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LIFE CYCLE MANAGEMENT

Black swans swimming in product streams: method for including unplanned events in life cycle assessment

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Abstract

Introduction Unplanned events such as accidents and more massive black-swan events are contingent to modern technology. However, varying approaches and inconsistent guidelines make the inclusion of unplanned events in life cycle assessment (LCA) uncommon and challenging. This paper discusses the relevance of considering unplanned events in LCA and shows how they can be included in LCA practice.

Method A theoretical background to the concepts of black swans, accidents, and unplanned events is first provided. We then propose a method for how unplanned events can be included in LCA practice, illustrated through three cases: (i) a sabotage in the energy system, (ii) an accident in the use phase, and (iii) a sudden policy change.

Results The results show that unplanned events can be included and may significantly affect LCA results, sometimes even fulfilling criteria for black-swan events.

Conclusions We suggest that unplanned events should be included in LCA when relevant, e.g. as one scenario in LCAs of product systems sensitive to accidents. We also suggest that changes in flows due to unplanned events should be considered in unit processes, so that their impacts become distributed across downstream product systems depending on demand for the unit-process output.

Keywords Life cycle assessment · Accident · Black swan · Risk assessment · Unit process

1 Introduction

The black-swan metaphor originates from the seventeenth century when European travellers encountered black swans in Australia (Fig. 1), overturning their belief that all swans are white (Ale et al. 2020). While somewhat different definitions can be found (see Section 2), black-swan events generally mean unlikely events with high impact. Life cycle assessment (LCA), in its original and most basic form, only considers impacts of product systems under normal or typical conditions (Ciroth et al. 2021). Black swans and similarly unplanned or accidental events are thus rarely considered in LCA. However, this exclusion could greatly influence results for systems where unplanned or accidental events with significant impacts could happen, resulting in decisions based on incomplete assessments or skewed comparisons (Finkbeiner et al. 2014; Fries and Hellweg 2014). LCA guidelines provide different and inconsistent guidance on whether to include unplanned events and accidents in LCA. The PAS 2050:2011 guidelines by the British Standards Institute (2011) state that when an unplanned change to a product system results in a 10% increase in inventoried greenhouse gas emissions for more than 3 months, a reassessment should be done. The ILCD guidelines (European Commission's Joint Research Center 2010) state that LCAs should not include accidents such as leakages and spills, but also that *if* accidents are included, they should be inventoried separately from the normal operations. The ISO 14044 guidelines (2006) do not mention unplanned events or accidents.

Some previous studies have attempted to go beyond the basic LCA framework by including unplanned or

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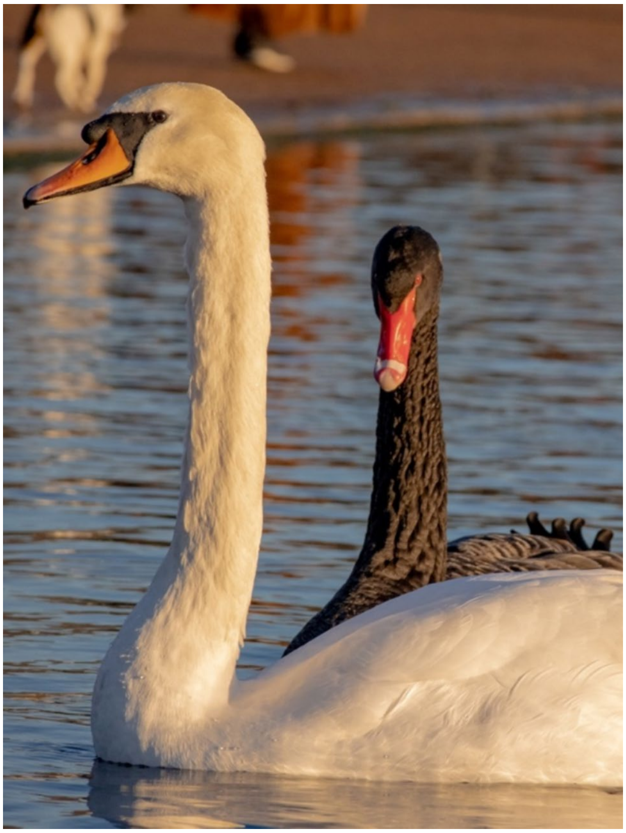

Fig. 1 European travellers first encountered black swans in the seventeenth century, overturning their belief that all swans are white. Photo by The Blowup (https://unsplash.com/@theblowup) on Unsplash (https://unsplash.com). Shared under the Unsplash License (https://unsplash.com/license)

accidental events in LCA. These studies show a wide range of approaches, often integrating elements from risk assessment. Simonson et al. (2005) introduce a framework for including the impacts of unplanned fires in LCAs of products for which fire performance is an important parameter (such as products treated with flame retardants). The impacts of fires are then included by using statistics on fire incidents. Sadiq and Khan (2006) proposed a "risk-based life cycle assessment" where hazards (e.g. fires, explosions and chemical release) are scored and aggregated into a joint risk reduction index for health, ecological and safety risks. These are then weighted against other aspects in a multicriteria decision analysis to enable a combined assessment of risks, environmental impacts, costs and technological feasibility. Ayoub et al. (2015) also called their approach "risk-based life cycle assessment" but instead identified risks along the life cycle as reported by stakeholders. This included a wide range of social, environmental, health, technical, operational and policy risks, where the environmental ones corresponded to conventional impact categories in LCA. All these different risks were then classified in a risk matrix with 1-to-5 scales based on their likelihood and severity to prioritize risk management efforts. Aissani et al. (2012) proposed a "life cycle risk assessment" approach, where "dangerous situations" are first identified along the life cycle, meaning situations that could cause or have already caused accidents, such as synthesis gas leakage from gasification leading to explosions or fire. They then scored the situations on a 1-to-3 scale regarding the probability of occurrence and extent of damage. Khakzad et al. (2017) proposed an "accident risk-based life cycle assessment" methodology that considers risks such as fires and explosions along the life cycle. These were converted to monetary values and compared to the monetized impact of greenhouse gas emissions along the life cycle. Sauve and Van Acker (2021) integrated risk assessment into LCA by first identifying risky scenarios, such as landfill emissions due to floodings. Secondly, they estimated the potential consequences of those scenarios. Finally, they calculated the probability of obtaining different environmental impacts given the scenarios.

Considering that the inclusion of unplanned or accidental events in LCA is necessary for a comprehensive assessment of the environmental impacts (Finkbeiner et al. 2014), along with the wide range of approaches suggested and the inconsistent guidelines regarding inclusion of unplanned events and accidents, the LCA community would benefit from a clear and unified approach. This paper discusses the relevance of considering unplanned events and accidents in LCA and shows how they can be included in LCA practice. Contrary to the previous approaches described in the literature review above, we suggest unplanned events and accidents can be considered in conventional LCA calculations and need not be assessed separately using risk assessment approaches. This is shown through three cases: (i) a sabotage in the energy system, (ii) an accident in the use phase, and (iii) a sudden policy change. Before these cases are presented, a brief theoretical background to the concepts of black swans, accidents and unplanned events is provided. Finally, recommendations on general approaches for including unplanned events and accidents in LCA are provided.

2 Theoretical background

An accident can be defined as "something bad that happens that is not expected, and that often damages something or injures someone" (Cambridge Advanced Learner's Dictionary and Thesaurus). However, whether an event is "not expected" depends on the observer's knowledge. The framework by Luft and Ingham (1961) provides four categories of events based on knowledge characteristics: (i) known to others and known to self, (ii) known to others and not known to self, (iii) not known to others and known to self, and (iv) not known to others and not known to self.

Regarding black-swan events, Taleb (2007) defines them as highly improbable events with three main characteristics: (i) highly unpredictable, (ii) have a massive impact and (iii) seem predictable in retrospect. Similarly, Aven (2013) defines a black-swan event as "an extreme, surprising event relative to the present knowledge" (p. 48). Aven (2015) adds that whether something constitutes a black swan is in the eyes of the beholder. To summarise, black-swan events can be seen as severe accidents with low probabilities but high consequences, either inherently difficult to predict or at least difficult to predict by a wide range of relevant actors.

Accidents and black-swan events both have negative connotations. However, although most unplanned events relevant to consider in LCA will likely lead to increased environmental impacts, unplanned events can sometimes also reduce impacts, thus having a positive effect. For example, while the sudden policy change discussed in Section 4.3 is prognosed to increase greenhouse gas emissions, sudden policy changes can also lead to emission reductions. This includes sudden prohibitions of fossil fuels and mandatory introduction of more environmentally benign technologies, such as electric vehicles. There could also be sudden introductions of safety measures in industry, reducing the probability of accidents. Additionally, exactly how "extreme" or "massive" an event must be to qualify as a black swan is unclear. To account for both positive and negative events and avoid the need to assess the severity of events a priori, we use the term "unplanned event" in this paper, which encompasses both accidents and black-swan events.

3 Method for including unplanned events in LCA

We suggest that the inclusion of unplanned events in LCA should depend on the goal of the study and what questions it intends to answer, and needs to be defined in the goal and scope, which is in line with the proposal by Finkbeiner et al. (2014). For example, if the goal of the study is to calculate the average impacts of a product system sensitive to accidents, then including impacts from accidents might be relevant, particularly when comparisons are made to product systems less sensitive to accidents. We also suggest that changes in product and elementary flows due to unplanned events should be considered at the unit-process level and thus treated in the same way as other flows in an inventory model, rather than considering unplanned events separately using risk matrices like in Aissani et al. (2012) and Ayoub et al. (2015). The changed flows then become included in the impact assessment calculations and their impacts can be compared to those of other flows in the life cycle.

In practice, we suggest two different ways of doing this. For unplanned events with historical frequency data, probabilistic calculations can be applied. A probability-weighted flow F_p can be estimated by multiplying the historical probability p of the unplanned event of the unit process with the flow F as shown in Eq. 1:

$$F_p = p \times F \quad (1)$$

For example, if a chemical factory operation has $p = 0.001$ probability for an accident emitting $F = 10^6$ kg of a chemical during its lifetime, then a flow F_p at $0.001 \times 10^6 = 1000$ kg of the chemical could be added to the unit process describing this operation. This approach is in line with Finkbeiner et al. (2014), who writes that the assessment of unplanned ("improbable") events requires the inclusion of a probability of deviating from the "standard case", i.e. the assessment of the system without the unplanned event. It also aligns with Simonson et al. (2005) who suggest using statistics, in their case for fires, to assess the probability of accidents.

In cases with no such historical data for the unplanned event (or similar events that can be used as proxies), scenarios presupposing that the unplanned event happens can be applied. This approach can be in line with the recommendation by the ILCD guidelines to consider unplanned events separately: by having one scenario without unplanned events and another scenario with unplanned events. The importance of including the unplanned event can then be assessed, as well as the influence if it actually happens. This also resonates with the proposal by Ciroth et al. (2021) to consider impacts from flows with low probability but high impact (such as radioactive emissions from nuclear power plants and oil leakages) in a sensitivity analysis.

In Section 4, three examples of unplanned events are provided to illustrate the two approaches described above.

4 Three cases of considering unplanned events

The first case is the (at least for most actors) unplanned sabotage in the energy system represented by the Nord Stream pipeline (cf. Section 4.1). The second case is unplanned accidents in the use phase, illustrated by a car door made from a structural battery composite (SBC) (cf. Section 4.2). The third case is a sudden, by many unplanned policy change (cf. Section 4.3). One of the cases illustrates the use of historical frequency data (the car door) and the other two cases illustrate scenarios presupposing the event happening (sabotage in the energy system and sudden policy change). For each of the cases, an example from the real world is provided, and the resulting changes in the flow chart and unit process compared to an LCA not including these unplanned events are shown.

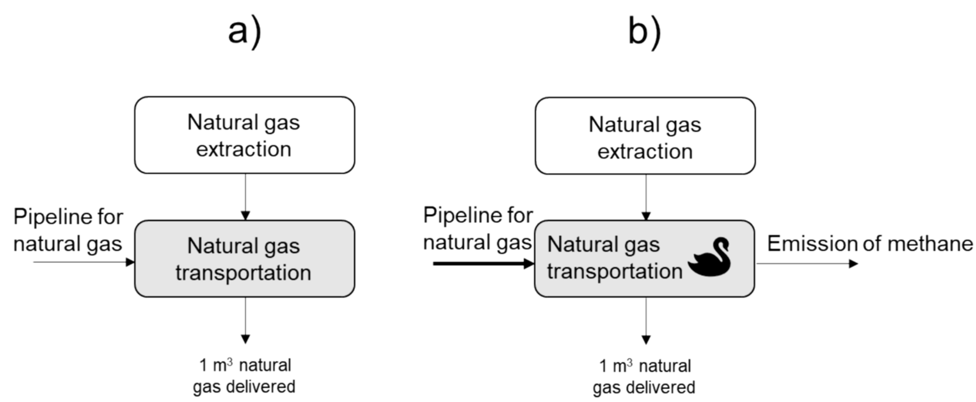

Fig. 2 Flowchart showing the production and delivery of natural gas to Germany **a** without the unplanned event and **b** with the Nord Stream sabotage, indicated by a black-swan symbol. Affected unit processes are shown in grey, and changes in input of capital goods (pipeline) by the thickness of the arrow

4.1 Sabotage in the energy system

Sabotage or other incidents can influence energy systems in various ways. An example is the Fukushima nuclear power plant accident in Japan in 2011, where a tsunami disabled three reactors' power supply and cooling, causing a nuclear accident (Perrow 2011). Another, even more recent, example is the sabotage by explosives of the Nord Stream pipelines in the Baltic Sea in 2022, leading to a massive release of natural gas (Kristensson 2022). In this section, we will use the latter as an example of how to construct a scenario with such an event and how that would influence the unit process of natural gas transportation to the German market.

The example considers the changes in unit-process flows for delivery of 1 m^3 of natural gas by the now-sabotaged Nord Stream 1 pipeline to Germany, which historically provided $27.5 \cdot 10^9$ m^3/year (Nord Stream 2023). In Fig. 2, the natural gas extraction and delivery to Germany are outlined for a scenario without the unplanned event and a scenario including the sabotage. The Nord Stream pipeline is not likely to be repaired (Soldatkin et al. 2023), so the de facto lifetime between its inauguration in 2011 and the sabotage in 2022 became 11 years. In comparison, a non-sabotaged natural gas pipeline has a typical design life of 50 years (Folga 2007). It is estimated that the Nord Stream sabotage released 250 kton of methane into the atmosphere (Benshof 2022). This release can be distributed over all natural gas delivered to Germany during the 11-year lifetime, resulting in $8.3 \cdot 10^{-4}$ kg methane/m^3 natural gas delivered. The capital goods for the pipeline can likewise be distributed over 11 instead of 50 years. Table 1 shows the magnitude of the methane emissions and capital goods at the unit-process level for the German market in a partial and modified unit process from Ecoinvent version 3.9 (called "natural gas, high pressure | natural gas, high pressure | Cutoff, U - DE"). As can be seen, the methane emissions in the sabotage scenario are in the same order of magnitude as all other methane emissions throughout the production and delivery of the natural gas, which otherwise mainly occur due to minor leakages. The total climate impact of the unit process in the scenario with the unplanned event thus becomes approximately doubled due to the inclusion of the methane emissions from the sabotage. Also, the impact related to capital goods increases more than four times due to the lower lifetime of the sabotaged pipeline.

4.2 Accidents in the use phase

Accidents that make products break or lose functionality have always happened—for some product types more often than for others. As products become increasingly complex and advanced, repairing damages from accidents in the use phase can become challenging. For example, the gluing of smartphone glass covers has made the exchange of

Table 1 Partial unit-process data table for producing and delivering 1 m^3 natural gas to Germany without the unplanned event and with the Nord Stream sabotage. Modified from the unit process "natural gas, high pressure | natural gas, high pressure | Cutoff, U - DE" from Ecoinvent 3.9 (Wernet et al. 2016)

Input flows	Amount, without unplanned event	Amount, with unplanned event	Unit
Natural gas	1.0	1.0	m^3
Pipeline for natural gas	$3.8 \cdot 10^{-8}$	$1.7 \cdot 10^{-7}$	km
Output flows	**Amount, without unplanned event**	**Amount, with unplanned event**	**Unit**
Natural gas, delivered to costumer	1.0	1.0	m^3
Methane, fossil, emission to air	$6.9 \cdot 10^{-4}$	$1.5 \cdot 10^{-3}$	kg

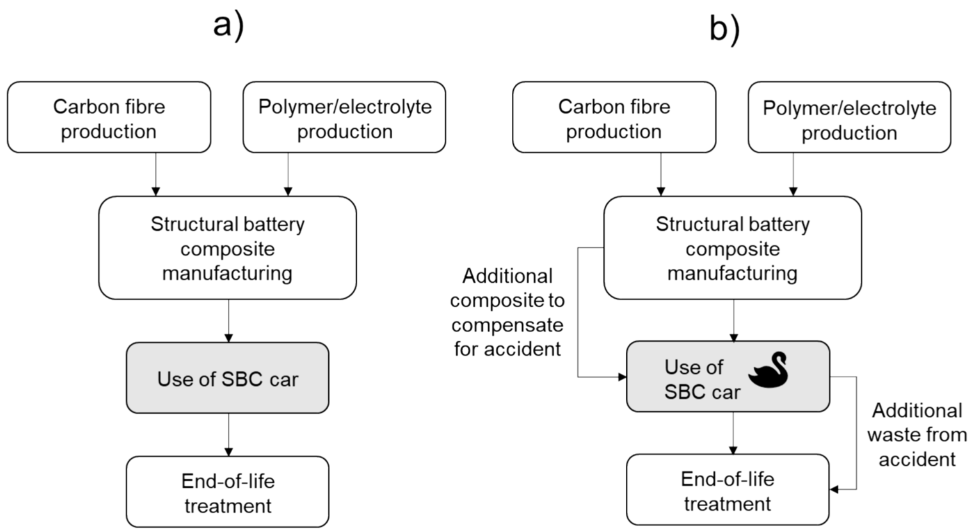

Fig. 3 Flowchart showing the use of structural battery composites (SBCs) in electric cars **a** without the unplanned event and **b** with an accident leading to SBC replacement, indicated by a black-swan symbol. Affected unit processes are shown in grey

broken screens difficult (Knight 2017). In this example, we consider a product not yet commercialized, for which comparisons with the incumbent technology are challenging because of differences in loss of functionality at accidents. The new product is part of a car door conventionally made from metal, but that could be replaced with a structural battery composite (SBC). SBCs are multifunctional carbon fibre composites that provide both mechanical integrity and energy storage (Asp et al. 2021). Compared to materials with only a structural function, such as metals, SBCs allow for a lower battery weight in electric cars, leading to energy savings in the use phase (Hermansson et al. 2023). A disadvantage with SBCs, however, is that the conduction and storage function could be compromised from a collision and they are challenging to repair if damaged (Ishfaq et al. 2023). They will, therefore, likely be replaced and discarded after a car accident to maintain the same multiple functions, whereas conventional metal car parts can be more easily repaired. This example illustrates how a built-in vulnerability can influence the environmental impact of products and thereby make comparisons challenging.

The example includes one accident during the lifetime of a car with four doors made partly from SBC, using data from Hermansson et al. (2023). We assume that there is a 30% chance of one car door being damaged (i.e. the probability p of the car door being damaged is 0.3), which is based on the probability of car damages calculated in Hermansson et al. (2023). The accident will likely require the replacement of the SBC part of the car door (weighing 1.5 kg, equal to F) to restore and maintain the car's function throughout the lifetime (a total of 200,000 km driven). Considering the probability factor and using Eq. 1, this results in $F_p = 0.3 \times 1.5 = 0.45$ kg additional material needed to compensate for the accident. The flow chart is shown in Fig. 3 and changes in the unit process are listed in Table 2. The accident requires more SBC to maintain the function of energy storage, which increases the environmental impact of the SBC car.

4.3 Sudden policy changes

Changes in the political landscape and subsequent policy changes can influence the environmental impact of products and services. Here, a wide range of changes can occur, potentially affecting the life cycle impacts of products and comparisons between them. We illustrate this with the example of how the unit process for driving 10 km in 2030 could change when adjusting the Swedish Greenhouse Gas Reduction Mandate after a shift in the political landscape. This legislation is a policy instrument implemented by the Swedish

Table 2 Partial unit process data table for the use phase of structural battery composites in an electric car, without the unplanned event and with an accident leading to replacement of a car door

Input flows	Amount, without unplanned event	Amount, with unplanned event	Unit
Replacement door	0	0.45	kg
Output flows	**Amount, without unplanned event**	**Amount, with unplanned event**	**Unit**
Driving distance	200,000	200,000	km
Waste, damaged parts	0	0.45	kg

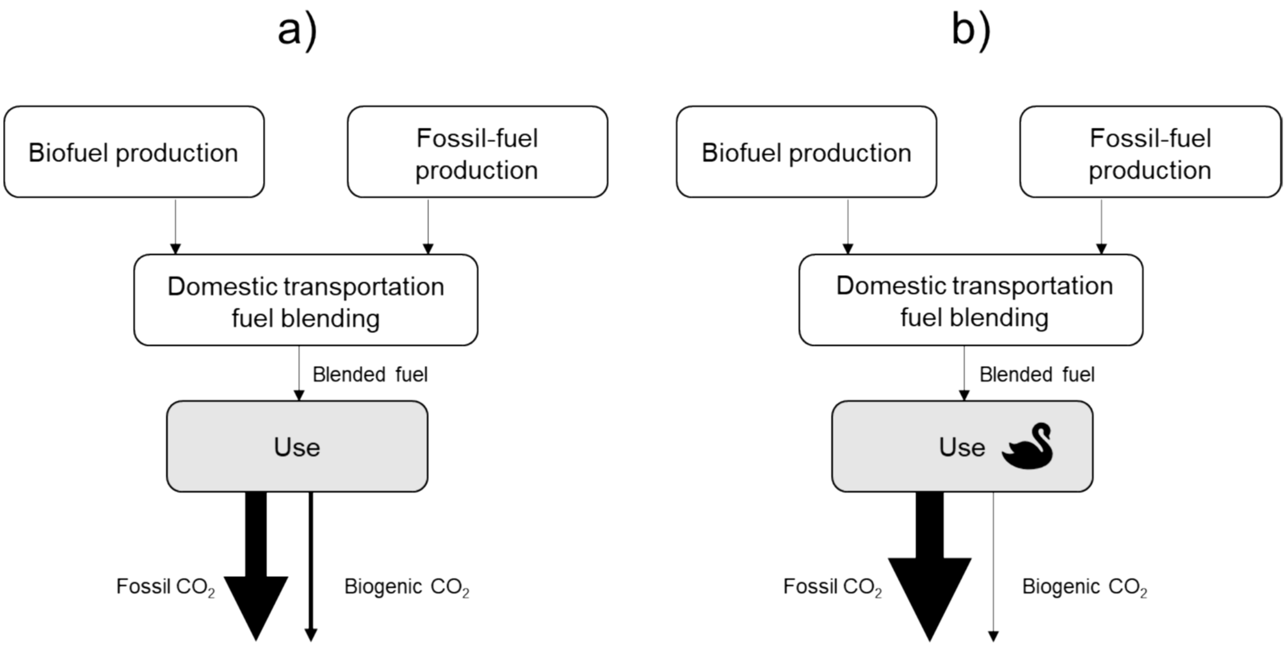

Fig. 4 Flowchart showing the well-to-wheel life cycle of gasoline used in Sweden **a** without the unplanned event and **b** after possible policy changes in the greenhouse gas reduction mandate, indicated by a black-swan symbol. Affected unit processes are shown in grey. The size of the carbon dioxide emission arrows indicates the relative size of the flows

government and stipulated by the European Renewable Energy Directive to encourage the use of biofuels (European Commission 2023). In essence, gasoline, diesel, and aviation fuel suppliers must reduce the greenhouse gas emissions from these fuels by a certain percentage each year by blending with biofuels. For gasoline, the blending level was 7.8% in 2023 and, if following the original plan, 28% in 2030. The purpose is to contribute to the national goal of decreasing greenhouse gas emissions from domestic transportation by 70% between 2010 and 2030 (Swedish Energy Agency 2023a). After the Swedish election in 2022, however, a new government was formed. The Greenhouse Gas Reduction Mandate was then up for discussion, and the Greenhouse Gas Reduction Mandate is now reduced to only require the blending of 6% biofuels into gasoline from 2024 (Swedish Energy Agency 2023b).

For simplicity, we assume that the biofuel mixed into the gasoline is 100% ethanol, while in reality, it might be many different biofuels or mixtures of them. We further assume, for simplicity, that the vehicle consumes 1.25 L/10 km of whatever fuel (in reality, this would differ depending on vehicle fuel economy) and that the density of both gasoline and ethanol is 0.8 kg/L. Further, it is assumed that 1 kg of conventional gasoline emits 3.3 kg of fossil carbon dioxide and 0 kg of biogenic carbon dioxide from the use phase, and that the combustion of 1 kg of ethanol emits 0 kg of fossil carbon dioxide and 1.9 kg of biogenic carbon dioxide (Engineering Toolbox 2009). We consider a fuel mixture of 28% ethanol and 72% gasoline given no change in the originally adopted policy (i.e. no unplanned event) and a scenario after the policy change where the fuel mixture is 6% ethanol and 94% gasoline. The changes to the life cycle are illustrated in Fig. 4, and the changes to the unit process

Table 3 Partial unit process data table for the combustion of fuel required for 10 km without the unplanned event and after policy changes in the greenhouse gas reduction mandate

Input flows	**Amount, without unplanned event**	**Amount, with unplanned event**	**Unit**
Gasoline	0.9	1.175	L
Ethanol	0.35	0.075	L
Output flows	**Amount, without unplanned event**	**Amount, with unplanned event**	**Unit**
Driving distance	10	10	km
Carbon dioxide, fossil	2.4	3.1	kg
Carbon dioxide, biogenic	0.5	0.1	kg

Table 4 Different types of unplanned events that can be included in LCA

Type of event	Example of event
Accidents in the use phase	• Traffic accidents • Product breakdowns
Industrial accidents	• Contamination • Flaring due to long emergency downtimes
Supply issues	• Raw material shortage • Contaminated raw materials
Policy changes	• Sudden prohibition • New taxes, leading to changed market conditions
Sabotage	• Terrorist attacks • Military conflict
Natural disasters	• Heavy rains • Earthquakes

are shown in Table 3. The total emission of carbon dioxide (i.e. fossil and biogenic) increases by approximately 0.3 kg per 10 km driven. However, if only considering the increase in fossil carbon dioxide emissions, the resulting value is approximately 0.7 kg fossil carbon dioxide per 10 km, or about 30%.

5 Concluding discussion

The three cases above illustrate that unplanned events can significantly affect LCA results. The high methane release from the Nord Stream pipeline might even be regarded as a black-swan event according to Taleb (2007) and Aven (2013), who restrict the term to "extreme" events with "massive impact". However, regardless of whether they are considered black swans, all three cases involve notable changes in flows: The Nord Stream sabotage involved a 100% increase in methane emissions, if allocating the impacts across the German natural gas market, the damaged car door led to almost 10% additional SBC input to the car doors to maintain its dual functionality, and the reduced greenhouse gas reduction mandate led to an approximately 30% increase in fossil carbon dioxide emissions per unit of fuel consumed. While these examples of unplanned events have a negative influence on the environmental impacts, an unplanned event could also have positive effects. One such example is a sudden policy change in the other direction. If, after the next Swedish election, the government would once again adopt the Greenhouse Gas Reduction Mandate, the sudden policy change would instead decrease the emission of fossil carbon dioxide—and if this is strengthened compared to the original plan to compensate for the lost time, this can be a change greater than 30%. Another way in which unplanned events could influence the results positively would be if suddenly safety measures were introduced for SBC cars, either for the cars themselves or in the surrounding traffic. The probability of an accident might then decrease from 30% to a lower value. Suggestions on other types of unplanned events that can be of importance to include in some LCAs are found in Table 4.

The cases also illustrate the two approaches outlined in Section 3, i.e. probabilistic calculations (for the use-phase accident) and scenarios (for the sabotage and sudden policy change). Regarding their implementation, the choice between the approaches does not necessarily depend so much on the case itself, but rather on whether historical frequency data is available. If frequency data is available or can be estimated, a probabilistic calculation can be performed according to Eq. 1 for the unit processes where the unplanned events can happen. Frequency statistics can sometimes be obtained from databases or other written sources, an example being the World Health Organization's data on road traffic mortality (see World Health Organization (2024)). Such data might need to be scaled to the reference flow of the unit process, e.g. 1 km driven in the case of personal transport. If no statistics about the unplanned event is available, probability estimations can sometimes be obtained from experts, e.g. in Delphi studies (see for example Svanström et al. (2017)), or with other techniques that involve stakeholder engagement to capture different types of knowledge and interests. If such procedures are not possible to perform, then specific scenarios that consider these events can be generated. Such scenarios could, for example, be informed by the established scenario typology by Börjeson et al. (2006), or be developed using the SIMPL approach for prospective scenario modelling (Langkau et al. 2023). Different scenarios can be employed to account for different unplanned events (and different magnitudes of their impacts) in an uncertainty analysis fashion.

The PAS 2050:2011 guidelines (British Standards Institute 2011) prescribe that if greenhouse gas emissions of a process increase by 10% for three subsequent months, a reassessment should be done. A reduced Greenhouse Gas Reduction Mandate would indeed last for more than

3 months and cause higher emission increases than 10%. In the Nord Stream example, the increase is much higher than 10%, but the actual release did not last for 3 months. This illustrates a potential problem with PAS 2050:2011; they exclude events that happen over short durations (typical for accidents) but nevertheless lead to considerable impacts. The ILCD guidelines' (2010) advice that accidents should not be included in LCA is also problematic considering their potentially high impacts. Somewhat contradictory, the ILCD guidelines also recommend that if unplanned events are to be included, these should be reported separately, which can be done by both approaches proposed in this study.

An important question regarding whether and how to include unplanned events in LCA is that of responsibility: Who should carry the burden of unplanned events? As illustrated by the three cases above, we live in a world where unplanned events with negative environmental impacts are abound. Indeed, Perrow (1999) points out that accidents are inherent to complex technical systems, to the extent that he refers to such accidents as "natural". Given this vulnerability of technical systems, we suggest that all users of technology must be prepared to carry the burden of unplanned events to some extent, collectively. By including unplanned events in unit processes, as in Tables 1, 2, and 3, the impacts become distributed over different product systems depending on their demand for the output of the unit process, which is in line with the idea of responsibility allocation in life cycle thinking where the functional outputs receive the burden of all activities throughout the life cycle. A similar discussion about the responsibility of the Nord Stream pipeline sabotage has taken place from the perspective of territorial emissions within EU's greenhouse gas emission reporting. The discussions were about whether Sweden and Denmark need to include the emissions from the sabotaged Nord Stream pipelines since they occurred in their economic zones. At the time of writing this paper, it had been decided that the emissions from the Nord Stream sabotage would not be included in Sweden's climate and air reports to the European Union and United Nations (Swedish Environmental Protection Agency 2024). However, no decision had been reached on who else (if anyone) should carry the burden of the emissions from the Nord Stream sabotage. In line with such territorial responsibility for unplanned events, also product-focused LCAs could include unplanned events potentially happening in the product system, which is what we suggest in this paper. LCAs can then guide towards a more resilient society where impacts from unplanned events become internalized rather than being external impacts that no one takes responsibility for.

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Author contribution Frida Hermansson: conceptualization, methodology, formal analysis, investigation, data curation, writing—original draft, visualization, project administration. Rickard Arvidsson: conceptualization, methodology, formal analysis, investigation, writing—original draft, visualization. Magdalena Svanström: conceptualization, methodology, writing—review and editing, funding acquisition, visualization, project administration.

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Data availability The data supporting this study's findings are provided in the article or the cited references within.

Declarations

Conflict of interest The authors declare no competing interests.

References

Aissani L, Jabouille F, Bourgois J, Rousseaux P (2012) A new methodology for risk evaluation taking into account the whole life cycle (LCRA): validation with case study. Process Saf Environ Prot 90(4):295–303. https://doi.org/10.1016/j.psep.2011.10.003

Ale BJM, Hartford DND, Slater DH (2020) Dragons, black swans and decisions. Environ Res 183:109127. https://doi.org/10.1016/j.envres.2020.109127

Asp LE, Bouton K, Carlstedt D, Duan S, Harnden R, Johannisson W, ... Liu F (2021) A structural battery and its multifunctional performance. Adv Energy Sustain Res 2(3):2000093. https://doi.org/10.1002/aesr.202000093

Aven T (2013) On the meaning of a black swan in a risk context. Saf Sci 57:44–51. https://doi.org/10.1016/j.ssci.2013.01.016

Aven T (2015) Implications of black swans to the foundations and practice of risk assessment and management. Reliab Eng Syst Saf 134:83–91. https://doi.org/10.1016/j.ress.2014.10.004

Ayoub N, Musharavati F, Pokharel S, Gabbar HA (2015) Risk based life cycle assessment conceptual framework for energy supply systems in large buildings. J Clean Prod 107:291–309. https://doi.org/10.1016/j.jclepro.2015.04.075

Benshof L (2022) The Nord Stream pipelines have stopped leaking. But the methane emitted broke records. Retrieved from https://www.npr.org/2022/10/04/1126562195/the-nord-stream-pipelines-have-stopped-leaking-but-the-methane-emitted-broke-rec

Börjeson L, Höjer M, Dreborg K-H, Ekvall T, Finnveden G (2006) Scenario types and techniques: towards a user's guide. Futures 38(7):723–739. https://doi.org/10.1016/j.futures.2005.12.002

British Standards Institute (2011) PAS 2050:2011-Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. Retrieved from https://shop.bsigroup.com/products/specification-for-the-assessment-of-the-life-cycle-greenhouse-gas-emissions-of-goods-and-services

Cambridge Advanced Learner's Dictionary and Thesaurus. Accident. Retrieved from https://dictionary.cambridge.org/dictionary/english/accident

Ciroth A, Recanati F, Arvidsson (2021) Principles of life cycle inventory modeling: the basic model, extensions, and conventions. Life Cycle Inventory Analysis: Methods and Data 15–51

Engineering Toolbox (2009) Combustion of fuels - carbon dioxide emission. Retrieved from https://www.engineeringtoolbox.com/co2-emission-fuels-d_1085.html

European Commission (2023) Renewable energy directive. Retrieved from https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-directive_en

European Commission's Joint Research Centre (2010) *International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidence* (First, edition. Publications Office of the European Union, Luxembourg

European Commission's Joint Research Center (2010) *I*LCD Handbook-General guide for life cycle assessment-detailed guidance. Publications Office of the European Union

Finkbeiner M, Ackermann R, Bach V, Berger M, Brankatschk G, Chang Y-J, . . . Wolf K (2014) Challenges in life cycle assessment: an overview of current gaps and research needs. In W. Klöpffer (Ed.), Background and future prospects in life cycle assessment (pp. 207–258). Dordrecht: Springer Netherlands.

Folga SM (2007) Natural gas pipeline technology overview. Retrieved from https://publications.anl.gov/anlpubs/2008/02/61034.pdf

Fries N, Hellweg S (2014) LCA of land-based freight transportation: facilitating practical application and including accidents in LCIA. The International Journal of Life Cycle Assessment 19(3):546–557. https://doi.org/10.1007/s11367-013-0657-2

Hermansson F, Edgren F, Xu J, Asp LE, Janssen M, Svanström M (2023) Climate impact and energy use of structural battery composites in electrical vehicles—a comparative prospective life cycle assessment. The International Journal of Life Cycle Assessment 28:1366–1381. https://doi.org/10.1007/s11367-023-02202-9

International Organization for Standardization (2006) Environmental management-Life cycle assessment-requirements and guidelines (ISO 14044). Retrieved from https://www.iso.org/obp/ui/#iso:std:iso:14044:ed-1:v1:en

Ishfaq A, Nguyen SN, Greenhalgh ES, Shaffer MS, Kucernak AR, Asp LE, ... Linde P (2023) Multifunctional design, feasibility and requirements for structural power composites in future electric air taxis. J Compos Mater 57(4):817–827. https://doi.org/10.1177/00219983221132621

Khakzad S, Khan F, Abbassi R, Khakzad N (2017) Accident risk-based life cycle assessment methodology for green and safe fuel selection. Process Saf Environ Prot 109:268–287. https://doi.org/10.1016/j.psep.2017.04.005

Knight S (2017) 10 tech products that are next to impossible to repair. Retrieved from https://www.techspot.com/article/1548-unrepairable-tech-devices/

Kristensson J (2022) Det här vet vi om Nord Stream-läckorna i Östersjön. *NyTeknik*. Retrieved from https://www.nyteknik.se/energi/det-har-vet-vi-om-nord-stream-lackorna-i-ostersjon/117904

Langkau S, Steubing B, Mutel C, Ajie MP, Erdmann L, Voglhuber-Slavinsky A, Janssen M (2023) A stepwise approach for Scenario-based Inventory Modelling for Prospective LCA (SIMPL). The International Journal of Life Cycle Assessment 28(9):1169–1193. https://doi.org/10.1007/s11367-023-02175-9

Luft J, Ingham H (1961) The johari window. Human Relations Training News 5(1):6–7

Nord Stream (2023) Operations. Retrieved from https://www.nord-stream.com/operations/

Perrow C (1999) Normal accidents: living with high-risk technologies. Princeton University Press, Princeton, New Jersey

Perrow C (2011) Fukushima and the inevitability of accidents. Bull at Sci 67(6):44–52. https://doi.org/10.1177/0096340211426395

Sadiq R, Khan FI (2006) An integrated approach for risk-based life cycle assessment and multi-criteria decision-making: selection, design and evaluation of cleaner and greener processes. Bus Process Manag J. https://doi.org/10.1108/14637150610710927

Sauve G, Van Acker K (2021) Integrating life cycle assessment (LCA) and quantitative risk assessment (QRA) to address model uncertainties: defining a landfill reference case under varying environmental and engineering conditions. Int J Life Cycle Assess 26(3):591–603. https://doi.org/10.1007/s11367-020-01848-z

Simonson M, Andersson P, Blomqvist P, Stripple H (2005) Environmental assessment of fires in products using the Fire-LCA model. Fire Safety Science 8:1071–1082

Soldatkin V, Astakhova O, Steitz C (2023) Exclusive: Russia set to mothball damaged Nord Stream gas pipelines - sources. Retrieved from https://www.reuters.com/business/energy/russia-set-mothball-damaged-nord-stream-gas-pipelines-sources-2023-03-03/

Svanström M, Heimersson S, Ekvall T (2017) Generating LCA partitioning factors for sewage sludge management using a Delphi procedure. Paper presented at the Proceedings of the 12th Conference on Sustainable Development of Energy, Water, and Environment Systems, SDEWES2017

Swedish Energy Agency (2023a). Greenhouse gas reduction mandate. Retrieved from https://www.energimyndigheten.se/en/sustainability/sustainable-fuels/greenhouse-gas-reduction-mandate/

Swedish Energy Agency (2023b). Reduktionsplikt. Retrieved from https://www.energimyndigheten.se/fornybart/hallbarhetskriterier/reduktionsplikt/

Swedish Environmental Protection Agency (2024) Ny bedömning - utsläpp från Nord Stream ska inte ingå i Sveriges rapportering. Retrieved from https://www.naturvardsverket.se/om-oss/aktuellt/nyheter-och-pressmeddelanden/2024/januari/ny-bedomning-utslapp-fran-nord-stream-ska-inte-inga-i-sveriges-rapportering/

Taleb NN (2007) The black swan: the impact of the highly improbable 2. Random house

Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E, Weidema B (2016) The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment 21(9):1218–1230. https://doi.org/10.1007/s11367-016-1087-8

World Health Organization (2024) Estimated road traffic deatch rate (per 100 000 population). Retrieved from https://www.who.int/data/gho/data/indicators/indicator-details/GHO/estimated-road-traffic-death-rate-(per-100-000-population)

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