Life Cycle Assessment of a Camera System for Automobiles

Master's thesis in Industrial Ecology

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Abstract

Today, there is a growing need for companies in different industries to disclose and report their environmental impact. This is the case for Magna company, which assembles a variety of automotive electronics.

This study aims to evaluate the environmental performance of Magna’s camera system throughout its lifecycle. To do this, a cradle-to-gate life cycle assessment (LCA) is conducted from raw materials extraction and acquisition to the final product transportation to the customer’s door. This assessment is performed in accordance with the ISO 14040-series. The LCA study is completed utilising OpenLCA software along with the Ecoinvent v3.10 database. Two impact categories are selected to be in focus when assessing the impacts: climate change, and mineral resource scarcity (with two different indicators). The product’s environmental performance is analysed for two scenarios: a base case and an alternative transport.

The key findings indicate that the total environmental performance of the alternative transport scenario, where air cargo is swapped for shipping at sea, is the lowest. The printed circuit board (PCB) is the main contributor to the total impact in both scenarios. A sensitivity analysis is done for the mass of integrated circuits mounted on the PCB, being the major contributor in all impact categories. Consequently, results are relatively sensitive to the integrated circuit mass alterations due to the energy-consuming production of this sub-component and its use of several hazardous and precious substances.

Keywords: LCA, camera system, sustainability, automotive industry, electronics

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List of Acronyms

Acronym	Definition
CFA	Camera Final Assembly
EEE	Electrical and Electronic Equipment
FU	Functional Unit
GHG	Greenhouse Gas
IMDS	International Material Data System
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Sustainability Assessment
OEM	Original Equipment Manufacturer
PCB	Printed Circuit Board
PLM	Product Life Cycle Management
RQ	Research Question
SLCA	Social Life Cycle Assessment
SMT	Surface Mount Technology

1 Introduction

The following chapter discusses Magna International's background as well as the aim and research questions stated for the study. In addition, it describes project limitations and presents a literature review.

1.1 Background

One of the biggest contributors to the world's greenhouse gases (GHG) is energy use in industry which accounts for 73% of the total global emissions (Ritchie, 2020). Today's system was built in an era when the use of energy was not an issue. According to climate science, there is an imperative need for a reduction of up to 85% in global carbon dioxide emissions below the 2000 levels by 2050 (Bhatia et al., 2011). This is crucial to prevent the global temperature from rising more than 2 degrees Celsius (°C) compared to before the Industrial Revolution. Going beyond this limit will affect both people and nature (Idowu et al., 2013). This risk highlights the importance of sustainability, as defined by the 1987 United Nations Brundtland Commission report as "meeting the needs of the present without compromising the ability of future generations to meet their own need" (Brundtland, 1985).

The current governmental policies alone are deemed insufficient to address this challenge (Bhatia et al., 2011). Therefore, it is crucial for businesses to take a leadership role and drive innovation to expedite progress in combating climate change. Until recently, companies primarily concentrated on addressing emissions from their own operations. However, there is a growing awareness among companies about the necessity to consider greenhouse gas emissions across their entire value chains and product portfolios. For firms to be able to reach this set goal, companies must understand the source and amount of GHGs generated not only by their products' use but also in all other life cycle stages set by choices made regarding their design, manufacturing, transportation, sell, and purchase processes. There is also a high demand from governance and investors for the magnitude of GHGs (Bhatia et al., 2011).

According to Magna (2023), Magna International is a leader in mobility solutions and is now shifting its climate commitment from carbon neutrality to a Science Based Targets Initiative (SBTi) net-zero approach. They aim to accomplish net zero and reduce carbon emissions by 90% by 2050. Furthermore, they have pledged to transition to 100% renewable electricity for their European operation by 2025 and for their global operations by 2030. Their focus is set on decarbonization efforts and energy reduction, with a commitment to engaging with OEM and customers to align expectations. The move to net zero aims to manage climate change risks, enhance business resilience, and achieve long-term cost savings.

Overall, Magna International's commitment reflects industry trends and that the company aims to be a sustainability leader in the automotive sector, demonstrating a proactive and impactful transition towards sustainability (Magna, 2023). Magna Electronics is a division of Magna International that assembles a camera system, for a customer.

1.2 Aim

Magna Electronics, hereafter referred to as Magna is interested in this investigation to understand and gain a comprehensive picture of the environmental effects associated with one of their camera systems. Furthermore, Magna has had the assumption that certain processes in the camera system assembly dominate these effects due to high energy consumption compared to other processes within its lifecycle. According to their expectations, a conditioning process in one of the two assembly lines at Magna is considered to be the major contributor due to its high energy-consuming activities.

The aim of the thesis is to identify the environmental impacts associated with the camera system throughout its lifecycle and to highlight the areas within the camera system's life cycle where components or processes contribute most to the environmental impact and give insight into opportunities for reducing these impacts. To achieve this, a life cycle assessment (LCA), of the camera system will be conducted from cradle-to-gate. The assessment will be completed in accordance with the ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b) standards.

1.3 Research questions

To achieve the aim, the following research questions are addressed in this study:

1. What are the core design elements or processes of the camera system contributing most to the environmental impact?
2. What can be done to reduce the burden of related emission hotspots found within the product lifecycle?

2 Theoretical framework

To obtain the orientation of the existing research, a review of earlier assessments of automotive camera systems has been done. In addition, to get a thorough understanding of life cycle assessment, the history behind it is analysed and described in the following chapter.

2.1 Review of previous studies

A literature review of previous similar studies is typically a first step in the project, to analyse similarities, differences, and gaps across various studies regarding the method, scope, functional unit, and results. Several online tools were used for finding articles, such as Google Scholar and ScienceDirect. The search was done by using several keywords: “LCA”, “electronics”, “camera system”, and “automotive industry”. To obtain relevant results from the literature review, the scientific papers selected were not older than 15 years.

Garbin et al. (2023) conducted research to identify the environmental effects of an automotive cage as part of a constant velocity joint (CV joint). The study was done according to ISO standards for LCA, i.e., the 14040-series, while the functional unit was one single cage, and the scope was cradle-to-gate. The attributional approach was selected together with the following midpoint impact categories such as ozone depletion, climate change, acidification, human toxicity, and resource use using EDIP 97 methodology. In addition, the product system modelling was completed with SimaPro software. Most of the data was collected manually by doing measurements at the suppliers’ site. One of the key findings is that environmental effects mainly stem from transportation activities. The authors concluded that mitigation activities in this case could include the reduction of the waste generated within manufacturing processes by raising the recycling rate and the optimisation of raw materials and input consumption.

Munnwer et al. (2012) carried out an LCA to identify the environmental performance of a night vision camera from a cradle-to-grave perspective produced by Autoliv. The functional unit considered was a single unit of night vision camera. The technical data regarding the camera materials composition and the description of its functions were retrieved from the International Material Data System (IMDS), the Product Life Cycle Management System (PLM), and the product web pages. The data regarding the company’s suppliers were collected through the Autoliv Global Purchasing system. However, the authors state that information about tier-3 suppliers is limited within the company, and in this case, various databases such as the Ecoinvent database or the Swedish Life Cycle Centre LCA database were used to retrieve the necessary data. On the one hand, results showed that the use phase keeps the predominant position in terms of global warming. On the other hand, the manufacturing of raw materials emerges as a process with the highest environmental impact regarding every impact category except for global warming. Furthermore, the manufacturing of camera lenses, heat sinks, and printed circuit boards (PCBs) constitutes one of the highest environmental impacts compared to other product components.

Villanueva-Rey et al. (2018) conducted a cradle-to-gate LCA of two signal cables that are produced from copper and copper alloy. In particular, the scope is from the extraction of raw materials to the stage when the product is fully assembled and prepared to be delivered to the customers. The functional unit was one kilometre of cable produced by a Portuguese company in 2014. While the foreground data regarding the cable manufacturing processes was collected directly from the company, the background data about raw materials and energy was gathered by using the Ecoinvent database. The authors used Sima Pro for system modelling and the ReCiPe 2008 methodology for life cycle impact assessment (LCIA). Furthermore, the midpoint impact categories selected were terrestrial acidification, ozone depletion, climate change, mineral depletion, fossil depletion, freshwater eutrophication, marine eutrophication, and photochemical oxidant formation. Key findings indicate that the raw and auxiliary materials production phase is considered the dominant regarding the environmental impacts. Auxiliary materials include lubricant oil and wastewater treatment chemicals.

Comparative LCA was done by Franz et al. (2018) to investigate the environmental performance of traditional and newly improved rear automotive camera systems. One camera system constituted the functional unit. The scope of the project was cradle-to-gate, and it was conducted following the ISO 14040-series. The data was collected through direct measurements, data from the manufacturer, a literature review, and the Ecoinvent database. The openLCA software was used along with the ReCiPe 2016 methodology and Ecoinvent database. The authors selected three impact categories such as terrestrial ecotoxicity, climate change, and human toxicity. Results indicate that the manufacturing of electronic devices has a substantial effect on human toxicity with 94% of the whole share. In addition, the modernised camera system has a lower environmental impact than the traditional one because of the reduced weight of the product itself and the smaller PCB.

Wazeem & Mohan (2023) conducted a cradle-to-grave LCA for an automotive forward-looking camera. The information that was necessary for the project was obtained from the manufacturing company and scientific literature. The investigation was completed following the ISO 14040-series of standards. The authors applied GaBi software along with the Sphera and Ecoinvent databases for system modelling. Regarding the impact assessment, they used ReCiPe 2016 methodology with the following key impact categories: terrestrial ecotoxicity, climate change, marine eutrophication, metal depletion, terrestrial acidification, and fossil depletion. The results show that the production phase contributes to around 90% of the whole product impact in terrestrial ecotoxicity, climate change, and terrestrial acidification impact categories. Whereas, for marine eutrophication, metal depletion, and fossil depletion impact categories the use phase dominates in terms of impact. In addition, housing and cover are identified as components with the highest environmental impact, which is attributed to 51% and 41% of the whole product effect respectively.

Another master thesis project was carried out by Almroth & Rehnberg (2023) to evaluate an automotive radar's environmental performance. The product is assembled and delivered to customers by Veoneer company, and its main function is to identify the objects near an automobile. A cradle-to-grave attributional LCA was applied to pinpoint the environmental hotspots throughout the product life cycle. The assessment was done according to ISO 14040-series, as well as the GHG Protocol Product Life Cycle Accounting and Reporting Standard (GHG Product Standard), since it was required by the commissioner. Although this report is claimed to follow both standards, it does not entirely cover all the requirements stated in the GHG Product Standard. For instance, the business goals of the company are not described and presented explicitly in the report. The authors chose GaBi software along with the Ecoinvent database for system modelling. Regarding LCIA, the ReCiPe 2016 midpoint methodology was chosen. Climate change was selected as the key impact category relevant to this. One of the key findings of the study is that the use phase is responsible for the highest environmental impact compared to other product life cycle phases followed by raw materials extraction and production. Furthermore, some processes were identified as the dominant environmental contributors such as PCB manufacturing and precious materials extraction such as gold and silver.

A prevalent feature in these studies was that a functional unit was usually chosen as a single unit of a product. In addition, the majority of the studies adhere to the ISO 14040-series of standards for LCA (Almroth & Rehnberg, 2023; Franz et al., 2018; Garbin et al., 2023; Wazeem & Mohan, 2023). The scope that authors chose varies among different studies – some of them applied a cradle-to-gate LCA (Franz et al., 2018; Garbin et al., 2023; Villanueva-Rey et al., 2018). On the other hand, others believed that the cradle-to-grave approach is more relevant (Almroth & Rehnberg, 2023; Munnwer et al., 2012; Wazeem & Mohan, 2023). Across all the studies, primary data was collected from the manufacturing company and suppliers, if possible, by taking direct measurements or investigating the company's databases, while secondary data was retrieved from literature reviews or LCA databases. Regarding LCIA, the vast majority of the projects were based on the ReCiPe 2016 midpoint methodology. However, Garbin et al. (2023) applied the EDIP 97 methodology, which is uncommon compared with other studies. The selection of impact categories varied and was dependent on the product characteristics. The most common impact categories that were selected by researchers were climate change, terrestrial ecotoxicity, and human toxicity. The software to model the product system varied among the investigations. SimaPro was used by Garbin et al. (2023) and Villanueva-Rey et al. (2018), while GaBi was selected by Almroth & Rehnberg (2023) and Wazeem & Mohan (2023). On the other hand, Franz et al. (2018) preferred to use OpenLCA software.

2.2 LCA history

The idea behind LCA formed in the 1960s when environmental degradation and limitation of resources became a concern and started to be brought up. Environmental pollution and energy and material scarcity motivated the development of life-cycle-oriented approaches for the environmental profiling of products (Bjørn et al., 2018).

The LCA framework originated in the US and Northern Europe in the 1970s, early methods focused on energy analysis with roots in packaging studies and life cycle assessment evolved into a comprehensive environmental burden analysis. This evolution continued with the introduction of LCIA and life cycle costing models throughout the 1980s and 1990s. The paradigm expanded further in the first decade of the 21st century with the rise of social LCA (Guinée et al., 2011).

During the 1970s, studies primarily targeted companies and were used internally and with limited communication with stakeholders. Initially, they were known as Resource and Environmental Profile Analysis or Ecobalances. There was an increased interest in methodological progress, driven by international collaboration and coordination within the community of scientists, researchers, scholars, and experts across various fields of study in the decades of the 1980s and 1990s, what is now commonly referred to as LCA (Bjørn et al., 2018).

Method development increasingly shifted toward academic institutions. As the methodological foundation solidified, the application of LCA broadened to encompass a diverse range of products and systems. Studies were commissioned or conducted by both industrial sectors and governmental organisations, and available to the public through various means, including academic papers, industry reports, and government reports. Additionally, the development of life cycle inventory databases, such as Ecoinvent, aimed to standardise data quality and coverage across industrial sectors. At the same time, in parallel with process-based LCA, a "top-down" approach based on input-output analysis emerged. Also, two widely used LCA software, SimaPro, and GaBi, were released around this time to meet the growing need for dedicated LCA software. In the 21st century, impact assessment methods continued to evolve, addressing spatial differentiation, and expanding to cover non-global impacts and social dimensions. This trend carries on today, with ongoing methodological refinement and a growing emphasis on international scientific consensus-building, which involves the collaborative establishment of widely agreed-upon principles and methodologies within the scientific community, aimed at achieving standardisation in LCA and related methodologies (Bjørn et al., 2018).

Today, the development of the framework is still ongoing, e.g., in the form of life cycle sustainability assessment (LCSA), which reflects a growing recognition of the multi-dimensional nature of sustainability. This method is built on the so-called "three pillars" of sustainability as ordinary LCA only covers the environmental aspects and does not take the social and economic aspects into account. The three pillars model of the life cycle sustainability assessment combines life cycle assessment, life cycle costing, and social life cycle assessment to provide a comprehensive framework: LCSA = LCA + LCC + SLCA (Kloepffer, 2008).

3 System under study

The following chapter describes the camera system and its main components. The data has been collected from Magna's suppliers, their internal databases, interviews with company experts, and through a literature review.

3.1 Product description

The camera system is assembled by Magna in Vårgårda and supplied to the customer. The camera system contains two camera modules, which are intended to create a three-dimensional picture of the surroundings. The vision system relies solely on the camera system itself. It is found in the rearview mirrors of most of the customer's car models. It works in combination with specifically developed windshields and onboard computers which can take pictures of the road and share them with other drivers. The camera system is classified as a level 2 product, referring to the fact that the system can drive the car autonomously for a short period of time, but it will require a driver to take over if necessary (Subaru, 2024). The camera system acts as an additional set of eyes, measuring the distances and traffic lanes while detecting potential road hazards such as vehicles, bicycles, or pedestrians. In the case of danger, the system can automatically apply brakes to mitigate damage or, under appropriate conditions, avoid collisions altogether (Subaru, 2024). The main functions of the camera system are presented in **Error! Not a valid bookmark self-reference.**.

Table 1. Camera system functions

Adaptive Cruise Control	This function maintains a desired distance to the car in front of you. If the car in front of your brakes, so does your car.
Pre-collision braking system	The function of this system keeps a constant eye on the surroundings. If any danger is detected the system will warn you and, if necessary, apply automatic braking to prevent any collision.
Autonomous emergency steering	The system will detect if any bigger object such as a vehicle pulls in front of you, it will then steer your steering wheel and turn for you to prevent a collision.
Lane departure prevention	It has a preventive function that detects that you are in the right lane when driving. If you slide over the system will warn you and if necessary, steer the car back into the lane.
Lead vehicles start alert	The system detects if the car in front of you has started to move forward after a standstill. If the car has stopped at a red light and the car in front of you starts moving, and your car is not, the system will notify the driver that the car in front has started moving.
Pre-collision throttle management	Prevents a collision by warning the driver and reducing speed, this system will function at low speeds such as driving the car in a park.
Lane centric control and preceding vehicle adaptive steering control	Detects distances to cars and objects with the adaptive cruise control system. It reduces speed if necessary to maintain a desired distance. The system also keeps track of lanes/lines and steers the car back to the middle of the lane if necessary.

3.2 Product components

The camera system consists of thirteen main components. A list of these components, their quantities, and weights are presented in Table 2. Some of the components are presented as assemblies, such as the camera module, clip, and PCB. To have a clear picture of these components' functions, each component is described in detail in the following sub-chapters. Furthermore, the illustration of the camera system is presented in Figure 1.

Table 2. Camera system's components

Component	Weight of one component, g	Quantity, st	Total weight, g
Housing	298.2	1	298.2
Cover	181.0	1	181.0
PCB assembly	79.6	1	79.6
Camera module (lens assembly)	10.8	2	21.5
Clip, retaining collar, assembly	2.1	2	4.1
Flex cable right	0.6	1	0.6
Flex cable left	0.6	1	0.6
Cooling fan	17.8	1	17.8
Screw	0.8	12	9.7
Label	0.1	1	0.1
Lens cap right	5.5	1	5.5
Lens cap left	5.4	1	5.4
Sealant	7.2	1	7.2

3.2.1 Housing

The housing is primarily made of aluminium alloy and its main function is to shield the internal components from environmental factors such as dust or debris. Since the camera system contains many electronic sub-components, which are necessary for proper camera system functionality, it is paramount to provide reliable protection for them. Furthermore, it is the heaviest component of the camera system.

3.2.2 Cover

The next component that serves nearly the same function as the housing is the camera system's cover. This cover is also made of aluminium alloy, which allows it to protect sensitive electronic components from damage or any other external influence. Furthermore, the cover along with the housing are good heat conductors due to their material composition. Therefore, it enables to dissipate heat coming from other components.

3.2.3 PCB assembly

Today, PCBs can be found as primary components within the majority of Electrical and Electronic Equipment (EEE) (Canal Marques et al., 2013). In this camera system, a double-sided, rigid PCB is used for the camera system assembly. Various electrical components are mounted on the naked board and interconnect via an etched pattern of conductors, referred to as traces. The main electrical board components that are mounted on the PCB are capacitors, connectors, integrated circuits, and inductors.

3.2.4 Camera module

Each camera module consists of several sub-components such as a small, fully mounted PCB (i.e. separate from the larger part referred to as the PCB assembly), an image sensor, and a lens assembled together. The primary aim of the camera module is to monitor surrounding objects, which leads to detecting and preventing potentially hazardous situations for the driver and passengers.

3.2.5 Clip, retaining collar, assembly

The key function of the clip assembly is to ensure the alignment of the components within the camera system. It holds the housing and camera module assembly together, preventing its displacement during vibrations or other external impacts.

3.2.6 Flex cable

The flex cable is a flexible cable that is used to transfer electrical signals between the camera module assembly and the PCB assembly. It is made of copper foil that is etched to form the pattern of copper tracks. Then, flex cables are laminated with polyimide and ready to be installed in the camera system.

3.2.7 Cooling fan

The key function of the cooling fan is to maintain the necessary temperature in the camera system by dissipating heat. The automotive camera system is usually exposed to high temperatures when the car is driving. Therefore, it is crucial to ensure the proper working conditions for the electronic components with the help of the cooling fan.

3.2.8 Screw

Twelve screws are used to fasten all the components together in the camera system. All the components must remain in place to ensure proper functionality of the camera system under different working conditions.

3.2.9 Label

The label is placed on the cover of the camera system and contains necessary information about the product. This information can include the product’s part number, parameters, or safety warnings. Thus, the label helps to indicate the product’s main characteristics.

3.2.10 Lens cap

The camera modules are sensitive, and it is paramount to protect them from physical damage. Lens caps are made of plastic and serve the function of securing the camera modules while transporting them from the company to the customer.

3.2.11 Sealant

Sealant is used for bonding the components together, thus providing stability even under harsh and high-vibrant conditions. Furthermore, the sealant has waterproof and thermal conditions, which protects the electrical components from moisture and overheating.

Figure 1. Illustration of the camera system (M.Popescu, personal communication, June 28, 2024)

4. Life cycle assessment methodology

LCA methodology is defined by two ISO standards in the same series: ISO 14040 identifies principles and framework for conducting LCA and ISO 14044 identifies the guidelines and requirements. The framework encompasses four main stages: goal and scope definition, life cycle inventory (LCI) analysis, LCIA, and interpretation of results. The relationship between the stages is summarised in Figure 2 (Rebitzer et al., 2004). The process of conducting LCA is iterative, i.e., implying that the original goal and scope of the project could require reformulation throughout the work. This is clearly depicted in Figure 2 by returning flows (Curran, 2017b).

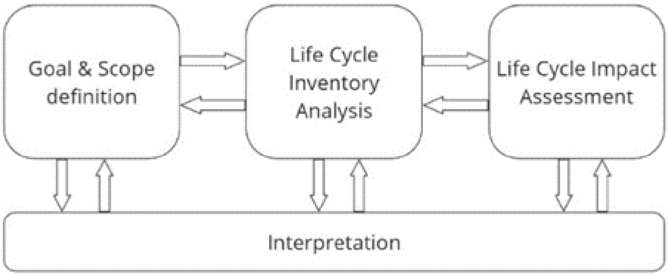


Figure 2. LCA framework according to ISO 14040

4.1 Goal and scope definition

The first step in conducting LCA is to *define the* project's *goal and scope*. A clear and well-defined goal must be established before starting the project since this will enable proper communication between the commissioner and practitioner of LCA (Curran, 2017b). In particular, the project boundaries, allocation procedures, functional unit, reference flow, assumptions, and limitations should be described (ISO, 2006a).

The goal of the study involves identifying the following points:

1. The intended project application, which often refers to the question of *why*. This part explains the motivation behind conducting the life cycle assessment and the intended application of the results. It could include reasons such as the environmental impact of an existing product or using the result as a basis for design and product improvements.
2. The intended audience, refers to the question *who*. This part clarifies who the life cycle assessment is communicated to which may include stakeholders within the company, customers, investors, the public, or regulators.
3. The product or system being assessed, referring to the question *what*. This part of the goal specifies what exactly is being assessed through the life cycle assessment. It could, for instance, be a product, a manufacturing process, or a service.

Defining the purpose of the study means to outline specific questions or objectives that the life cycle assessment aims to address, and it also guides the definition of the scope. The scope states the boundaries of the assessment, including which life cycle phases and environmental impact categories will be considered. It also includes modelling aspects such as the functional unit, type of LCA, allocation, and data quality requirements. The functional unit describes the function delivered by the product or service that is under examination. The scale of the functional unit must be set properly. If the set is extremely little or huge, it may lead to the impact assessment reporting the wrong amount of the total input or emissions (Curran, 2017a).

The system boundary outlines the coverage of the study including considerations regarding the technical system, for example, the inclusion of capital goods and its relation to surrounding natural systems, as well as geography, time horizon, or system boundaries in relation to other product life cycles. Impact categories categorise the environmental impacts that will be assessed during the LCIA. These categories can range from greenhouse gas emissions and energy consumption to water usage and land occupation. The data quality requirements are also an important part of the scope to ensure robust and reliable results. This includes considerations for data collection methods, accuracy, completeness, and consistency.

4.2 Inventory analysis

The *life cycle inventory analysis* (LCI) - the second step in LCA - covers the compiling and quantifying the inputs, often in the form of resources such as materials and energy flows, and outputs, often as wastes and emissions, generated in each step (unit process) of the product's or service's lifecycle (Horne et al., 2009). Combining all these single steps into a complete product system enables a calculation of the total amounts of all elementary flows between the natural and technical systems, the LCI, which is the main result of this step.

According to Ciroth & Arvidsson (2021), life cycle inventory analysis can be described as three key steps described below.

1. Construction of flow chart. Flow models are constructed and analysed based on data collection on inputs and outputs at each stage of the product life cycle meaning from raw material extraction, transportation, manufacturing, and usage to waste management.
2. Gathering data. Collection of more detailed data including primary data sources include producing companies, waste management firms, wastewater treatment plants, and measurements of consumer behaviour, and secondary data sources encompass LCA databases, software, branch organisations, and LCA reports.
3. Conducting LCI calculations. Flows from the environment include inputs and outputs identified in the flow model. Calculations based on the established functional unit result in performing calculations based on the established functional unit for the LCA.

4.3 Impact assessment

The third stage, *life cycle impact assessment* (LCIA), is the process of quantifying the environmental impacts resulting from the inventory analysis and identifying how different processes and flows contribute to the total results. LCIA enables stakeholders to assess environmental impacts relevant to their concerns, simplifies complex environmental data, makes it easier to understand, and facilitates the comparison of environmental impacts across different products, processes, or scenarios.

LCIA can be divided into three main sub-stages described below (Hauschild & Huijbregts, 2015).

1. Selection of impact categories. Environmental impacts are effects of the activities in the investigated life cycle, for example, climate change, resource depletion, or human health effects. This step is a part of the goal and scope of the study.
2. Classification. The inventory result is organised according to the type of environmental impacts it contributes to.
3. Characterization. The relative contributions of the emissions and resource consumption to each type of environmental impact are calculated.

The environmental impact is calculated using so-called characterisation factors as shown in Equation 1. These calculations are completed automatically in OpenLCA.

$$Impact\ assessment_i = Inventory\ result_a \times Charaterisation\ factor_{a,i}$$

Equation 1: Calculation of the impact assessment result, where
i – certain impact category, a– certain inventory flow

According to ISO (2006a), the selection of impacts category and classification are seen as mandatory elements of LCIA. There are also optional steps for LCIA which are defined within ISO standards, including relating the impact indicators to reference conditions (normalisation), sorting and ranking impact categories based on characteristics such as emissions, location (grouping), and comparison of results across impact category based on preferences or other criteria (weighting) (Hauschild & Huijbregts, 2015).

4.4 Interpretation

The fourth stage of the LCA is the *interpretation*, which entails the compilation and evaluation of the results obtained in the LCI analysis and LCIA. The purpose of the interpretation stage is to assess the accuracy and completeness of the results and communicate them to the intended audience in a clear way. Recommendations are made according to the objective of the study. This means interpretation is directly related to the goal and scope. It includes systematically identifying, quantifying, checking, and evaluating information from the LCI and LCIA results, and summarising these findings. Furthermore, during the interpretation stage, it is necessary to assess to what extent the study addresses the questions stated in the goal and scope stage. Appropriate conclusions and recommendations for the commissioner can be made (Curran, 2023).

5 Data collection

To conduct the LCA a lot of information was collected from various sources. The primary and secondary data collection process is described in this chapter.

5.1 Primary data

Primary data was collected in different ways. Magna's assembly lines in Vårgårda were explored and we were introduced to the product, its manufacturing, and assembly processes. This provided us with an overview of the product system, its main functions, and its characteristics. In addition to that, several interviews with employees were conducted to receive data regarding the camera system. Edwards & Holland (2013) state that the interview is an essential tool for collecting the primary data for the research and indicates three main types of interviews: structured, semi-structured, and unstructured interview. Semi-structured interviews are more commonly used compared to the other types, since the interviewer has more flexibility with questions, while the structured interview has a rigid framework (Adhabi & Anozie, 2017).

Therefore, semi-structured interviews were conducted with design engineers, quality managers and process engineers to collect data regarding the product's technical characteristics, design features and key components. Some unstructured interviews were held with logistics managers to trace the camera system's supply chain and enable contact with suppliers for acquiring additional information. Furthermore, Magna's internal databases such as IMDS along with PLM were explored to retrieve more data. While IMDS has provided us with the material composition and weight of the camera system, and its components, PLM was used to get the data about each step of the camera system's life cycle. PLM was thoroughly explored to obtain the product's list of subcomponents, typically referred to as a bill of materials (BOM), and data regarding camera system assembly and manufacturing processes.

5.2 Secondary data

Primary data alone is not sufficient to complete the analysis. Commonly, LCA requires the use of secondary data, especially if the study is done within a limited timeframe. Therefore, various secondary data sources were also explored, i.e., scientific literature such as articles, reports, and books were read to fill data gaps when necessary. Foremost, an existing commercial LCI database was chosen as an extensive source of secondary data for the product system modelling, the Ecoinvent database (cutoff, v3.10). This database consists of 20,000 different unit process datasets, spanning over several industrial sectors including chemicals, metals, transport, energy, plastics, etc. (Ecoinvent, 2024).

6 Goal and scope definition

This chapter explains the goal and the scope of the LCA study of the camera system. Furthermore, the system boundaries and limitations of the study are explicitly described.

6.1 Goal and scope

The goal of this study is to identify the process and component of the camera system that has the highest environmental impact throughout the life cycle of the camera system. In particular, this goal entails determining the hotspots throughout the different phases of the product life cycle with a cradle-to-gate perspective, i.e., including raw materials extraction and processing, components manufacturing, assembly at Magna in Vårgårda, Sweden, and transportation to the customer's door.

The conclusions of this study are mainly relevant for Magna, the commissioner of the LCA study, and its customers. Thus, they are the intended audience of the research. Magna is obligated to meet the customer requirements regarding the camera assembly processes but also aims to use the findings of the LCA to engage in constructive communication with their customers for further improvements. To achieve this, an attributional cradle-to-gate life cycle assessment of the camera system is conducted. The assessment is completed in accordance with ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b).

6.2 Product system

The product system is divided into four main phases including raw materials extraction and production, manufacturing, assembly, and transportation phases. First, the necessary raw materials are extracted and processed for all included components. Then, thirteen main components, i.e., the central PCB panel including sub-devices, the camera module, lenses left and right, the housing, the cover, the cooling fan, flex cables, clips, screws, sealants, and the label, are manufactured and transported to Magna Electronics in Vårgårda, Sweden.

After surface mounting, which is completed at the site, the PCBs are sent to the camera assembly stage, where all the main components are assembled into the camera system. Then, the complete camera system is sent to go through the conditioning process and final assembly tests. Finally, after packaging and an interim inspection of the product, it is transported to the customer. All these steps are described more in detail in the following chapters.

6.3 Functional unit

To ensure the comparability of the results the functional unit is defined as one camera system, measured in units. This camera system is used in the automobile throughout its life cycle as an intermediate product and the average life span of the automobile is 150,000 km (Felipe-Falgas et al., 2022).

6.4 System boundary

The system boundaries including all the inputs and outputs along with the foreground and background systems are depicted in Figure 3. The foreground system constitutes all the processes directly related to the camera assembly at the Magna's site in Vårgårda along with the transportation from suppliers to Magna and from Magna to the customer. The data for the foreground system was gathered as described in the chapter 5. The background system constitutes all the other parts of the technical system that were mainly modelled using the Ecoinvent database.

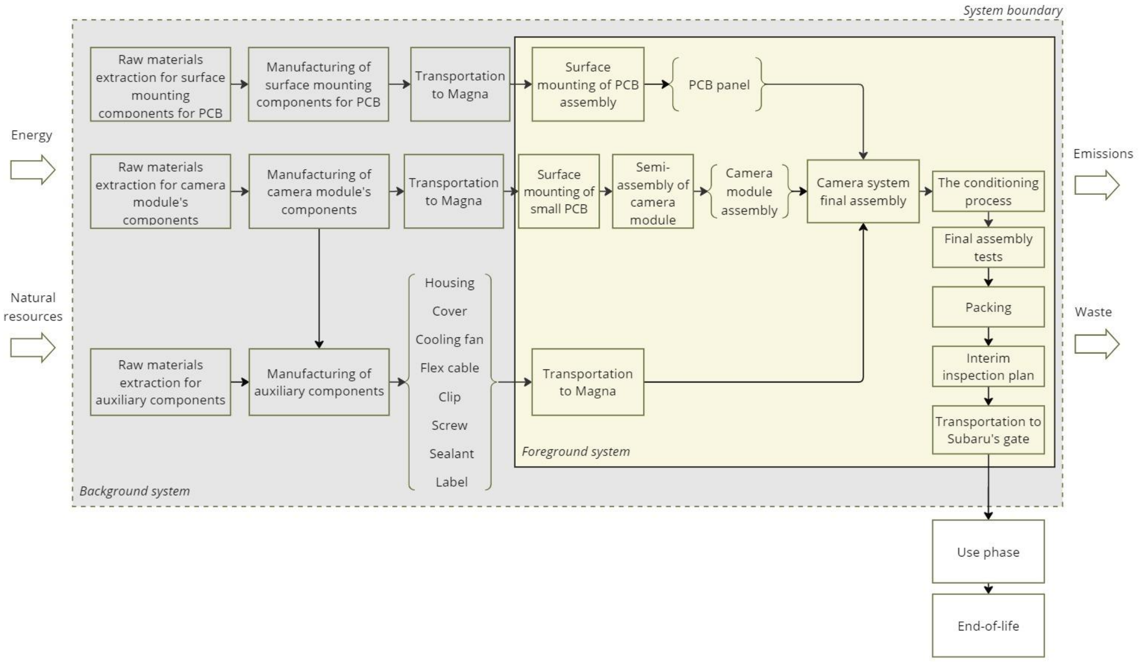


Figure 3. System boundary and life cycle flowchart for the camera system

The materials and energy input flows are all included in the manufacturing phase for each component. In addition, the manufacturing of the packaging used for the product and its components is also included in the system boundary. The assembly phase consists of two main steps: the surface mount technology (SMT) process and the camera system final assembly (CFA). For an in-depth understanding of the SMT process, all its stages are depicted in Figure 4. It is a technique used to mount small electronic components on the PCB. These components are typically referred to as surface mount devices (SMDs). The key elements that are necessary for surface mounting are the bare or unmounted PCB, solder paste, and the SMDs. First, the bare PCB is organised and cleaned. Then, the solder paste is applied to the PCB and inspected for the correct solder paste volume during the next stage. After that, SMDs are placed onto the solder paste on PCB and go through a reflow oven where the change in temperature leads to the solder paste melting and forming a bond between the PCB and components. During the next stage, named solder inspection, the PCB is checked for soldering defects. Finally, in-circuit testing (ICT) is applied to determine the electrical defects of PCB such as open or short circuits. In the case of this camera system, four PCBs are located on one panel and they go through the surface mounting together. Only during the camera system final assembly stage, the panel will be cut down into four separate printed circuit boards.

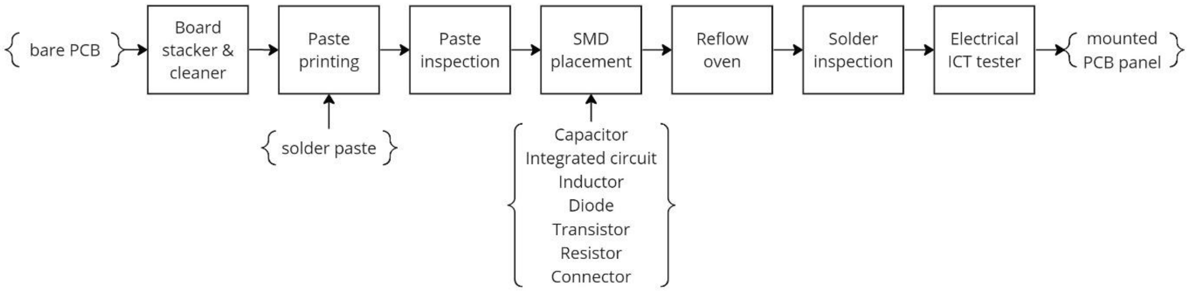


Figure 4. Surface mount technology process

The camera system final assembly is considered the second step and it includes several stages that are described in Figure 5. The first stage is a flash, where software is installed into the PCB panel. Then, this panel is divided into four separate PCBs, which is called cutting. The third stage is assembling all the components into a single unit on an index table. Most of the work at this point is done automatically by robots, while several other activities in the camera system assembly are done by operators manually. Operators install flex cables, the fan connector, and handle errors that may occur. The next stage is the conditioning process that the camera system goes through. In accordance with confidentiality requirements, all the details related to the conditioning process cannot be disclosed.

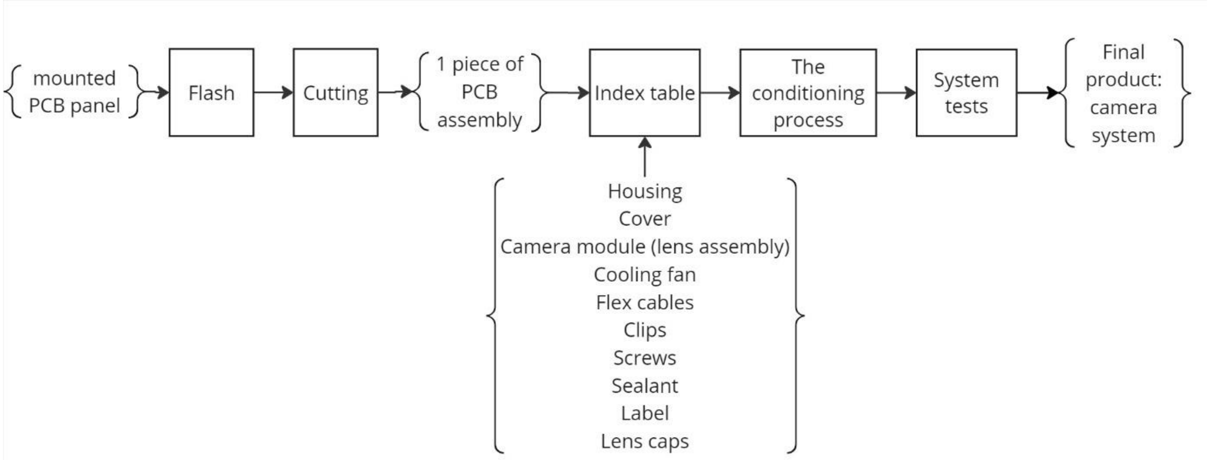


Figure 5. Camera system final assembly process

The last stage is to perform several system tests on the assembled camera system. First, camera lenses are checked if they are marked by fingerprints or dust. Then, the camera system is calibrated by taking pictures of potential objects in a calibration room. Third, the electrical test is carried out and the quality of pictures taken during the previous test is checked. Finally, the label is put on the camera system, before it is placed in packaging, and checked again for any visual defects before it has been sent to the customer. This step is called the interim inspection plan.

The packaging of the PCB naked board and camera lens solely is included in the scope. It is done since these components incorporate a plethora of sub-components, each with its separate packaging. Due to the time constraint and high complexity of these components, it is decided to focus only on the PCB naked board and camera lens packaging.

6.5 Allocation procedure

No specific allocation methods are chosen for this study, as no allocation issues are encountered in the foreground system. Co-product allocation in the background system follows the ISO 14040-series as implemented by the Ecoinvent database.

6.6 Selection of impact categories

To assess the environmental impact of the camera system, two impact categories are chosen. First, the climate change impact category is considered the most important, both by the practitioner and the commissioner. Therefore, the IPCC 2021 impact assessment methodology is chosen and more specifically the indicator for global warming with a 100-year perspective (GWP100). Two indicators are chosen to assess the impact of mineral resource depletion: the crustal scarcity indicator and the ReCiPe mineral resource scarcity indicator. The first is applied in accordance with the Crustal Scarcity Indicator 2020 methodology, and the mineral resource scarcity is utilised based on the ReCiPe 2016 v1.03, midpoint hierarchist (H), impact assessment methodology.

6.7 Transportation

Transports between suppliers, Magna, and the customer are included in the study. Transportation from suppliers to Magna and from Magna to the customer is included in the foreground system, whereas the transportation between raw materials extraction and manufacturing phases is part of the background system.

Two different scenarios are applied in this study to assess how changes in the selection of transportation mode in the foreground system affect the results of the study. Comparing two different scenarios enables us to understand how a specific process contributes to the environmental burden. The base case scenario describes the current transportation setup using aircraft. The second or alternative scenario includes a different type of transportation used by Magna and its suppliers, i.e. it is altered from aircraft to ship in two transportation processes: transportation from Magna to the customer and transportation from suppliers to Magna. Based on the literature review and our expectations, the transportation phase is usually considered one of the major environmental contributors in the electronics industry. Therefore, it is decided to perform a scenario assessment varying the transportation mode.

6.8 Data quality requirements

Each material and substance contained in the camera system is gathered from IMDS specifically for the camera system. Respective handling processes regarding the extraction and production phases are gathered and quantified based on secondary sources, a literature review and communications from the suppliers. Inputs regarding energy consumption of the assembly processes are measured and calculated directly at the site. Packaging input flows are also collected and calculated directly at the site. For the transportation, the appropriate freight method and location have been calculated.

6.9 Limitations

This LCA study provides a cradle-to-gate perspective and not the whole life cycle of the camera system. The main consequence of this narrowed scope is the fact that no environmental impacts are reported for the use and end-of-life stages of the product.

Furthermore, the project is conducted within a limited timeframe of approximately five months. This is a limitation primarily due to the challenges in obtaining specific data from suppliers during the extraction and production phases of key components, including lens production. In this case, generic data from sources such as Ecoinvent are used.

Sector-averaged data for the freight between Magna’s suppliers and sub-suppliers is obtained from already existing Ecoinvent market processes. This can be considered one more limitation of this study since the data regarding transportation between the company’s sub-suppliers is not available. In addition to that, assumptions are made regarding the distances between suppliers and airports or seaports.

7 Inventory analysis

In the following chapter, the process of data gathering for the inventory analysis is described. This chapter consists of four subchapters describing each stage of the product life cycle: raw materials extraction and acquisition, manufacturing, assembly, and transportation.

7.1 Raw materials extraction and acquisition

Every component of the camera system consists of various materials and substances. This data is retrieved from IMDS, and a list of materials and substances is made for each component individually. Using Ecoinvent, substances are matched to the most appropriate dataset. The PCBs contain hundreds of different substances. Therefore, a ready-made Ecoinvent dataset is used, covering the majority of the substances automatically. However, to obtain more accurate results in the end, substances, which weigh more than one gram are added to the process. In IMDS, some substances are identified as miscellaneous and cannot be declared. These are not included in the product system. Also, substances that demonstrate a negligible mass in comparison with other substances, are not included in the product system modelling.

7.2 Manufacturing of the camera system's components

Before being delivered to Magna, each component is going through manufacturing processes. These processes are identified in several ways. Firstly, a thorough literature review is done to have an initial perspective of the component's production processes at the site. Secondly, unstructured interviews are held with Magna's design engineers to get the list of manufacturing processes that each component undergoes. Finally, suppliers are contacted to receive the full picture of how the product is being manufactured before being supplied to Magna. This comprehensive data-gathering process enabled us to identify the main manufacturing process for each component. Next, this is matched with data in the Ecoinvent database. Each manufacturing process is associated with the most appropriate dataset. The dataset is selected based on its description by analysing the provider and input and output flow tracing upstream in the supply chain. By selecting a market dataset for each input flow, such activities as product selling or purchasing, its losses, and transport freight are considered. Therefore, there is no need to calculate the transport freight separately for each process from raw materials extraction to the manufacturing stage.

The packaging that is used for delivery of the components to Magna and when the camera system is sent from Magna is included in the scope of the project. The packaging is divided into three categories: carton box, plastic wrapping, and tray. However, there is no production and waste handling of the pellets, while the black plastic box used for the delivery of the ready-made camera system to the customer is recycled at the customer's location. Therefore, they are not included in the scope of the project. The inventory data regarding packaging is received from Magna's supply chain department after a thorough investigation of the packaging specifications for each component. If there is no packaging specification, the data is collected manually at the site in Vårgårda by taking direct measurements of the packaging size and weight.

The PCB panel consists of many sub-components, which are assembled in Vårgårda into one ready-made product. Including the packaging of each sub-component that is supplied to Magna in the inventory analysis would require much time and effort. Therefore, it was decided to consider the packaging of naked board solely due to the time constraints of the project. The same method was applied to the camera module assembly, for which only the camera module lens packaging is included.

Components arrive at Magna in cardboard boxes and trays of different sizes depending on product characteristics, quantity, and weight. Furthermore, the plastic wrapping is used for the transportation of the majority of the components. Therefore, three different types of packaging are quantified: carton box, tray, and plastic wrapping. Based on the direct measurements of the packaging, communication with employees, and the literature review, it is decided to make an average estimation of the packaging weight for carton boxes and trays. Thus, for the carton boxes, the average weight is 500 grams, and for the trays, it is 1100 grams. However, the weight of the plastic wrapping packaging per FU is calculated manually.

First, the weight of the packaging is divided by the number of components that this packaging delivers. This is to obtain the weight of the packaging per one component. Second, it is multiplied by the number of components used per one FU (e.g. twelve screws are necessary for the assembly of one camera system, then, it is multiplied by twelve). After that, the weight of each packaging type is summed up and included in the product system as a separate process, which is listed in Table 3.

Table 3. Packaging weight per 1 FU

Packaging type	Weight per FU, g
Carton box	152
Tray	158
Plastic wrapping	127

7.3 Assembly of the camera system

To calculate the energy consumed for the assembly of one camera system, several consecutive steps were taken. For the sake of coherency, the energy consumption calculations are made separately for SMT and camera final assembly lines.

Firstly, the power consumption for each machine involved in each SMT process is collected in kW manually at the site in Vårgårda for investigation. Secondly, the machine operation time is obtained from the interviews with the company's employees. February 2024 was chosen as the reference month for these calculations. For example, for the SMT line, the average time spent on the production of one PCB was calculated, along with the number of units produced during that time. Next, the average time was divided by the average number of units. Then, this value was multiplied by the power value to get the energy consumption in kWh/unit for each process of the SMT line. The energy consumption calculations for the SMT line are collected in Table 4.

Table 4. SMT processes – energy consumption

Process	Power, kW	Energy consumption per FU, kWh/unit
Board stacker & cleaner	0.57	0.004
Paste Printer	5.48	0.04
Paste Inspection (SPI)	2.20	0.02
SMD Placement	10.50	0.08
Reflow Oven	93.00	0.67
Solder Inspection (AOI)	2.20	0.02
Electrical ICT Tester	12.45	0.09

Handling processes	6.65	0.05

The energy consumption for the camera final assembly line is calculated based on the same method as the SMT line. However, in this case, the energy consumption is calculated per one unit of the camera system, whereas the SMT line is accounted for one unit of PCB. The energy consumption calculations for the camera final assembly line are summarised in Table 5.

Table 5. Camera final assembly processes – energy consumption

Process	**Power, kW**	**Energy consumption per FU, kWh/unit**
Flash	1.00	0.01
Cutting	4.75	0.04
Index table	33.00	0.26
The conditioning process	671.40	3.30
System tests	14.00	0.11
Interim inspection plan	0.20	0.002
Handling processes	0.10	0.001

7.4 Transportation

Magna delivers the product to the customer in three different locations mostly by aircraft. Each component of the camera system is supplied to Magna by a different supplier. Thus, a list of suppliers is compiled for the camera system. This is done with the assistance of the Magna’s supply chain department. They provide the list of the suppliers for each component and the type of transport they use to deliver the product to Magna. The distance between suppliers and Magna is calculated manually by using online tools such as Google Maps. Three modes of transport are used to deliver the goods to Magna: truck, aircraft, and ship. Since these suppliers are located in various countries and the distance between the airport and the supplier’s location differs in each case, it is decided to make an assumption. For the aircraft, it is assumed that the distance between the supplier and the airport is 100 km by truck. For the ship, it is assumed to be 150 km by truck from the supplier to the seaport. The same assumption is made for calculating the distance from Magna to the customer.

To consider packaging when calculating the transport freight, several steps are taken. Firstly, the transportation weight for one component is calculated by dividing the total weight of the pallet by the total quantity of the components per pallet. Here, the term transportation weight refers to the weight of the component and its packaging, including the pallet. Secondly, to calculate the freight of each type of transport, the transportation weight per component is multiplied by the distance it is transported. Then, all the results for each transport category are summed up and summarised in Table 6. The same method is used for calculating the transport freight from Magna to the customer for each transport mode, which is listed in Table 7. In terms of modelling, transportation is included as a separate stage, summarising all transportation from the supplier to Magna and from Magna to the customer. Thus, it is possible to analyse these processes and identify their contribution separately.

Table 6. The transport freight from the supplier to Magna

Transport	Freight, t*km
Truck	31.22
Aircraft	1.07
Ship	17.20

Table 7. The transport freight from Magna to the customer

Transport	Freight, t*km
Truck	4.29
Aircraft	14.27
Ship	-

8 Impact assessment results and interpretation

This chapter provides the results of the camera system's LCA. The product life cycle's result is divided into two phases: (1) component production and camera assembly, and (2) transportation. The component production and camera assembly phase comprise a list of input flows such as product components and energy consumption. The transportation phase consists of the transportation from suppliers to Magna and from Magna to the customer.

The total contribution of the component production and camera assembly phase for the base case and alternative transport scenarios is the same, which is expected since the second scenario implies altering the transport mode solely. Therefore, it was decided to include the results only for the base case scenario in Table 8. It is apparent that the PCB constitutes the highest environmental effect in all three impact indicators with around 43% of the total contribution in GWP100, 76% in mineral resource scarcity, and 91% in crustal scarcity impact indicator. Furthermore, the integrated circuit, which is the sub-component of the PCB stands for the largest environmental contribution compared to the other sub-components. This will be explained more in detail further in the following sub-chapters.

Table 8. Contribution results for component production and camera assembly phase for three impact indicators

	GWP100, in kg CO_2-Eq	**Mineral resource scarcity, in kg Cu-Eq**	**Crustal scarcity, in kg Si-Eq**
	Base Case	**Base Case**	**Base Case**
PCB	3.98E+01	1.72E+00	7.92E+04
Housing	1.21E+01	1.23E-01	8.01E+02
Cover	9.33E+00	9.51E-02	6.73E+02
Camera module assembly	1.54E+00	5.82E-02	2.46E+03
Flex cable right	4.77E+00	1.92E-02	4.76E+02
Flex cable left	4.70E+00	1.89E-02	4.69E+02
Cooling fan	2.24E-01	1.15E-02	1.55E+03
Packaging, tray	8.03E-01	8.86E-03	9.86E+01
Screw	2.51E-02	6.41E-03	3.58E+00
Packaging, plastic wrapping	4.85E-01	5.68E-03	6.31E+01
Energy consumption (conditioning process)	1.00E+00	6.36E-02	3.88E+02
Energy consumption (other)	2.04E-02	1.30E-03	7.92E+00
Packaging, carton box	2.04E-01	2.89E-03	1.42E+01
Clip	3.09E-02	1.59E-03	1.56E+02

Sealant	4.01E-02	1.24E-03	5.46E+00
Lens cap right	2.24E-02	2.93E-04	2.64E+00
Lens cap left	2.23E-02	2.92E-04	2.63E+00
Label	3.17E-04	1.11E-05	4.33E-02
Total contribution	7.51E+01	2.14E+00	8.64E+04

Apparently, the total environmental contribution of the transportation phase for the alternative transport scenario is considerably lower than for the base case scenario, which is summarised in Table 9. This outcome is expected since the shift in the transportation mode from aircraft to ship entails lower environmental contribution for all impact categories. It is worth mentioning that the degree to which the contribution of the alternative transport scenario has decreased is different for the two inventory flows. While the contribution of transportation from suppliers to Magna declined slightly, the contribution of transportation from Magna to the customer is substantially lower in the second scenario. The reason behind this is that only a few suppliers use aircraft to transport components to Magna, whereas Magna relies mostly on aircraft when transporting the camera system to the customer. In addition, the total life cycle contribution, which is indicated in Table 9, is the sum of the total contribution of transportation and component production and camera assembly phases.

Table 9. Contribution results for the transportation phase for the impact categories

	GWP 100, in kg CO_2-Eq		Mineral resource scarcity, in kg Cu-Eq		Crustal scarcity, in kg Si-Eq	
	Base Case	Alternative Transport	Base Case	Alternative Transport	Base Case	Alternative Transport
Transportation from suppliers to Magna	4.30E+00	3.43E+00	6.73E-02	6.48E-02	3.61E+02	3.17E+02
Transportation from Magna to the customer	1.23E+01	5.92E-01	5.67E-02	1.05E-02	7.88E+02	5.10E+01
Total contribution	1.66E+01	4.03E+00	1.24E-01	7.53E-02	1.15E+03	3.68E+02
Total life cycle contribution	9.17E+01	7.91E+01	2.26E+00	2.21E+00	8.75E+04	8.67E+04

8.1 Global warming

In this sub-chapter, the results for the global warming impact indicator are described in more detail. The total environmental impact for the two product life cycle phases is summarised in absolute values in Figure 6. Evidently, the component production and camera assembly phase are the dominant contributor to the total environmental impact. Therefore, to have a more detailed picture, the six unit processes of this phase that contribute the most to the result are analysed among each other in Figure 7. These six components are the PCB, the housing, the cover, the flex cable right, the camera module assembly, and the cooling fan. In terms of the global warming indicator, the PCB has the highest environmental impact with 43%. The housing, the cover, and the flex cable have 13%, 10%, and 5% environmental contributions respectively. In contrast, the camera module (lens assembly) and the energy consumption of the conditioning process each stand for the lowest percentage with less than 2% of the total impact.

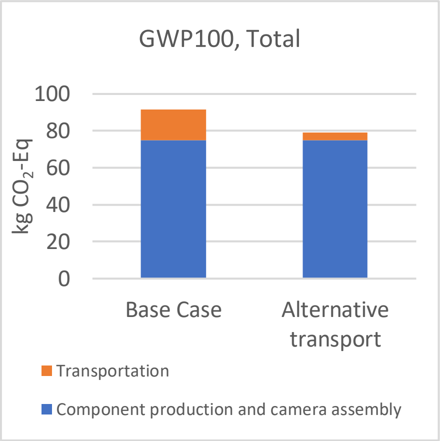


Figure 6. Global warming results, total, in kg CO_2-Eq

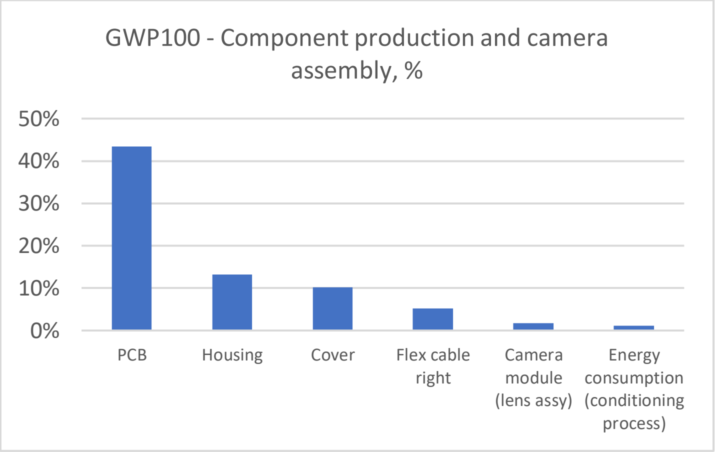


Figure 7. Global warming results for the component production and camera assembly phase, % contribution

8.2 Mineral resource scarcity

This sub-chapter discusses the results of the mineral resource scarcity indicator in-depth. While Figure 8 shows the results for the two product life cycle phases comparing both scenarios, Figure 9 describes the dominating six components' contribution in percentage values. Regarding mineral resource scarcity, the PCB remains the major contributor with 76%, outnumbering the other component with a huge gap. The housing, the cover, and the flex cable stand for 5%, 4% and 1% of the total environmental impact, respectively. Furthermore, the camera module assembly and the energy consumption of the conditioning process each constitute around 3% of the total impact.

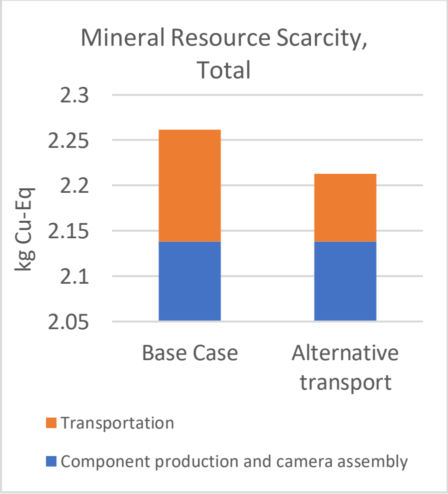


Figure 8. Mineral resource scarcity results, total, in kg Cu-Eq

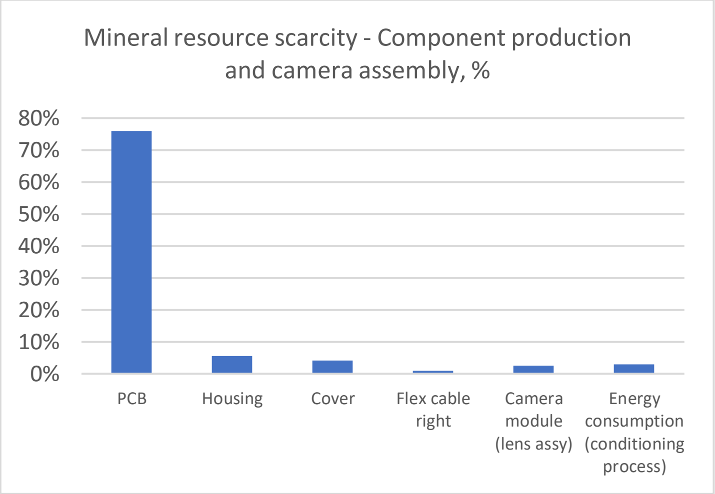
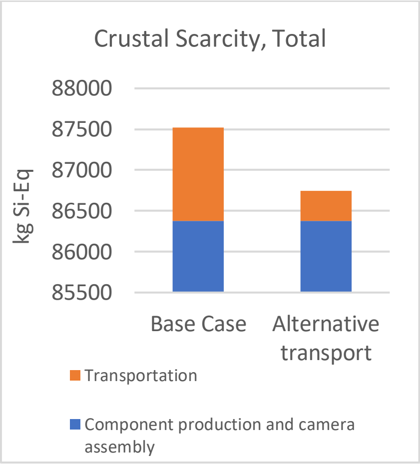


Figure 9. Mineral resource scarcity results for the component production and camera assembly phase, % contribution

8.3 Crustal scarcity

This sub-chapter presents the crustal scarcity indicator results for the product life cycle. They are represented in absolute values for both scenarios in Figure 10, along with the component production and camera assembly phase breakdown in Figure 11. The same tendency can be noticed as for the previous impact indicators, with the PCB component holding the highest impact, which can be observed in Figure 11. It should be noted that for the crustal scarcity indicator results, the gap between the PCB and the other components is the largest. While the PCB stands for 91% of the total environmental impact, the five other components constitute only 9% altogether.



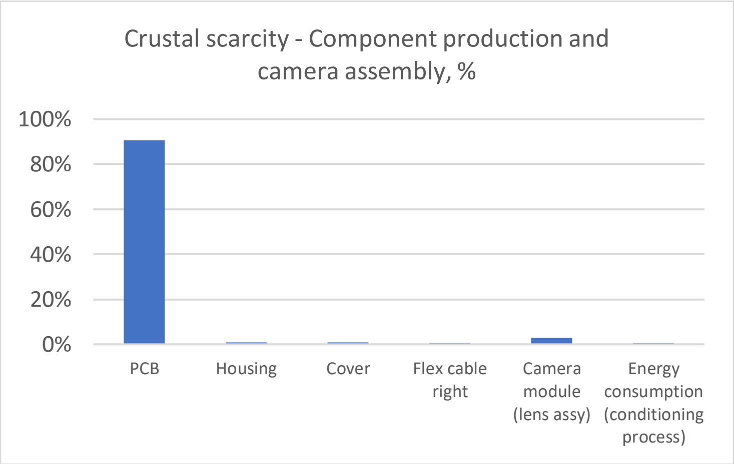
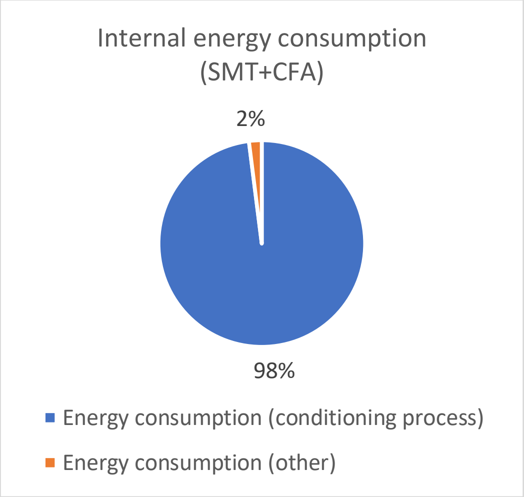


Figure 10. Crustal scarcity results, total, in kg Si-Eq

Figure 11. Crustal scarcity results for the component production and camera assembly phase, %

8.4 Energy consumption

It was assumed by Magna in the beginning that the conditioning process within the facility lines has the highest environmental impact compared to the other processes and components. Therefore, in this subchapter, the results for the two assembly lines - CFA and SMT - are shown and analysed. The conditioning process constitutes 98% of both SMT and CFA assembly lines' energy consumption at Magna, thereby, being the major contributor to the environmental impact at the internal level of energy consumption. This is clearly presented and summarised in Figure 12. However, for the global warming indicator result, the conditioning process is somewhat more than 1% of the camera system's total environmental impact, which is depicted in Figure 13. This indicates that the environmental contribution of the conditioning process is considerably low in comparison with other camera system's life cycle processes and components and contradicts the assumption made in the beginning.



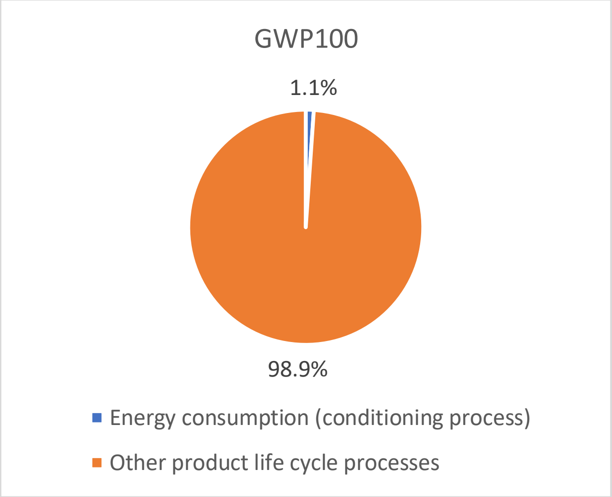
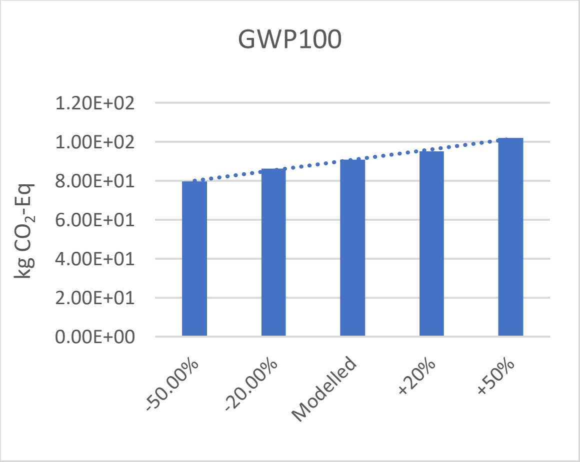


Figure 12. Internal energy consumption (SMT+CFA) in Magna, %

Figure 13. Global warming results for the conditioning process and the whole product life cycle, %

8.5 Sensitivity analysis

Integrated circuits, as a part of the PCB, contribute significantly to all impact categories. Thus, it is decided to investigate the robustness of the results by doing the sensitivity analysis of the integrated circuits. The sensitivity analysis is completed by changing the mass of the integrated circuits in according to the following scheme: -50%, -20%, +20%, +50%. This enables us to analyse how the results are changed as a result of different integrated circuits' mass. This sensitivity analysis is completed for the base case scenario and all three impact indicators: GWP100, mineral resource scarcity and crustal scarcity. The alternative transport scenario is not included since the change in the integrated circuit mass does not affect the results for transportation contribution.



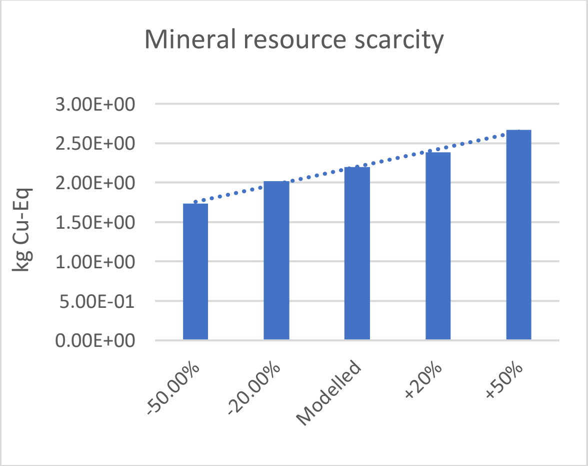


Figure 14. Integrated circuit sensitivity analysis for GWP100, in kg CO_2-Eq

Figure 15. Integrated circuit sensitivity analysis for mineral resource scarcity, in kg Cu-Eq

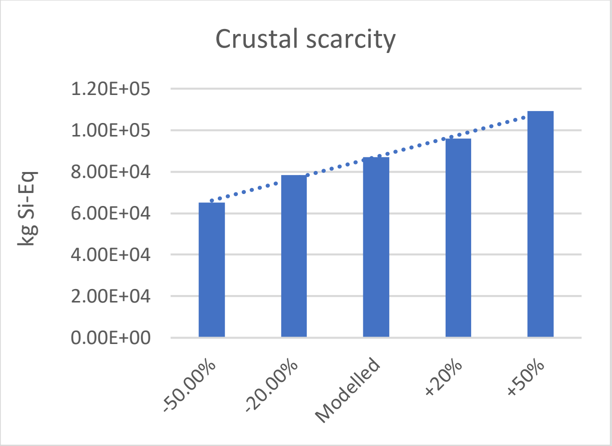


Figure 16. Integrated circuit sensitivity analysis for crustal scarcity indicator, in kg Si-Eq

Figure 14, Figure 15, Figure 16 summarise the sensitivity analysis results for the integrated circuits' mass. For the GWP100 impact indicator, when decreasing 50% of the integrated circuit mass, the total environmental effect decreases by 12%. For mineral resource scarcity, a 50% reduction of the integrated circuit mass leads to a total environmental impact decline of 21%. When it comes to crustal scarcity, it shows the highest reduction among all three impact categories. If the integrated circuit mass is decreased by 50%, the total environmental effect is reduced by 25%. This tendency for the results to be sensitive to the integrated circuit mass change is explained by the fact that this PCB sub-component is the major contributor among all other sub-components. The integrated circuit usually requires the application of hazardous substances and precious minerals such as gold and silver. Furthermore, the production of the integrated circuit is an energy-intensive process. Therefore, the environmental load of this sub-component type is relatively sensitive to mass changes.

9 Discussion

Magna's primary reason for conducting the LCA of the camera system is based on the high energy consumption from the SMT and CFA lines with a special focus on the conditioning process. The conditioning process constitutes a significant portion of 98% of the energy consumption across both assembly lines at Magna's facility in Vårgårda. Initially, Magna identified the conditioning process as a key factor contributing to the overall environmental impact of the camera system production.

When considering the conditioning process, Magna can approach it from two different perspectives. First, it can be analysed from an energy consumption perspective internally within Magna's facility. Removing the conditioning process would result reduce 98% of the energy consumption for both assembly lines. Second, it can be seen from the total life cycle environmental impact perspective. This perspective indicates that the removal of the conditioning process would only results in a reduction of around 1% for the camera system's contribution to global warming. These results indicate that while the conditioning process significantly affects energy consumption internally within Magna's facility, its impact on the overall environmental footprint of the camera system is low and it is not identified as recommended focus area for improvements. Instead, the results of this report show that Magna should focus on other strategies and areas for improvement, to make meaningful reductions in their environmental impact. Thus, Magna should prioritise addressing the components and processes such as the PCB and transportation, as it would bring about the most significant changes to the three impact indicators.

During the LCA, we observed extensive transportation activities, from suppliers to Magna and from Magna to the customer, where the primary transportation method is aircraft. Based on our assumptions and literature review, two different scenarios have been selected to assess the total environmental impact of the camera system. As can be observed from the results, the highest environmental impact of all impact categories is in the base case scenario. Although the contribution of the component production and camera assembly phase remains similar across the two scenarios, the result in the alternative transport scenario shows a major impact reduction potential. According to the results, a shift from aircraft to ship reduces the total environmental impact of the camera system by 14%, specifically regarding contributions to global warming. Thus, altering the transport mode from aircraft to ship is the most feasible solution for Magna to decrease its environmental impact.

The total number of integrated circuits, a sub-component of the PCB, makes a significant contribution to all three impact indicators and, therefore, is chosen for sensitivity analysis. Extraction of metals such as silver, copper and gold, along with other crucial materials is needed for the PCB and the integrated circuits, which contributes to the environmental impact. Additionally, during manufacturing, processes such as etching and soldering require a significant amount of energy. However, due to its complex and miniaturised nature, reducing the total environmental impact of the PCB can be considered only in the long-term perspective. Therefore, no specific recommendation will be provided to address the environmental impact of the PCB. Nevertheless, further exploration and investigation of the PCB and the integrated circuits can be expected to provide valuable insights into how to decrease the total environmental impact of the camera system life cycle.

Finally, certain limitations of the study should be described. First, this LCA should be perceived as an initial and foundational step for future LCA studies regarding the camera system, meaning that Magna can use it for continued, refined and expanded assessment in subsequent rounds. Furthermore, regarding data collection, achieving a more accurate and comprehensive result requires dedicated data collection over a longer time period, preferably on the scale of a few years, and further developed modelling procedures. This may involve a detailed investigation of raw material extraction as well as mapping out various processes for each sub-component sourced from the numerous suppliers in the supply chain. Applying such a comprehensive approach would enhance the credibility and accuracy of the analysis of the camera system.

10 Conclusion

The study aims to identify the environmental effects of the camera system throughout its life cycle. Answering the first research question, the major contributor to the total environmental impact of the product is the PCB and in particular, its sub-component, the integrated circuits. The extraction of materials that are used in integrated circuit production such as gold, silver and copper are energy-intensive processes, which makes up a large share of environmental impact of the camera system. Furthermore, it was identified that the change in the transportation mode from aircraft to ship considerably reduces the total contribution to global warming impact from the camera system.

Initially, it was emphasised by Magna that the conditioning process was expected to have a high or even the highest environmental impact out of all life cycle steps. However, during the assessment, it was revealed that the conditioning process stands for only a small share of the total life cycle environmental impact compared to other unit processes. Therefore, removing the conditioning process from the assembly lines does not affect the impact as much as expected and, therefore, it is not recommended to be made a priority in the company’s strategy to minimise the effects of their emissions.

Also, regarding the second research question, and recommendations for how Magna can reduce the environmental effect of the camera system, it can be seen in two perspectives: a short-term and a long-term perspective. In the short-term perspective, Magna is recommended to alter the mode of transportation from aircraft to ship, both when it comes to the transportation from suppliers to Magna and from Magna to the customer. In the long-term perspective, it is suggested to prioritise changing the design or material composition of the PCB and its sub-components, foremost the integrated circuits.

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Appendix A

A.1 Component production and camera assembly phase – input/output flows

Table A.1.1 Camera module assembly, lens production

Input	**Amount**	**Unit**	**Provider**
adhesive, for metal	0.7037	g	market for adhesive, for metal - RoW
aluminium, primary, ingot	5.109	g	market for aluminium, primary, ingot - RoW
aluminium, primary, ingot	0.599	g	market for aluminium, primary, ingot - RoW
brass	0.081	g	market for brass - RoW
extrusion of plastic sheets and thermoforming, inline	0.001	g	market for extrusion of plastic sheets and thermoforming, inline - GLO
flat glass, uncoated	2.24	g	market for flat glass, uncoated - RoW
polyethylene terephthalate, granulate, amorphous	0.001	g	market for polyethylene terephthalate, granulate, amorphous - GLO
printed wiring board, surface mounted, unspecified, Pb free	2.002186	g	market for printed wiring board, surface mounted, unspecified, Pb free - GLO
silicon, metallurgical grade	0.0394	g	market for silicon, metallurgical grade - GLO
tempering, flat glass	2.24	g	market for tempering, flat glass - GLO
Output	**Amount**	**Unit**	
Camera module assembly	1	Item(s)	

Table A.1.2 Clip, plastic injection molding, steel wire bending

Input	**Amount**	**Unit**	**Provider**
acrylonitrile-butadiene-styrene copolymer	0.5525	g	market for acrylonitrile-butadiene-styrene copolymer - GLO
antimony	0.0425	g	market for antimony - GLO
glass fibre reinforced plastic, polyamide, injection moulded	0.255	g	market for glass fibre reinforced plastic, polyamide, injection moulded - GLO
injection moulding	2.05	g	market for injection moulding - GLO
steel, chromium steel 18/8	1.2	g	market for steel, chromium steel 18/8 - GLO
wire drawing, steel	2.05	g	market for wire drawing, steel - GLO
Output	**Amount**	**Unit**	
Clip	1	Item(s)	

Table A.1.3 Cooling fan, assembling

Input	**Amount**	**Unit**	**Provider**
acrylonitrile-butadiene-styrene copolymer	9.00181	g	market for acrylonitrile-butadiene-styrene copolymer - GLO
adhesive, for metal	0.0035	g	market for adhesive, for metal - RoW
aluminium alloy, AlMg3	0.5	g	market for aluminium alloy, AlMg3 - GLO
antimony	0.707	g	market for antimony - GLO
copper, anode	1.79759	g	market for copper, anode - GLO
extrusion of plastic sheets and thermoforming, inline	0.551	g	market for extrusion of plastic sheets and thermoforming, inline - GLO
ferrite	0.7035	g	market for ferrite - GLO
glass fibre reinforced plastic, polyamide, injection moulded	3.03	g	market for glass fibre reinforced plastic, polyamide, injection moulded - GLO
injection moulding	15.55481	g	market for injection moulding - GLO
polyethylene terephthalate, granulate, amorphous	0.551	g	market for polyethylene terephthalate, granulate, amorphous - GLO
printed wiring board, surface mounted, unspecified, Pb free	0.289	g	market for printed wiring board, surface mounted, unspecified, Pb free - GLO
sheet rolling, steel	1.622	g	market for sheet rolling, steel - GLO
solder, paste, Sn95.5Ag3.9Cu0.6, for electronics industry	0.05	g	market for solder, paste, Sn95.5Ag3.9Cu0.6, for electronics industry - GLO
steel, low-alloyed, hot rolled	1.622	g	market for steel, low-alloyed, hot rolled - GLO
wire drawing, copper	1.79759	g	market for wire drawing, copper - GLO
Output	**Amount**	**Unit**	
Cooling fan	1	Item(s)	

Table A.1.4 Cover, aluminium die casting

Input	**Amount**	**Unit**	**Provider**
acrylic acid	4.3852	g	market for acrylic acid - RoW
aluminium, primary, ingot	171	g	market for aluminium, primary, ingot - RoW
butyl acetate	0.37505	g	market for butyl acetate - RoW
electricity, medium voltage	2.6	kWh	market for electricity, medium voltage - CN-ECGC
electrostatic paint	5.77	g	market for electrostatic paint - GLO
graphite	0.8175	g	market for graphite | graphite - GLO
heat, central or small-scale, natural gas	10.8	kWh	market for heat, central or small-scale, natural gas - RoW
lubricating oil	20	g	market for lubricating oil - RoW
melamine formaldehyde resin	1.00975	g	market for melamine formaldehyde resin - RoW
nickel, class 1	1.635	g	market for nickel, class 1 - GLO
polydimethylsiloxane	1.7475	g	market for polydimethylsiloxane - GLO
Output	**Amount**	**Unit**	
Cover	1	Item(s)	

Table A.1.5 Flex cable, left, etching, lamination

Input	**Amount**	**Unit**	**Provider**
acetone, liquid	0.0006	g	market for acetone, liquid - RoW
adhesive, for metal	0.03909	g	market for adhesive, for metal - RoW
cable, unspecified	0.596566	g	market for cable, unspecified - GLO
chemical, organic	0.00045	g	market for chemical, organic - GLO
chlorine, gaseous	0.0011	g	market for chlorine, gaseous - RoW
cobalt	1.76E-07	g	market for cobalt - GLO
electricity, medium voltage	0.0002	kWh	market for electricity, medium voltage | electricity, medium voltage | Cutoff, U - CN-SWG
electricity, medium voltage	13	kWh	market for electricity, medium voltage - CN-SWG
gold	0.0001958	g	market for gold - GLO
hydrochloric acid, without water, in 30% solution state	0.0009	g	market for hydrochloric acid, without water, in 30% solution state - RoW
isopropanol	0.0006	g	market for isopropanol - RoW
laminating service, foil, with acrylic binder	1	m2	market for laminating service, foil, with acrylic binder - GLO
polyvinylchloride, bulk polymerised	0.05158	g	market for polyvinylchloride, bulk polymerised - GLO
potassium carbonate	0.0013	g	market for potassium carbonate - GLO

potassium hydroxide	0.0013	g	market for potassium hydroxide - GLO
silver	0.0000003	g	market for silver - GLO
water, deionised	0.024	g	market for water, deionised - RoW
water, deionised	0.0066	g	market for water, deionised - RoW
Output	**Amount**	**Unit**	
Flex cable, left	1	Item(s)	

Table A.1.6 Flex cable, right, etching, lamination

Input	Amount	Unit	Provider
acetone, liquid	0.0006	kg	market for acetone, liquid - RoW
adhesive, for metal	0.03615	g	market for adhesive, for metal - RoW
cable, unspecified	0.593036	g	market for cable, unspecified - GLO
chemical, organic	0.00045	kg	market for chemical, organic - GLO
chlorine, gaseous	0.0011	kg	market for chlorine, gaseous - RoW
cobalt	1.76E-07	g	market for cobalt - GLO
electricity, medium voltage	0.2	kWh	market for electricity, medium voltage - CN-SWG
electricity, medium voltage	13	kWh	market for electricity, medium voltage - CN-SWG
gold	0.0002	g	market for gold - GLO
hydrochloric acid, without water, in 30% solution state	0.0009	kg	market for hydrochloric acid, without water, in 30% solution state - RoW
isopropanol	0.0006	kg	market for isopropanol - RoW
laminating service, foil, with acrylic binder	1	m2	market for laminating service, foil, with acrylic binder - GLO
polyvinylchloride, bulk polymerised	0.05148	g	market for polyvinylchloride, bulk polymerised - GLO
potassium carbonate	0.0013	kg	market for potassium carbonate - GLO
potassium hydroxide	0.0013	kg	market for potassium hydroxide - GLO
silver	0.0000003	g	market for silver - GLO
water, deionised	0.0066	kg	market for water, deionised - RoW
water, deionised	0.024	kg	market for water, deionised - RoW
Output	**Amount**	**Unit**	
Flex cable, right	1	Item(s)	

Table A.1.7 Housing, aluminium die casting

Input	Amount	Unit	Provider
adhesive, for metal	0.2	g	market for adhesive, for metal - RoW
aluminium, primary, ingot	298	g	market for aluminium, primary, ingot - RoW

electricity, medium voltage	2.6	kWh	market for electricity, medium voltage - CN-ECGC
heat, central or small-scale, natural gas	10.8	kWh	market for heat, central or small-scale, natural gas - RoW
lubricating oil	20	g	market for lubricating oil - RoW
Output	**Amount**	**Unit**	
Housing	1	Item(s)	

Table A.1.8 Label, printing, die-cutting

Input	**Amount**	**Unit**	**Provider**
adhesive, for metal	0.01431	g	market for adhesive, for metal - RoW
polyethylene terephthalate, granulate, amorphous	0.03869	g	market for polyethylene terephthalate, granulate, amorphous - GLO
printed paper	0.03869	g	market for printed paper - GLO
Output	**Amount**	**Unit**	
Label	1	Item(s)	

Table A.1.9 Lens cap, left, plastic injection molding

Input	**Amount**	**Unit**	**Provider**
injection moulding	5.42	g	market for injection moulding - GLO
polypropylene, granulate	4.336	g	market for polypropylene, granulate - GLO
Talc	1.084	g	
Output	**Amount**	**Unit**	
Lens cap left	1	Item(s)	

Table A.1.10 Lens cap, right, plastic injection molding

Input	**Amount**	**Unit**	**Provider**
injection moulding	5.45	g	market for injection moulding - GLO
polypropylene, granulate	4.36	g	market for polypropylene, granulate - GLO
Talc	1.09	g	
Output	**Amount**	**Unit**	
Lens cap right	1	Item(s)	

Table A.1.11 Packaging, carbon box

Input	**Amount**	**Unit**	**Provider**
corrugated board box	152	g	market for corrugated board box – RoW
Output	**Amount**	**Unit**	

Packaging, carbon box	1	Item(s)	

Table A.1.12 Packaging, plastic wrapping

Input	**Amount**	**Unit**	**Provider**
extrusion, co-extrusion	131.06295	g	market for extrusion, co-extrusion - GLO
polyethylene, low density, granulate	127	g	market for polyethylene, low density, granulate - GLO
Output	**Amount**	**Unit**	
Packaging, plastic wrapping	1	Item(s)	

Table A.1.13 Packaging, tray

Input	**Amount**	**Unit**	**Provider**
extrusion, co-extrusion	163.0547	g	market for extrusion, co-extrusion - GLO
polyethylene terephthalate, granulate, amorphous	158	g	market for polyethylene terephthalate, granulate, amorphous - GLO
thermoforming of plastic sheets	167.01903	g	market for thermoforming of plastic sheets - GLO
Output	**Amount**	**Unit**	
Packaging, tray	1	Item(s)	

Table A.1.14 PCB, manufacturing, ready for assembling

Input	**Amount**	**Unit**	**Provider**
capacitor, electrolyte type, < 2cm height	3.14086	g	market for capacitor, electrolyte type, < 2cm height - GLO
electric connector, peripheral component interconnect buss	3.028	g	market for electric connector, peripheral component interconnect buss - GLO
inductor, ring core choke type	3.792	g	market for inductor, ring core choke type - GLO
integrated circuit, logic type	6.5837	g	market for integrated circuit, logic type - GLO
integrated circuit, logic type	7.2066	g	market for integrated circuit, logic type - GLO
printed wiring board, surface mounted, unspecified, Pb free	52.637	g	market for printed wiring board, surface mounted, unspecified, Pb free - GLO
solder, paste, Sn95.5Ag3.9Cu0.6, for electronics industry	3.207	g	market for solder, paste, Sn95.5Ag3.9Cu0.6, for electronics industry - GLO
Output	**Amount**	**Unit**	
PCB	1	Item(s)	

Table A.1.15 Screw, cold forming from wire

Input	**Amount**	**Unit**	**Provider**
impact extrusion of steel, cold, deformation stroke	0.80907	g	market for impact extrusion of steel, cold, deformation stroke - GLO
sheet rolling, steel	0.80907	g	market for sheet rolling, steel - GLO
steel, low-alloyed	0.80907	g	market for steel, low-alloyed - GLO
Output	**Amount**	**Unit**	
PCB	1	Item(s)	

Table A.1.16 Sealant, formulation

Input	**Amount**	**Unit**	**Provider**
aluminium oxide, metallurgical	6.4918667	g	market for aluminium oxide, metallurgical - RoW
seal, natural rubber based	7.24	g	market for seal, natural rubber based - GLO
silicon carbide	0.7481333	g	market for silicon carbide - GLO
Output	**Amount**	**Unit**	
PCB	1	Item(s)	

A.2 Transportation phase – input/output flows

Table A.2.1 Transportation from Magna to the customer

Input	**Amount**	**Unit**	**Provider**
transport, freight, aircraft, long haul	14.274	t*km	market for transport, freight, aircraft, long haul - GLO
transport, freight, lorry >32 metric ton, EURO6	4.287	t*km	market for transport, freight, lorry >32 metric ton, EURO6 - RER
Output	**Amount**	**Unit**	
Transportation from Magna to the customer	1	Item(s)	

Table A.2.2 Transportation from suppliers to Magna

Input	**Amount**	**Unit**	**Provider**
transport, freight, aircraft, long haul	1.077	t*km	market for transport, freight, aircraft, long haul - GLO
transport, freight, lorry >32 metric ton, EURO6	31.222	t*km	market for transport, freight, lorry >32 metric ton, EURO6 - RER
transport, freight, sea, container ship	17.202	t*km	market for transport, freight, sea, container ship - GLO
Output	**Amount**	**Unit**	
Transportation from suppliers to Magna	1	Item(s)	

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