict-related DALY caused by the gold was estimated in a similar manner as work environment health impacts were assessed by Scanlon et al. (2015) (Eq. 5). The number of DALY caused by the gold was calculated by dividing the DALY caused in the conflict with the gold production from 1998 to 2006 and allocated to gold by economic value:

$$\mathrm{DALY}_{\mathrm{conflict,Au}} = a \times \frac{\mathrm{DALY}_{\mathrm{conflict,total}}}{m_{\mathrm{Au}}} \tag{7}$$

where a is an allocation factor and m_{Au} is the mass of gold (Au) produced in the DRC between 1998 and 2006. The allocation by economic value is conducted between gold, tin, tantalum, cobalt, diamonds and copper, since these are the economically most important minerals in the region. The allocation factor a is thus a ratio between the economic value of the produced gold between 1998 and 2006, and the total economic value of all included minerals during the same time period. This allocation gives gold a share of approximately 7 % of the conflict casualties.

The net DALY of the gold jewellery was calculated as:

$$\mathrm{DALY}_{\text{gold jewellery}} = \mathrm{DALY}_{\text{emissions}} + \mathrm{DALY}_{\text{workplace accidents}} + \mathrm{DALY}_{\text{conflict}} \tag{8}$$

The baseline result for the DRC shows that the DALY per gold ring (containing 4 g of gold) is approximately 0.4 years, and the DALY per kilogram gold is approximately 100 years. The main contributors are, as suspected, the conflict (ca 99 %) and emissions of mercury (ca 1 %). Other contributions were minor. For gold production in South Africa and Sweden, the net DALY per gold ring was approximately 5×10^{-4} and 1×10^{-4} years, respectively.

A number of parameters were varied in a sensitivity analysis, such as the value perspectives in ReCiPe (individualist, hierarchist, and egalitarian), the magnitude of mercury emissions, transport distances, the amount of gold produced in the DRC (m_{Au}), the allocation factor of conflict DALY between minerals (a), the number of casualties in the conflict ($\mathrm{DALY}_{\text{conflict,total}}$), working environmental characterization factors ($CF_{\mathrm{WE},n}$) and gold recycling. In general, although the numerical values of the results varied, the results presented above proved to be robust in terms of relative impact between the countries of origin and main contributing processes. Even if the gold is allocated a smaller share of the conflict casualties (e.g. 1 % instead of 7 %), it is still the largest contributor to the DALY of gold jewellery from the DRC.

4 Results and discussion

4.1 A human health impact assessment method

Notably, there is a progression over the course of three case studies (Table 1). The airbag system study only considered emissions contributing to human toxicity, and not health impacts due to global warming and other more indirect emission-related impacts. In addition, only work environment impacts from electricity generation and mining were included. In the catalytic converter study, this was expanded to include all emissions that contribute to human health impacts and work environment impacts from all processes (as far as available data allowed). In the gold jewellery study, this expanded scope was kept and health impacts from the conflict were added.

Based on the three case studies, and as a generalization of Eqs. 4, 6 and 8, a generic method for human health impact assessment can be derived:

$$\mathrm{DALY}_X = \sum_i \mathrm{DALY}_i + \sum_j \mathrm{DALY}_j \tag{9}$$

where X is the product studied, i are the negative health impacts identified along the life cycle and j are the positive health impacts identified (which are quantified as negative DALY). It should be noted that this method is not restricted to any specific health human health impacts, such as the ones assessed in the three case studies.

Two examples of health impacts not included in the three case studies are those caused by the Preston and Wilkinson pathways. However, following Eq. 9, health impacts from these pathways could have been included, provided that they could be recalculated into DALY. Feschet et al. (2013) list four prerequisites that should be fulfilled in order for the Preston pathway to be relevant to assess: (1) Processes must occur in poor countries where the added income makes a notable change to people's health, (2) processes must constitute a notable share of the national income in order to have a notable health impact, (3) processes must have a duration long enough to have an impact and (4) the income from processes must be distributed among the population so that it does not only benefit a small fraction of the people. They also write that the Preston pathway could not be applied to Cameroon for the time before 2010 due to a number of national crises, including armed conflicts. For the DRC as well, an armed conflict is present. It is also uncertain whether the wealth obtained from gold mining is distributed equally among the population. It is thus possible that the Preston pathway cannot be applied to the DRC at the moment. For the airbag system and the catalytic converter, particularly the first and second prerequisites above may not necessarily be fulfilled. However, this was not assessed in detail in any of the three case studies.

Arvidsson et al. (2014) emphasized the importance of having a scientific basis when assessing social impacts in SLCA. It is thus worth mentioning the scientific basis of three of the most prominent health impacts considered in the case studies. The impact assessment method used for assessing health impacts from emissions originates from ELCA and is mainly based on knowledge from the fields of toxicology and environmental chemistry. The work environment impacts assessed largely rely on knowledge from the field of occupational health and safety. The assessment of conflict health impacts draws upon knowledge from the field of conflict and development studies.

4.2 Life cycle health typology for products

From the three case studies, it is clear that products can have a net positive DALY, a net negative DALY and a DALY close to zero. The latter would happen if the product's positive and negative health impacts are of approximately equal (high or low) magnitude. Based on the method described by Eq. 9, we propose the term *health saver* to denote products with a net negative DALY (i.e. $\Sigma\mathrm{DALY}_i < \Sigma\mathrm{DALY}_j$). We further suggest *health taker* to denote products with a net positive DALY (i.e. $\Sigma\mathrm{DALY}_i > \Sigma\mathrm{DALY}_j$). For products with a DALY close to zero (i.e. $\Sigma DALY_i \approx \Sigma DALY_j$), we say that they are *health neutral*. Table 1 shows this typology applied to the three cases studied.

In addition to these terms, some products studied caused health impacts at geographical locations different from where the health benefits occurred. For the airbag systems, health impacts were comparatively low, but they often occurred in other places than where the airbag system was used for saving lives and avoiding injuries. The catalytic converter clearly avoided health impacts where it was used but caused health impacts at other locations along its life cycle, primarily where the PGM were mined. There were also notable contributions to global warming from the converter, which causes health impacts all around the globe. Such products, where health impacts are avoided at one location and health impacts are caused at another, can be said to 'export' health impacts. They are therefore referred to as *health exporters* and require that the positive DALY (i.e. $\Sigma DALY_i$) and negative DALY (i.e. $\Sigma DALY_j$) occur at different geographical locations. It is thus important to note that even though the net health impacts of a product may be positive, the product could still be considered problematic if people at one location avoid health impacts while people at another location experience high health impacts (i.e. if health impacts are 'exported' between different geographical locations). This method thus provides a basis for analysis and interpretation of different health impacts to different actors along product life cycles. An important quality of the method is that it makes health-related trade-offs visible.

5 Conclusions and further studies

During the three case studies, a continuous progression towards a method for human health impact assessment can be traced. Based on knowledge and experience from the case studies, a generic human health impact assessment method was developed. This method entails the assessment of both positive and negative human health impacts quantified in terms of DALY and is described mathematically by Eq. 9. This developed impact assessment method can be used in the case studies to identify products as health savers (for which the positive health impacts are higher than the negative), health takers (for which the negative health impacts are higher than the positive) or health neutral (for which positive and negative health impacts of similar magnitude). We also suggest the term health exporters for products that avoid health impacts in some geographical locations but cause health impacts in other locations.

The developed method is generic with regard to which health impacts are included, and is ready to be tested and scrutinized in further case studies of additional products. For instance, medicines are used in health care to cure, treat or prevent disease. Considering this, it should be expected that most medicines have negative DALY, similarly to the airbag system. However, pharmaceuticals generally have high life cycle environmental impact compared to base chemicals (Wernet et al. 2010) and may become emitted and cause adverse environmental and health impacts themselves (Daughton and Ruhoy 2009). Studies trying to confirm a negative DALY of medicines also from a life cycle perspective would thus be relevant to conduct. A non-exhaustive list of additional products that may be particularly interesting to investigate with the developed method includes seat belts, drugs, other conflict minerals such as tantalum, tin, tungsten, and diamonds, cigarettes, alcoholic beverages and products with a high chemical impact, such as cotton textiles. Further studies could also try to assess net health impacts from gold used in devices that have positive health impacts, such as medical equipment for early cancer detection.

Besides these, more unexpected products may benefit from assessments of human health impacts along the life cycle. Gilbertson et al. (2014) assessed the net DALY for a gas sensor using a method similar to that developed in this article. The gas sensor contained carbon nanotubes and could detect the hazardous substance hydrogen sulphide (H_2S) at lower concentrations than other sensors, thus avoiding exposure and subsequent health impacts. DALY from emissions during production were quantified by the ReCiPe method and compared to estimations of how many DALY the sensor could save during its lifetime. The result showed that that the DALY caused during production were approximately 8×10^{-5} years, while the DALY avoided were approximately 20 years. It is thus clear that the gas sensor had a beneficial impact on human health from a life cycle perspective, in a similar way as the airbag system. Using the typology suggested above, the carbon nanotube-enhanced gas sensor seems to be a health saver.

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