Environmental Life Cycle Assessment of a Surface Radar System

Master's thesis in Industrial Ecology

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Abstract

This study was undertaken with the primary objective to assess the environmental impacts of a surface radar system called Arthur by applying environmental life cycle assessment (LCA). The project was initiated and spearheaded by Saab AB, the proprietor of the system. In addition to assessing its environmental impact, the project was geared towards enabling Saab AB to acquire an understanding of the LCA methodology and to determine its usefulness in their present context.

The LCA was conducted following the guidelines in ISO14040. Data on the foreground system was mainly obtained from the collaboration with Saab AB, and the Ecoinvent database was utilised for obtaining data on the background system. To evaluate the potential environmental impacts, the ReCiPe method was employed, with particular emphasis on four impact categories: climate change, fossil fuel, terrestrial acidification, and surplus ore. The first three were selected for the purpose of facilitating a comparison with a previous LCA study conducted in 2015. Furthermore, an additional impact indicator for mineral resource scarcity, the crustal scarcity indicator, was applied to complement the surplus ore indicator.

The results showed that the highest impacts occurred during the use phase, primarily due to the combustion of diesel fuel in the vehicle. Considering this finding, an alternative fuel, fatty acid methyl ester (FAME), was also assessed. Using FAME led to a reduction in, e.g., climate change, but there was a trade-off with other impact categories, such as terrestrial acidification. The results also showed that the two components main computer and cable set have the highest potential for reducing environmental impacts, and should therefore be given the highest priority for improvement efforts. Comparing the results with those of the previously-conducted LCA on the same product system in 2015 revealed lower overall impact results in the present study. However, this does not necessarily entail a reduction in actual environmental impacts, as variations in the methodology and data could instead be the reasons.

Finally, it is recommended that the collaborating company Saab AB would benefit from establishing a more comprehensive database within the organisation to improve the reliability of LCA results and reduce the time required for data collection in future LCA projects.

Keywords: life cycle assessment, surface radar system, climate change, fossil fuel, terrestrial acidification, mineral resource scarcity, ISO14040, ReCiPe, Ecoinvent

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Mimmi Johansson and Frida Schmidt, Gothenburg, June 2023

Table of Contents

Abbreviations

AC/DC = Alternating current/direct current

BoM = Bill of materials

EoL = End of life

ECHA = The European Chemicals Agency

FAME = Fatty acid methyl esters

GHG = Greenhouse gas

IFS = Industrial and Financial Systems

ISTAR = Intelligence, Surveillance, Target Acquisition, and Reconnaissance

LCA = Life cycle assessment

LCIA = Life cycle impact assessment

LCU = Liquid cooling unit

SDG = Sustainable development goal

SOP = Surplus ore potential

SVHC = Substances of very high concern

TWT = Travelling wave tube

WLS = Weapon locating system

1. Introduction

This section provides an introductory overview of environmental sustainability and assessment. It proceeds to present the industry considered, the collaborating company, and the product studied, while also detailing the aim of the thesis and outlining the associated research questions.

1.1 Environmental sustainability and assessment

The degradation of natural resources, the acceleration of climate change, the loss of biodiversity, and the proliferation of pollution are happening at a pace that cannot be sustained (Steffen et al., 2015). A new paradigm is urgently needed to harmonise the development of human societies with the resilience of the Earth's system. The current trajectory of unsustainable practices necessitates a transformative shift that integrates sustainable development principles, recognises planetary boundaries, and fosters a symbiotic relationship between human societies and the environment. This shift requires enhancing the environmental efficiency of products across their life cycle while promoting a shift in consumer behaviour towards sustainable consumption practices.

As awareness of the impact of production and use of products on the climate continues to increase globally, the ability to quantitatively assess a product's environmental footprint throughout its life cycle becomes increasingly significant (Hellweg & Milà i Canals, 2014). There are various methods and tools to promote the development of more environmentally friendly products, of which life cycle assessment (LCA) is the most established and well-developed (Ness et al., 2007). Since the 1980s, LCA has been applied in different forms to assess the environmental impacts of a product or service across its entire life cycle (Guinée et al., 2011).

1.2 The industry, collaborating company and product studied

The product studied in this thesis belongs to the aerospace and defence industry. This industry involves the production of aircraft, space vehicles, engines, and parts, as well as maintenance and repair services (Statista, n.d.). The industry has two segments: commercial and defence aerospace. The United States, France, and Germany are major markets for aerospace products, with the United States leading in sales value. Military aircraft are expected to drive the defence industry's growth, with growth areas including ISTAR (Intelligence, Surveillance, Target Acquisition, and Reconnaissance), cybersecurity, and drones.

The collaborating company within this industry is Saab AB, which was founded in 1937 to develop Sweden's defence capabilities, following a decision by the Swedish government (Saab AB, 2016). Initially, the business was primarily oriented towards military aircraft, with its only customer being the Swedish Air Force. Today, Saab AB provides products, services, and solutions to the global market, encompassing both military defence and civil security. As a company operating in the defence and security sector, Saab AB has obligations to various governments, including the Swedish Government (Saab AB, 2016). The industry in which the company operates is heavily regulated, and it is imperative for the company to abide by necessary authorizations, licences, and conditions to maintain its status as a trustworthy organisation.

The product assessed in this study is a surface radar system called Arthur (Figure 1.1). Arthur is a weapon locating system (WLS), used for detecting and tracking multiple enemy artillery rounds simultaneously, along with calculating the location from which the target originated, and setting the coordinates for counter-fire (Saab AB, n.d.). The term ‘radar’ is an acronym for ‘radio detection and ranging’ and refers to the utilisation of radio waves for detecting an object and determining its range. The basic principle of radar involves emitting an electromagnetic wave, which reflects off a target and returns as an echo. The time elapsed between the transmission and reception of the wave allows for the calculation of the object's distance. The difference in frequency between the transmitted and received signal can be used to determine the speed of the target. In military applications, radar systems are used for a multitude of purposes, including wide-area surveillance, fire control, artillery location, weather observation, navigation, target identification, and tracking.

Figure 1.1: Photo of Arthur on a vehicle. Obtained from the collaborating company with permission.

1.3 Defence industry and sustainability

There exist several interconnections between sustainability and defence (AeroSpace and Defence Industries Association of Europe, 2021). Defence can improve security, and security can contribute to peace. Peace is reflected in the Sustainable Development Goal (SDG) 16 – peace, justice, and strong institutions. In Saab AB's sustainability strategy, their contribution to the United Nations SDGs is reflected, and those where the company has the greatest impact are identified (Saab AB, n.d). That mapping suggests that Saab AB mainly influences SDG 3, 4, 5, 8, 13, 16, and 17, shown in Figure 1.2. The present study contributes additionally to SDG 13 (climate action), but also to two other environmentally related SDGs (14 – life below water, and 15 – life on land), since these are related to the impact categories examined in this thesis, which include climate change and acidification.

Figure 1.2: SDG 3, 4, 5, 8, 13, 14, 15, 16 and 17.

Saab AB, as outlined in their Code of Conduct, aims at promoting sustainable development through the mitigation of their environmental footprint and the reduction of associated risks (Saab AB, 2016). Given that a significant proportion of the systems and products developed by Saab AB consist of components and subsystems produced by subcontractors, the company's approach to addressing environmental concerns is reflected in the guidelines and requirements implemented within its procurement processes.

Saab AB also participates in several different organisations and sustainability initiatives, one of which is the business ethics committee of the Aerospace and Defense Industries Association of Europe (ASD). Important ethical aspects for Saab AB include preventing corruption and bribery, which is especially vital for a company in the defence industry (Gyllengahm, n.d.). This is prevented through, for instance, rules and processes, conducting risk analyses, and strict hiring processes. Furthermore, deciding which countries and customers are ethically appropriate to export to is a challenging issue that Saab AB together with the Inspection for Strategic Products (ISP) authority have responsibility for.

The United Kingdom's Ministry of Defence reports that half of the governmental greenhouse gas (GHG) emissions are connected to defence (Salerno-Garthwaite, 2022). Both the United Kingdom's Ministry of Defence and the United States' Department of Defence support the ambition to reach net-zero emissions by 2050, and NATO has pledged to a Climate Change and Security Agenda (Dimitrova et al., 2021). The defence industry is thus responding to pressure from regulators, customers, investors, and the public to address the issue of climate change. However, the defence industry is still relatively early regarding the reduction of its carbon footprint compared to other sectors. If no actions are taken, the industry could stand for 25% of the world's carbon dioxide emissions by 2050 (Dimitrova et al., 2021). Furthermore, the defence industry's efforts are mainly directed towards reducing emissions arising from their own operations and manufacturing, as well as through energy consumption. These only account for approximately 5-10% of the defence industry's emissions. The industry is still in the early stages of addressing emissions generated indirectly through the upstream supply chain and downstream usage of products by customers, which on average account for over 90% of the defence industry´s emissions (Dimitrova et al., 2021).

An increasing demand for LCA has arisen among the customers of the defence industry, which stresses the strategic importance of implementing the method (Dimitrova et al., 2021). Few LCA studies of defence products and other military products have been performed. A notable exception is the LCA of a hand grenade performed by Hochschorner et al., (2006), standing out as one of few projects studying the life cycle of military materiel. The results showed that a warlike use phase scenario was the most environmentally burdensome process, where metals and other non-renewable resources largely contributed to the impact.

1.4 Aim and research questions

The aim of this thesis is to assess the environmental impacts of the surface radar system Arthur. The study considers a cradle-to-grave system, meaning that all steps in the product's life cycle from the extraction of raw material over production and use to end of life (EoL) are included. The study applies LCA as the method, and a comparison is made to the results from a previous LCA study on the same system conducted eight years ago (Gustafsson & Rönnblom, 2015). The main audience for this study is the collaborating company, which can use the results and methodological description provided to improve the environmental performance of their products. Additional audiences are researchers and organisations interested in LCA of defence products, as well as individuals generally interested in sustainability.

The following specific research questions are addressed in the project:

Research question 1: What are the environmental impacts of the radar system?

Research question 2: Which steps of the product's life cycle have the highest impacts?

Research question 3: Which components of the system have the highest impacts?

Research question 4: Are the impacts different compared to those of the previously conducted LCA study and, if so, why?

2. Life cycle assessment method

In this section, the method chosen for conducting the project is presented. The section further explains and justifies the application of these methods and the rationale behind their selection, supported by relevant academic literature. Figure 2.1 illustrates the LCA framework outlined in the ISO 14040 standard and applied in this study, which includes the four steps (i) goal and scope definition, (ii) inventory analysis, (iii) impact assessment, and (iv) interpretation in an iterative manner (ISO, 2006). To answer the research questions of the study, an LCA is a suitable choice as it is the most established method used for assessing the environmental burden of products (Ness et al., 2007). The method is under continuous development but has been used since the 1980s (Finnveden et al., 2009). The ISO standard established to harmonise the LCA method is used as guidance when applicable (ISO, 2006). For the practical implementation of the LCA, the software OpenLCA (GreenDelta, version 1.11.0) is used together with the database Ecoinvent (version 9.3.1).

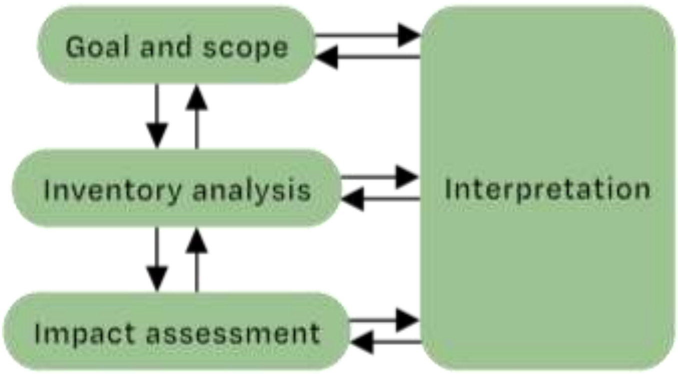

Figure 2.1: The LCA framework. The author's own image based on ISO (2006).

2.1 Goal and scope definition

When defining the goal, it needs to be clarified why the LCA is done, who the audience is, and what the product is (Baumann & Tillman, 2004). In the scope definition, the functional unit is defined, along with what type of LCA has been chosen (e.g., attributional or consequential). The system boundaries should be described together with the impact categories chosen for the study. An initial flowchart should be drawn, and the technical system of the product should be described. If multifunctionality occurs in the product system, the method to solve this should also be described, e.g., partitioning, system expansion or a higher level of modelling detail, where partitioning is often preferred in attributional LCA (Guinée et al., 2021).

2.2 Life cycle inventory analysis

An inventory analysis often contains the three steps: (i) constructing a more detailed flowchart, (ii) gathering data, and (iii) conducting life-cycle inventory calculations (Arvidsson et al., 2021). Departing from the initial flowchart in the goal and scope definition, a more detailed flowchart is initially derived. Environmentally relevant data for all activities in the system is then collected, including material and energy requirements as well as emissions. Finally, all flows are related to the functional unit and a life-cycle inventory table with elementary flows is calculated.

2.3 Life cycle impact assessment

The impact assessment contains a classification, meaning that all the results from the inventory table are assigned to the appropriate impact category (Baumann & Tillman, 2004). A characterization is then conducted to determine how much an inventory flow contributes to its assigned impact category. Here, the contribution of each classified inventory result is quantified, which tells how high the environmental burden is for this specific elementary flow. Ready-made impact assessment methods, such as ReCiPe 2016 and IMPACT World+, can be utilised in the impact assessment, in which the classification and characterization steps have already been performed (Huijbregts et al., 2017; Bulle et al., 2019).

These are the mandatory steps of an impact assessment according to ISO 14040 (Baumann & Tillman, 2004). However, to put the results into perspective, normalisation is sometimes used, which means relating the LCIA results to a common reference unit (Pizzol et al., 2017). This helps to interpret and communicate the outcome. Weighting is another approach that could be used subsequently to further support interpretation, communication, and highlight trade-offs. However, according to ISO14040, weighting is not allowed if the product is to be compared to competing products, as this method includes value judgement (ISO, 2006).

2.4 Interpretation

In the last step in the LCA framework, the results are presented and interpreted (Baumann & Tillman, 2004). The impact assessment is evaluated, and significant issues are identified. To present the results, approaches such as dominance analysis, break-even analysis, and contribution analysis can be applied, depending on the goal of the study. To test the robustness of the results, methods such as an uncertainty analysis and sensitivity analysis can be applied. Last, to gain credibility and accuracy, a critical review or data quality analysis can be performed by experts.

3. Goal and scope definition

In this section, the goal of this study is presented. Furthermore, the function unit, type of LCA chosen, impact categories, and system boundaries are described.

3.1 Goal definition

The goal of this study is to fulfil the aim and answer the research questions presented in Section 1.4 above.

3.2 Type of LCA

A conventional attributional LCA is carried out, where conventionally implies that an already existing technology is examined, and the system is modelled at a current or proximate time (Baumann & Tillman, 2004). An attributional LCA considers the environmental loads related to the flows to and from a system's life cycle, and answers the question of what impacts the system is accountable for (Finnveden et al., 2009).

3.3 Functional unit

The functional unit in the present LCA is one unit of Saab AB's mobile surface radar system, Arthur. It should be noted that the radar system itself is not inherently mobile, but gains mobility when mounted onto a vehicle. In this study, a medium-duty truck is considered. The life cycle of the vehicle, however, is not included in this study, except for the environmental impacts arising from the vehicle's operation. The functional unit is defined as the use of one Arthur unit for 20 years. The operational lifetime of the radar system is assumed to be 20 years, during which an average of 20 000 km/year of vehicle operation and 1000 hours/year of radar operation are required to fulfil the system's function.

3.4 Impact categories

The ReCiPe 2016 midpoint method (with a hierarchist perspective) is used to calculate the impacts of all 18 impact categories covered in that method (Huijbregts, 2017), relying on the implementation of the method by the Ecoinvent database (version 3.9.1). In addition, the mineral resource impact assessment method called the crustal scarcity indicator (CSI)

(Arvidsson et al., 2020) has been applied as a complement, since it captures the long-term depletion impacts of mineral resources. Again, we rely on the implementation of the method by the Ecoinvent database (version 3.9.1), which in turn is based on Arvidsson et al. (2020). All these 19 midpoint impact categories were considered (18 from ReCiPe + 1 CSI), but the four categories listed in Table 3.1 have been chosen for detailed analysis, while the rest are presented in Appendix D. The four selected impact categories are climate change, fossil fuel, acidification, and surplus ore, representing two resource-based categories and two emissions-based categories. The first three are chosen to increase comparability, as these were the categories chosen in LCA2015. Surplus ore was then added as a fourth category as it is an important category for products with a high content of (rare) metals.

Table 3.1: Chosen impact categories.

Impact category	**Characterization factor**	**Unit**	**LCIA method**
Climate change	Global warming potential (GWP100)	kg CO_2-eq	ReCiPe midpoint (H)
Fossil fuel	Fossil fuel depletion (FFP)	kg oil-eq	ReCiPe midpoint (H)
Surplus ore	Surplus ore potential (SOP)	kg Cu-eq	ReCiPe midpoint (H)
Acidification	Terrestrial acidification potential (TAP)	kg SO_2-eq	ReCiPe midpoint (H)

3.5 System boundaries

Defining the system boundaries is a crucial aspect of conducting an LCA since it establishes the scope of the analysis and determines which stages of the life cycle that are included (Tillman et al., 1994). The present section defined the system boundaries for this study, encompassing natural system boundaries, geographical boundaries, time horizons, and technical system boundaries.

3.5.1 System under study

The foreground system consists of assembly, verification and testing, as well as use and maintenance. These are the steps within the collaborating company's immediate sphere of influence and mostly product-specific data has been gathered for these steps. The maintenance includes replacing used components with new components. The background system includes material production and processing, transport, and EoL. Market averages are used for material production and processing, which thus include the input of both primary and secondary materials. Material production involves the extraction of raw materials. The EoL scenario chosen for this study is a combination of incineration and open-loop recycling, where the latter takes place outside of the system boundaries of the studied product as per the cut-off approach to open-loop recycling (Ekvall & Tillman, 1997). A flowchart showing the system under study is presented in Figure 3.1.

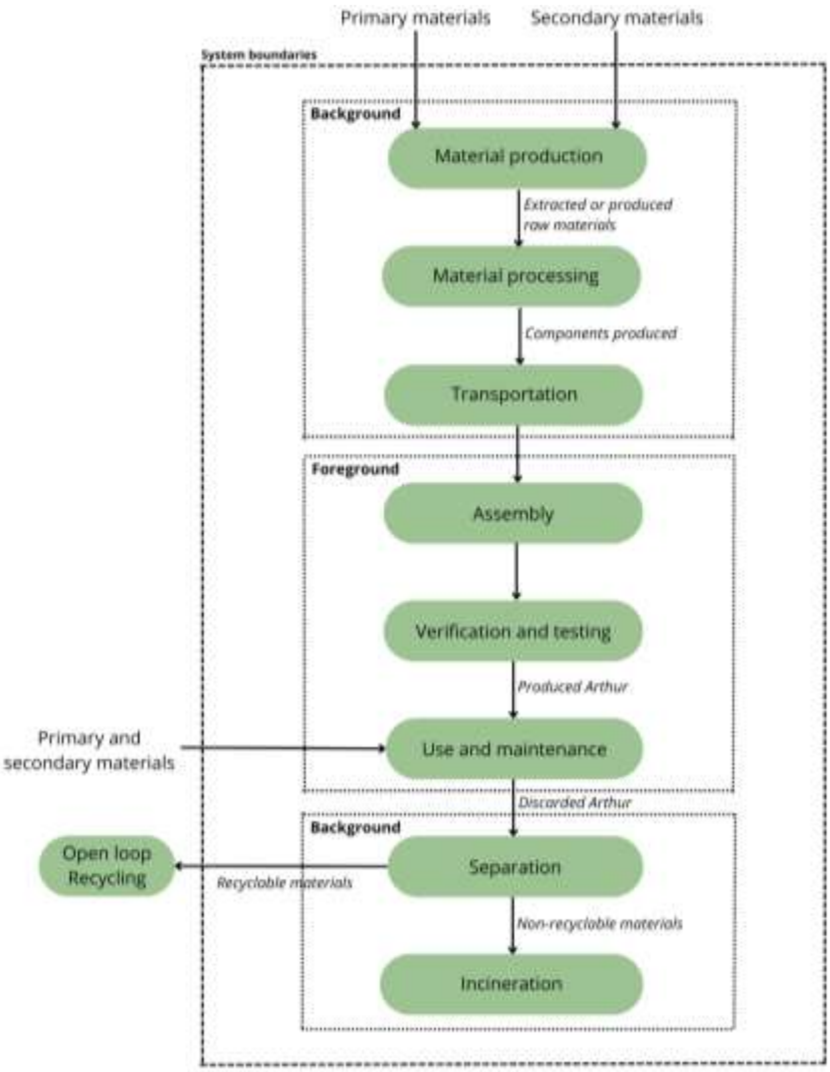

Figure 3.1: Flowchart describing the studied product system. The author's own image.

3.5.2 Geographical boundaries

In this study, material production and processing, as well as the EoL stage are assumed to happen in a global geographical context, which is why they are modelled by market datasets with an average global coverage. The assembly and testing stages are located in Gothenburg, while the use and maintenance stage is also assumed to occur globally. The transports involve moving the components from the material production sites to the assembly in Gothenburg, as well as from Gothenburg to customers. However, both the material production and processing sites as well as customer locations vary and are therefore unknown. In order to enable a modelling of transport impacts, a central location in Europe is thus assumed as both component production and customer site: the city of Kassel in Germany. While neither all production sites nor all of Saab AB's customers are located in Kassel, it constitutes a reasonable average for material production and processing as well as customer locations within Europe.

3.5.3 Temporal boundaries

This is a current LCA, meaning that the product system modelled reflects the product at approximately the current time (Arvidsson et al., 2018). To ensure the temporal accuracy of the data utilised in the LCA, it is important to gather data from a year close to when the product was produced. The most recent production of the studied type of radar system was in 2017, as large defence products such as Arthur are normally not mass produced but custom-made as per customer demand. The origin of the collected internal data from the collaborative company varies between the years 2015-2023, as some data originates from the first production in 2015 of this specific radar system, and some data originates from meetings with experts at the company during spring 2023. The product studied is relatively long-lived with a lifespan of 20 years, but no consideration of future use and EoL (e.g., in 20 years) was done in this study. Additionally, the impact assessment has a 100-year time frame according to ReCiPe's hierarchist perspective, which is an often-employed middle-ground scenario reflecting a level of evidence considered acceptable by international bodies (Huijbregts, 2017).

3.5.4 Boundaries within the technical system

The vehicle on which the radar system is mounted is only included when calculating impacts from fuel combustion in the use phase, however, the production and EoL of that vehicle is not included. Furthermore, due to time-constraints, some components in the radar system are omitted. These excluded components encompass customised components that customers typically install themselves, thereby presenting a challenge to influence in the design. The total weight of an Arthur radar system is 4495 kg, but only 3564 kg of that weight is accounted for in the composition. However, in the assembly, use phase, and transport steps, the whole weight is accounted for, but not in the remaining processes in the life cycle. It is important to note that the eleven components (presented in Section 4.1) included in the analysis are assigned their accurate weights. Consequently, the remaining quantity comprises additional components that, as decided by experts at Saab AB, are mainly customised components and thus not possible for the company to influence.

During the lifespan of an Arthur, a number of components are in need of maintenance. This is executed by either repairing the existing components or replacing them with new components. As it is assumed that reparation of an original component is done mainly through manpower, which is not accounted for in this project, only the replacement by new components are included in the assessment. Moreover, the energy required to replace a component is not accounted for. Finally, capital goods for manufacturing are not considered within the system boundaries.

3.6 Allocation

In the EoL step of the life cycle, the dismantling and separation of an Arthur results in multiple outputs of recyclable materials, which are assumed to undergo open-loop recycling. Allocation of recycling impacts between product life cycles is consequently necessary, for which the cut-off approach is chosen. Cut-off allocation attributes the environmental burden directly caused by a system to that system (Ekvall & Tillman, 1997), meaning in this case that Arthur is not considered responsible for the further recycling processes that produce recycled materials used in other products. The product consequently does not receive any credit for these materials, but instead benefits from recycled contents in upstream market processes in Ecoinvent. Cut-off is a well-established method and easy to use as no data from outside the system is needed (Ekvall et al., 2020). As no byproducts are generated in the foreground system, no conventional allocation method for byproducts is required.

3.7 Comparison

In 2015, a thesis project similar to this was carried out, where an LCA was performed on Arthur (Gustafsson & Rönnblom, 2015). The present study includes a comparison to that previous LCA. However, the modelling choices are not entirely replicated as some methodological updates and improvements have happened since the previous LCA (e.g., a new version of the impact assessment ReCiPe was released), and other methodological choices were considered more suitable. Additionally, the previous LCA was partly challenging to decipher. Throughout the thesis, the previously conducted LCA is referred to as 'LCA2015', while the current LCA is referred to as 'LCA2023'. Section 7.2 discusses the comparative analysis of the total impact and individual life cycle phases of the selected impact categories between LCA2015 and LCA2023.

4. Inventory analysis

This section includes a technical description and flowchart of the system, along with a presentation of the collected data and inventory calculations.

4.1 Technical description

Figure 4.1 presents a structure diagram to illustrate the composition of Arthur.

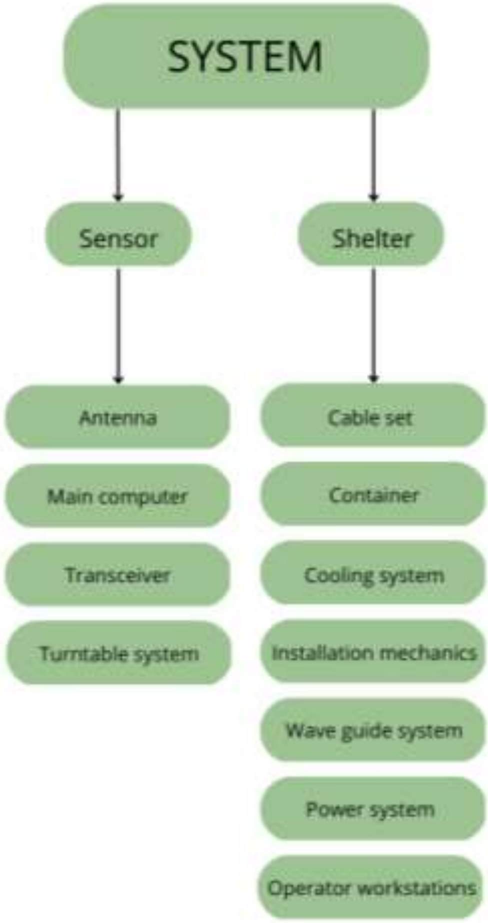

Figure 4.1: Structure diagram showing the composition of Arthur. The author's own image.

Below, each of the sensor components are described.

Antenna - The antenna is mounted on top of the container. It is a phased array antenna, meaning that it is possible to change the direction and shape of radiated signals without moving the antenna.

Main computer - Consists of signal and data processing units, where main signal processing functions include sensor control and sequencer, tracking channel, and search channel. The primary data processing functions are tracking and track correlation, target classification and group target formation, trajectory estimation and impact point calculation, as well as call for fire processing.

Transceiver - The transceiver can both transmit and receive radio waves with the antenna, where the transmitter uses a travelling wave tube (TWT) to amplify radio frequency signals in the microwave range. Control and supervision of the transmitter is executed with the help of a processor.

Turntable system - The system on which the antenna is installed, enabling turning of the antenna around the x and y axes. It includes a locking beam for locking the antenna in a lowered position, a control unit located inside the container, and a control panel for steering.

Below, each of the shelter components are described.

Cable set - Set of cables and cords.

Container - Consists of a metal box in which the other shelter components are placed.

Cooling system - Contains coolant distributors, hoses, a liquid cooling unit (LCU), an ethylene glycol water liquid, and a cooling liquid. The LCU cools the EGW liquid, which is transferred from the cooling system to warm areas in the system, the air condition unit, the electronics cooling unit, and then back to the cooling system.

Installation mechanics - Miscellaneous remaining components including cable chutes, frames, and interior fittings.

Power system - Distributes energy to the system. Consists of a generator, a diesel engine, and a switch that selects between internal and external power. It also includes an AC/DC circuit converting alternating current voltage to direct current voltage, two power distribution units that distribute voltage, as well as backup batteries and chargers.

Operator workstations - The system includes two workstations for operators. Each of the workstations has a screen, keyboard, chair, and all the associated mechanics to keep the different components in place.

Waveguide system - Consists of a metal pipe connected between the antenna and the transceiver that leads microwaves between the two.

4.2 Data collection

Two main methods for data collection are applied. The first is collecting data from the internal company database Industrial and Financial Systems (IFS). The second method is collecting estimations from consultations with experts at the collaborating company. Assumptions, aggregations, scaling, and exclusions are also described in this section. The data collected from each phase of the life cycle is presented in Table A1, Appendix A, in a bill of materials (BoM) list.

4.2.1 Data collected from IFS

IFS is Saab AB's database that stores information such as material declarations and internal documents. The material declarations are used in this study to collect data for the BoM. This method for gathering data mainly provides smaller quantities of substances related to legal reporting requirements, such as those of the REACH candidate list. Larger quantities of more commonly used and non-toxic materials, such as aluminium, are mostly obtained through the second data gathering method: assumptions based on expert consultation. Furthermore, data on quantities in the IFS are lacking for some materials. Table 4.1 presents the declaration level for each component. Full material declaration means that full quantities are declared for all legal substances, according to Saab AB’s compiled list of legal requirements. Partial material declaration means that some substance quantities are declared for the component. Blank material declaration means that no substance quantities are declared for the component. All in all, the data gathered from this method stands for a minor part of the total weight of the components.

Table 4.1: Material declaration level from IFS for each component in %.

Component	Full declaration	Partial declaration	Blank
Antenna	41%	48%	11%
Cable set	7%	85%	8%
Container	100%	0%	0%
Cooling system	63%	21%	16%

Installation mechanics	63%	29%	8%
Main computer	37%	55%	8%
Power system	53%	40%	7%
Transceiver	31%	62%	6%
Turntable system	50%	32%	17%
Operator workstations	76%	10%	14%
Waveguide system	88%	3%	10%
Mean value	**51%**	**32%**	**9%**

4.2.2 Data collected from company expert consultations

For the remaining weights not declared in the IFS database, these were estimated by experts at the company with good knowledge in the area. The communication with the experts consisted mainly of email conversations and meetings, and entailed communication with approximately 30 employees. The employees' areas of expertise were primarily related to the technical system, material declaration, as well as purchase and logistics.

4.2.3 Extrapolation

As the available data was incomplete in some areas, different extrapolation methods have been applied to cover gaps. For instance, aggregation has been used to a large extent, especially for plastics and electronics. Also, some exclusions of uncertain or minor flows have been done due to time constraints. Nevertheless, a few risks related to these assumptions are raised below.

In the REACH candidate list, substances of very high concern (SVHC) are listed, aimed to be controlled, and later on phased out (ECHA, 2022). A material included in this list is chromium VI, currently in great focus at Saab AB. As it apparently constitutes a health and environmental hazard, it would be relevant to include when evaluating the sustainability of the radar system.

However, during the process of gathering data for the BoM, it was observed the presence of chromium VI was documented in most components, but the exact quantities were not. Consequently, it was decided that chromium VI should not be included in the analysis. This decision was based on information provided by company experts, who indicated that the quantity of chromium VI never exceeds 0.1 weight percentage, which is the maximum amount approved by ECHA (ECHA, n.d.). Similar exclusions have been made for most adhesives, as often only the presence and no quantities are disclosed in the IFS database.

4.2.4 Bill of materials

Appendix A, Table A1 presents the BoM of the product system, derived from the two data collection methods described in Section 4.2.1-4.2.2. For a description of the distribution between declared and assumed weight per material, see Table A2-A3, Appendix A. In the following subsections, detailed assumptions leading up to the BoM for each component are described.

Antenna

The antenna consists of polysiloxane, glass fibre, epoxy, aluminium, circuit boards, stainless steel, copper, tin, and zinc. Stainless steel mainly consists of iron, as well as some chromium and carbon. This composition applies to stainless steel in all components. All electronics reported in the database IFS for the antenna are assumed by experts to be circuit boards. Glass fibre and epoxy originate from glass fibre composite, for which proportions of 70% and 30% are assumed based on Suhas et al., (2014). The amounts of stainless steel, aluminium, epoxy, glass fibre, and copper are primarily estimated by company experts. The quantities of the remaining materials are found in the IFS database, where polysiloxane was selected to represent all undefined plastic, as most plastic parts are likely present in silicone seals.

Cable set

The cable set component consists of copper, aluminium, polyethylene, electronic connectors, and stainless steel. The type of electronics in the component, i.e., connectors, is also assumed based on expert consultations. Copper and polyethylene are common materials in cables and their respective amounts were derived from company expert consultations. The quantities of the remaining materials are obtained from IFS. The weight of the copper was increased (+1 kg) to match the total weight of the component, since copper constitutes the majority of the weight of the cables. The amount of aluminium is similarly adjusted to match the total weight for other components, except the cable set and the container.

Container

As noted in Table 4.1, all data on the container constituents is fully declared and collected from IFS. However, only an undefined content of plastics was reported, which is assumed based on company experts to consist of sealings and is thus likely polyethylene. Moreover, the rubber is assumed to be synthetic rubber, which applies to all rubber in the studied product. The activated carbon reported is present in an air filter.

Cooling system

The cooling system consists of computers, refrigerant, aluminium, copper, stainless steel, and synthetic rubber. The several undefined polymers reported in IFS are assumed to be synthetic rubber, specifically in the form of tubes. Data regarding the computers and aluminium is again obtained from expert consultations. The amounts of the other materials are obtained from IFS.

Installation mechanics

The installation mechanics consist of aluminium, connectors, stainless steel, copper, and polyamide. All electronic material data is again estimated by experts to consist of connectors. All undefined polymers reported in IFS on the installation mechanics component are assumed to be polyamide, as this is concluded to be used in the connectors, a common application due to polyamide’s high strength and flexibility (AREOUSA, n.d.). The estimated quantities of stainless steel and aluminium are primarily obtained through consultation with experts, while the quantities of the remaining materials are retrieved from IFS.

Main computer

The main computer consists of copper, aluminium, tin, lead, stainless steel, polysiloxane, and circuit boards. All electronics data found in IFS is assumed by experts to be circuit boards. Approximately 20% of the copper quantity is retrieved from IFS and the remaining 80% from estimations of likely copper content by company experts. Most of the aluminium and two-thirds of the circuit board quantities are also estimated by company experts. The quantities of tin and lead are fully obtained from IFS. Quantities of stainless steel and polysiloxane are also obtained from IFS, where several undefined metals and polymers are again assumed to consist of these two likely materials. For example, as for the antenna, the polymers are mainly present in seals, a component that commonly consists of polysiloxane.

Power system

The power system consists of aluminium, stainless steel, copper, lead, polyester, polycarbonate, polyamide, computers, and capacitors. All electronic data found in IFS is assumed by experts to be computers and capacitors. The plastic is assumed to consist of the three most common polymers obtained from IFS: polyester, polycarbonate, and polyamide. The declared weights of these three materials are scaled up to match the total weight of the power system (+0.25, 0.28, and 0.35 kg, respectively). Nearly all aluminium, copper, and stainless steel data is obtained from expert estimations, while the weight of the lead is obtained from IFS.

Transceiver

The transceiver consists of a converter, aluminium, polyethylene terephthalate, polyester, stainless steel, ceramics, copper, epoxy, glass fibre, lead, and tin. All electronic data found in IFS is judged by experts to be a converter. The quantities of stainless steel and aluminium are predominantly estimated from expert consultations, while the remaining material quantities are obtained from IFS. As for the antenna, the glass fibre and epoxy originate from glass fibre composite with an assumed 70/30 proportion. Polyester is fully declared in IFS. Furthermore, the highest quantity of polymer declared in IFS is polyethylene terephthalate, which is assumed by experts to be plastic sheets. The remaining declared plastic weights are also assumed to be polyethylene terephthalate. Ceramics are fully declared in IFS and assumed to exist in ceramic resistors, specifically.

Turntable system

The turntable system consists of aluminium, stainless steel, polysiloxane, copper, and circuit boards. The quantities of copper and polysiloxane are obtained from IFS, where all plastics are assumed to be polysiloxane as this is assumed by company experts to be seals. Most of the aluminium, stainless steel, and circuit boards are also estimated through consultations with company experts.

Operator workstations

The operator workstations consist of polyamide, polyurethane, aluminium, stainless steel, rubber, and a computer. The computer is estimated by experts to consist of two sets of keyboards, mouses, screens, and similar devices. Polyamide, polyurethane, rubber, and 6 kg of aluminium are present in the two chairs mounted to the floor. The total weight of the chairs is obtained from IFS. The material content of the chairs is assumed equal to that of an office chair based on consultation with experts. The office chair used as a proxy is the IKEA Långfjäll chair (IKEA, n.d.). The remaining 70 kg of aluminium is estimated by experts, as well as the majority of the stainless steel.

Waveguide system

The waveguide system consists of stainless steel, aluminium, and polyamide. The quantity of stainless steel is obtained from the internal IFS. The amount of polyamide is also declared in IFS. The amount of aluminium is estimated by company experts and the weight of the material is adjusted to reach the total weight of the component (+3.9 kg).

4.2.5 Material production and processing

Background datasets applied for the production and processing of materials, including input quantities and providers in OpenLCA, are listed in Appendix B, Table B1-B11. As described in Section 4.2.2, the composition data is derived from IFS and consultation with experts at Saab AB. In the event that a global (GLO) location is not available, Europe (RER) is chosen as an alternative. In the component transceiver, the ceramic material is assumed to be part of a ceramic resistor, which likely consists mainly of aluminium oxide (BOURNS, 2016). For simplicity, it is modelled as 100% aluminium oxide.

General metalworking is assumed to be the processing method for all aluminium, stainless steel, copper, zinc, and lead. Injection moulding is assumed to be the technique employed for processing plastic and composite of epoxy and glass fibre unless otherwise stated. For this, default datasets are available in the Ecoinvent database. The remaining processing processes are already included in the respective datasets in OpenLCA, marked with footnotes in Appendix B. Some processes have been omitted due to likely negligible impacts. For instance, the mixing of epoxy resin and glass fibre before moulding the mixture is excluded. The same applies to the process where polyvinyl chloride is rolled into films to produce the tarpaulin fabric on the container, as well as for the final process when the synthetic rubber is formed into its desired shape.

4.2.6 Transports

As mentioned in Section 3.5.2, Kassel, Germany is assumed as the location of the material production sites and customers. The weight of the vehicle on which the system is mounted is estimated at 10 000 kg by experts at Saab AB, and the weight of all components is 4495 kg, which gives a total weight of transported goods at 14 495 kg.

After material production and processing, the components are assumed to be transported by truck to Gothenburg for assembly, which involves covering a distance of approximately 900 km (Distance, n.d). For the same reason, transport of the finished product to the customer is assumed to be approximately 900 km from Gothenburg to Kassel. Calculations for transport are shown below.

Material production to assembly

$$14.495\ t\ \times\ 900\ km = 13\ 045.5\ t \times km$$

Verification and testing to use

$$14.495\ t\ \times\ 900\ km = 13\ 045.5\ t \times km$$

These transports are expected to occur via truck, thus the dataset ‘Transport, freight, lorry, unspecified’ in Ecoinvent was applied in the modelling. Domestic transport to the EoL facility after the use phase of the radar system is assumed negligible and therefore omitted in this study. Transports occurring in upstream and downstream processes in the background system are already integrated into various market-process datasets, which is why their impacts are not assessed separately.

4.2.7 Assembly

Table 4.2 presents the necessary inputs for mounting one Arthur. Due to time constraints, new data regarding energy use during assembly could not be gathered. Therefore, all data for this phase is gathered from LCA2015, where the energy required for the assembly of all components is reported, including soldering, electrical assembly, and electronic measurement (Gustafsson & Rönnblom, 2015). The LCA2015 study states that the tools used for assembly are connected to the grid and therefore on constant standby, resulting in relatively high durations for electronic measurements and soldering (2000 h), even though the actual active time used is much lower. Calculations for energy use of electronic measurements, soldering, and electrical assembly are shown below. The hours represent the duration of the process steps, which are multiplied with the respective powers of each step.

Electronic measurements

$$2000\ h \times\ 0.036\ kW\ = 72\ kWh$$

Soldering

$$2000\ h \times 0.048\ kW\ = 96\ kWh$$

Electrical assembly

$$20\ h \times 0.72\ kW\ = 14.4\ kWh$$

Table 4.2: Unit processes for assembly of the radar system.

Process	Quantity	Unit	Dataset
Input			
Antenna	1	item	Appendix B, Table B1
Cable set	1	item	Appendix B, Table B2
Container	1	item	Appendix B, Table B3
Cooling system	1	item	Appendix B, Table B4
Electrical assembly	14.4	kWh	Market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - SE
Electronic measurements	72	kWh	Market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - SE
Installation mechanics	1	item	Appendix B, Table B5
Main computer	1	item	Appendix B, Table B6

Operator workstations	1	item	Appendix B, Table B7
Power system	1	item	Appendix B, Table B8
Transceiver	1	item	Appendix B, Table B9
Transport, material production to assembly	13 616.6	t · km	Market for transport, freight, lorry, unspecified | transport, freight, lorry, unspecified | Cutoff, U - RER
Turntable system	1	item	Appendix B, Table B10
Soldering	96	kWh	Market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - SE
Waveguide system	1	item	Appendix B, Table B11
Output			
Arthur assembled	1	item	Reference flow

4.2.8 Verification and testing

Testing and verification of Arthur is carried out in the testing facilities in Gothenburg. Similar to the assembly phase, time constraints limited the ability to collect data for this phase. Therefore, verification and testing is only included in the modelling as an empty process dataset, similar to a ‘bridging process’ (Ingwersen et al., 2018), and does not contribute to the impacts of Arthur.

4.2.9 Use and maintenance

Data gathered for the use phase contains the operational profile of the radar and vehicle, and their separate diesel consumption during one life cycle. Thereafter, maintenance data is presented, which includes the average replacements per component during one life cycle. Presented in Appendix C, Table C1, is the data collected for the use and maintenance phase, with their associated quantities, datasets, and providers.

All data for the radar operation is collected and assumed internally by company experts. Data for the vehicle operation is gathered both internally and externally. The lifespan, operation, distribution between highway and terrain, and diesel consumption for terrain is assumed by company experts, while the diesel consumption for highway driving is obtained from Pääkönen et al., (2019). As the vehicle varies between customers, data on the diesel consumption in the use phase is based on an average medium-duty truck in Finland (Pääkönen et al., 2019), and the weight of the truck is estimated by Saab AB experts to be 10 000 kg. The vehicle is estimated by Pääkönen et al. (2019), to consume 374 kWh diesel per 100 km, where 1 litre = 9.96 kWh diesel. Presented below are the calculations on diesel consumption of the radar and vehicle, which are derived from an internal operational profile of Arthur:

Radar

Lifespan: $20\ yr$

Operation: $1000\ h/yr$

Diesel consumption per hour: $6.67\ l/h$

Diesel consumption over one lifespan: $6.67 \times 1000 \times 20 = 133\ 400\ l$

Vehicle

Lifespan: $20\ yr$

Operation (80% highway, 20% terrain): $20\ 000\ km/yr$

Diesel consumption per kilometre, highway: $374 \times 1 \div 9.96 \div 100 = 0.38\ l/km$

Diesel consumption per kilometre, terrain: $1\ l/km$

Diesel consumption over one lifespan: $(0.38 \times 20\ 000 \times 0.8 \times 20) + (1 \times 20\ 000 \times 0.2 \times 20) = 201\ 600\ l$

As presented in Section 3.5.4, several components require replacements with new counterparts. In each component, a large number of sub-parts are included. The number of times each such part needs to be replaced or repaired during a lifetime therefore differs. An average of all ancillary parts has been calculated for each component, resulting in the figures presented in Table 4.3. Replacement frequency data is found for all components except the Installation mechanics, which is therefore excluded in this step of the life cycle. In Appendix C, Table C1, these replacement components are presented as one aggregated item of 'Arthur replaced components'.

Table 4.3: Average number of parts replaced during the lifetime of components.

Component	**Average No of parts replaced during one lifecycle**
Operator workstations	0.59
Antenna	0.27
Main computer	0.18
Turntable system	0.18
Power system	0.10
Cooling system	0.09
Transceiver	0.07
Cable set	0.06
Container	0.04
Waveguide system	0.04
Installation mechanics	n.a.

4.2.10 End of life

Because of its long lifespan, no Arthur radar system has ever been taken out of service thus far. Additionally, every customer can decide on which EoL a discarded Arthur should undergo. Due to these factors, data on the EoL of Arthur does not exist yet. However, a disposal plan of a radar system similar to Arthur has been developed, where recycling and incineration are the two most common treatments (Karlsson, 2016). The same scenario has thus been assumed for Arthur, where a combination of recycling and incineration has been adopted, with a probable distribution of the constituting materials between the two EoL treatments. Additional potential EoL scenarios, such as if the system is left in nature or destroyed by enemies, are not considered in this report.

Municipal incineration is modelled for all plastics, paint, rubber, and wood, while so-called 'final disposal' is modelled for the refrigerant, which also refers to incineration. For municipal incineration, as a global or European location is not available, the 'rest of the world' (RoW) is chosen as provider. As the adhesive and epoxy-glass composite is assumed to be applied to plastic components, these are included in the incineration for waste plastics. Because cut-off is applied as the method for allocating recyclable materials, impacts from their recycling processes are excluded from this assessment.

All electronic components are assumed to end up as electronic scrap, and thereafter recycled. The same applies to all metals, as well as activated carbon from the air filter as spent activated carbon can be reactivated and is thus seen as recyclable. The ceramics are assumed to consist of 100% aluminium oxide, which is also considered recyclable. The EoL treatment unit process is presented in Table 4.4, and Table 4.5 lists the recyclable materials that are cut off.

Table 4.4: Unit process for the EoL treatment.

Incineration			
Material	**Quantity**	**Unit**	**Dataset**
Input			
Arthur discarded	1	item	Reference flow
Output			
Adhesive	21 000	g	Treatment of waste plastic, mixture, municipal incineration | waste plastic, mixture | Cutoff, U - RoW
Epoxy + glass fibre	16 000	g	Treatment of waste plastic, mixture, municipal incineration | waste plastic, mixture | Cutoff, U - RoW
Paint	40 000	g	Treatment of waste emulsion paint, municipal incineration | waste emulsion paint | Cutoff, U - RoW
Plastics	140 000	g	Treatment of waste plastic, mixture, municipal incineration | waste plastic, mixture | Cutoff, U - RoW
Refrigerant	19 000	g	Treatment for used refrigerant R13a, final disposal |

			used refrigerant R134a | Cutoff, U - GLO
Synthetic rubber	43 000	g	Treatment of waste rubber, unspecified, municipal incineration | waste rubber, unspecified | Cutoff, U - RoW
Wood	110 000	g	Treatment of waste wood, untreated, municipal incineration | waste wood, untreated | Cutoff, U - RoW

Table 4.5: Materials with recycling as EoL treatment, which are cut off from the modelling.

Recycling		
Material	**Quantity**	**Unit**
Aluminium	2 300 000	g
Stainless steel	1 300 000	g
Copper	220 000	g
Electronics	32 000	g
Lead	20 000	g
Activated carbon	3000	g
Tin	420	g
Zinc	89	g

5. Impact assessment

The following section presents the results of the total impacts, as well as the impacts distributed between life cycle phases and distributed between components. As stated in Section 3.4, the LCIA is performed utilising the ReCiPe method and its characterization models. This methodology encompasses the categorization of elementary flows into 18 impact categories. In addition, the CSI is used to complement the ReCiPe method.

5.1 Total impact

Figure 5.1 presents the total impact for each of the four impact categories in focus, as well as the contribution of each stage in the life cycle. At the top of each bar, the total result for the impact category is shown. The total impact results for all 18 categories from the ReCiPe method, along with the CSI, are presented in Appendix D, Table D1. For results from all impact categories for each separate life cycle stage, see Appendix D, Table D2-D7.

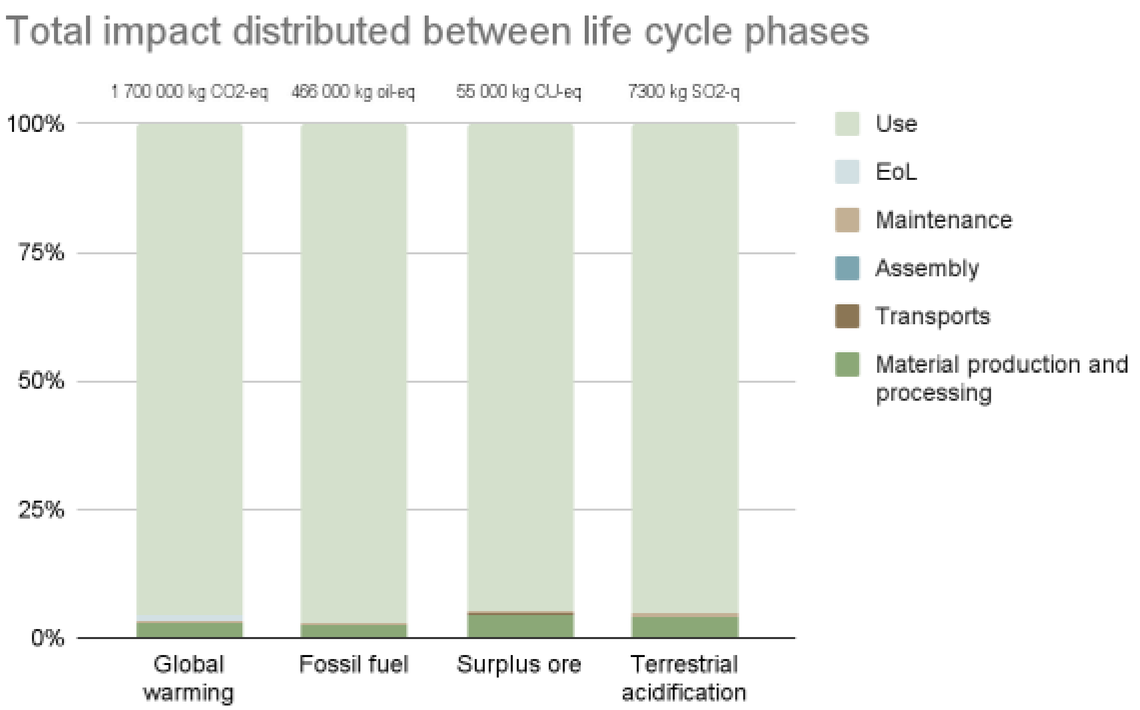

Figure 5.1: Total impact distributed between life cycle phases for the four impact categories in focus.

5.2 Dominance analysis

The dominance analysis provides an in-depth investigation of the key contributors to the overall impacts. This section includes an evaluation of the contribution from each life cycle phase, the contribution from the use phase, and the contribution from each of the 11 components.

5.2.1 Contribution from each life cycle phase

As Figure 5.1 above illustrates the distribution between life cycle phases, a dominance analysis based on this can be performed. The figure shows that the use phase is the dominant contributor, accounting for 95-97% of the total impacts. Material production and processing is the second largest contributor, accounting for 3-4% of the impacts. The other stages (Eol, maintenance, assembly, and transport) together contribute only about 1% of the impacts. These results suggest that efforts to reduce the environmental impacts of Arthur should primarily focus on the use phase. To enhance the understanding of the other stages in the life cycle, Figure 5.2 provides an illustration that excludes the use phase, while the separate contribution from the use phase will be further investigated in Section 5.2.2.

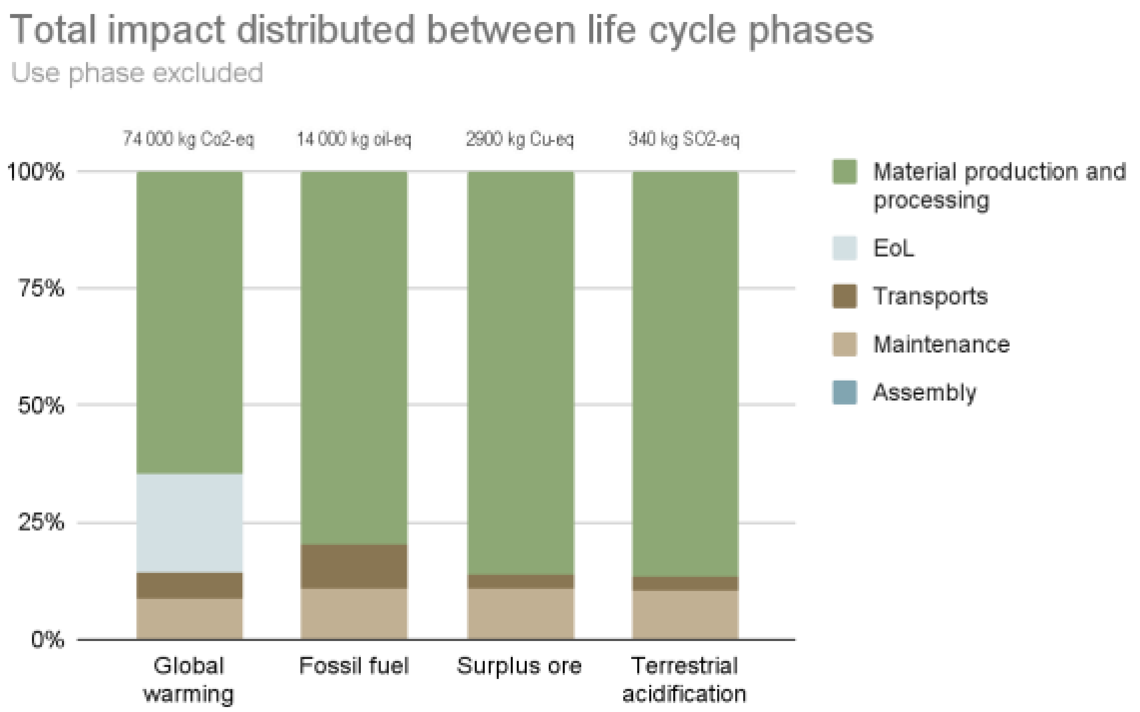

Figure 5.2: Global warming, fossil fuel, surplus ore, and terrestrial acidification impact from all stages of the life cycle. Use phase excluded.

The result in Figure 5.2 reveals that assembly stands for a very small fraction of the total impact, as well as EoL in all categories except global warming. The noticeable contribution to global warming is due to GHG emissions released from the incineration of waste plastic. Transports have a slightly higher contribution to fossil fuel compared to other impact categories, which could be explained by the extraction of fossil resources (e.g., crude oil) to produce the fuel for the transports. Lastly, maintenance contributes similarly to all categories.

5.2.2 Contribution from the use phase

As the results above show a dominant contribution from the use phase, this stage of the life cycle is analysed further to pinpoint the hotspot. The contributions from operating the vehicle and radar are compared in Figure 5.3.

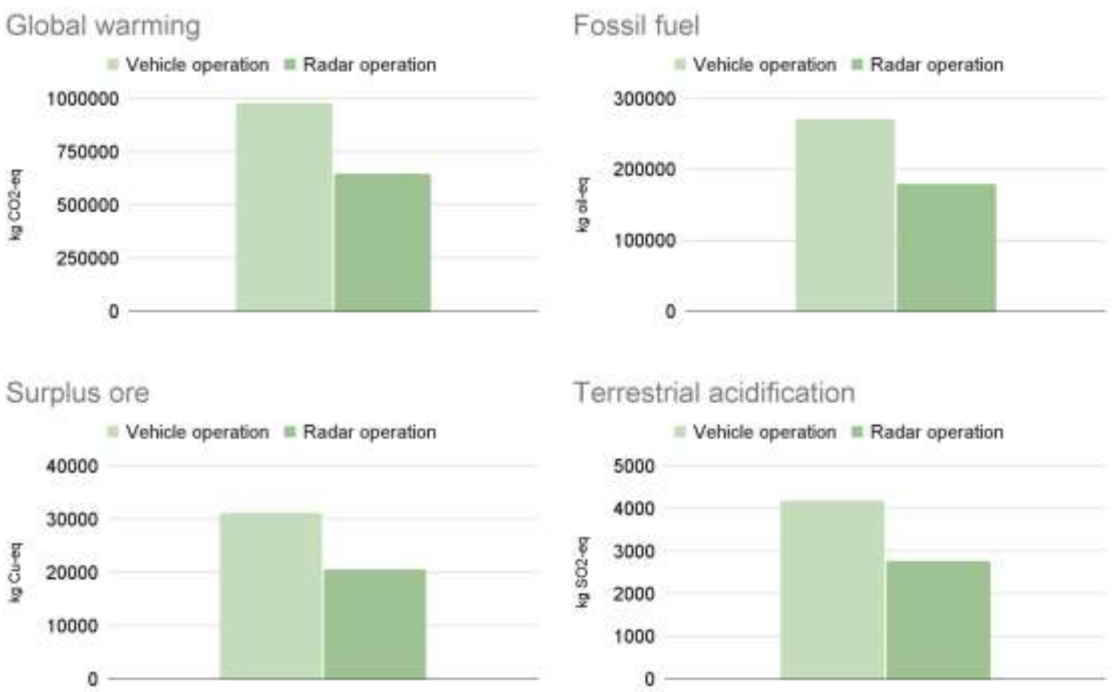

Figure 5.3: Global warming, fossil fuel, surplus ore, and terrestrial acidification impact from vehicle and radar operation in the use phase.

One can distinguish a higher impact from operating the vehicle, although both are of the same order of magnitude. As the two operating profiles are modelled with the same diesel in OpenLCA, the reason for the different results is different diesel consumptions. Since the unit of operation for the vehicle is kilometres per year and hours per year for the radar system, a direct comparison between the two is not straightforward.

5.2.3 Contribution from each component

The following section presents the contributions from each component, cradle-to-gate, to the four impact categories in focus. Illustrated in Figure 5.4 are the components' contributions adding up to 100%, with the total impact value presented at the top of each bar. Note that the assessment does not include use, maintenance or EoL.

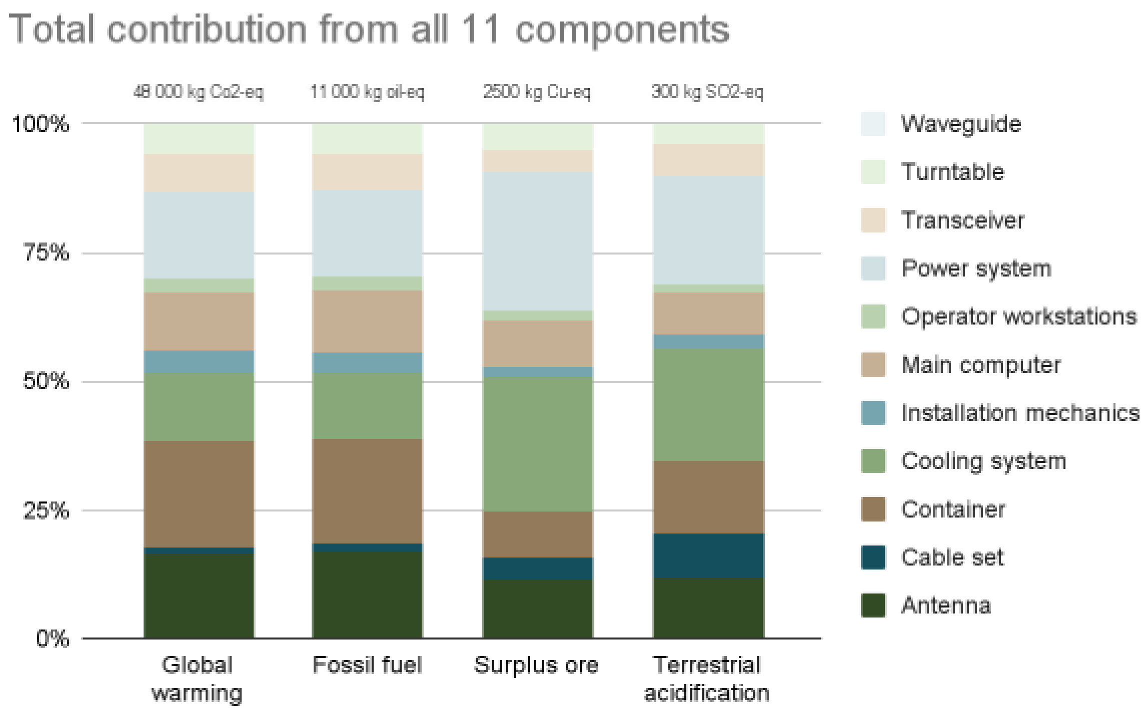

Figure 5.4: Global warming, fossil fuel, surplus ore, terrestrial acidification impact contribution from all 11 components only.

Figure 5.4 demonstrates that the container, antenna, and power system exert the largest influence on global warming and fossil fuel. Subsequently, the cooling system and main computer exhibit notable contributions. In terms of surplus ore and terrestrial acidification, the power system and cooling system emerge as the dominant contributors, followed by the antenna, container, main computer, and cable set. The observed high impacts may be attributed to the high quantity of aluminium and stainless steel in all of the highly contributing components. Aluminium also appeared as the most impacting material in the LCA2015 study, and stainless steel (iron) as the third-most impacting material.

The impacts of the components have furthermore been analysed in relation to their weight, see Table E1-E4 and Figure E1-E4 in Appendix E. This can assist in investigating if the components' weights may be the reason behind the figures in Figure 5.4, or if other factors influence as well. It is notable that the main computer contributes the most in relation to its weight for global warming, fossil fuel, and surplus ore, and second highest for terrestrial acidification. For terrestrial acidification, the cable set stands out by having the highest impact in relation to its weight, which mostly consists of copper. Copper was also reported as the second-most contributing material in the LCA2015 study. Conversely, the container has a lower impact in relation to its weight, followed by the power system for global warming, which are also the two clearly largest components. It should, however, be noted that even though several components have a large impact in relation to their weight, the factors contributing to this may still be difficult to address. For example, the main computer likely consists of electronic parts that cause high impacts, which might be challenging to remove or change.

6. Interpretation

The following section includes a comparative analysis to LCA2015, and an uncertainty analysis.

6.1 Comparisons to LCA2015

Since LCA2015 was conducted, the impact categories have been altered and renamed between different versions of the ReCiPe method, i.e., the 2008 (Goedkoop et al., 2008) and 2016 (Huijbregts, 2017) versions. Thus, each compared category might have different reference units and have in some cases even been separated into two categories. The latter has happened through the differentiation of (i) human toxicity, non-carcinogenic and (ii) human toxicity, carcinogenic, as well as (a) photochemical oxidant formation, ecosystems, and (b) photochemical oxidant formation, humans. Additionally, as the data collection has undergone modifications and advancements, the results might also differ as a consequence. The comparisons undertaken focused solely on impact categories that exhibited a sufficient degree of similarity across the two ReCiPe versions.

6.1.1 Comparison between total impacts

Compared results of the total impact from the impact categories global warming, fossil fuel, and terrestrial acidification are presented in Figure 6.1. Due to variation in the reference units and underlying characterization model for mineral resource scarcity between LCA2015 and LCA2023, those results are not comparable. The residual impact categories (except CSI as it was not adopted in LCA2015 and thus not comparable) are presented numerically in Figure F1 and as percentage in Table F1 in Appendix F.

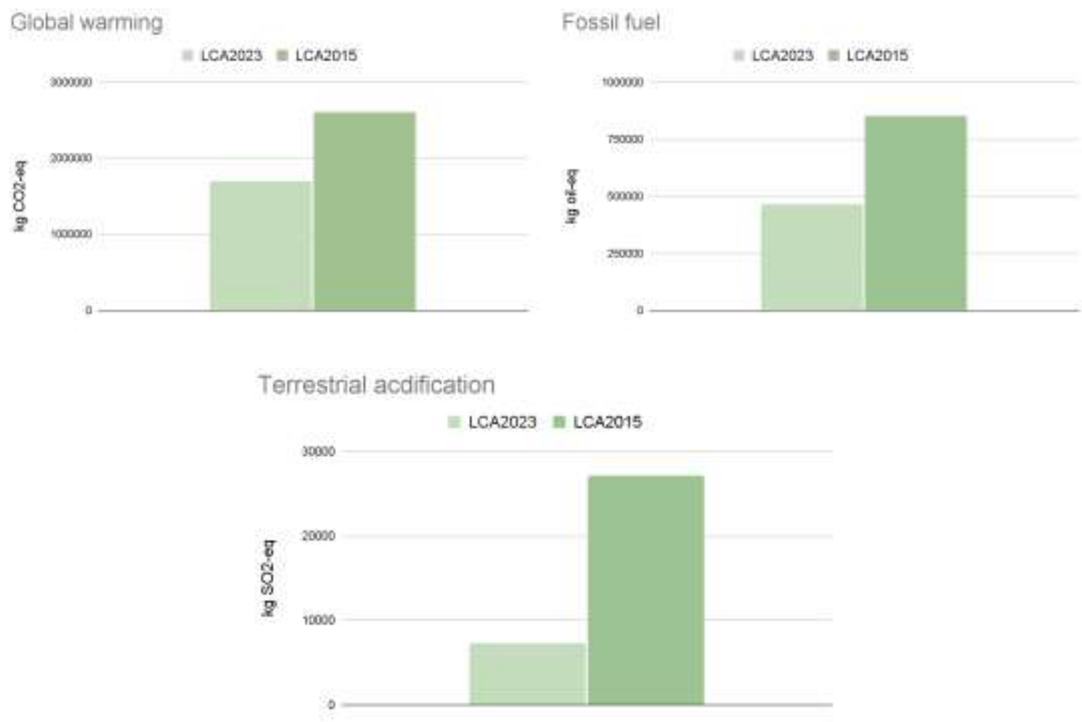

Figure 6.1: Total results from global warming, fossil fuel, and terrestrial acidification compared LCA2015 and LCA2023.

As shown in Figure 6.1, it is apparent that the impact values from the present LCA2023 study are lower than that of LCA2015 for all three impact categories, particularly for terrestrial acidification. The impact results compared to LCA2015 has decreased by approximately 30% for global warming. Further analysis of the three impact categories are presented in Section 6.1.2, which outlines the respective contributions of each stage of the product's life cycle towards the overall impact.

6.1.2 Comparison between life cycle phases

Comparing the results of the total impact from the impact categories global warming, fossil fuel, and terrestrial acidification from the different life cycle phases are presented in Figure 6.2-6.4. As maintenance is included in the use phase in LCA2015, it could not be directly compared and is thus not distinguished in this analysis. The same applies to EoL, as LCA2015 applied a closed-loop modelling compared to open-loop modelling applied in the present study, and is hence also not included in this comparison.

The overall findings could indicate lowered impacts in LCA2023 compared to LCA2015. However, differences in data collection and modelling could be the reason for these differences, rather than actual reduced impacts. It was discovered that the operational profile for the vehicle during usage (in km/year) was nearly 12 times higher than that of LCA2015, whereas the operational profile for the radar (in h/year) was almost 6 times lower than that of LCA2015. The reason for these large differences has been investigated, but without finding the reason for these considerable differences. While an average operational profile was used in LCA2023, different scenarios were used in LCA2015, but the origins of these scenarios were not possible to identify within the limited time frame of the study. Thus, the difference in impact results for the use phase is difficult to explain.

Global warming

Figure 6.2: Results for global warming divided between lifecycle phases from LCA2015 and LCA2023.

Figure 6.2 illustrates that the LCA2023 has comparatively low global warming impact results for material production and production, assembly, and use phase. However, the LCA2023 findings reveal a slightly higher impact result on transport when compared to LCA2015. The reason for this likely derives from a difference in estimating the weight of the transported goods. The LCA2015 study has likely excluded the transport of the vehicle on which the system is mounted, which can be deduced from their calculated transported weight. Thus, even though LCA2015 considers a higher total transport distance, the total t·km is half of those of LCA2023.

Furthermore, the chosen dataset for truck transport differs, which could also explain the differing results.

Fossil fuel

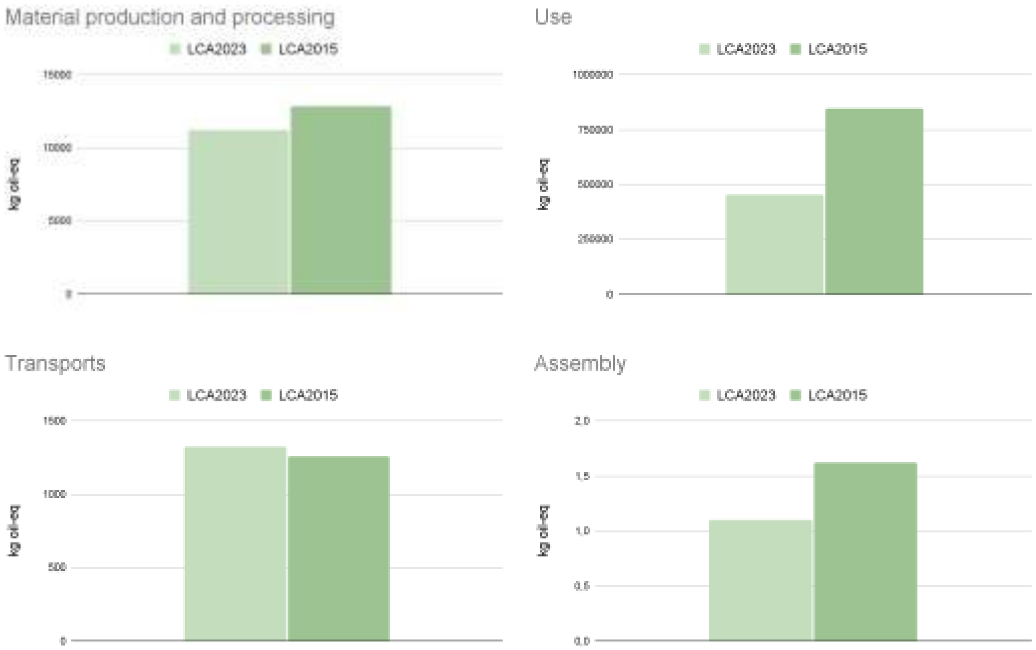

Figure 6.3: Results for fossil fuel divided between lifecycle phases from LCA2015 and LCA2023.

As for global warming, Figure 6.3 demonstrates that LCA2023 receives a lower fossil fuel impact result for material production and processing, assembly, and use phase compared to LCA2015. Nonetheless, LCA2023 shows a higher impact result on transport, which presumably can be explained with the same reasoning as for global warming (i.e., higher weight transported).

Terrestrial acidification

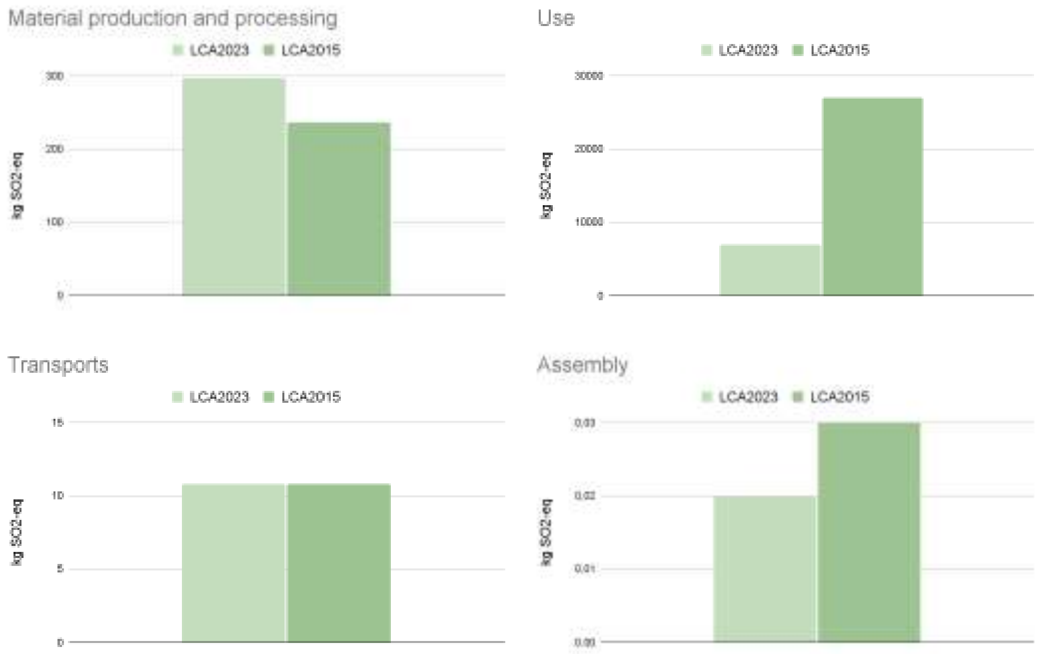

Figure 6.4: Results for terrestrial acidification divided between lifecycle phases from LCA2015 and LCA2023.

Figure 6.4 indicates that the total terrestrial acidification impact result for LCA2023 compared to that of LCA2015 is substantially lower for the use phase and 20% lower for the assembly phase. However, LCA2023 receives a higher impact for material production and processing. The impact from transport is effectively equal between the two studies.

6.2 Uncertainty analysis

Considering the dominance of the use phase for the impacts of Arthur (Section 5.2.2), the factor selected for the uncertainty analysis is an alternative fuel during the use phase. This factor has been identified as potentially beneficial to the final outcomes of the study, as the results reveal fuel consumption during the use phase as the hotspot. The biofuel chosen for investigation is fatty acid methyl esters (FAME), which is a biofuel made from renewable sources and is produced by transesterification of animal and vegetable oils (Ližbetin et al., 2018).

FAME has been implemented with a simplified model, where the Ecoinvent dataset ‘diesel, burned in agricultural machinery’ was copied and subject to a number of changes. Most importantly, the fossil diesel input was replaced by a corresponding input of FAME. Furthermore, the same energy consumption was assumed, so the input of FAME was set equal to the previous input of fossil diesel in terms of energy. This results in a slightly higher mass input of FAME, since FAME has a slightly lower energy content compared to fossil diesel (39 MJ/kg vs 44 MJ/kg) (Hoekman et al., 2012). Most emissions from the fossil diesel process were duplicated as well, except for the fossil emissions such as fossil carbon dioxide, which were changed to the corresponding biogenic emissions.

The comparison between FAME and diesel for global warming, fossil fuel, surplus ore and terrestrial acidification is presented in Figure 6.5, while all 19 impact category results are presented in Table G1, Appendix G.

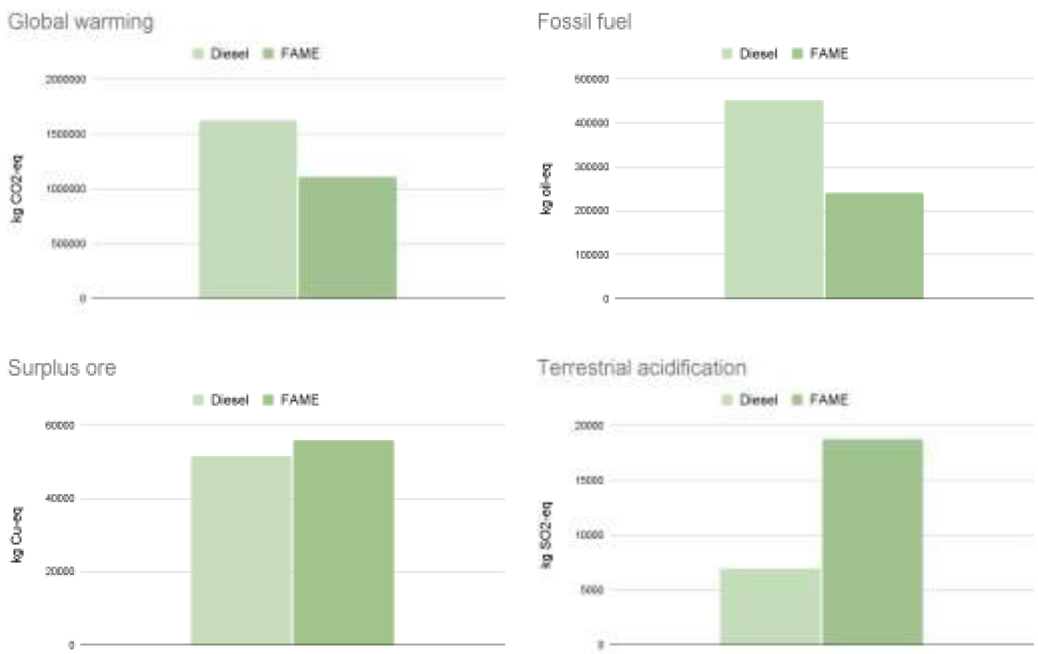

Figure 6.5: Global warming, fossil fuel, surplus ore, and terrestrial acidification impact results for diesel compared to FAME.

The impact category global warming exhibits a higher value for diesel when compared to FAME. This finding can be explained by the shift from fossil to biogenic GHG emissions, that is carbon dioxide, carbon monoxide, and methane. As FAME derives from renewable resources, it exhibits a lower carbon intensity, leading to a reduced release of fossil GHG emissions into the atmosphere. As fossil fuel measures the depletion of finite resources, the large increase for diesel fuel can be explained through the need for extracting fossil raw materials.

However, as FAME requires agricultural land to produce soybean, rapeseed, and palm fruit, trade-offs may occur. For instance, global ammonia emissions are mainly attributed to the use of ammonia-based fertilisers and animal manure (Ma et al., 2021), which hence may be linked to the notable increase in terrestrial acidification results when substituting diesel with FAME. Furthermore, the outcome for surplus ore closely resembles the result obtained for diesel, with a slight increase in the FAME results. However, when comparing the difference in the impact category CSI (both categories covering the metal and mineral resource scarcity), the results for diesel are somewhat higher than for FAME, going against the surplus ore result. Due to the small differences between the two fuels and partly contradictory results, the source behind is not further investigated in the study.

7. Discussion

This section discusses the study with a focus on the four research questions stated in Section 1.4. By analysing the strengths and weaknesses of the study, potential areas for improvement and future research are identified.

7.1 Research question 1

What are the environmental impacts of the radar system?

Section 5.1 provides a clear result of the total environmental impact of the system, thus answering research question 1. Section 5 contains data and information that can be used to evaluate and analyse the impact of one Arthur produced.

7.2 Research question 2

Which steps of the product's life cycle have the highest impact?

Based on the results of this study, it was found that three steps in the product's life cycle contribute the most to its environmental impacts. The use phase was found to have the absolute highest impacts, which can be traced to the diesel consumption of the vehicle and radar. The analysis carried out in Section 5.2.2 shows that the vehicle has higher impacts than the radar in the use phase. Further analysis was then conducted where the fuel was substituted to FAME, showing reduced impact for global warming and fossil fuel, but increased for terrestrial acidification. The overall indication is that FAME would be a preferable substitution, but the ammonia emissions should be investigated further. Other biofuels, such as hydrotreated vegetable oil (HVO), could also be assessed as alternative options.

Material production and processing were identified as the second highest contributor. Finally, the EoL and maintenance phases were identified as the third and fourth largest contributors, respectively, even though these were considerably smaller than the top two contributors. The impacts from EoL can likely be traced to the emissions that occur during incineration of waste plastic, whereas maintenance impacts can be traced to the material production and processing as they require the production of additional components.

By identifying the major contributing steps in the life cycle of the product, the study was able to provide recommendations for improvements to reduce the environmental impact of the product system. Specifically, implementing strategies aimed at mitigating emissions during the use phase holds potential for substantial reductions in the overall environmental impacts of the product. This can be achieved by exploring alternative fuel types, thus replacing conventional diesel with cleaner alternatives, such as the previously-mentioned FAME. Additionally, careful consideration of alternative materials and innovative material manufacturing processes can further contribute to reducing the product's environmental impacts. For instance, incorporating a higher proportion of recycled materials, such as aluminium and steel, can reduce impacts of the material production and subsequently reduce the product's environmental impacts.

7.3 Research question 3

Which components of the system have the highest impact?

The results showed that the container, antenna, and power system had the highest environmental impacts for both global warming and fossil fuel. Similarly, the power system and cooling system were identified as the components with the highest impacts for the surplus ore and terrestrial acidification categories, respectively.

It should be mentioned that components with high total impact but with low impacts in relation to their weight could likely be difficult to decrease the impact of, as the high impacts are presumably due to the high weight. Rather, the components with high impacts in relation to their weight should be in focus, as the issue then lies in other factors than the weight itself, such as the material content. The main computer and cable set have low weight, yet have high impacts in relation to their weight, thereby warranting a detailed evaluation. Nonetheless, as mentioned above, the high impacts could also be due to a large content of high-impact materials that are difficult to substitute, such as in electronics.

Redesigning the components with the highest environmental impacts may involve altering the design specifications or manufacturing processes to make them more environmentally benign. For instance, designing components that are easily disassembled and thus improving recyclability could help reduce the environmental impacts. Moreover, reviewing the suppliers of these components could involve exploring environmentally preferable supply chain practices, such as sourcing materials with lower environmental impacts or higher share of recycled materials (Boons, 2002).

7.4 Research question 4

Are the impacts different compared to those of the previously conducted LCA study and, if so, why?

LCA methodology is evolving over time, reflecting the increasing understanding of the environmental impacts of products. With a further developed methodology, more comprehensive data has presumably been collected in the present study, which may have resulted in both lower and higher impact values compared to LCA2015. However, it is also important to note that the differences in impact results may not be solely attributed to changes in the methodology, as other factors such as changes in the fuel consumption (discussed in Section 6.1.2) may also contribute to variations in the results. As mentioned above, most impacts are reduced in LCA2023 compared to LCA2015, but impacts from transports are higher. This can be explained by the inclusion of the vehicle's weight in LCA2023.

Notably, the use-phase data collected for LCA2015 differs significantly from the corresponding data obtained for LCA2023. Although expert consultation from Saab AB has verified the accuracy of the values applied in the present study, it may be worthwhile for future LCA endeavours to reassess this data again. Despite efforts invested in understanding the calculation methodology for the use phase applied in LCA2015, the precise origin of its data remains elusive, thereby hindering a clear comprehension of the underlying basis for the substantial variation observed.

7.5 Future research

In order to expand and improve on the present LCA study, several areas could be targeted for future work. First, further data collection on assembly as well as verification and testing is important to accurately assess the environmental impacts of these stages in the life cycle. While this data is likely obtainable at Saab AB, obtaining the data within this project was impeded by time constraints. The reason for this was communication challenges, which could be improved by developing a centralised area where internal LCA data could be retrieved. Moreover, a closer collaboration between departments at the company, as well as with suppliers, would facilitate the communication and the collection of data. Additionally, tracking data from suppliers, including the location of production, specific material contents, packaging materials and transport routes would provide valuable information for a more detailed LCA that relies less on generic global market processes.

It would be valuable for Saab AB to establish proper waste disposal plans for their products, in order for the EoL in future LCA studies at the company to have higher accuracy and relevance. Different usage scenarios would be interesting to explore, such as inactive storage or detonation during use. It is possible that the product may be purchased by the customer but remain nearly unused, or be destroyed in combat and left in nature to decay. Such scenarios can provide valuable insights into the product system's performance under different conditions, which can be used to inform product design and decisions.

To obtain a better understanding of hotspots and make changes to reduce environmental impacts, the contribution of each individual material could be considered. This information can inform the selection of materials and design strategies regarding material efficiency, waste reduction, and energy consumption. However, such a detailed analysis was not possible within the time frame of this project.

Normalisation was not applied in the present study as it involves subjective judgement. As a consequence, the possibility to compare the present LCA findings with those of LCA2015 was impeded, since the latter study presented normalised results. Normalisation can help communicate results, as it converts complicated numbers to relative magnitude. If more extensive comparisons or external communication of the results are desired, the company can consider conducting normalisation in future research.

Given the omission of several components in this study, there is a considerable amount of Arthur’s weight missing in the assessment. As a result, it is imperative for future research to address this limitation and undertake a more comprehensive LCA that includes the excluded components. By doing so, researchers can bridge the weight gap and provide a more comprehensive understanding of the environmental impacts associated with the product system under investigation.

8. Conclusion

The results show that the use phase contributes by far the most compared to the other life cycle stages. This is due to the diesel fuel consumed when operating the vehicle and radar, which could be reduced for some impact categories by replacing the diesel with biofuel, such as FAME. The components with highest impacts are the power system, antenna, cooling system, and container. However, it is recommended to focus on the main computer and cable set as these have the highest impacts relative to their weight, which indicates that these impacts might originate from other causes than the pure weight and therefore be easier to mitigate. The results also show very low impacts from transports, maintenance, and assembly. The comparison to LCA2015 shows overall reduced impact results. However, this does not necessarily imply that the actual environmental impact has decreased, as differences in data and modelling also influence the results. Additional analyses are recommended to identify the reason for these differences.

From the results obtained, it can be hypothesised that aluminium, stainless steel, and copper are the top contributing materials. Moving forward, if the current LCA is pursued further, an analysis of the materials' separate impacts is recommended. This will establish if the hypothesis is correct and guide efforts towards improvements. In addition, to achieve a more comprehensive analysis, it is essential to incorporate all components of the system without exclusion. Future LCA practices at the collaborating company should focus on improving data accessibility, ensuring more reliable results and decreasing the time required. Lastly, this report can be used as inspiration for future LCA studies within the defence industry and at Saab AB.

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Appendix A

Bill of materials with distribution of declared and assumed material weights summed.

Table A1. Bill of materials for one Arthur radar system.

Component	**Quantity [g]**	**Component**	**Quantity [g]**
Antenna	*Tot 334 000*	Waveguide system	*Tot 4000*
Aluminium	280 643	Aluminium	3959
Stainless steel	30 000	Stainless steel	38
Epoxy	10 500	Polyamide	3
Copper	5000	Cable set	*Tot 64 000*
Glass fibre	4500	Copper	50 001
Circuit boards	3000	Polyethylene	13764
Polysiloxane	234	Connector	196
Zinc	89	Stainless steel	30
Tin	34	Aluminium	10
Main computer	*Tot 75 000*	Operator workstation	*Tot 130 000*
Aluminium	68 672	Aluminium	76 000
Copper	3000	Stainless steel	26 000
Circuit boards	3001	Polyamide	13 000
Stainless steel	205	Polyurethane	7000

Polysiloxane	102	Synthetic rubber	4000
Tin	14	Computer	4000
Lead	6	Cooling system	*Tot 682 000*
Transceiver	*Tot 315 000*	Aluminium	326 532
Aluminium	262 412	Stainless steel	227 508
Stainless steel	27 001	Copper	86 413
Converter	15 000	Synthetic rubber	19 345
Copper	6205	Refrigerant	19 200
Polyethylene terephthalate	2130	Computer	3001
Polyester	1089	Power system	*Tot 959 000*
Tin	379	Stainless steel	730 000
Glass fibre	331	Aluminium	135 177
Lead	288	Copper	70 000
Epoxy	142	Lead	19 943
Ceramics	32	Computer	2000
Turntable system	*Tot 269 000*	Capacitor	1000
Aluminium	138 300	Polyamide	350
Stainless steel	130 159	Polycarbonat	280

Circuit boards	301
Polysiloxane	205
Copper	36
<u>Container</u>	*Tot 1 200 000*
Aluminium	839 000
Wood	105 000
Polyurethane	85 000
Stainless steel	72 500
Paint	40 000
Glue	21 000
Synthetic rubber	20 000
Polyvinyl chloride	10 000
Polyethylene	3500
Activated carbon	3000
Copper	1000
Polyester	250
<u>Installation mechanics</u>	*Tot 214 000*
Aluminium	189 905
Stainless steel	23 766
Copper	190
Polyamide	130
Connector	9

Table A2. Material weight distribution of components in the shelter. The total weight of the chairs in operator workstations are declared, however, the distribution and content of the chairs are assumed. The total weight of plastics in the power system is assumed, where the three most common plastics declared from IFS (polyester, polycarbonate, and polyamide) are scaled to match the total weight.

Parts	**Quantity [g]**		**Parts**	**Quantity [g]**		**Parts**	**Quantity [g]**	
Waveguide sys	***(total 4000 g)***		***Cable set***	***(total 64 000 g)***		***Operator workstations***	***(total 130 000 g)***	
	Declared	*Assumed*		*Declared*	*Assumed*		*Declared*	*Assumed*
Stainless steel	58		Copper	360	49641	Polyamide		13000
Aluminum		3959	Aluminium	10		Polyurethane		7000
Polyamide	3		Polyethylene	1701	12063	Aluminium		76000
			Connector	196		Stainless steel	178	25822
			Stainless steel	30		Synthetic rubber		4000
						Computer		4000

Parts	**Quantity [g]**		**Parts**	**Quantity [g]**		**Parts**	**Quantity [g]**		**Parts**	**Quantity [g]**	
Cooling sys	***(total 682 000 g)***		***Power sys***	***(total 959 000 g)***		***Installation mechanics***	***(total 214 000 g)***		**Container**	***(total 1 200 000 g)***	
	Declared	*Assumed*		*Declared*	*Assumed*		*Declared*	*Assumed*		*Declared*	*Assumed*
Computer	38	2963	Aluminium	12	135165	Aluminium	195	189710	Aluminium	839000	
Refrigerant	19200		Copper	5370	64630	Connector	9		Stainless steel	72500	
Aluminum	49000	277532	Stainless steel	935	729065	Stainless steel	766	23000	Copper	1000	
Copper	86413		Lead	19943		Copper	190		Wood	105000	
Stainless steel	227508		Computer	2000		Polyamide	130		Synthetic rubber	20000	
Synthetic rubber	19345		Capacitor	1000					Polyurethane	85000	
			Polyester		250				Glue	21000	
			Polycarbonate		280				Paint	40000	
			Polyamide		350				Polyvinyl chlorid	10000	
									Activated carbor	3000	
									Polyethylene	3500	

Table A3. Material weight distribution of components in the sensor. Glass fibre and epoxy are assumed to have a 70/30 distribution as a composite, even though the declared weights in IFS are distributed differently.

Parts	**Quantity [g]**		**Parts**	**Quantity [g]**		**Parts**	**Quantity [g]**		**Parts**	**Quantity [g]**	
Antenna	***(total 334000 g)***		***Main computer***	***(total 75000 g)***		***Transceiver***	***(total 315000 g)***		***Turntable sys***	***(total 269 000 g)***	
	Declared	*Assumed*		*Declared*	*Assumed*		*Declared*	*Assumed*		*Declared*	*Assumed*
Polysiloxane	234		Copper	511	2489	AC/DC converter	15000		Aluminium		138300
Glass fiber		4500	Aluminium	11	68662	Aluminium	3074	259338	Stainless steel	159	130000
Epoxy	1	10499	Tin	14		Polyethylene terephthalate	2130		Polysiloxane	205	
Aluminium	473	280171	Lead	6		Polyester	1089		Copper	36	
Circuit board	3000		Circuit board	3001		Stainless steel	1349	25652	Circuit board	17	284
Stainless steel	39	29961	Stainless steel	205		Ceramics	32				
Copper	846	4154	Polysiloxane	102		Copper	6205				
Tin	34					Epoxy	142				
Zinc	89					Glass fiber	331				
						Lead	288				
						Tin	370				

Appendix B

Unit processes for material production and processing as modelled in OpenLCA.

Table B1. Unit process for antenna production, including material production and processing.

Input	Quantity	Unit	Dataset
Material production			
Aluminium	280 000	g	Market for aluminum, cast alloy | aluminum, cast alloy | Cutoff, U - GLO
Circuit board[1]	3000	g	Market for integrated circuit, logic type | integrated circuit, logic type | Cutoff, U - GLO
Copper	5000	g	Market for copper, cathode | copper, cathode | Cutoff, U - GLO
Epoxy	11 000	g	Market for epoxy resin, liquid | epoxy resin, liquid | Cutoff, U - RER
Glass fibre	4500	g	Market for glass fibre | glass fibre | Cutoff, U - GLO
Polysiloxane[2]	230	g	Market for silicone product | silicone product | Cutoff, U - GLO
Stainless steel	30 000	g	Market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, U - GLO
Tin[3]	34	g	Market for tin | tin | Cutoff, U - GLO
Zinc	89	g	Market for zinc | zinc | Cutoff, U- GLO
Material processing			
Aluminium working	280 000	g	Market for metal working, average for aluminum product manufacturing | metal working, average for aluminum product manufacturing | Cutoff, U - GLO

[1] This input includes both material production and processing.
[2] This input includes both material production and processing.
[3] This input includes both material production and processing.

Copper working	5000	g	Market for metal working, average for copper product manufacturing | metal working, average for copper product manufacturing | Cutoff, U - GLO
Epoxy, glass fibre working[4]	15 000	g	Market for injection moulding | injection moulding | Cutoff, U - GLO
Stainless steel working	30 000	g	Market for metal working, average for chromium steel product manufacturing | metal working, average for chromium steel product manufacturing | Cutoff, U - GLO
Zinc working	89	g	Market for metal working, average for metal product manufacturing | metal working, average for metal product manufacturing | Cutoff, U - GLO
Output	**Quantity**	**Unit**	**Dataset**
Antenna	1	item	Reference flow

[4] Mixing of epoxy and glass fibre before moulding is excluded.

Table B2. Unit process for cable set production, including material production and processing.

Input	Quantity	Unit	Dataset
Material production			
Aluminium	10	g	Market for aluminum, cast alloy | aluminum, cast alloy | Cutoff, U - GLO
Connector[5]	200	g	Market for electric connector, peripheral component interconnect buss | electric connector, peripheral component interconnect buss | Cutoff, U - GLO
Copper	50 000	g	Market for copper, cathode | copper, cathode | Cutoff, U - GLO
Polyethylene	14 000	g	Market for polyethylene, high density, granulate | polyethylene, high density, granulate | Cutoff, U - GLO
Stainless steel	30	g	Market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, U - GLO
Material processing			
Aluminium working	10	g	Market for metal working, average for aluminum product manufacturing | metal working, average for aluminum product manufacturing | Cutoff, U - GLO
Stainless steel working	30	g	Market for metal working, average for chromium steel product manufacturing | metal working, average for chromium steel product manufacturing | Cutoff, U - GLO
Copper working	50 000	g	Market for metal working, average for copper product manufacturing | metal working, average for copper product manufacturing | Cutoff, U - GLO

[5] This input includes both material production and processing.

Polyethylene moulding	14 000	g	Market for injection moulding | injection moulding | Cutoff, U - GLO
Output	**Quantity**	**Unit**	**Dataset**
Cable set	1	item	Reference flow

Table B3. Unit process for container production, including material production and processing.

Input	Quantity	Unit	Dataset
Material production			
Activated carbon	3000	g	Market for activated carbon, granular | activated carbon, granular | Cutoff, U - GLO
Adhesive[6]	21 000	g	Market for adhesive, for metal | adhesive, for metal | Cutoff, U - RER
Aluminium	840 000	g	Market for aluminum, cast alloy | aluminum, cast alloy | Cutoff, U - GLO
Copper	1000	g	Market for copper, cathode | copper, cathode | Cutoff, U - GLO
Paint[7]	40 000	g	Market for alkyd paint, white, without solvent, in 60% solution state | alkyd paint, white, without solvent, in 60% solution state | Cutoff, U - RER
Polyethylene	3500	g	Market for polyethylene, high density, granulate | polyethylene, high density, granulate | Cutoff, U - GLO
Polyurethane[8]	85 000	g	Market for polyurethane, flexible foam | polyurethane, flexible foam | Cutoff, U - RER

[6] This input includes both material production and processing.
[7] This input includes both material production and processing.
[8] This input includes both material production and processing.

Polyvinyl chloride	10 000	g	Market for polyvinylchloride, bulk polymerised | polyvinylchloride, bulk polymerised | Cutoff, U - GLO
Rubber[9]	20 000	g	Market for synthetic rubber | synthetic rubber | Cutoff, U - GLO
Stainless steel	73 000	g	Market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, U - GLO
Wood[10]	0.19[11]	m^3	Market for plywood | plywood | Cutoff, U - RER
Material processing			
Aluminium working	840 000	g	Market for metal working, average for aluminum product manufacturing | metal working, average for aluminum product manufacturing | Cutoff, U - GLO
Stainless steel working	73 000	g	Market for metal working, average for chromium steel product manufacturing | metal working, average for chromium steel product manufacturing | Cutoff, U - GLO
Copper working	1000	g	Market for metal working, average for copper product manufacturing | metal working, average for copper product manufacturing | Cutoff, U - GLO
Polyethylene extrusion	3500	g	Market for extrusion, plastic pipes | extrusion, plastic pipes | Cutoff, U - GLO
Output	**Quantity**	**Unit**	**Dataset**
Container	1	item	Reference flow

[9] Material processing of this input is excluded.
[10] This input includes both material production and processing.
[11] Quantity of plywood specified as m^3 in OpenLCA, where a density of 550 kg/m^3 is used to convert the unit

Table B4. Unit process for cooling system production, including material production and processing.

Input	Quantity	Unit	Dataset
Material production			
Aluminium	330 000	g	Market for aluminum, cast alloy | aluminum, cast alloy | Cutoff, U - GLO
Computer[12]	0.27[13]	item	Market for computer, desktop, without screen | computer, desktop, without screen | Cutoff, U - GLO
Coolant[14]	19 000	g	Market for refrigerant R134a | refrigerant R134a | Cutoff, U - GLO
Copper	86 000	g	Market for copper, cathode | copper, cathode | Cutoff, U - GLO
Rubber[15]	19 000	g	Market for synthetic rubber | synthetic rubber | Cutoff, U - GLO
Stainless steel	228 000	g	Market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, U - GLO
Material processing			
Aluminium working	327 000	g	Market for metal working, average for aluminum product manufacturing | metal working, average for aluminum product manufacturing | Cutoff, U - GLO
Stainless steel working	228 000	g	Market for metal working, average for chromium steel product manufacturing | metal working, average for chromium steel product manufacturing | Cutoff, U - GLO
Copper working	86 000	g	Market for metal working, average for copper product manufacturing | metal working, average for copper product manufacturing | Cutoff, U - GLO

[12] This input includes both material production and processing.
[13] The quantity adjusted based on the weight of 1 item in the dataset.
[14] This input includes both material production and processing.
[15] Material processing of this input is excluded.

Output	Quantity	Unit	Dataset
Cooling system	1	item	Reference flow

Table B5. Unit process for installation mechanics production, including material production and processing.

Input	Quantity	Unit	Dataset
Material production			
Aluminium	190 000	g	Market for aluminum, cast alloy | aluminum, cast alloy | Cutoff, U - GLO
Connector[16]	9	g	Market for electric connector, peripheral component interconnect buss | electric connector, peripheral component interconnect buss | Cutoff, U - GLO
Copper	190	g	Market for copper, cathode | copper, cathode | Cutoff, U - GLO
Polyamide	130	g	Market for nylon 6-6 | nylon 6-6 | Cutoff, U - RER
Stainless steel	24 000	g	Market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, U - GLO
Material processing			
Aluminium working	190 000	g	Market for metal working, average for aluminum product manufacturing | metal working, average for aluminum product manufacturing | Cutoff, U - GLO
Stainless steel working	24 000	g	Market for metal working, average for chromium steel product manufacturing | metal working, average for chromium steel product manufacturing | Cutoff, U - GLO

[16] This input includes both material production and processing.

Copper working	190	g	Market for metal working, average for copper product manufacturing | metal working, average for copper product manufacturing | Cutoff, U - GLO
Polyamide moulding	130	g	Market for injection moulding | injection moulding | Cutoff, U - GLO
Output	**Quantity**	**Unit**	**Dataset**
Installation mechanics	1	item	Reference flow

Table B6. Unit process for main computer production, including material production and processing.

Input	Quantity	Unit	Dataset
Material production			
Aluminium	69 000	g	Market for aluminum, cast alloy | aluminum, cast alloy | Cutoff, U - GLO
Copper	3000	g	Market for copper, cathode | copper, cathode | Cutoff, U - GLO
Circuit board[17]	3000	g	Market for integrated circuit, logic type | integrated circuit, logic type | Cutoff, U - GLO
Lead	6	g	Market for lead | lead | Cutoff, U - GLO
Polysiloxane[18]	100	g	Market for silicone product | silicone product | Cutoff, U - GLO
Stainless steel	200	g	Market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, U - GLO
Tin[19]	14	g	Market for tin | tin | Cutoff, U - GLO

[17] This input includes both material production and processing.
[18] This input includes both material production and processing.
[19] This input includes both material production and processing.

Material processing			
Aluminium working	69 000	g	Market for metal working, average for aluminum product manufacturing | metal working, average for aluminum product manufacturing | Cutoff, U - GLO
Stainless steel working	200	g	Market for metal working, average for chromium steel product manufacturing | metal working, average for chromium steel product manufacturing | Cutoff, U - GLO
Copper working	3000	g	Market for metal working, average for copper product manufacturing | metal working, average for copper product manufacturing | Cutoff, U - GLO
Lead working	6	g	market for metal working, average for metal product manufacturing | metal working, average for metal product manufacturing | Cutoff, U - GLO
Output	**Quantity**	**Unit**	**Dataset**
Main computer	1	item	Reference flow

Table B7. Unit process for operator workstations production, including material production and processing.

Input	Quantity	Unit	Dataset
Material production			
Aluminium	76 000	g	Market for aluminum, cast alloy | aluminum, cast alloy | Cutoff, U - GLO
Computer[20]	1.3[21]	item	Market for computer, laptop | computer, laptop | Cutoff, U - GLO
Polyamide	13 000	g	Market for nylon 6-6 | nylon 6-6 | Cutoff, U - RER
Polyurethane[22]	7000	g	Market for polyurethane, flexible foam | polyurethane, flexible foam | Cutoff, U - RER

[20] This input includes both material production and processing.
[21] The quantity adjusted based on the weight of 1 item in the dataset.
[22] This input includes both material production and processing.

Rubber[23]	4000	g	Market for synthetic rubber | synthetic rubber | Cutoff, U - GLO
Stainless steel	26 000	g	Market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, U - GLO
Material processing			
Aluminium working	76 000	g	Market for metal working, average for aluminum product manufacturing | metal working, average for aluminum product manufacturing | Cutoff, U - GLO
Stainless steel working	26 000	g	Market for metal working, average for chromium steel product manufacturing | metal working, average for chromium steel product manufacturing | Cutoff, U - GLO
Polyamide moulding	13 000	g	Market for injection moulding | injection moulding | Cutoff, U - GLO
Output	**Quantity**	**Unit**	**Dataset**
Operator workstations	1	item	Reference flow

Table B8. Unit process for power system production, including material production and processing.

Input	**Quantity**	**Unit**	**Dataset**
Material production			
Aluminium	135 000	g	Market for aluminum, cast alloy | aluminum, cast alloy | Cutoff, U - GLO
Capacitor[24]	1000	g	Market for capacitor, electrolyte type, > 2cm height | capacitor, electrolyte type, > 2cm height | Cutoff, U - GLO

[23] Material processing of this input is excluded.
[24] This input includes both material production and processing.

Computer[25]	0.2[26]	item	Market for computer, desktop, without screen | computer, desktop, without screen | Cutoff, U - GLO
Copper	70 000	g	Market for copper, cathode | copper, cathode | Cutoff, U - GLO
Lead	20 000	g	Market for lead | lead | Cutoff, U - GLO
Polyamide	350	g	Market for nylon 6-6 | nylon 6-6 | Cutoff, U - RER
Polycarbonate	280	g	Market for polycarbonate | polycarbonate | Cutoff, U - GLO
Polyester	250	g	Market for fibre, polyester | fibre, polyester | Cutoff, U - RER
Stainless steel	730 000	g	Market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, U - GLO
Material processing			
Aluminium working	135 000	g	Market for metal working, average for aluminum product manufacturing | metal working, average for aluminum product manufacturing | Cutoff, U - GLO
Stainless steel working	730 000	g	Market for metal working, average for chromium steel product manufacturing | metal working, average for chromium steel product manufacturing | Cutoff, U - GLO
Copper working	70 000	g	Market for metal working, average for copper product manufacturing | metal working, average for copper product manufacturing | Cutoff, U - GLO
Lead working	20 000	g	Market for metal working, average for metal product manufacturing | metal working, average for metal product manufacturing | Cutoff, U - GLO
Polyester, polyamide and polycarbonate moulding	880	g	Market for injection moulding | injection moulding | Cutoff, U - GLO

[25] This input includes both material production and processing.
[26] The quantity adjusted based on the weight of 1 item in the dataset.

Output	Quantity	Unit	Dataset
Power system	1	item	Reference flow

Table B9. Unit process for transceiver production, including material production and processing.

Input	Quantity	Unit	Dataset
Material production			
Aluminium	260 000	g	Market for aluminum, cast alloy | aluminum, cast alloy | Cutoff, U - GLO
Ceramics	32	g	Market for aluminium oxide, metallurgical | aluminium oxide, metallurgical | Cutoff, U - RoW
Converter[27]	15 000	g	Market for converter, for electric passenger car | converter, for electric passenger car | Cutoff, U - GLO
Copper	6200	g	Market for copper, cathode | copper, cathode | Cutoff, U - GLO
Epoxy	140	g	Market for epoxy resin, liquid | epoxy resin, liquid | Cutoff, U - RER
Glass fibre	330	g	Market for glass fibre | glass fibre | Cutoff, U - GLO
Lead	290	g	Market for lead | lead | Cutoff, U - GLO
Polyethylene terephthalate	2100	g	Market for polyethylene terephthalate, granulate, amorphous | polyethylene terephthalate, granulate, amorphous | Cutoff, U - GLO
Polyester	1100	g	Market for fibre, polyester | fibre, polyester | Cutoff,

[27] This input includes both material production and processing.

			U - RER
Stainless steel	27 000	g	Market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, U - GLO
Tin[28]	370	g	Market for tin | tin | Cutoff, U - GLO
Material processing			
Aluminium working	260 000	g	Market for metal working, average for aluminum product manufacturing | metal working, average for aluminum product manufacturing | Cutoff, U - GLO
Stainless steel working	27 000	g	Market for metal working, average for chromium steel product manufacturing | metal working, average for chromium steel product manufacturing | Cutoff, U - GLO
Copper working	6200	g	Market for metal working, average for copper product manufacturing | metal working, average for copper product manufacturing | Cutoff, U - GLO
Lead working	290	g	Market for metal working, average for metal product manufacturing | metal working, average for metal product manufacturing | Cutoff, U - GLO
Epoxy, polyester, glass fibre, polyethylene terephthalate moulding	3700	g	Market for injection moulding | injection moulding | Cutoff, U - GLO
Output	**Quantity**	**Unit**	**Dataset**
Transceiver	1	item	Reference flow

[28] This input includes both material production and processing.

Table B10. Unit process for turntable system production, including material production and processing.

Input	Quantity	Unit	Dataset
Material production			
Aluminium	140 000	g	Market for aluminum, cast alloy | aluminum, cast alloy | Cutoff, U - GLO
Circuit board[29]	300	g	Market for integrated circuit, logic type | integrated circuit, logic type | Cutoff, U - GLO
Copper	36	g	Market for copper, cathode | copper, cathode | Cutoff, U - GLO
Polysiloxane[30]	200	g	Market for silicone product | silicone product | Cutoff, U - GLO
Stainless steel	130 000	g	Market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, U - GLO
Material processing			
Aluminium working	140 000	g	Market for metal working, average for aluminum product manufacturing | metal working, average for aluminum product manufacturing | Cutoff, U - GLO
Stainless steel working	130 000	g	Market for metal working, average for chromium steel product manufacturing | metal working, average for chromium steel product manufacturing | Cutoff, U - GLO
Copper working	36	g	Market for metal working, average for copper product manufacturing | metal working, average for copper product manufacturing | Cutoff, U - GLO
Output	**Quantity**	**Unit**	**Dataset**
Turntable sys	1	item	Reference flow

[29] This input includes both material production and processing.
[30] This input includes both material production and processing.

Table B11. Unit process for waveguide system production, including material production and processing.

Input	Quantity	Unit	Dataset
Material production			
Aluminium	4000	g	Market for aluminum, cast alloy | aluminum, cast alloy | Cutoff, U - GLO
Polyamide	3	g	Market for nylon 6-6 | nylon 6-6 | Cutoff, U - RER
Stainless steel	38	g	Market for steel, chromium steel 18/8 | steel, chromium steel 18/8 | Cutoff, U - GLO
Material processing			
Aluminium working	4000	g	Market for metal working, average for aluminum product manufacturing | metal working, average for aluminum product manufacturing | Cutoff, U - GLO
Stainless steel working	38	g	Market for metal working, average for chromium steel product manufacturing | metal working, average for chromium steel product manufacturing | Cutoff, U - GLO
Polyamide moulding	3	g	Market for injection moulding | injection moulding | Cutoff, U - GLO
Output	**Quantity**	**Unit**	**Dataset**
Waveguide system	1	item	Reference flow

Appendix C

Unit process for use and maintenance as modelled in OpenLCA.

Table C1. Unit process for use and maintenance.

Use and maintenance			
Material	**Quantity**	**Unit**	**Dataset**
Input			
Arthur replaced components[31]	1	item	Arthur replacement components, production - GLO
Arthur verified and tested	1	item	Arthur verification and testing - SE
Diesel consumption over one lifespan, radar	1 300 000[32]	kWh	Market for diesel, burned in agricultural machinery | diesel, burned in agricultural machinery | Cutoff, U - GLO
Diesel consumption over one lifespan, vehicle	2 000 000[33]	kWh	Market for diesel, burned in agricultural machinery | diesel, burned in agricultural machinery | Cutoff, U - GLO
Transport, assembly to use	14 000	t · km	Market for transport, freight, lorry, unspecified | transport, freight, lorry, unspecified | Cutoff, U - RER
Output			
Arthur discarded	1	item	Waste flow, to unit process in Table 4.4
Arthur used	1	item	Reference flow

[31] Arthur replaced components include all figures presented in Table 4.3.
[32] The quantity is calculated with the unit conversion of 1 litre = 9.96 kWh.
[33] The quantity is calculated with the unit conversion of 1 litre = 9.96 kWh.

Appendix D

Impact assessment results from all 19 impact categories.

Table D1. Total impact results.

Impact category	Result	Reference unit	LCIA method
Crustal scarcity indicator	197 000 000	kg Si-eq	CSI
Terrestrial ecotoxicity	7 300 000	kg 1,4-DCB-eq	ReCiPe midpoint
Human toxicity, non-cancerogenic	6 300 000	kg 1,4-DCB-eq	ReCiPe midpoint
Global warming	1 700 000	kg CO_2-eq	ReCiPe midpoint
Fossil fuel	470 000	kg oil-eq	ReCiPe midpoint
Human toxicity, cancerogenic	150 000	kg 1,4-DCB-eq	ReCiPe midpoint
Land occupation	140 000	m^2·yr-eq	ReCiPe midpoint
Marine ecotoxicity	130 000	kg 1,4-DCB-eq	ReCiPe midpoint
Freshwater ecotoxicity	97 000	kg 1,4-DCB-eq	ReCiPe midpoint
Surplus ore	55 000	kg Cu-eq	ReCiPe midpoint
Ionising radiation	25 000	kBq Co-60-eq	ReCiPe midpoint
Photochemical oxidant formation, ecosystems	13 000	kg NO_x-eq	ReCiPe midpoint
Photochemical oxidant formation, humans	13 000	kg NO_x-eq	ReCiPe midpoint
Terrestrial acidification	7300	kg SO_2-eq	ReCiPe midpoint
Particulate matter formation	4000	kg PM2.5-eq	ReCiPe midpoint
Water consumption	3900	m^3-eq	ReCiPe midpoint
Freshwater eutrophication	270	kg P-eq	ReCiPe midpoint
Marine eutrophication	50	kg N-eq	ReCiPe midpoint
Ozone depletion	0.57	kg CFC-11-eq	ReCiPe midpoint

Table D2. Impact results from material production and processing.

Impact category	**Result**	**Reference unit**	**LCIA method**
Crustal scarcity indicator	36 000 000	kg Si-eq	CSI
Terrestrial ecotoxicity	1 300 000	kg 1,4-DCB-eq	ReCiPe midpoint
Human toxicity, non-cancerogenic	320 000	kg 1,4-DCB-eq	ReCiPe midpoint
Global warming	48 000	kg CO_2-eq	ReCiPe midpoint
Marine ecotoxicity	35 000	kg 1,4-DCB-eq	ReCiPe midpoint
Freshwater ecotoxicity	27 000	kg 1,4-DCB-eq	ReCiPe midpoint
Human toxicity, cancerogenic	19 000	kg 1,4-DCB-eq	ReCiPe midpoint
Fossil fuel	11 000	kg oil-eq	ReCiPe midpoint
Ionising radiation	2700	kBq Co-60-eq	ReCiPe midpoint
Surplus ore	2500	kg Cu-eq	ReCiPe midpoint
Land occupation	1600	m^2·yr-eq	ReCiPe midpoint
Water consumption	360	m^3-eq	ReCiPe midpoint
Terrestrial acidification	300	kg SO_2-eq	ReCiPe midpoint
Photochemical oxidant formation, ecosystems	140	kg NO_x-eq	ReCiPe midpoint
Photochemical oxidant formation, humans	140	kg NO_x-eq	ReCiPe midpoint
Particulate matter formation	140	kg PM2.5-eq	ReCiPe midpoint
Freshwater eutrophication	40	kg P-eq	ReCiPe midpoint
Marine eutrophication	2.7	kg N-eq	ReCiPe midpoint
Ozone depletion	0.03	kg CFC-11-eq	ReCiPe midpoint

Table D3. Impact results from transports.

Impact category	**Result**	**Reference unit**	**LCIA method**
Crustal scarcity indicator	370 000	kg Si-eq	CSI
Terrestrial ecotoxicity	83 000	kg 1,4-DCB-eq	ReCiPe midpoint
Global warming	4100	kg CO_2-eq	ReCiPe midpoint
Human toxicity, non-cancerogenic	3300	kg 1,4-DCB-eq	ReCiPe midpoint
Fossil fuel	1300	kg oil-eq	ReCiPe midpoint
Human toxicity, cancerogenic	210	kg 1,4-DCB-eq	ReCiPe midpoint
Land occupation	210	m^2·yr-eq	ReCiPe midpoint
Marine ecotoxicity	180	kg 1,4-DCB-eq	ReCiPe midpoint
Freshwater ecotoxicity	110	kg 1,4-DCB-eq	ReCiPe midpoint
Surplus ore	81	kg Cu-eq	ReCiPe midpoint
Ionising radiation	58	kBq Co-60-eq	ReCiPe midpoint
Photochemical oxidant formation, ecosystems	21	kg NO_x-eq	ReCiPe midpoint
Photochemical oxidant formation, humans	20	kg NO_x-eq	ReCiPe midpoint
Terrestrial acidification	11	kg SO_2-eq	ReCiPe midpoint
Water consumption	9.3	m^3-eq	ReCiPe midpoint
Particulate matter formation	4.9	kg PM2.5-eq	ReCiPe midpoint
Freshwater eutrophication	0.32	kg P-eq	ReCiPe midpoint
Marine eutrophication	0.12	kg N-eq	ReCiPe midpoint
Ozone depletion	0.00	kg CFC-11-eq	ReCiPe midpoint

Table D4. Impact results from assembly.

Impact category	Result	Reference unit	LCIA method
Crustal scarcity indicator	1200	kg Si-eq	CSI
Terrestrial ecotoxicity	80	kg 1,4-DCB-eq	ReCiPe midpoint
Ionising radiation	55	kBq Co-60-eq	ReCiPe midpoint
Human toxicity, non-cancerogenic	18	kg 1,4-DCB-eq	ReCiPe midpoint
Global warming	6.8	kg CO_2-eq	ReCiPe midpoint
Land occupation	2.4	m^2·yr-eq	ReCiPe midpoint
Marine ecotoxicity	1.4	kg 1,4-DCB-eq	ReCiPe midpoint
Freshwater ecotoxicity	1.1	kg 1,4-DCB-eq	ReCiPe midpoint
Fossil fuel	1.1	kg oil-eq	ReCiPe midpoint
Human toxicity, cancerogenic	0.97	kg 1,4-DCB-eq	ReCiPe midpoint
Water consumption	0.84	m^3-eq	ReCiPe midpoint
Surplus ore	0.23	kg Cu-eq	ReCiPe midpoint
Terrestrial acidification	0.02	kg SO_2-eq	ReCiPe midpoint
Photochemical oxidant formation, ecosystems	0.02	kg NO_x-eq	ReCiPe midpoint
Photochemical oxidant formation, humans	0.02	kg NO_x-eq	ReCiPe midpoint
Particulate matter formation	0.01	kg PM2.5-eq	ReCiPe midpoint
Freshwater eutrophication	0.00	kg P-eq	ReCiPe midpoint
Marine eutrophication	0.00	kg N-eq	ReCiPe midpoint
Ozone depletion	0.00	kg CFC-11-eq	ReCiPe midpoint

Table D5. Impact results from the use phase.

Impact category	Result	Reference unit	LCIA method
Crustal scarcity indicator	150 000 000	kg Si-eq	CSI
Human toxicity, non-cancerogenic	5 900 000	kg 1,4-DCB-eq	ReCiPe midpoint
Terrestrial ecotoxicity	5 800 000	kg 1,4-DCB-eq	ReCiPe midpoint
Global warming	1 600 000	kg CO_2-eq	ReCiPe midpoint
Fossil fuel	450 000	kg oil-eq	ReCiPe midpoint
Land occupation	140 000	m^2·yr-eq	ReCiPe midpoint
Human toxicity, cancerogenic	130 000	kg 1,4-DCB-eq	ReCiPe midpoint
Marine ecotoxicity	86 000	kg 1,4-DCB-eq	ReCiPe midpoint
Freshwater ecotoxicity	66 000	kg 1,4-DCB-eq	ReCiPe midpoint
Surplus ore	52 000	kg Cu-eq	ReCiPe midpoint
Ionising radiation	22 000	kBq Co-60-eq	ReCiPe midpoint
Photochemical oxidant formation, ecosystems	13 000	kg NO_x-eq	ReCiPe midpoint
Photochemical oxidant formation, humans	13 000	kg NO_x-eq	ReCiPe midpoint
Terrestrial acidification	7000	kg SO_2-eq	ReCiPe midpoint
Particulate matter formation	3900	kg PM2.5-eq	ReCiPe midpoint
Water consumption	3500	m^3-eq	ReCiPe midpoint
Freshwater eutrophication	230	kg P-eq	ReCiPe midpoint
Marine eutrophication	46	kg N-eq	ReCiPe midpoint
Ozone depletion	0.54	kg CFC-11-eq	ReCiPe midpoint

Table D6. Impact results from maintenance.

Impact category	**Result**	**Reference unit**	**LCIA method**
Crustal scarcity indicator	6 100 000	kg Si-eq	CSI
Terrestrial ecotoxicity	130 000	kg 1,4-DCB-eq	ReCiPe midpoint
Human toxicity, non-cancerogenic	46 000	kg 1,4-DCB-eq	ReCiPe midpoint
Global warming	6500	kg CO_2-eq	ReCiPe midpoint
Marine ecotoxicity	4700	kg 1,4-DCB-eq	ReCiPe midpoint
Freshwater ecotoxicity	3700	kg 1,4-DCB-eq	ReCiPe midpoint
Human toxicity, cancerogenic	2200	kg 1,4-DCB-eq	ReCiPe midpoint
Fossil fuel	1500	kg oil-eq	ReCiPe midpoint
Ionising radiation	420	kBq Co-60-eq	ReCiPe midpoint
Surplus ore	310	kg Cu-eq	ReCiPe midpoint
Land occupation	200	$m^2 \cdot yr$-eq	ReCiPe midpoint
Water consumption	49	m^3-eq	ReCiPe midpoint
Terrestrial acidification	35	kg SO_2-eq	ReCiPe midpoint
Photochemical oxidant formation, ecosystems	20	kg NO_x-eq	ReCiPe midpoint
Photochemical oxidant formation, humans	19	kg NO_x-eq	ReCiPe midpoint
Particulate matter formation	17	kg PM2.5-eq	ReCiPe midpoint
Freshwater eutrophication	5.9	kg P-eq	ReCiPe midpoint
Marine eutrophication	0.39	kg N-eq	ReCiPe midpoint
Ozone depletion	0.00	kg CFC-11-eq	ReCiPe midpoint

Table D7. Impact results from EoL.

Impact category	**Result**	**Reference unit**	**LCIA method**
Global warming	16 000	kg CO_2-eq	ReCiPe midpoint
Human toxicity, non-cancerogenic	2000	kg 1,4-DCB-eq	ReCiPe midpoint
Terrestrial ecotoxicity	340	kg 1,4-DCB-eq	ReCiPe midpoint
Marine ecotoxicity	91	kg 1,4-DCB-eq	ReCiPe midpoint
Freshwater ecotoxicity	65	kg 1,4-DCB-eq	ReCiPe midpoint
Human toxicity, cancerogenic	9.8	kg 1,4-DCB-eq	ReCiPe midpoint
Fossil fuel	5	kg oil-eq	ReCiPe midpoint
Surplus ore	0.96	kg Cu-eq	ReCiPe midpoint
Water consumption	0.74	m^3-eq	ReCiPe midpoint
Ionising radiation	0.50	kBq Co-60-eq	ReCiPe midpoint
Land occupation	0.48	$m^2 \cdot yr$-eq	ReCiPe midpoint
Photochemical oxidant formation, ecosystems	0.18	kg NO_x-eq	ReCiPe midpoint
Photochemical oxidant formation, humans	0.18	kg NO_x-eq	ReCiPe midpoint
Terrestrial acidification	0.098	kg SO_2-eq	ReCiPe midpoint
Particulate matter formation	0.037	kg PM2.5-eq	ReCiPe midpoint
Freshwater eutrophication	0.0068	kg P-eq	ReCiPe midpoint
Marine eutrophication	0.0047	kg N-eq	ReCiPe midpoint
Crustal scarcity indicator	0.0025	kg Si-eq	CSI
Ozone depletion	0.0019	kg CFC-11-eq	ReCiPe midpoint

Appendix E

Results of each component´s contribution in relation to their weight.

Table E1. Global warming. The results have been calculated by dividing the impact results with each component´s weight in kg. The component characterised by the greatest kg CO_2-eq per kg weight is scaled to one unit, against which the remaining components' emissions are proportionally related.

Component	**kg CO_2-eq / kg weight**	**Component / component with highest [kg CO_2-eq / kg weight] (i.e., main computer)**
Main computer	5534 / 75 = 74	74 / 74 = 1
Antenna	7994 / 334 = 24	24 / 74 = 0.32
Cable set	564 / 64 = 8.8	8.8 / 74 = 0.12
Container	9890 / 1200 = 8.2	8.2 / 74 = 0.11
Cooling system	6378 / 682 = 9.4	9.4 / 74 = 0.13
Installation mechanics	2091 / 214 = 9.8	9.8 / 74 = 0.13
Operator workstations	1362 / 130 = 10	10 / 74 = 0.14
Power system	7964 / 959 = 8.3	8.3 / 74 = 0.11
Transceiver	3546 / 315 = 11	11 / 74 = 0.15
Turntable	2889 / 269 = 11	11 / 74 = 0.15
Waveguide system	40 / 4 = 10	10 / 74 = 0.14

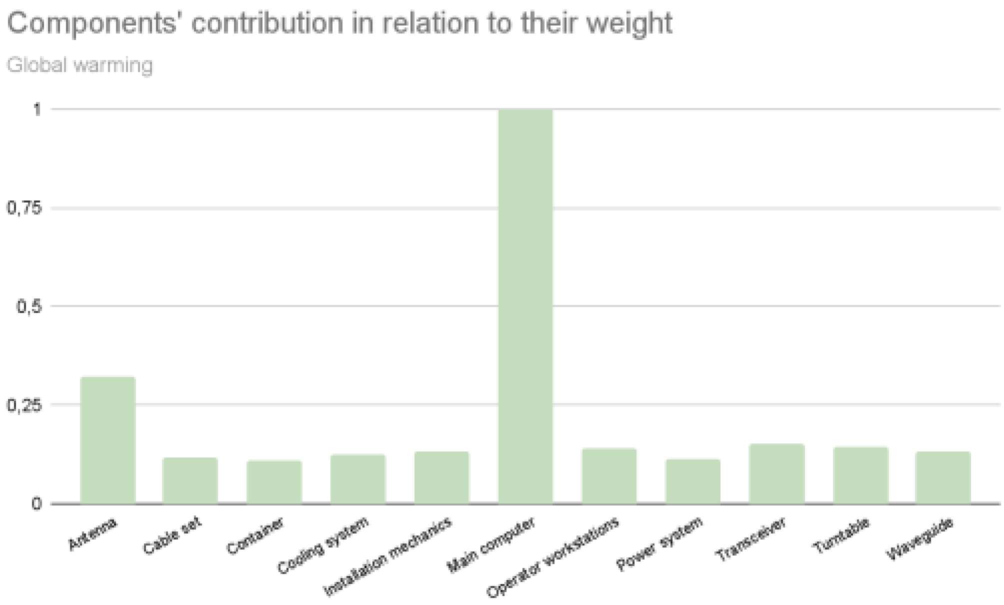

Figure E1. Global warming results for each component in relation to their weight, scaled based on the component with the highest global warming per weight (main computer). Calculations for Figure E1 can be found in Table E1.

Table E2. Fossil fuel. The results have been calculated by dividing the impact results with each component´s weight in kg. The component characterised by the greatest kg oil-eq per kg weight, is designated as one unit, against which the remaining components' emissions are proportionally determined.

Component	**kg oil-eq / kg weight**	**Component / component with highest [kg oil-eq / kg weight]***
Main computer	1357 / 75 = 18*	18 / 18 = 1
Antenna	1908 / 334 = 5.7	5.7 / 18 = 0.32
Cable set	154 / 64 = 2.4	2.4 / 18 = 0.13
Container	2284 / 1200 = 1.9	1.9 / 18 = 0.11
Cooling system	1433 / 682 = 2.1	2.1 / 18 = 0.12
Installation mechanics	457 / 214 = 2.1	2.1 / 18 = 0.12
Operator workstations	328 / 130 = 2.5	2.5 / 18 = 0.14
Power system	1854 / 959 = 1.9	1.9 / 18 = 0.11
Transceiver	787 / 315 = 2.5	2.5 / 18 = 0.14
Turntable	660 / 269 = 2.5	2.5 / 18 = 0.14
Waveguide system	8.7 / 4 = 2.2	2.2 / 18 = 0.12

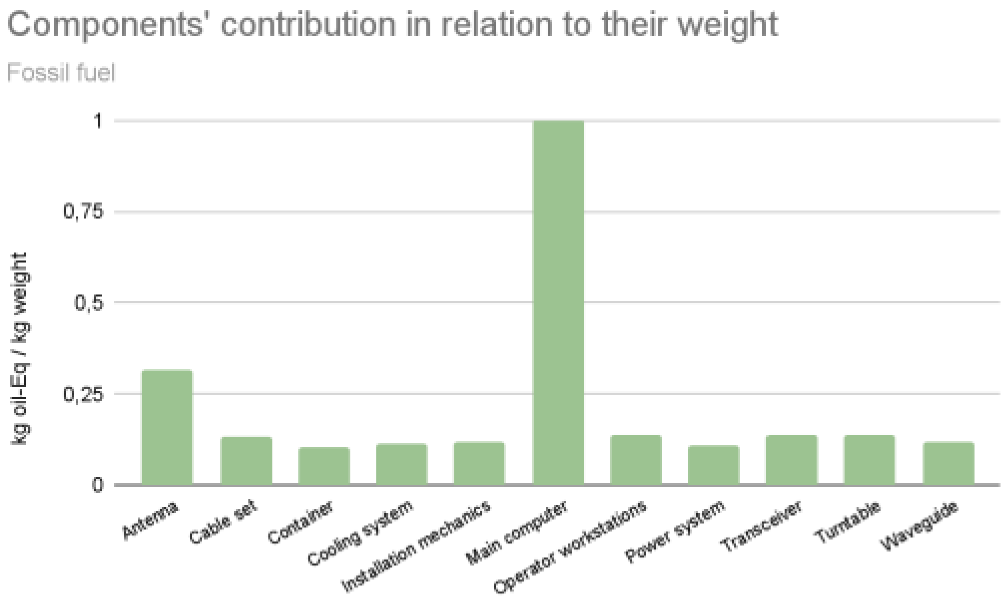

Figure E2. Fossil fuel results for each component in relation to their weight, scaled based on the component with the highest fossil fuel per weight (main computer). Calculations for Figure E2 can be found in Table E2.

Table E3. Surplus ore. The results have been calculated by dividing the impact results with each component´s weight in kg. The component characterised by the greatest kg Cu-eq per kg weight, is designated as one unit, against which the remaining components' emissions are proportionally determined.

Component	**kg Cu-eq / kg weight**	**Component / component with highest [kg Cu-eq / kg weight]***
Main computer	221 / 75 = 2.9*	2.9 / 2.9 = 1
Antenna	283 / 334 = 0.85	0.85 / 2.9 = 0.29
Cable set	110 / 64 = 1.7	1.7 / 2.9 = 0.58
Container	220 / 1200 = 0.18	0.18 / 2.9 = 0.062
Cooling system	643 / 682 = 0.94	0.94 / 2.9 = 0.32
Installation mechanics	48 / 214 = 0.22	0.22 / 2.9 = 0.076
Operator workstations	40 / 130 = 0.31	0.31 / 2.9 = 0.10
Power system	669 / 959 = 0.69	0.69 / 2.9 = 0.24
Transceiver	99 / 315 = 0.32	0.32 / 2.9 = 0.11
Turntable	129 / 269 = 0.48	0.48 / 2.9 = 0.16
Waveguide system	0.69 / 4 = 0.17	0.17 / 2.9 = 0.058

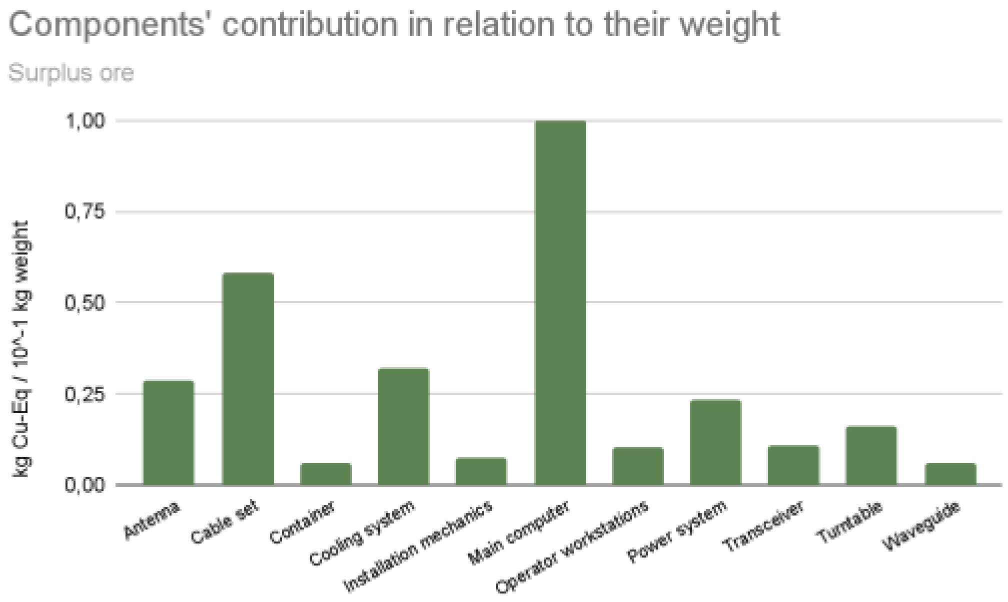

Figure E3. Surplus ore results for each component in relation to their weight, scaled based on the component with the highest surplus ore per weight (main computer). Calculations for Figure E3 can be found in Table E3.

Table E4. Terrestrial acidification. The results have been calculated by dividing the impact results with each component´s weight in kg. The component characterised by the greatest kg SO_2-eq per kg weight, is designated as one unit, against which the remaining components' emissions are proportionally determined.

Component	**kg SO_2-eq / kg weight**	**Component / component with highest [kg SO_2-eq / kg weight]***
Main computer	24 / 75 = 0.32*	0.32 / 0.40 = 0.80
Antenna	35 / 334 = 0.10	0.10 / 0.40 = 0.26
Cable set	26 / 64 = 0.40	0.40 / 0.40 = 1
Container	41 / 1200 = 0.035	0.035 / 0.40 = 0.086
Cooling system	65 / 682 = 0.095	0.095 / 0.40 = 0.24
Installation mechanics	8.6 / 214 = 0.040	0.040 / 0.40 = 0.10
Operator workstations	5.3 / 130 = 0.041	0.041 / 0.40 = 0.10
Power system	62 / 959 = 0.065	0.065 / 0.40 = 0.16
Transceiver	18 / 315 = 0.059	0.059 / 0.40 = 0.15
Turntable	11 / 269 = 0.042	0.042 / 0.40 = 0.11
Waveguide system	0.16 / 4 = 0.04	0.04 / 0.40 = 0.10

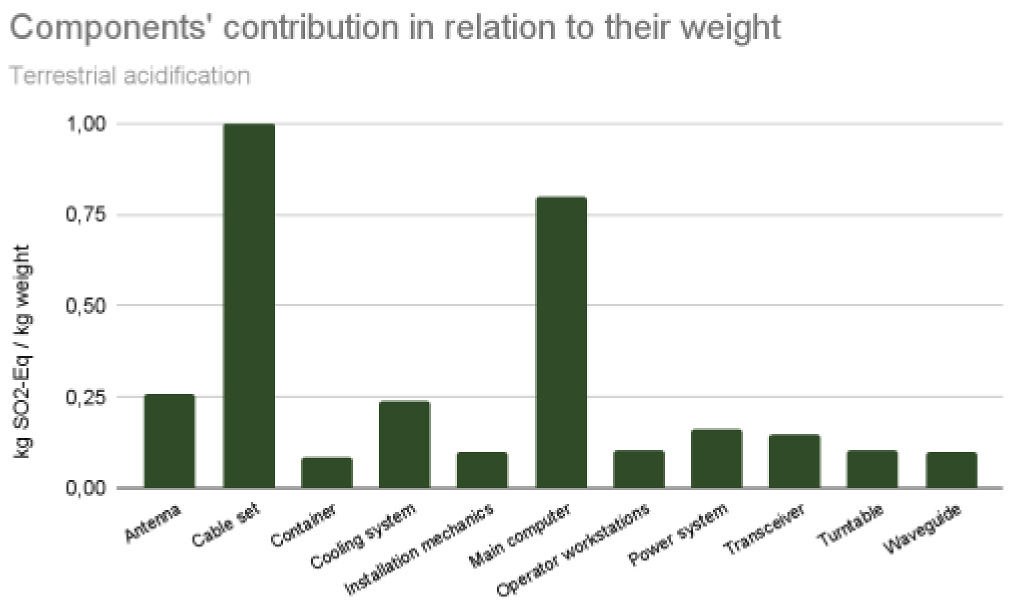

Figure E4. Terrestrial acidification results for each component in relation to their weight, scaled based on the component with the highest terrestrial acidification per weight (cable set). Calculations for Figure E4 can be found in Table E4.

Appendix F

Results from comparisons with LCA2015.

Figure F1. Impact category comparison, in percentage. The sum of LCA2015 and LCA2023 represents 100%. The exclusion of material resources, photochemical oxidant formation, ionising radiation, and particulate matter formation from Figure F1 is because of the dissimilarity in their units, rendering them irrelevant for direct comparison.

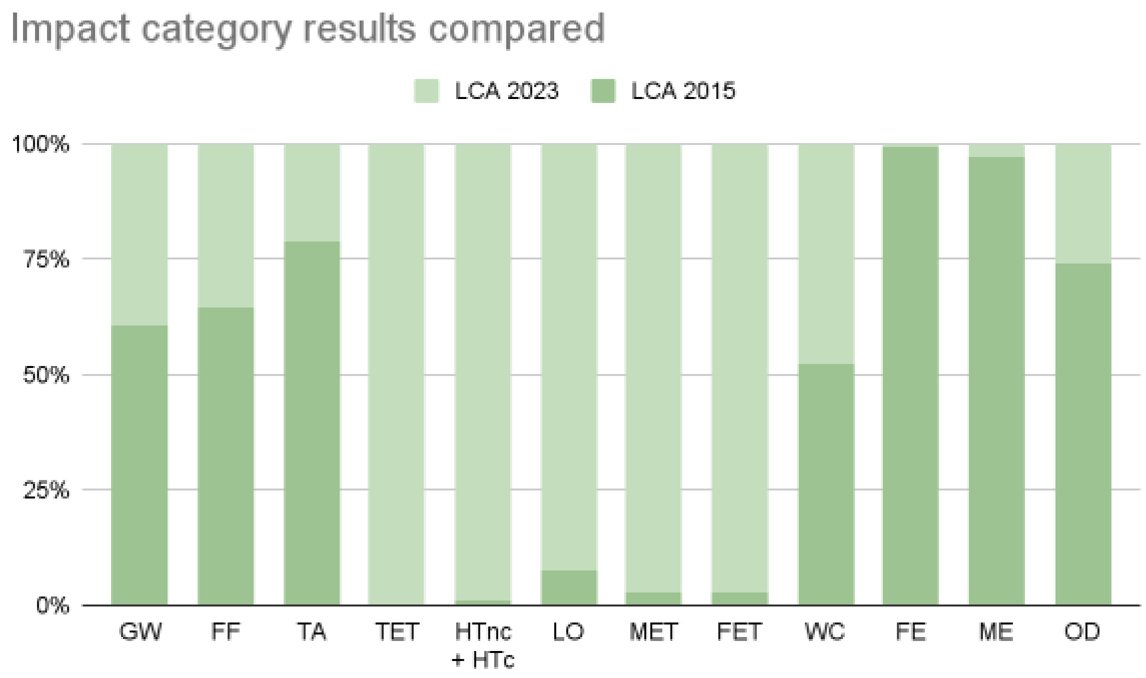

Table F1. Impact category comparison, in figures and with each individual's reference unit.

	LCA2023			LCA2015		
	Abbreviation	**Result**	**Reference unit**	**Abbreviation**	**Result**	**Reference unit**
Terrestrial ecotoxicity	TET	7 300 000	kg 1,4 DCB-eq	TET	60	kg 14 DCB-eq
Global warming	GW	1 700 000	kg CO_2-eq	CC	260 000	kg CO_2-eq
Fossil fuel	FF	470 000	kg oil-eq	FD	850 000	kg oil-eq
Land occupation	LO	140 000	m^2·yr-eq	ALO + ULO	11 000	m^2·yr-eq
Marine ecotoxicity	MET	130 000	kg 1,4 DCB-eq	MET	3800	kg 1,4 DCB-eq
Freshwater ecotoxicity	FET	97 000	kg 1,4 DCB-eq	FET	2800	kg 1,4 DCB-eq
Human toxicity	HTnc + HTc	67 000	kg 1,4 DCB-eq	HT	67 000	kg 1,4 DCB-eq
Surplus ore	SO	55 000	kg Cu-eq	MRD	73 000	kg Fe-eq
Photochemical oxidant formation	EOF + HOF	45 000	kg NO_x-eq	POF	45 000	kg NMVOC-eq
Ionising radiation	IR	25 000	kBq Co-60-eq	IR	92 000	kg U235-eq
Terrestrial acidification	TA	7300	kg SO_2-eq	TA	27 000	kg SO_2-eq
Particulate matter formation	PMF	4000	kg PM2.5-eq	PMF	15 000	kg PM10-eq
Water consumption	WC	3900	m^3-eq	WD	4200	m^3-eq
Freshwater	FE	270	kg P-eq	FE	45 000	kg P-eq

eutrophication						
Marine eutrophication	ME	49	kg N-eq	ME	1600	kg N-eq
Ozone depletion	OD	0.57	kg CFC-11-eq	OD	1.6	kg CFC-11-eq

Appendix G

Results from uncertainty analysis.

Table G1. Compared uncertainty analysis results for all impact categories, diesel and FAME.

Impact category	Reference unit	Diesel result	FAME result
Crustal scarcity indicator	kg Si-eq	280 000 000	120 000 000
Human toxicity, non-cancerogenic	kg 1,4 DCB-eq	5 900 000	8 300 000
Terrestrial ecotoxicity	kg 1,4 DCB-eq	5 800 000	7 200 000
Land occupation	m^2·yr-eq	140 000	2 000 000
Global warming	kg CO_2-eq	1 600 000	1 100 000
Fossil fuel	kg oil-eq	450 000	240 000
Human toxicity, cancerogenic	kg 1,4 DCB-eq	130 000	140 000
Marine ecotoxicity	kg 1,4 DCB-eq	86 000	110 000
Freshwater ecotoxicity	kg 1,4 DCB-eq	65 000	83 000
Surplus ore	kg Cu-eq	52 000	56 000
Ionising radiation	kBq Co-60-eq	22 000	48 000
Water consumption	m^3-eq	3500	27 000
Photochemical oxidant formation, ecosystems	kg NO_x-eq	13 000	24 000
Photochemical oxidant formation, humans	kg NO_x-eq	13 000	24 000
Terrestrial acidification	kg SO_2-eq	7000	19 000
Particulate matter formation	kg PM2.5-eq	3900	6100
Marine eutrophication	kg N-eq	46	4000
Freshwater eutrophication	kg P-eq	65 000	370
Ozone depletion	kg CFC-11-eq	0.53	10

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