

# **Life Cycle Assessment of the Framework Laptop 2022**

LCA Report (ISO 14044 and ISO 14067)

## Implementation

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## Declaration

This report is a deliverable from a study carried out by Fraunhofer IZM and commissioned by Framework Computer Inc. The study was commissioned to reach objective and unbiased conclusions. Fraunhofer IZM declares no conflict of interest.

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## Abbreviations

ADPe	Abiotic resource depletion of elements
ALS	Ambient light sensor
BID	Bill of Material Identifier
BOM	Bill of Material
CFP	Carbon footprint of products (sometimes PCF)
CO <sub>2</sub> e	Carbon dioxide equivalents
ei	Ecoinvent Database
EOL	End of life
EPD	Environmental Product Declaration
EPS	External power supply
EU	European Union
FU	Functional unit
GHG	Greenhouse gases
GWP	Global warming potential
IC	Integrated circuit
ICT	Information and communication technology
ISO	International Organization for Standardization
LCA	Life cycle assessment
LCA FE	Sphera LCA for Experts
MWI	Municipal Waste Incineration
NDA	Non-disclosure agreement
OEM	Original Equipment Manufacturer
PAIA	Product Attribute to Impact Algorithm
PAS	Publicly Available Specification
PCB	Printed circuit board
PCR	Product Category Rule
PEF	Product environmental footprint
PEFCR	Product environmental footprint category rules
PCF	Product Carbon Footprint (sometimes CFP)
PSF	Product Specific Rule



# 1 Executive summary

A life cycle assessment of the Framework Laptop 2022 was conducted focusing on the two impact categories:

- Climate change displayed as Global Warming Potential (GWP)
- Abiotic resource depletion as Abiotic Resource Depletion of elements (ADPe)

The Framework Laptop is a high-performance notebook that is designed to be upgradeable, repairable, and customizable. The functional unit used in this study is the use of this notebook over 5 years. Although the laptop is modular and repairable, no product failure and thus no repair was assumed. The configuration was assumed to include 16 GB of memory, 256 GB of storage, and two expansion cards with USB-A and USB-C connectors. In addition, an external power supply from Framework Computer Inc. and the screwdriver kit shipped with each notebook were included in the model.

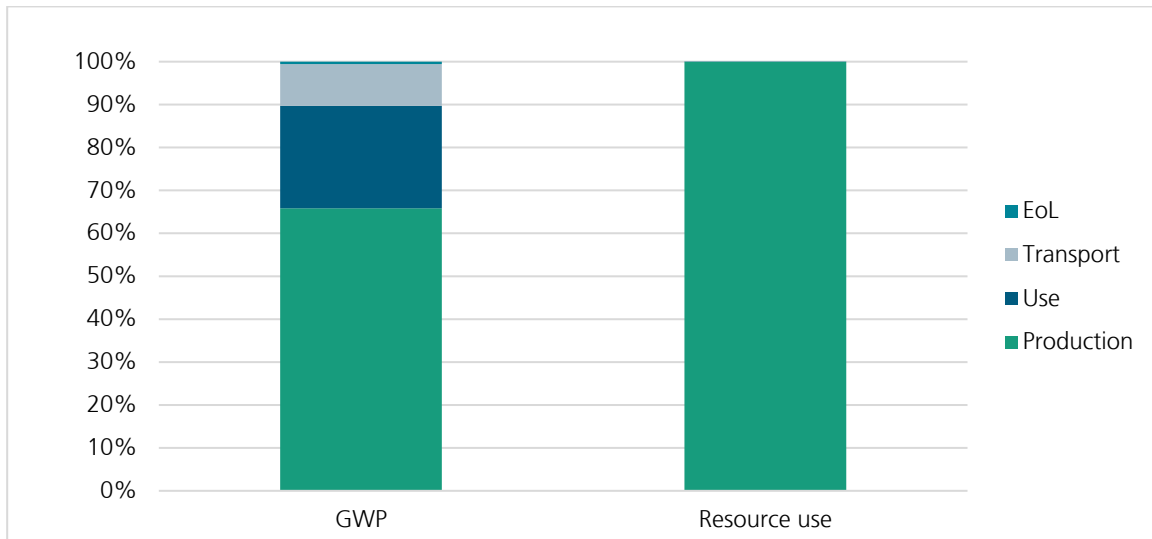
The inventory was based on the teardown of the notebook and the bill of materials provided by Framework for most of the modules (especially the mainboard). The analysis and teardown was supported by laboratory analysis: X-ray and grinding of the main ICs on the mainboard, RAM and memory module, and microscopic analysis of the contact areas.

## Results

The total impact for the Framework Laptop is estimated to be a GWP of 200 kg CO<sub>2</sub>e and an ADPe of 1.7E-02 kg Sb-e.

The cradle-to-gate, meaning the manufacturing and raw material acquisition phase, has the highest impact in both impact categories. As shown in Figure 1-1 the resource use is almost exclusively caused by the production phase. Use phase follows in its relative contribution, although this is only a relevant order of magnitude for GWP. For EoL only impacts were considered and no credits were given for recycling, so this phase also has a small contribution. Transportation has a smaller impact, mainly due to distribution and less due to transportation during the manufacturing phase or to EoL treatment.

Figure 1-1: Relative impact of life cycle phase to the total impact per impact category

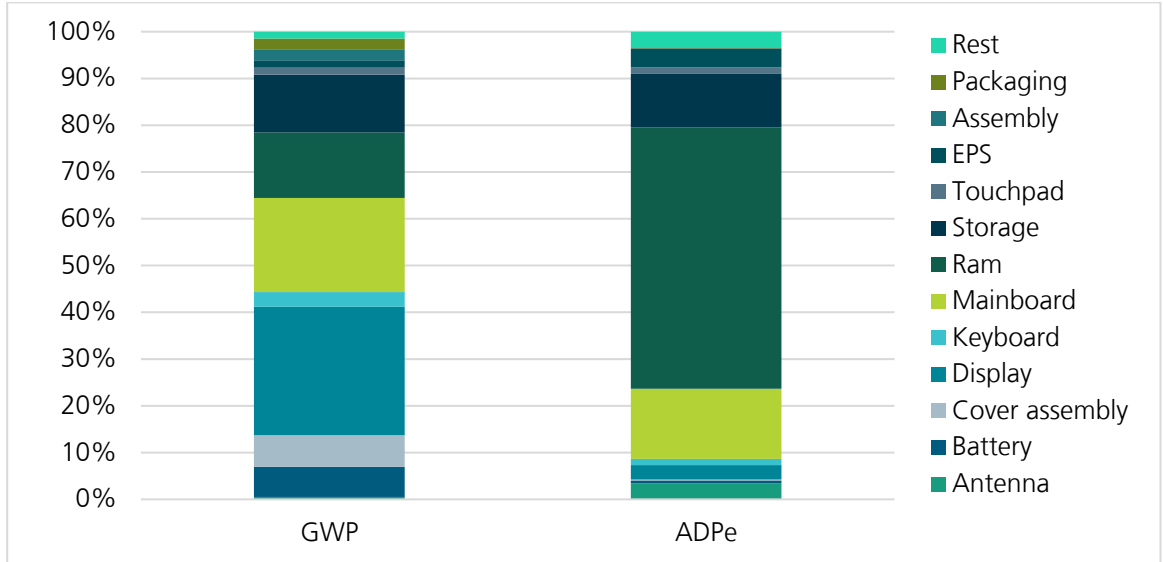


The production causes 132 kg CO<sub>2</sub>e and 1.73E-02 kg Sb-e.

The relative impact of the production is displayed in the following Figure 1-2 (rest includes all modules with an individual contribution <1.5% in both impact categories). The highest contribution to the GWP

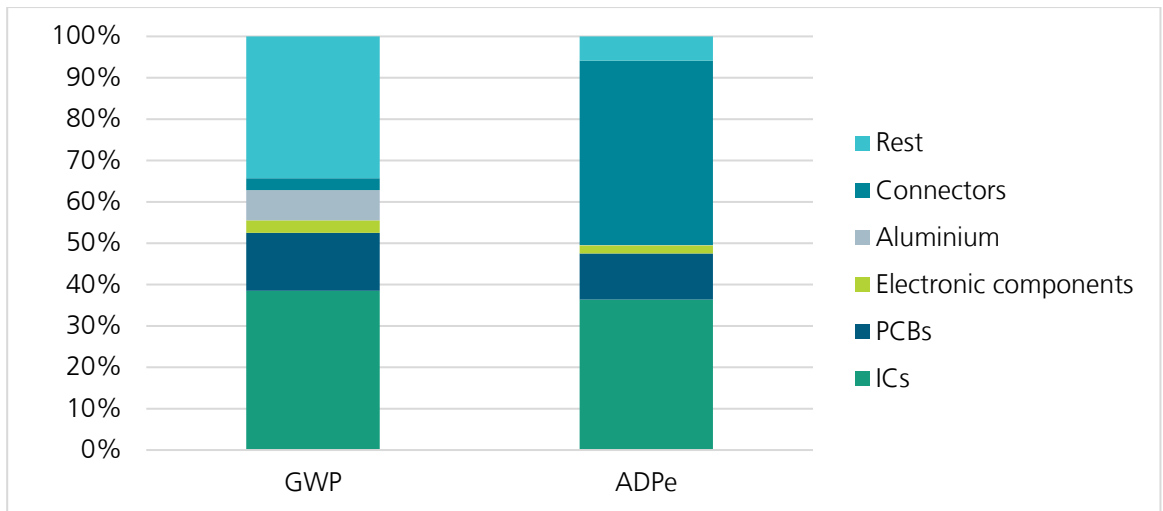
has the display module, whereas the ADPe is mainly influenced by the RAM (and thereby by the assumed amount of gold on the connector of the RAM bar). Mainboard and storage have also a significant impact in both impact categories.

Figure 1-2: Relative impact per module to the production phase



Across the different modules, ICs cause the highest contribution to GWP, followed by the PCBs. The ADPe is mainly caused by the connectors, followed by the ICs (see Figure 1-3, electronic components incl. passive and active components on the printed circuit boards excl. ICs).

Figure 1-3: Relative impact of component types across modules



## 2 Goal of the study

This document draws on principles, requirements and guidance from existing international standards on life cycle assessment (LCA) and aims to assess the carbon footprint of the Framework Laptop 2022 covering the life cycle stages of production, distribution, use phase and end of life of the product.

The impact assessment is carried out according to the ISO 14044 and ISO 14067, so that the results are directly usable for communicating the carbon footprint (CFP) of the mentioned product. This report contains the impact assessment according to characterization factors of the Environmental Footprint Reference Package 3.1 (abbreviated as EF 3.1) and gives a detailed analysis on the following impact categories:

- Global Warming Potential (GWP100)
- Abiotic resource depletion of elements (ADPe)

This study does allow for the communication of the carbon footprint of the product. Due to the limited scope of impact categories in this study it is not possible to make general statements on the environmental performance of the product nor direct product comparison. The study was carried out without a critical review by an independent party.

## 3 Scope of the study

The project report and life cycle assessment (LCA) were prepared according to the following standards:

- *ISO 14044:2021-02 – General principles and requirements for LCA*
- *ISO 14067:2019-02 – Requirement and guidelines for carbon footprints of products*

In the absence of a unified approach for LCAs of ICT devices (cf., Schischke et al. 2023) and product-specific rules (PSR) for notebooks and laptops, additional standards and guidelines have been applied without claiming full conformity, as follows:

- *EN 50963 – PCR for LCA of electronic and electrical products and systems*, is used for setting the system boundaries.
- *PEFCR IT Equipment v1.2* is used for generic assumptions in the modelling of missing data in the fore- and background system.
- *Environmental Footprint Reference Package 3.1* is used to carry out the life cycle impact assessment (LCIA)

Where necessary additional standards guidelines were applied and referenced in the study.

### 3.1 Functional Unit

The functional unit is defined as the use of the Framework Laptop over an average service life of 5 years. The reference flow is one Framework Laptop incl. two extension cards and a charger.

### 3.2 Reference Service Life (RSL)

The reference service life describes the expected service life of a product under a certain set of use conditions (reference conditions), which can be used to estimate the service life under other use conditions (EN50693, Ch. 3.36). This LCA study does not consider the use phase (Module B) in its entirety (e.g. repair, refurbishment) and does not compare different use scenarios, so the RSL cannot be adequately determined and is not declared at this point.

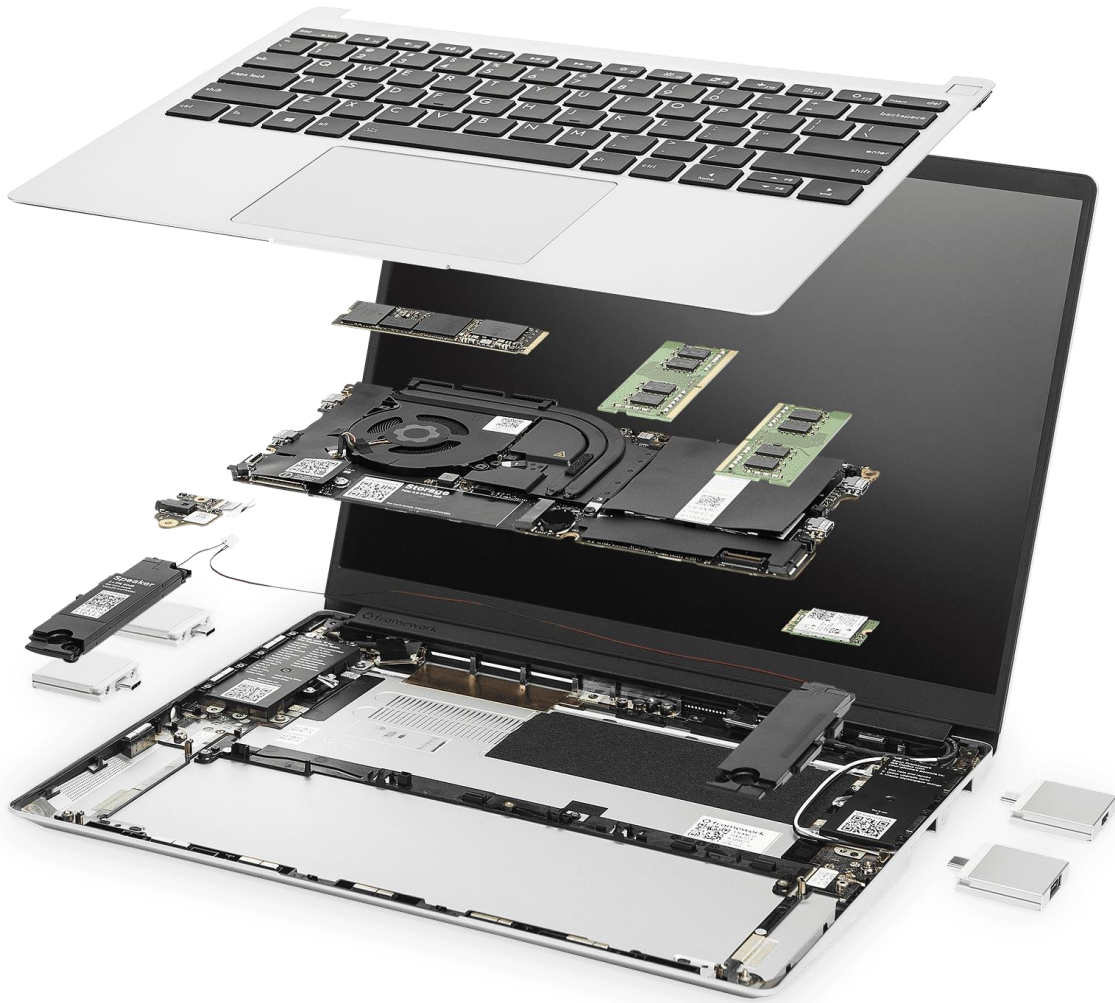
In the LCA, the energy consumption is considered for an exemplary service life of 5 years for the use phase. However, in general it can be assumed that the typically RSL of a Framework Laptop exceeds 5 years.

### 3.3 Product description

#### 3.3.1 Product description

The Framework Laptop is a high-performance notebook that is designed to be upgradeable, repairable, and customizable. It is a thin and light notebook that comes with a 13.5-inch display and weighs 1.3 kilograms. The laptop is built with a modular design that allows users to easily swap out components such as the mainboard, keyboard, and ports (see Figure 3-1). Framework Laptop's modular design also allows users to customize their laptop's ports. The laptop comes with a USB-C port that can be swapped out for other ports such as USB-A, HDMI, DisplayPort, and microSD.

Figure 3-1: Schematic image of the modular product approach (Framework 2022)



### 3.3.2 Product configuration and specifications

The following product configuration the Framework Laptop is considered for the LCA study.

Table 3-1: Product configuration and specifications

Position	Description
Product name	Framework Laptop 13 (12 <sup>th</sup> Gen Intel® Core™)
Modell year	2022

<sup>1</sup> Images Source: <https://frame.work/de/de/products/laptop-diy-13-gen-amd>

Position	Description
Typical Energy Consumption (TEC) per year	15.4 kWh <sup>2</sup>
Processor	i5-1240P, 4.4GHz, 4+8 cores
Display	13.5" diagonal, 2256x1504 resolution, > 400 nit max brightness
Memory	16GB (2 x 8GB) DDR4-3200
Graphics	Iris Xe Graphics
Storage	<ul style="list-style-type: none"> <li>256 SSD WD BLK SN770 NVME</li> </ul>
Expansion Cards	<ul style="list-style-type: none"> <li>USB-C</li> <li>USB-A</li> </ul>
Connectivity	WiFi 6E, Bluetooth 5.2
Audio	<ul style="list-style-type: none"> <li>Stereo 2W speakers</li> <li>Dual MEMS microphones with hardware privacy switch</li> <li>3.5mm combo headphone jack</li> </ul>
Battery	55Wh (80% capacity after 1000 cycles)
Camera	1080p 60fps
Power Adapter	60W USB-C
Keyboard	Backlit
Material	Aluminum CNC Top Cover Aluminum formed Input Cover and Bottom Cover
Weight	1.3 kg

### 3.4 System boundaries

This study covers the whole life cycle of the laptop from raw material acquisition, manufacturing, use and disposal incl. transport in the different phases.

The selected boundaries of the system are in accordance with the minimum requirements of *EN 50693* and the draft version of an upcoming *PSR on Electronic Equipment, and Electronic Components (Non-Construction)* by EPD International (EPD International 2023)<sup>3</sup>.

In the following, the declared modules within the system boundaries are shown in tabular form.

<sup>2</sup> According to Framework Energy Star Datasheet: Framework - FRANPC0000 : FRANPC00N4, URL: <https://www.energystar.gov/productfinder/product/certified-computers/details/2401061> (retrieved on 2023-09-06).

<sup>3</sup> EPD International (2023): Electronic and electric equipment and electronic components (non-construction). Product Category Rules (PCR) – Draft. URL: <https://www.datocms-assets.com/37502/1679565591-pcr-electronic-and-electric-equipment-and-electronic-components-non-construction-draft-v1-for-open-consultation.pdf> (retrieved on 2023-04-25).

Table 3-2: System boundaries and modules considered in the study

PRODUCT STAGE			DISTRIBUTION		USE PHASE							END OF LIFE STAGE				BENEFITS AND LOADS BEYOND THE SYSTEM BOUNDARIES
Raw materials and intermediary	Transport	Manufacturing/ Fulfillment center	Transport to PoS	Installation at PoU	Use	Maintenance	Repair	Reuse	Refurbishment	Operational energy use	Operational water use	De-installation at PoU	Transport	Waste processing	Disposal	Reuse- Recovery- Recycling- potential
<b>A1</b>	<b>A2</b>	<b>A3</b>	<b>A4</b>	<b>A5</b>	<b>B1</b>	<b>B2</b>	<b>B3</b>	<b>B4</b>	<b>B5</b>	<b>B6</b>	<b>B7</b>	<b>C1</b>	<b>C2</b>	<b>C3</b>	<b>C4</b>	<b>D</b>
X	X	X	X	X	ND	ND	ND	ND	ND	X	ND	X	X	X	X	ND

Legend: X = declared; ND = not declared

In this study one end-of-life scenario will be considered:

- Recycling scenario (100% recycling and disposal of the product, cut-off waste-content approach)

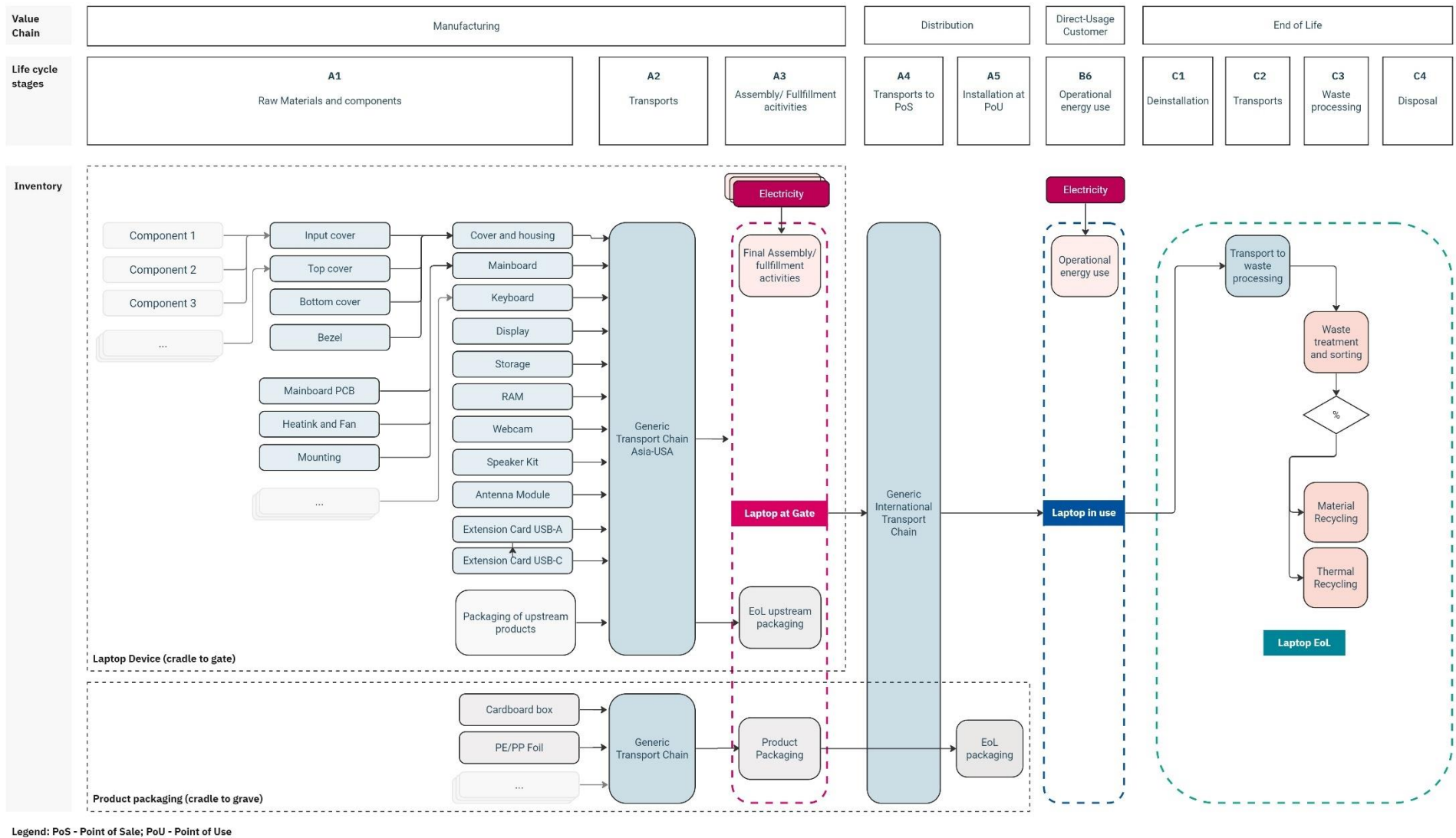
### 3.4.1 Life cycle stages

This chapter describes the system boundaries, including all upstream, core and downstream processes and activity data considered in this LCA. According to EN50693 and PCR Draft for EEE and electronic components the life cycle inventory covers the following sections:

- Raw material acquisition and manufacturing (A1-3)
- Transports to Point of Sale (A4)
- Installation at Point of Usage (A5)
- Use phase (B6)
- Transports to End of Life (C2)
- End-of-life (C3-4)

An overview of the included processes and components and their attribution to the respective life cycle stages can be found in Figure 3-2. A detailed description of each life stage can be found in the following sections.

Figure 3-2: System boundaries of the lifecycle modell (own illustration)





### 3.4.1.1 Material and components supply (A1)

The Framework Laptop and all accessories are designed by Framework Computer Inc. (Framework) in the USA and Taiwan and manufactured by contract manufacturers mainly in Asia. Framework does not have its own manufacturing facilities and fulfilment centres for shipping products. All components and individual modules are manufactured by various contract manufacturers in Asia, which may include further upstream suppliers of sub-components and modules. Most components are manufactured to the specific requirements of Framework, while some components are available as commercial off-the-shelf (COTS) components (e.g., memory storage, WiFi module, ICs, etc.).

In the lack of primary production data from OEMs and upstream suppliers all components were specified, where possible, based on technical data sheets and specific bill of materials (BOMs) provided by the contract manufacturers to Framework and the LCA practitioner (see Chapter 4.1). No specific process and activity data from the production of single components or modules were obtained (e.g., direct emission in production of subcomponents, energy usage, use of secondary materials, material losses due to manufacturing and processing, etc.). Missing activity and process data was modelled on base of secondary LCIA databases (i.e., LCA FE, ecoinvent) which is described in detail in Chapter 4 and 4.5. In the lack of specific information on packaging materials for components in the upstream supply chain, a packaging mix was estimated using a specific mass factor (see Table 3-4).

Where specific data was not available, individual components were identified through teardowns, desk research or approximated using secondary data as described in Chapter 4.1.

### 3.4.1.2 Transports to assembly site (A2)

Individual components and packaging materials are purchased from different suppliers which mainly operate in Asia and shipped to the main assembly site in Taiwan. As no specific transport data could be obtained all transports are based on the default transport scenarios on a region level provided in the Product Category Rule *EN50693 Chapter 4.3.2* and described in detail in the table below.

All transports for upstream supplies and packaging material are modelled as one-ways distance with a payload of 85%.

Table 3-3: Transport scenario to assembly site (A2)

Process	Description	Region	Transport scenario according EN 50693	Background dataset from LCA FE
Upstream modules and components from Asia	84 wt.-% of components	Intracontinental transport (Asia) {RAS}	3.500 km LKW (85% Utilization)	GLO: Truck-trailer, Euro 5, 34 - 40t gross weight / 27t payload capacity Sphera <e-ep>;
Upstream modules and components from USA	16 wt.-% of components (e.g., CPU, ICs., Memory, Storage)	International transport (Global) {GLO}	Transport chain: 19.000 km Transport ship + 1.000 km LKW (85% Utilization)	GLO: FW_Transports Intracontinental   Truck-trailer, Euro 5, 34-40t (GLO) IZM <LZ>; based on:  GLO: Truck-trailer, Euro 5, 34 - 40t gross weight / 27t payload capacity Sphera <e-ep>;

Process	Description	Region	Transport scenario according EN 50693	Background dataset from LCA FE
				FW_Container ship ocean incl. fuel, 27,500 dwt payload capacity, ocean going;
Packaging materials (Downstream)	Packaging materials for shipping to consumer	Local transport (Taiwan) {TW}	1.000 km LKW (85% Utilization)	GLO: Truck-trailer, Euro 5, 34 - 40t gross weight / 27t payload capacity Sphera <e-ep>;

### 3.4.1.3 Assembly and shipping preparation (A3)

Individual components are purchased from different suppliers and shipped to the main assembly site, where they are then assembled into the Framework Laptop. The final assembly includes the commissioning of components, the assembly of the components into a laptop, the packaging of the final product and additional modules, and the preparation of the final product for shipment. The assembly is carried out by a contract manufacturer of Framework in Taiwan. No specific activity data (e.g., energy usage, intralogistics, etc.) could be obtained and was therefore estimated by the LCA practitioner on base of industrial data from other LCA studies and public industry data.

During the assembly phase, there is a small amount of packaging waste from intermediate products in the upstream supply chain that needs to be disposed of. In the absence of specific data, a packaging mix was estimated using a mass factor of 1.12 (12%) of the total mass of all inputs and supplementary modules.

Table 3-4: Mass inputs at assembly (A3) and est. upstream packaging waste (A1)

#	Material	BOM-ID	Mass [g]	Relative (%)	Description
1	Framework Laptop, incl. all modules	-	1,302.97	100	Laptop with all supplementary modules
1.1	<i>Framework Laptop</i>	BID-115	1,262	96.86	Laptop with core modules assembled
1.2	<i>USB-A_EC Kit</i>	BID-672	7.19	0.55	Supplementary module
1.3	<i>USB-C_EC Kit</i>	BID-692	6.97	0.53	Supplementary module
1.4	<i>RAM</i>	BID-XXX	8.81	0.68	Supplementary module
1.5	<i>Storage SSD</i>	BID-XXX	18	1.38	Supplementary module
2	External Power Supply	-	113	100	Supplementary part
2	Upstream packaging	-	169.92	100	Estimated as 12% of #1+#2
2.1	<i>Cardboard Box</i>	-	135.93	80	Estimated as 80% of #3

#	Material	BOM-ID	Mass [g]	Relative (%)	Description
2.2	PE Foil	-	33.98	20	Estimated as 20% of #2

For the disposal of upstream packaging waste, a generic municipal waste incineration process was assumed, which is the common treatment practice in Taiwan for packaging waste.<sup>4</sup> According to the cut-off approach, no credits are given for energy recovery. Transports of upstream packaging waste from the assembly stage to waste facility were estimated by the LCA practitioner and described in Table 3-5. According to *EN50693 Chapter 4.3.2* waste Transports include a full outward journey and empty return journey by truck and thus modelled with a utilization of payload of 50% over a single distance. The transport distance of 100km is estimated by the LCA practitioner based on the area coverage and number of MWIs in Taiwan.<sup>5</sup> The payload of the dataset from LCA FE was adjusted to 20t.

Table 3-5: Waste transport scenario for gate to waste facility (A3)

Process	Region	Transport scenario according EN 50693	Background dataset from LCA FE
Transport of upstream packaging waste to MWI	Local transport (Taiwan) {TW}	100 km LKW (50% Utilization), Payload 20t	Truck-trailer, Euro 5, 34 - 40t gross weight / 27t payload capacity

#### 3.4.1.4 Transport from gate to point of sale (A4)

Due to a lack of information about the exact transport routes from the final assembly stage in Taiwan (gate) to the US Market (point of sale) a default transport scenario was applied which is provided in the Product Category Rule EN50693 Chapter 4.3.2 and described in detail in the table below. The transports process included the final Laptop Device and its packaging. No additional transport packaging or weights of additional transportation aids (e.g., palletes) are considered in the model. Transport modelled as one-ways distance with a utilization of the payload of 85%.

Table 3-6: Transport scenarios from gate to point of sale (A4)

Process	Region	Transport scenario according EN 50693	Background dataset from LCA FE
Framework Laptop, incl. packaging	International transport (Global) {GLO}	Transport chain: 12.000 km Cargo plane + 1.000 km LKW (85% Utilization)	GLO: FW_Transports Chain Global-Truck-Cargo plane IZM <LZ> based on:

<sup>4</sup>

[https://english.dep.gov.taipei/News\\_Content.aspx?n=010EDE53B1F4A4AF&sms=85FBABE70858A8D4&s=98C0E979E6454330#:~:text=Taipei%20currently%20has%20three%20municipal,incineration%20rate%20has%20been%2099.23%25.](https://english.dep.gov.taipei/News_Content.aspx?n=010EDE53B1F4A4AF&sms=85FBABE70858A8D4&s=98C0E979E6454330#:~:text=Taipei%20currently%20has%20three%20municipal,incineration%20rate%20has%20been%2099.23%25.)

<sup>5</sup> Ebd.

Process	Region	Transport scenario according EN 50693	Background dataset from LCA FE
			Truck-trailer, Euro 5, 34 - 40t gross weight / 27t payload capacity;  GLO: Cargo plane, 113 t payload Sphera <e-ep>;

### 3.4.1.5 Use phase (B6)

Energy consumption is calculated based on the laptop being used in the U.S. for a period of 5 years on base of if its annual Typical Energy Consumption (TEC), which is derived from the Energy Star Certification of the product.<sup>6</sup>

According to Energy Star Program Requirements for Computers (Version 5.0), the TEC is: "A method of testing and comparing the energy performance of computers, which focuses on the typical electricity consumed by a product while in normal operation during a representative period of time. For Desktops and Notebooks, the key criterion of the TEC approach is a value for typical annual electricity use, measured in kilowatt-hours (kWh), using measurements of average operational mode power levels scaled by an assumed typical usage model (duty cycle)."<sup>7</sup>

Table 3-7: Modelling parameters for the energy consumption during use phase

Position	Value
TEC of Model per year	15.4 kWh
Use time	5 years
Energy consumption over 5 years	77 kWh
Background Dataset from LCA FE	US: grid mix Sphera

### 3.4.1.6 Transport to waste processing (C2)

According to EN50693 Chapter 4.3.2 waste Transports include a full outward journey and empty return journey by truck and thus modelled with a Payload of 50% over a single distance.

<sup>6</sup> Framework - FRANPC0000 : FRANPC00N4, URL: <https://www.energystar.gov/productfinder/product/certified-computers/details/2401061> (retrieved on 2023-09-06).

<sup>7</sup> ENERGY STAR® Program Requirements for Computers Version 5.0, URL: [https://www.energystar.gov/ia/partners/prod\\_development/revisions/downloads/computer/Version5.0\\_Computer\\_Spec.pdf?0f42-51d9](https://www.energystar.gov/ia/partners/prod_development/revisions/downloads/computer/Version5.0_Computer_Spec.pdf?0f42-51d9)

Table 3-8: Waste transport scenario for gate to waste facility (A3)

Process	Region	Transport scenario according EN 50693	Background dataset from LCA FE
Transport of downstream packaging waste to MWI	Local transport (USA) {US}	100 km LKW (50% Payload)	GLO: Truck-trailer, Euro 5, 34 - 40t gross weight / 27t payload capacity Sphera <e-ep>;  Payload capacity adjusted to 20t with 50% utilization.

### 3.4.1.7 Waste processing (C3)

In EoL, the laptop, the external power supply (EPS) and the screwdriver are subject to 100% material and thermal recycling. In this scenario, the device and its related supplies are shredded and sorted into two material fractions. The total mass of the plastic and metal fractions is based on measurements and approximations based on the detailed bill of materials. The proportion of unknown material compositions was divided in the same ratio and assigned to the plastic and metal fractions (see Table 3-9). After shredding and sorting the plastic fraction will be incinerated. All burdens for the incineration of plastic fractions are assigned to the product system and no credits for energy recovery are given (cut-off, "polluter pays" principle). Shredded and sorted metal waste has a market value and will lose its waste status after the sorting process and no additional waste processing is needed (e.g., melting). The reuse of the recovered material in another product system is not part of the study and therefore no credits for substitution are given.

Table 3-9: Material fractions in EoL

#	Position	Material	Mass [g]	wt.-% tot. weight	Data source
A	Framework Laptop Enddevice		<b>1302.97</b>	<b>100%</b>	<b>Measured</b>
1	Separable metal parts (e.g., cover, screws)	Metals	913.12	70%	Measured
2	Separable plastic parts (e.g., fan, display bezel)	Plastics	48.83	5%	Measured
3	Unseparable metal and plastic fractions (e.g., PCBs, component packages)	Compounds	341.02	26%	Calculated
3a	Metal Share	Plastics	170.51	13%	Estimated as 50% of #3
3b	Plastic Share	Metals	170.51	13%	Estimated as 50% of #3
<b>4</b>	<b>Metal (waste for recovery)</b>	<b>Metals</b>	<b>1083.63</b>	<b>83%</b>	<b>Calculated as #1+#3a</b>
<b>5</b>	<b>Plastic (waste incineration)</b>	<b>Plastics</b>	<b>219.34</b>	<b>17%</b>	<b>Calculated as #2+#3b</b>

Table 3-10: Material fractions in EoL for the External Power Supply

#	Position	Material	Mass [g]	wt.-% tot. weight	Data source
A	External Power Supply		<b>112.61</b>	<b>100%</b>	<b>Measured</b>
1	Separable metal parts	Metals	3.2	2.84%	Measured
2	Separable plastic parts	Plastics	41.09	36.49%	Measured
3	Inseparable metal and plastic fractions (e.g., PCBs, component packages)	Compounds	68.32	60.67%	Measured
3a	Metal Share	Plastics	34.16	30.33%	Estimated as 50% of #3
3b	Plastic Share	Metals	34.16	30.33%	Estimated as 50% of #3
<b>4</b>	<b>Metal (waste for recovery)</b>	<b>Metals</b>	<b>37.36</b>	<b>33.18%</b>	<b>Calculated as #1+#3a</b>
<b>5</b>	<b>Plastic (waste incineration)</b>	<b>Plastics</b>	<b>75.25</b>	<b>66.82%</b>	<b>Calculated as #2+#3b</b>

Table 3-11: Material fractions in EoL for the Screwdriver

#	Position	Material	Mass [g]	wt.-% tot. weight	Data source
A	Screwdriver		<b>12.4</b>	<b>100%</b>	<b>Measured</b>
1	Separable metal parts	Metals	1.984	16%	Measured
2	Separable plastic parts	Plastics	10.416	84%	Measured
<b>3</b>	<b>Metal (waste for recovery)</b>	<b>Metals</b>	<b>1.984</b>	<b>16%</b>	<b>Based on #1</b>
<b>4</b>	<b>Plastic (waste incineration)</b>	<b>Plastics</b>	<b>10.416</b>	<b>84%</b>	<b>Based on #2</b>

### 3.4.1.8 Disposal (C4)

In the applied EoL scenario, the product can be fully recycled and thermally recovered (module C3), so there are no additional burdens for the final disposal (module C4).

## 3.5 Power Mix

The Framework Laptop consists of components and modules from different countries and where possible the national electricity mixes for the reference year 2022 were applied accordingly. Most of the electronic components are modelled using generic and aggregated data sets from Gabi LCA FE and therefore power mixes could not be further specified directly in the upstream processes. Where possible, generic datasets have been selected to match the target region.

The average national grid mix was used because more specific data on electricity consumption were not available and most of the regionalised datasets in the background database LCA FE used are

modelled based on the national grid mix and not based on the residual grid mix, contrary to EPA recommendation.<sup>8</sup>

For the use phase, the residual electricity grid-mix for the US market and the reference year 2022 was used.

Table 3-12: Electricity mixes used for different processes and lifecycle stages

Process	Region	Lifecycle stage	Background dataset from LCA FE
Laptop Assembly	(Taiwan) {TW}	A3	CN: Electricity grid mix Sphera
Use phase	(USA) {US}	B6	US: Electricity grid mix Sphera
End of Life	USA {US};	B6	US: Electricity grid mix Sphera

### 3.6 Reference Year

The foreground system was modelled based on annual product data for the reference year 2022.

### 3.7 Criteria for the exclusion of inputs and outputs

The foreground system was modelled on base of a detailed bill of material (BOM) of the product, containing all relevant physical specifications and other technical information for single components and material fractions. Where necessary and appropriate further in-depth physical inspections (e.g., X-ray, grinding) were carried out. Due to the complexity of the inventory, we assume measurement or classification errors of single components and materials to be less than 1 wt.-% of total product weight.

No primary process and manufacturing data could be obtained from the upstream supply chain and assembly phase, so the completeness of the LCA model is based on the background data sets used from secondary LCIA databases. Where possible, additional material inputs (e.g., material cut-offs in the manufacture of the laptop covers) were accounted for by estimation and adjustment in the background data sets.

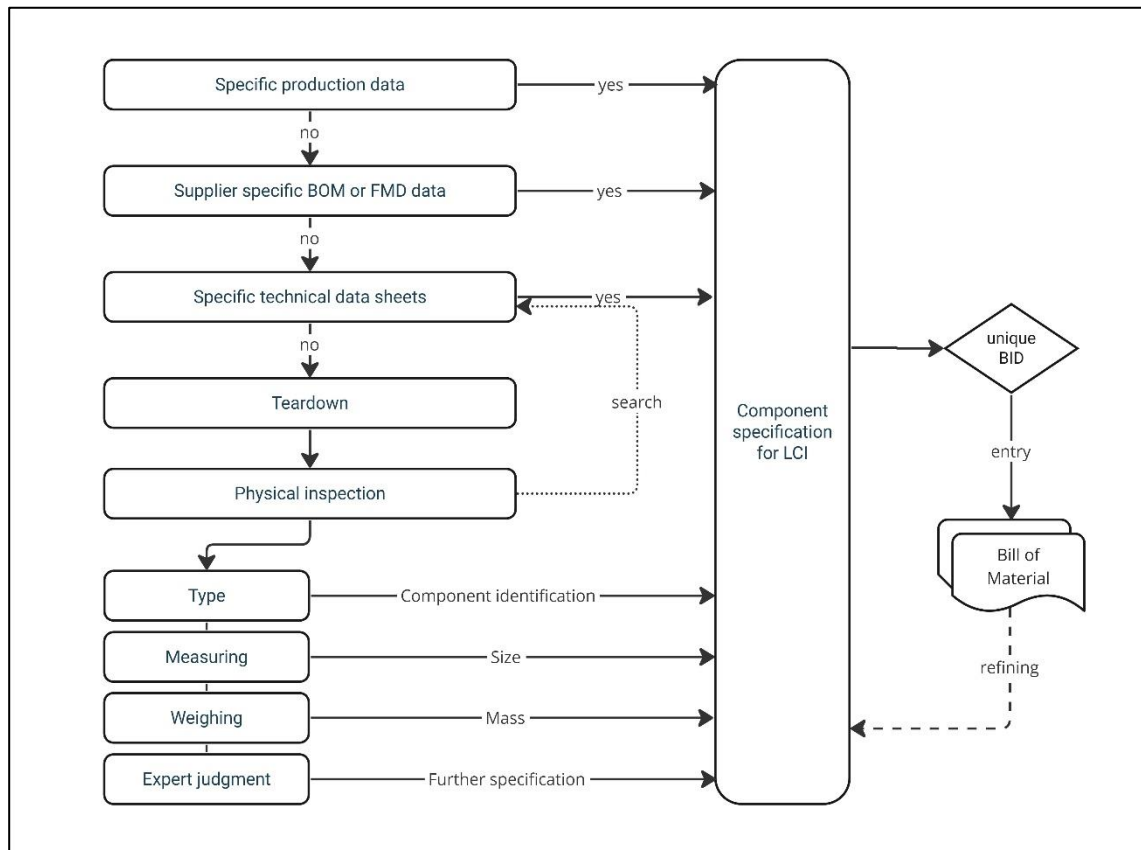
<sup>8</sup> Greenhouse Gas Inventory Guidance. Indirect Emissions from Purchased Electricity (S. 20). (2016). United States Environmental Protection Agency (EPA).

## 4 Life cycle inventory

### 4.1 Data collection and calculation procedures

Depending on availability and relevance, different data collection methods are used to specify the product system and related processes, which is described as a multi-stage process in Figure 4-1. A general and exemplary description can be found in the following sections, specific collection procedures and assumptions for individual modules or components can be found in Chapter 4.5.

Figure 4-1: Data collection procedure for component specification at Fraunhofer IZM



The data collection has two main objectives: The first is to describe the product system as completely as possible (e.g. mass, number of components, component types and materials, etc.). The second is to collect as much primary data as possible on the origin and production methods of the various components, or to make plausible approximations that will later allow modelling that is as granular and accurate as possible. As the availability of primary data is relatively scarce or not always accessible to the LCA practitioner or OEM (i.e. confidentiality, lack of supplier data, etc.), Fraunhofer IZM applies a multi-stage collection procedure as visualized in Figure 4-1, which combines already available information (e.g. technical datasheets, BOMs, FMDs, etc.) with dedicated technical analysis (e.g. teardowns, IC grading, X-ray scans, etc.).

All data collection is consolidated into a comprehensive Bill of Material (BOM) for the entire product system (including all components, packaging, etc.), where each data point is given a unique identifier (BID) to ensure seamless documentation and appropriate modelling. The consolidated BOM list as part of the LCA documentation is confidential and will not be published, but may be viewed by authorized third parties upon request (see Appendix 8.1.1).



The manufacturing phase was modelled on the basis of technical information from Framework and its suppliers and an analysis of the actual hardware. For some modules, a bill of materials was provided by Framework and the manufacturers of the various components. In addition, a complete teardown of the product was undertaken to further specify components and fill data gaps. The product was first disassembled into its various modules. Wherever possible, these modules were subsequently disassembled into their different components and material fractions. If possible, all components and materials were specified according to their type, quantity, material, mass, size, finishing and other relevant information (e.g., part numbers or labels).

*Figure 4-2: Teardown example of the keyboard module*



When visual inspection was unclear or impossible for the LCA practitioner, expert judgment (i.e., internal expertise, external expertise) and additional literature searches were conducted to gather modeling data.

Electronic components on the PCBAs were additionally investigated using microscopic imaging techniques (see Figure 4-3), as well as x-rays (see Figure 4-5). For the biggest and most relevant ICs, grinding techniques were used to further investigate the material structure and identify the die size within the chips (Figure 4-5).

For the assessment, the life cycle assessment software Sphera LCA for Experts (LCA FE) with its own database (at its 2023.1 version), the electronics extension as well as the ecoinvent 3.8 (ei3.8) database was used. If data is used from additional sources, this is specifically mentioned in the description of the unit processes in Chapter 4.5)

Figure 4-3: Microscopic image and measurements of connectors

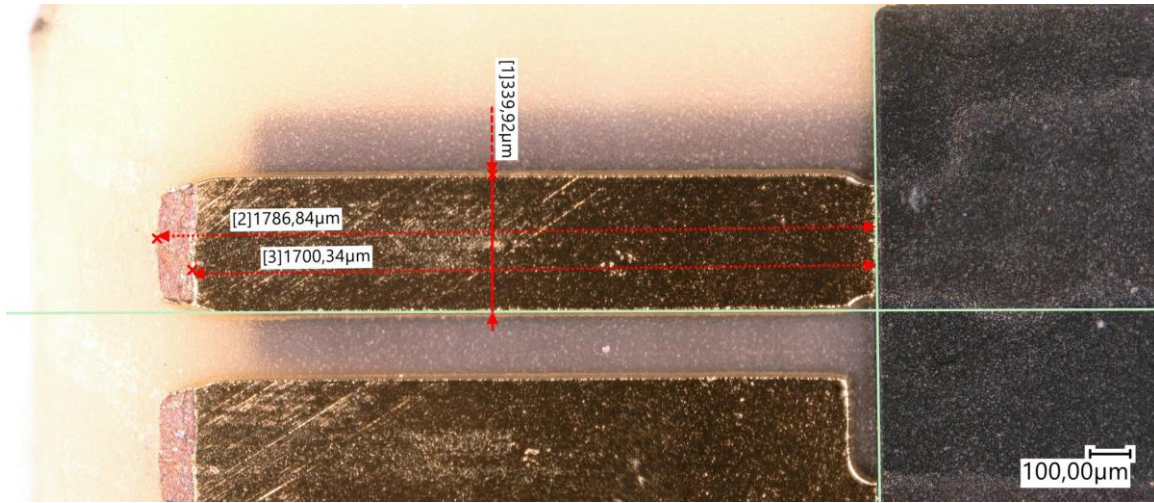


Figure 4-4: X-ray scan of a RAM module

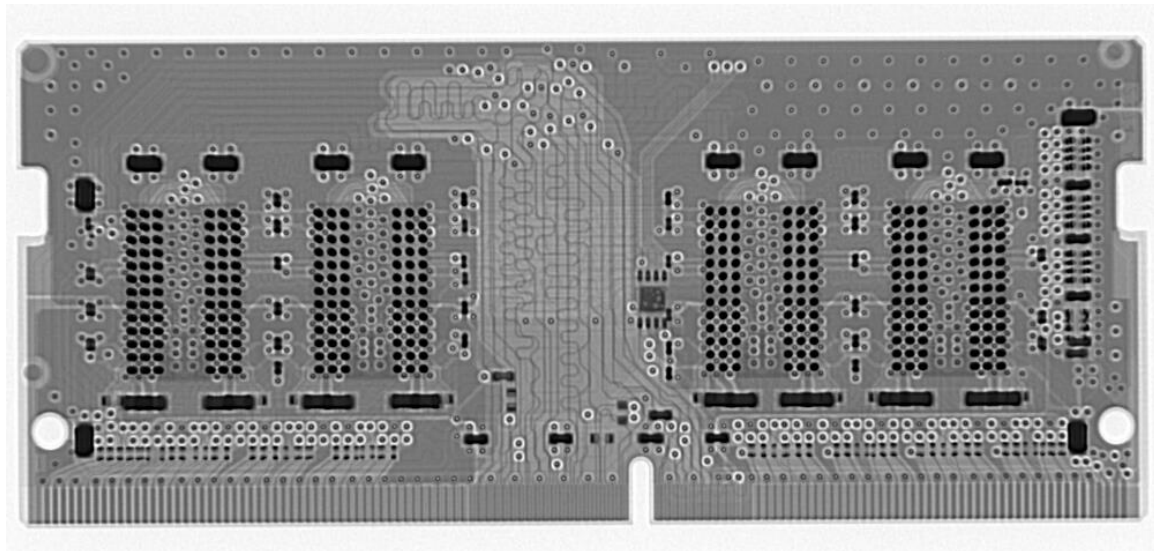
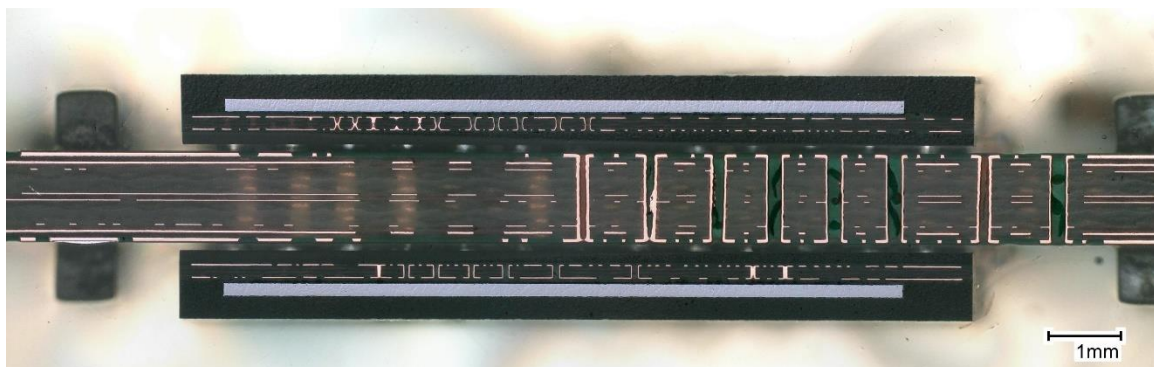


Figure 4-5: Cross-section view of a grinded multilayer PCB and two ICs



## 4.2 Background data

The LCA software Sphera LCA for Experts (version 10.7.0.183) and the corresponding database, including the "Electronics" extension database (both in their version 2023.1), are used for modelling. This is supplemented by the ecoinvent v3.8 (ei3.8) database and other databases for processes where no suitable Sphera dataset is available.

Due to the complexity of the LCA model, which consists of 891 individual plans and processes, only an aggregated summary of the data sets used from secondary LCIA databases can be presented in this section (see Table 4-1).

*Table 4-1: Summary of used background datasets from secondary LCIA databases*

Database	Process datasets total		Process datasets unique	
	pcs.	%	pcs.	%
Datasets from secondary LCIA databases	669	100%	187	100%
Datasets from Sphera LCA FE	525	78%	133	71%
Datasets from ecoinvent	101	15%	36	19%
Other databases	43	6%	18	10%

A detailed list of the background data used can be found in the appendix of this report (see Appendix 8.1.3).

## 4.3 Data quality

Due to the complexity of the inventory and the lack of specific primary data for upstream processes, the assessment of overall data quality will be descriptive and qualitative.

Life cycle assessment (LCA) requires accurate, relevant, and representative data to ensure the credibility of results. The quality of data used in an LCA can significantly influence the outcomes, making it crucial to understand the sources, reliability, and appropriateness of the data employed.

- **Primary Data:** This refers to original data collected directly from the source, specific to the processes or products being assessed, which includes the specific data for the energy intensity of manufacturing or material used for a single process or component.
- **Secondary Data:** These are data obtained from existing sources, such as literature, LCIA databases, and previous studies. While they might not be specific to the exact processes or products in question, they can be adjusted and tailored to fit the requirements of the current LCA.

The study faced challenges in accessing primary data for all upstream processes, particularly regarding the specific energy intensity or material used to produce specific electronic components. However, based on a comprehensive product teardown and other primary product data from Framework and some suppliers (e.g. mainboard), an accurate and detailed bill of materials (BOM) could be compiled (see Data collection and calculation procedures in Chapter 4.1.).

In the absence of primary process data, the following steps were taken to ensure the robustness of the LCA model:

1. **Use of secondary datasets:** Secondary datasets were sourced from respected LCIA databases. These databases contain aggregated data from multiple studies and are a credible source of industry averages (see previous Section 4.2).
2. **Adjustment to fit specifications:** Recognizing that secondary data may not perfectly match the component specifications, adjustments were made to these data sets and documented in detail for the unit processes (see Chapter 4.5). Adjustments were based on known relationships, scaling factors, or other relevant parameters to ensure that the data were as close as possible to the specific components. Particularly dominant impact contributors, such as ICs, were specified in detail through extensive physical inspection.

Using secondary data with adjustments offers a pragmatic approach to address data gaps. However, it's important to recognize that:

- There's an inherent level of uncertainty associated with using adjusted secondary data.
- The results should be interpreted with caution, especially when making direct comparisons or drawing definitive conclusions.
- Further studies or updates to this LCA could benefit from more specific primary data, if available in the future.

## 4.4 Allocations

No co-product allocations had to be made in the model, but could be part of the background datasets from LCA FE<sup>9</sup> and ecoinvent.<sup>10</sup> When possible, datasets were used that avoid allocation or substitution via cut-off approach.

### 4.4.1 Use of secondary materials

In the manufacturing of the products secondary aluminium is partly used for the manufacturing of the cover but not considered due to lack of background data in the LCA model.

Secondary products and material could be part of the intermediary products from the upstream supply chain and background datasets used in the LCA model.

### 4.4.2 Allocation for reuse, recycling and recovery

According to the cut-off, waste content approach, all burdens attributed to the product system, without giving credits for the energy and material recovery.

Packaging waste from up- and downstream processes will be incinerated without credits for the energy and thermal recovery.

In the modelling of the end-of-life of the notebook and external power supply (EPS), a collection rate of 100% after the use phase was assumed. All burdens for the treatment of waste are assigned to the product system, without credits for energy and material recovery.

<sup>9</sup> See: Kupfer, T., Baitz, M., Colodel, C. M., Kokborg, M., Schöll, S., Rudolf, M., Bos, U., Bosch, F., Gonzalez, M., Schuller, O., Hengstler, J., Stoffregen, A., Thylmann, D., & Koffler, C. (2021). GaBi Databases & Modelling Principles. sphera. <https://sphera.com/wp-content/uploads/2020/04/Modeling-Principles-GaBi-Databases-2021.pdf>

<sup>10</sup> Weidema, B., Bauer, C., Hischier, C., Mutel, C., Nemecek, T., Reinhard, J., Vadenbo, C., & Wernet, G. (2013). Overview and Methodology. Data quality guideline for the ecoinvent database version 3 (Ecoinvent Report 1(v3)). The ecoinvent Centre.

## 4.5 Unit processes

The presentation of the unit processes is mainly based on screen shots of the LCA software Sphera *LCA for Experts (LCA FE)* and additional descriptions. In the screenshots it can be seen how data from the BOM and process activities (foreground system) is mapped to LCI data from the background data (background system) used. As direct impact measurements of environmental impacts of processes from the foreground system are rarely possible in practice, LCIA databases such as *LCA FE* and *ecoinvent* provide inventory data of real-world processes that can be used as a proxy to classify and characterize the environmental profile of the specific process.

Life cycle data sets were allocated to all parts based on weight (mechanical parts), number of pieces (electronic components) or size/area (e.g. printed circuit boards). For reasons of confidentiality, the data presented here does not allow any precise conclusion to be drawn about specific component information which is not already public or critical for business interest (e.g., part number, manufacturer). In addition, similar components from the BOM can be clustered together (e.g., screws of different size) or aggregated (resistors with same size and resistance etc.). Where possible and appropriate, the screenshots contain references to the respective BOM components with the help of a unique identification number, which follows the scheme "BID-XXX". The BOM is not publicly disclosed but may be disclosed to a third party under certain conditions as part of an independent critical review (see Appendix 8.1.1).

The modelling is based on the assumptions declared in Chapter 3.4.1 and availability and quality of background data sets. The individual approach for each module and component group is described in the following sections.

### 4.5.1 Laptop Lifecycle (A-C)

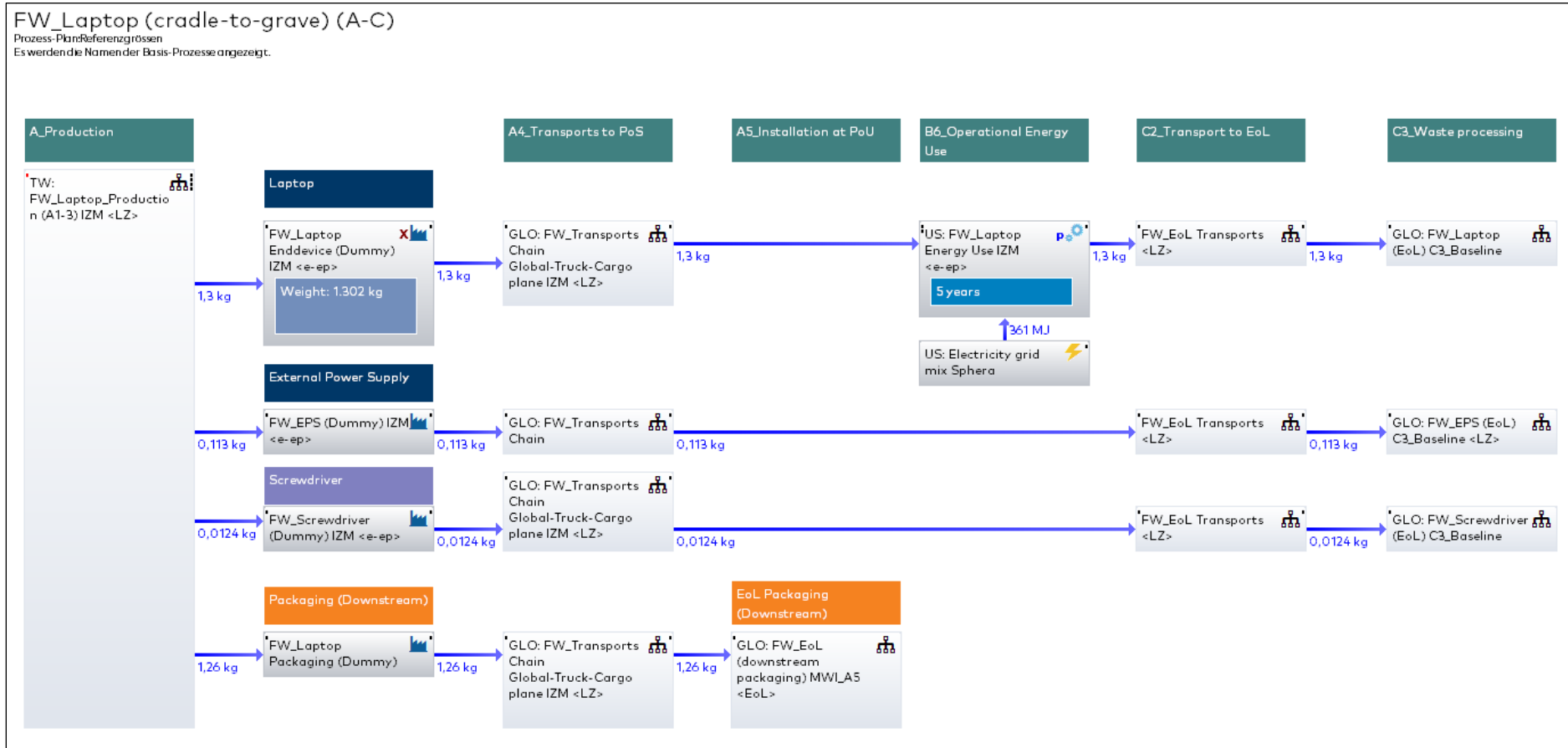
Lifecycle stages were modelled across hierarchical plan levels, that allow the aggregation and nesting of detailed plans.



### 4.5.1.1 Complete Lifecycle (A-C)

Figure 4-6 shows the top-level plan for all life cycle stages considered in this study.

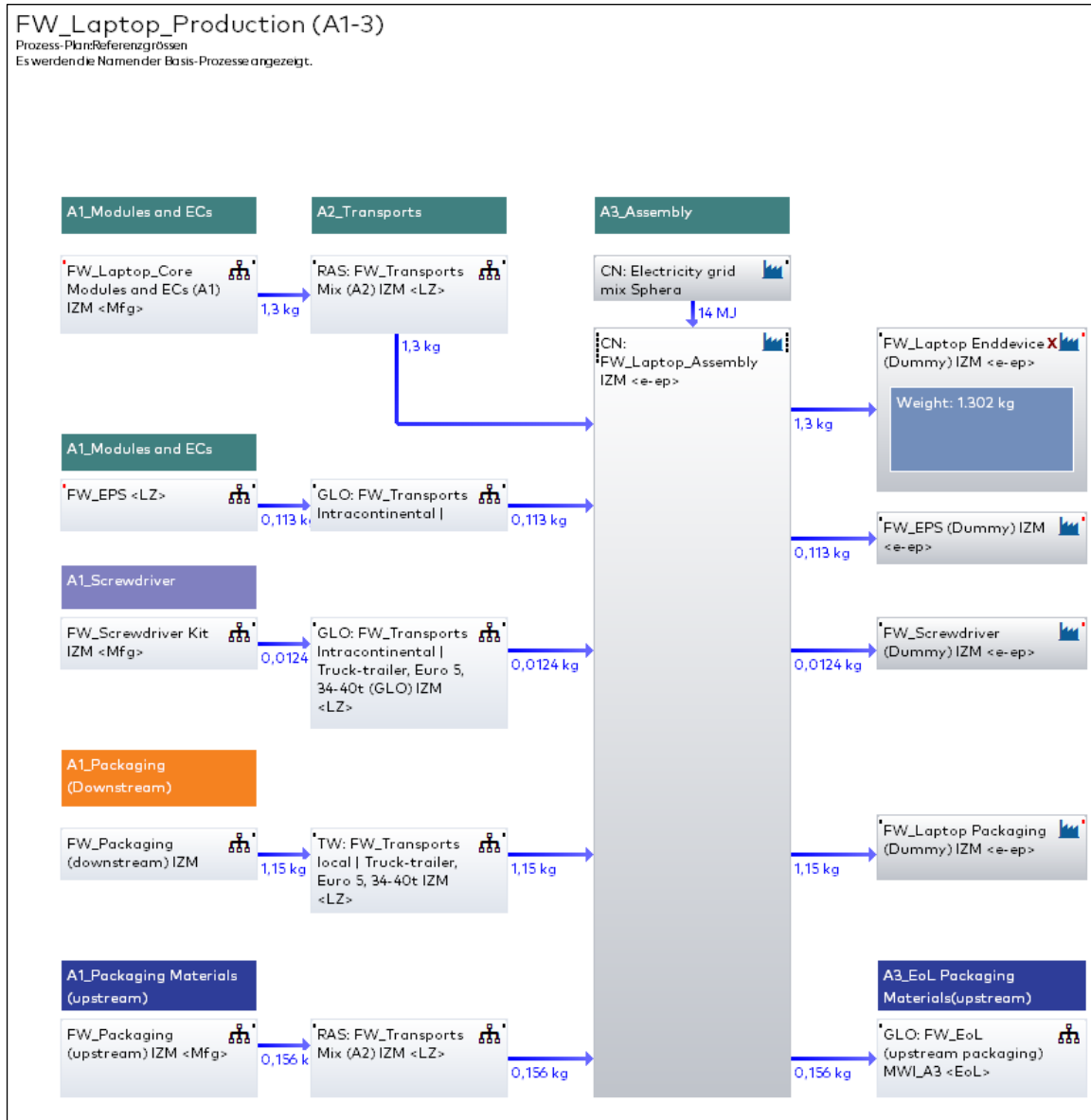
Figure 4-6: Overview of the top-level plan for the lifecycle the product from gate to grave



### 4.5.1.1 Cradle to gate (A1-A3)

Figure 4-7 shows the detailed plan of the cradle-to-gate system boundary of the product system and its nested sub-plans.

Figure 4-7: Overview of the cradle to gate model



### 4.5.2 Components and modules (A1)

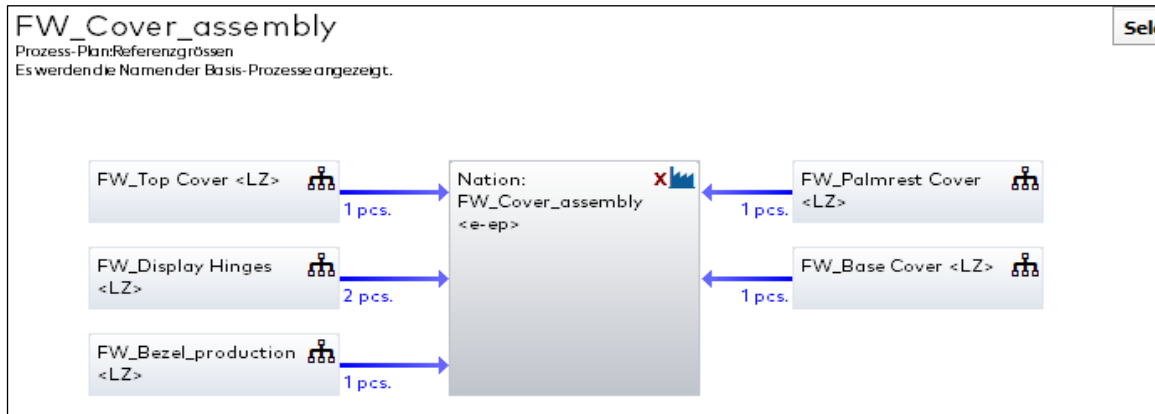
The components and modules are described in the following sections. Approaches across modules, especially for printed circuit boards and electronics components are described in section 4.5.2.17 to 4.5.2.20.

### 4.5.2.1 Cover and housing

#### Cover assembly and sub-modules

The cover is modelled based on four sub-modules (see screenshot below), which are described separately in the following sections.

Figure 4-8: Overview of the Cover assembly model on LCA FE

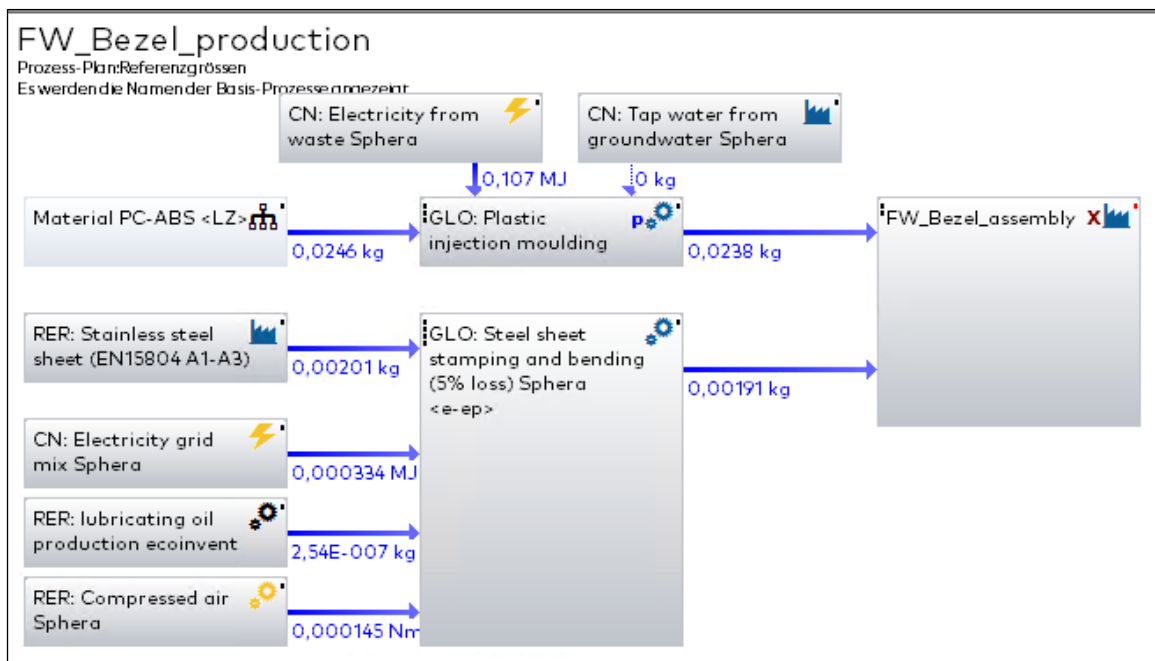


The data for the modelling was provided by Framework, and the LCA practitioner used a teardown to further specify and weight the different material fractions. The energy used in the final assembly of the cover and chassis is not part of this modelling stage and is considered as an aggregated factor in the final assembly stage of the Framework Laptop (see Chapter 4.5.5).

#### Bezel

The bezel is a plastic component that acts as an intermediary, anchoring the display module to the top cover. This component is not only plastic but is also integrated with stainless steel components for the connection of the LCD cover.

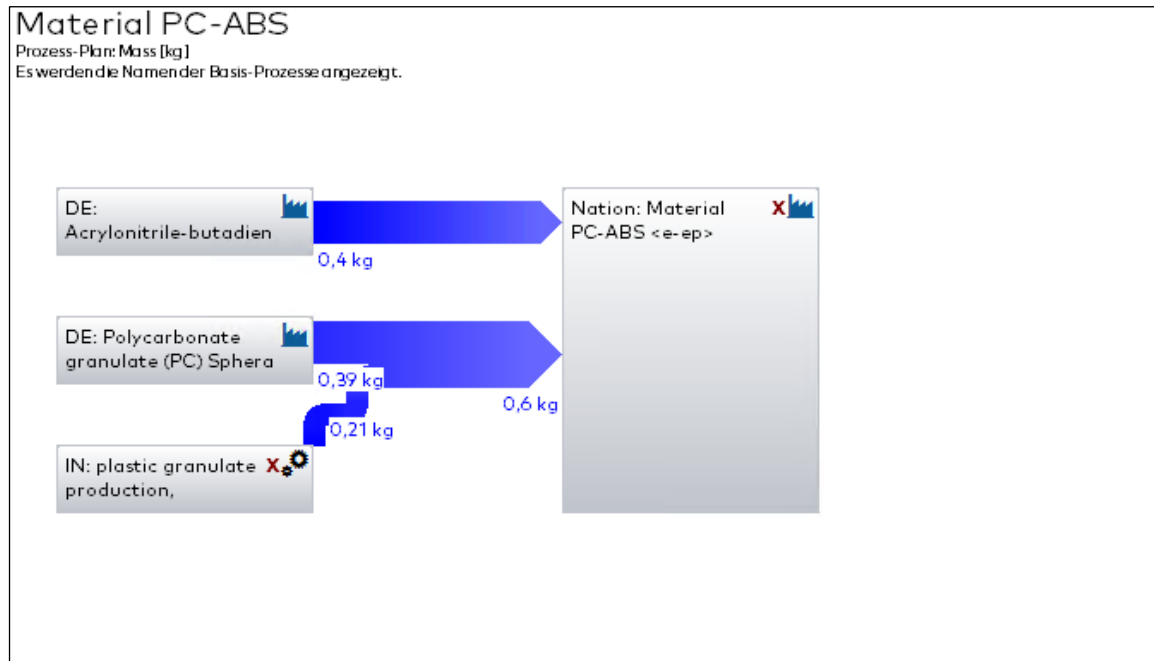
Figure 4-9: Overview of the Bezel production model in LCA FE





The plastic is sourced from Covestro's Bayblend range.<sup>11</sup> For LCA modelling, the plastic is composed of 100% virgin ABS and polycarbonate in a 35:65 ratio of recycled to virgin content. Optimal blend considerations for ABS-PC, based on mechanical properties and cost analysis, favoured a 40:60 ratio<sup>12,13</sup>, which was subsequently incorporated into the model. Recent research highlights the effectiveness of incorporating recycled content into polycarbonate (PC).<sup>14</sup> Empirical evidence suggests that the addition of virgin ABS polymer and a suitable compatibilizer can significantly improve the properties of recycled PC/ABS blends (60/40%), potentially allowing over 57% recycled PC content, with selected blends achieving up to 75% recycled content.

Figure 4-10: Overview of the PC-ABS model in LCA FE



### Top Cover (LCD-Cover)

The top cover, also referred to as the LCD cover, is the protective outer casing that houses and secures the display screen. For the modelling, the top cover was disassembled and all major component were specified and weighted. The primary material of the cover is metal, supplemented by a minor presence of foam. In the analysis, the foam was disregarded and the entire weight was accredited to the metal component. Incorporated within the cover are several magnets. To account for their weight, a single magnet was weighed and its weight was then subtracted from the overall weight of the cover.

<sup>11</sup> [https://solutions.covestro.com/de/products/bayblend/bayblend-fr3040-r35\\_00021925-05125431?SelectedCountry=US](https://solutions.covestro.com/de/products/bayblend/bayblend-fr3040-r35_00021925-05125431?SelectedCountry=US)

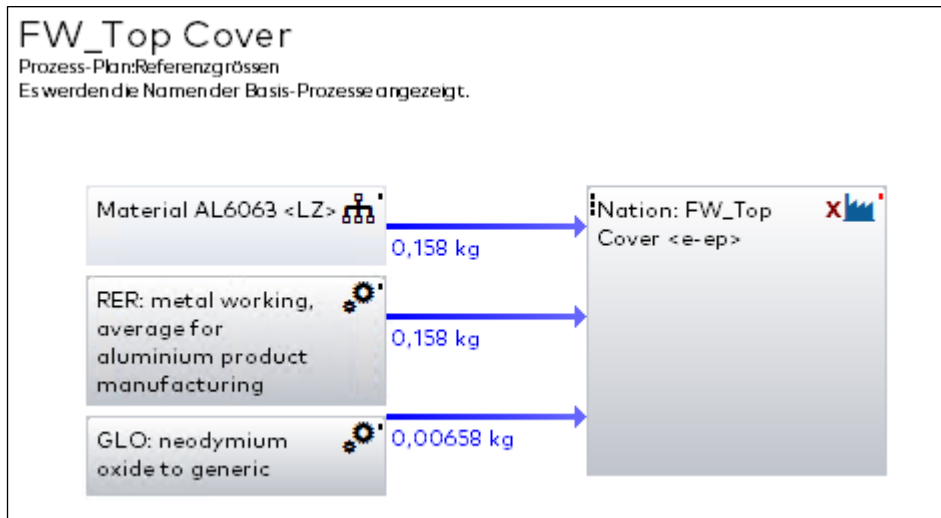
<sup>12</sup> <https://doi.org/10.1016/j.polymertesting.2023.107969>

<sup>13</sup> [https://www.researchgate.net/publication/237602272\\_MECHANICAL\\_PROPERTIES\\_OF\\_HIGH\\_IMPACT\\_ABS\\_PC\\_BLENDS\\_-\\_EFFECT\\_OF\\_BLEND\\_RATIO](https://www.researchgate.net/publication/237602272_MECHANICAL_PROPERTIES_OF_HIGH_IMPACT_ABS_PC_BLENDS_-_EFFECT_OF_BLEND_RATIO)

<sup>14</sup> Ebd.

The metal used for the top cover is an aluminium alloy of type AL6063. For further details on this alloy, please refer to the ALUMERO technical data sheet.<sup>15</sup>

Figure 4-11: Overview of the Top Cover model in LCA FE

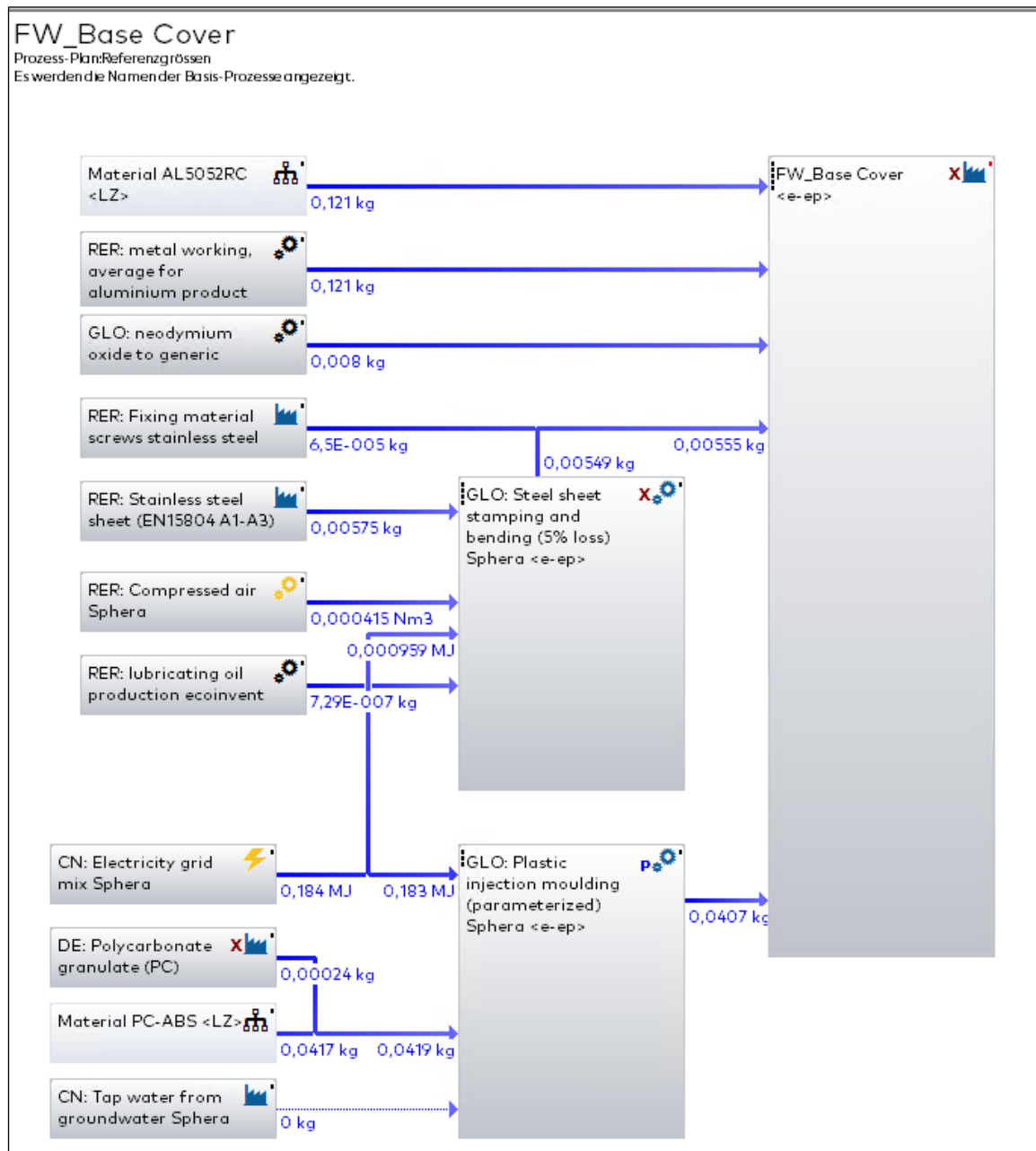


### Base cover

The base cover, also termed the bottom casing or chassis, is the protective underside panel that shields the internal components, also providing access points for upgrades and maintenance.

<sup>15</sup> [https://www.alumerogroup.eu/fileadmin/user\\_upload/downloads/technologien/legierungen/ALUMERO\\_Legierungen-EN-AW-6063-AIMg0\\_web.pdf](https://www.alumerogroup.eu/fileadmin/user_upload/downloads/technologien/legierungen/ALUMERO_Legierungen-EN-AW-6063-AIMg0_web.pdf)

Figure 4-12: Overview of the Base Cover model in LCA FE



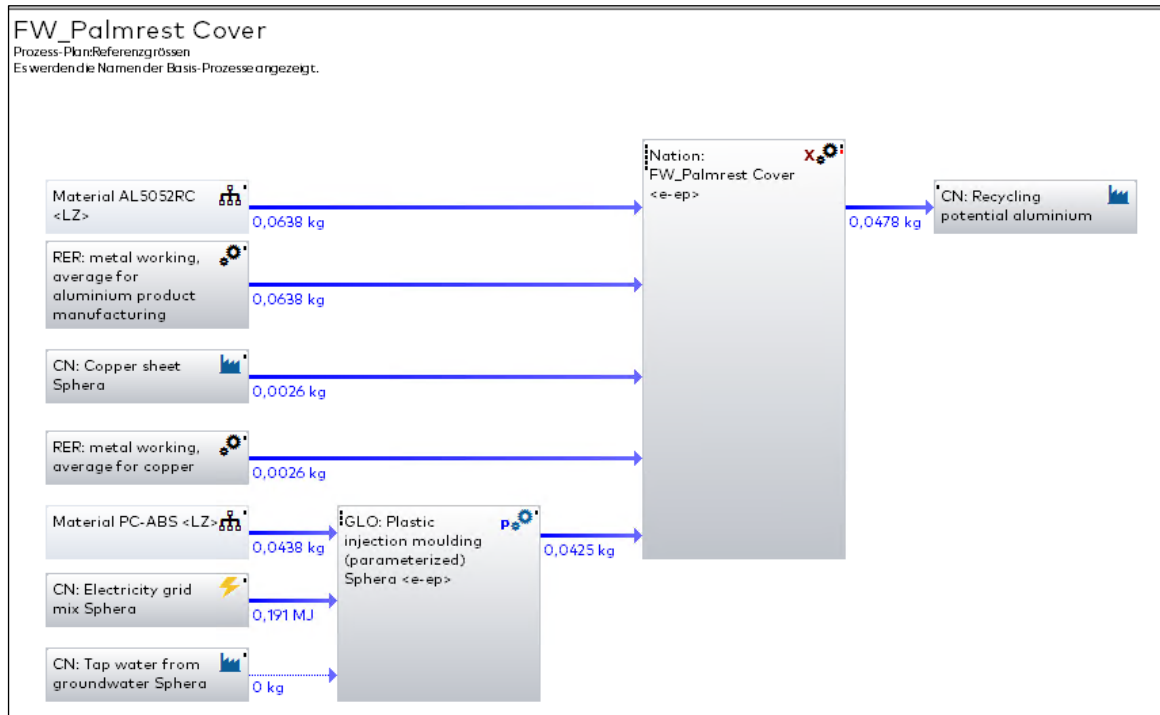
The back of the laptop consists of a metal plate, magnets, and several plastic parts. The magnets were removed and weighed. It was not possible to separate all factions during the disassembly; therefore, the composition of the back cover was estimated to be 25% plastic and 75% metal. The plastic is glued to the back cover and is used primarily as a mounting base for other modules, such as the mainboard. The plastics was specified as to be the same blend as described before in the Bezel section. At the outer side the back cover contains some plastic bottom feet. Expansion card covers, protection slots for expansion cards and their screws are considered in the model. In addition, all screws to for the general case were included.

The metal used for the back cover is an aluminium alloy of type AL5052RC H32. For further details on this alloy, please refer to the technical data sheet<sup>16</sup>.

### Palmrest cover

The palmrest cover consists as the other cover parts of mainly stamped aluminium and injection-molded plastic parts. Additionally, it includes two small copper sheets.

Figure 4-13: Overview of the Palmrest Cover model

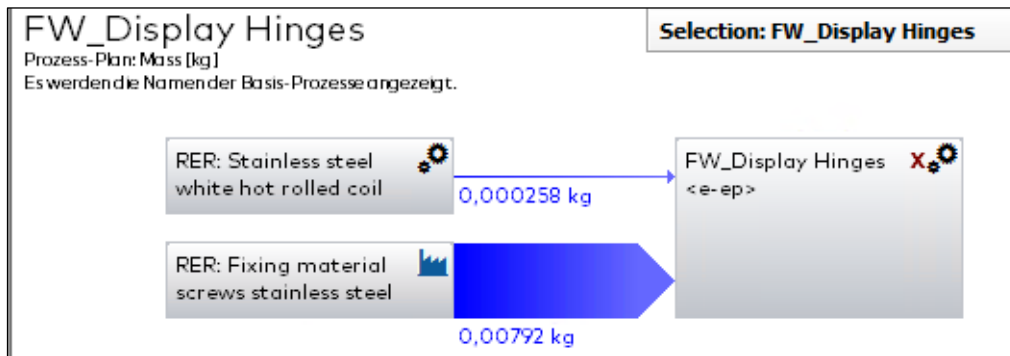


### Display hinge

The display hinge is a pivotal mechanism that allows the top cover to open and close smoothly while providing structural support and maintaining the screen's desired position. Amount in the screenshots below is only for one hinge each, as they were set to 2 in the cover assembly model

<sup>16</sup> <https://www.matweb.com/search/DataSheet.aspx?MatGUID=96d768abc51e4157a1b8f95856c49028&ckck=1>

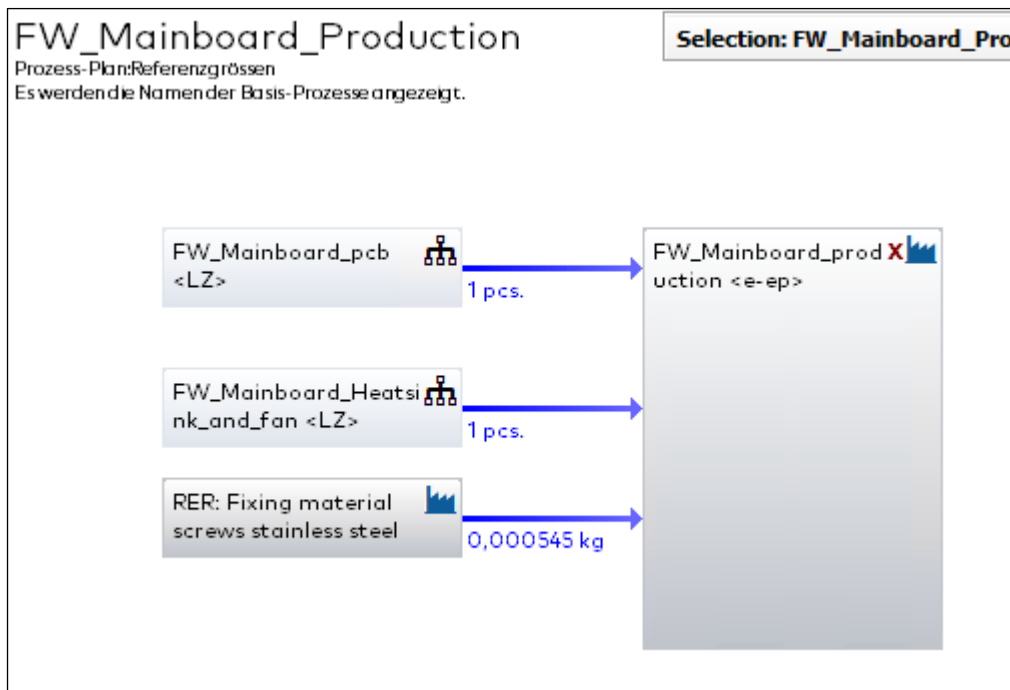
Figure 4-14: Overview of the Display hinge model in LCA FE



#### 4.5.2.2 Mainboard

The mainboard module was divided in two parts: the heatsink and fan on the one hand, and the PCB on the other. Additionally, five screws are present on the mainboard module.

Figure 4-15: Overview of the mainboard model in LCA FE



#### Mainboard PCB

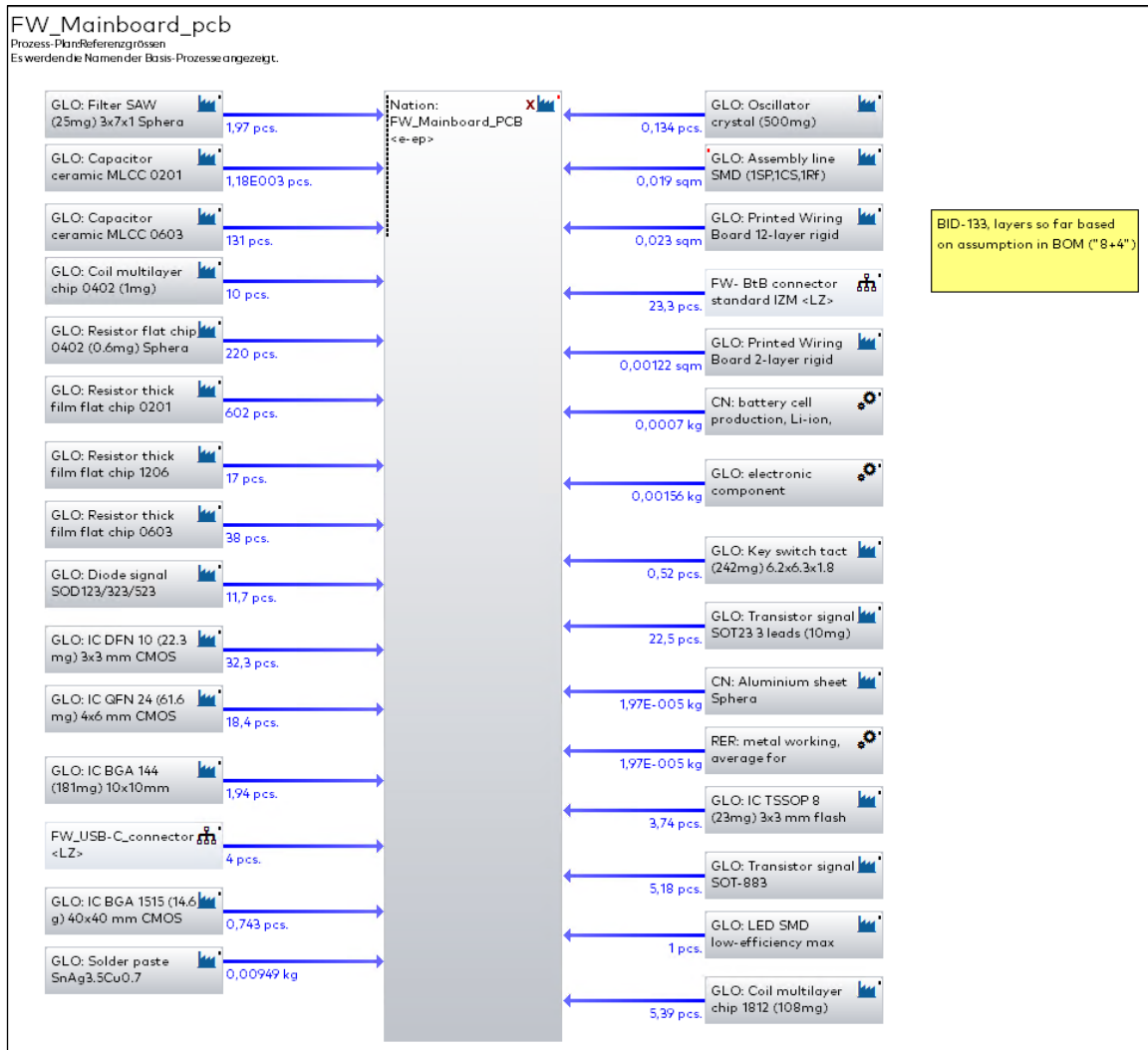
The mainboard PCB was modelled based on the BOM provided by Framework Computer Inc. RAM and storage module are included as separate modules, see sections 4.5.2.7 and 4.5.2.8.

The board itself is a 12 layer board with an outer area of 229.5 cm<sup>2</sup>. Cut-outs were included in the production as the area of the PCB was produced (see section 4.5.2.17). The sub-board for the processor has a rectangular shape of 12.2 cm<sup>2</sup> and assumed to have two layers. Electronic components were modelled with generic datasets for electronic components from the Sphera data base according to the BOM, supported by microscope and x-ray analysis of main components. An assembly process was added based on the size of the mainboard, excluding cut-outs.

The lithium manganese button cell on the mainboard was modelled with an existing data set scaled by weight.

Aluminium parts and connectors were modelled based on material composition and weight.

Figure 4-16: Overview of the mainboard PCB model in LCA FE



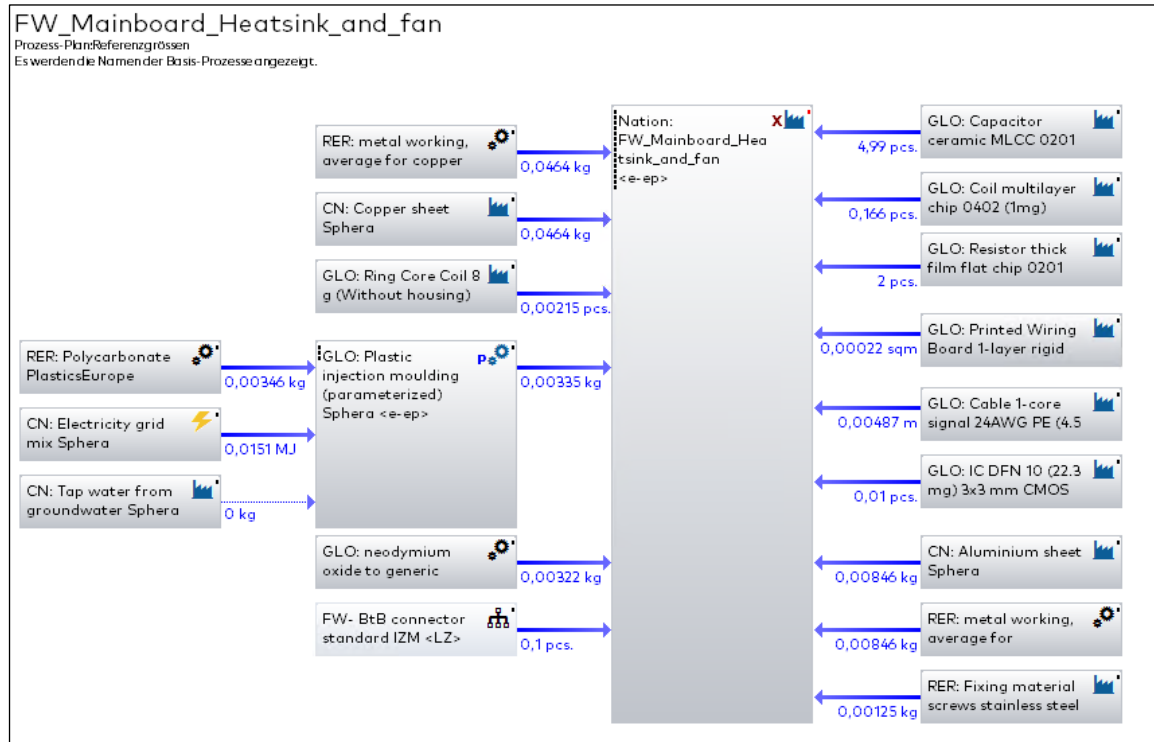
### Fan and Heatsink

The fan and heatsink in detail consist of fan, heatsink, PCB with some electronic components, cables and housing. Screws were modelled as fixing materials based on weight. The PCB was modelled as a single-layer PCB scaled by area according to the outer rectangular. Passive electronic components were scaled according to weight and one IC was scaled according to the packaged area.

The connector was scaled based on the number of pins (see section 4.5.2.18).

The heatsink consists of copper, aluminium and plastic. The fan consists of copper coils, a magnet and plastic. Exact material composition was not available and based on teardown.

Figure 4-17: Overview of the heatsink and fan model in LCA FE

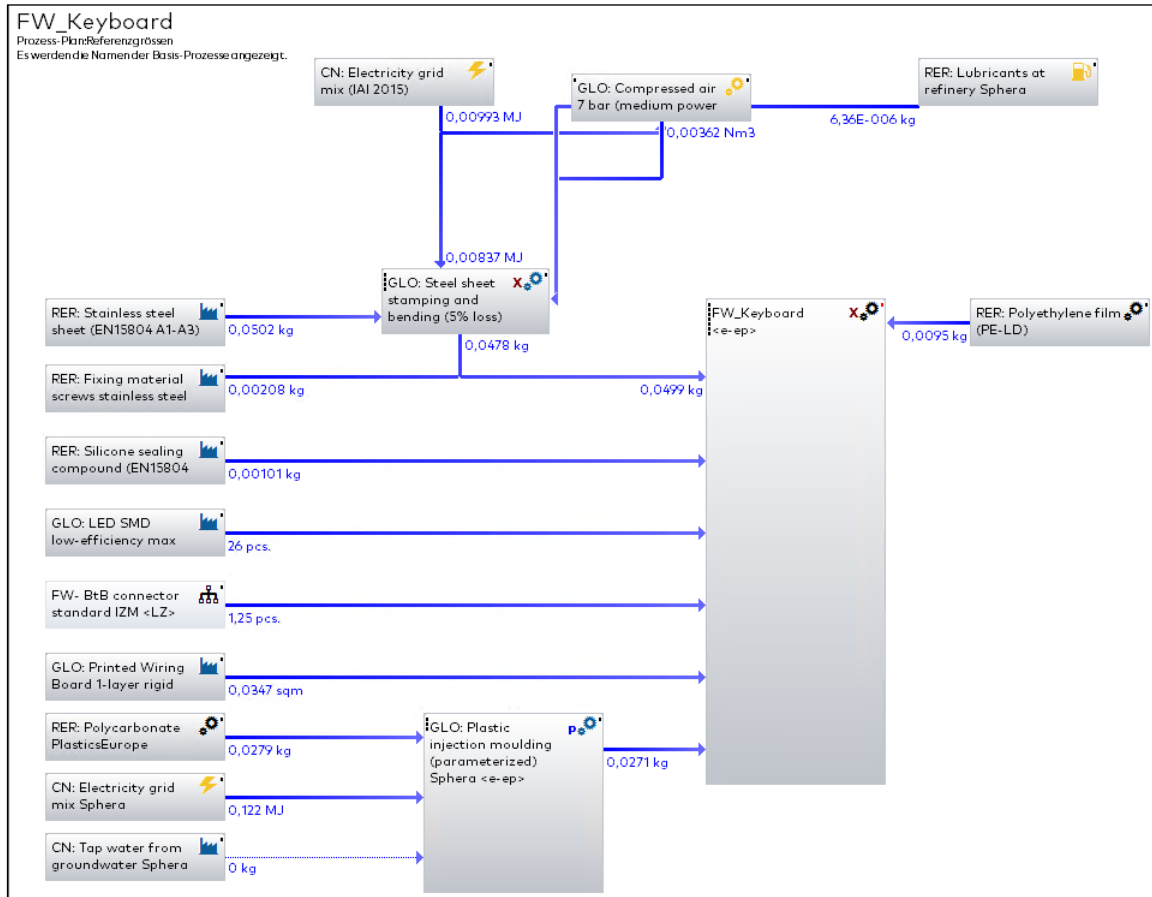


#### 4.5.2.3 Keyboard

The keyboard consists of a flex board covering almost the full area of the keyboard, 78 LEDs, a steel base plate, screws, a connector and several plastic parts.

Weights and materials were determined through the teardown of the keyboard. The flex board was modelled as a single layer PCB with an area of 305.2 cm<sup>2</sup>. The connectors were scaled according to the number of pins. LEDs were modelled with a Sphera dataset scaled by weight. The base plate was modelled as a steel plate with a stamping process. Manufacturing of the full plate was assumed and cut-offs assumed to be closed-loop recycled. Keys are assumed to be PET.

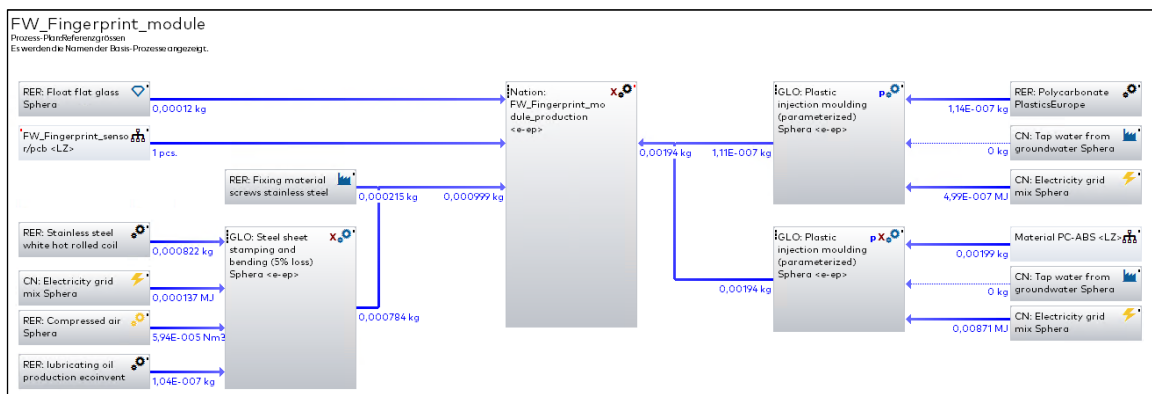
Figure 4-18: Overview of the keyboard model in LCA FE



#### 4.5.2.4 Fingerprint module

The fingerprint module was modelled based on the BOM and the teardown. It consists mainly of the sensor, the glass cover and housing as displayed in Figure 4-19.

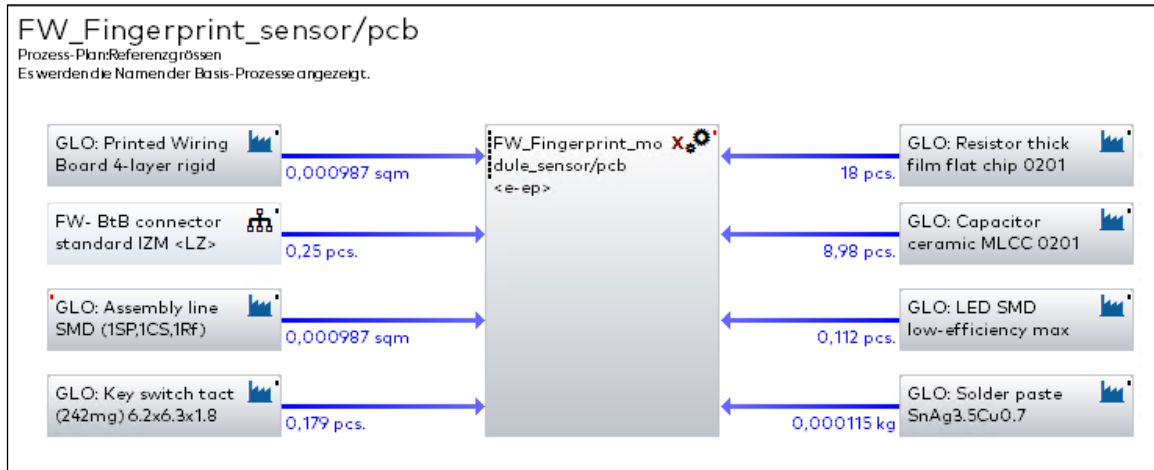
Figure 4-19: Overview of the fingerprint model in LCA FE



The fingerprint sensor consist of a 4-layer PCB, a connector a some electronic components as displayed in Figure 4-20.



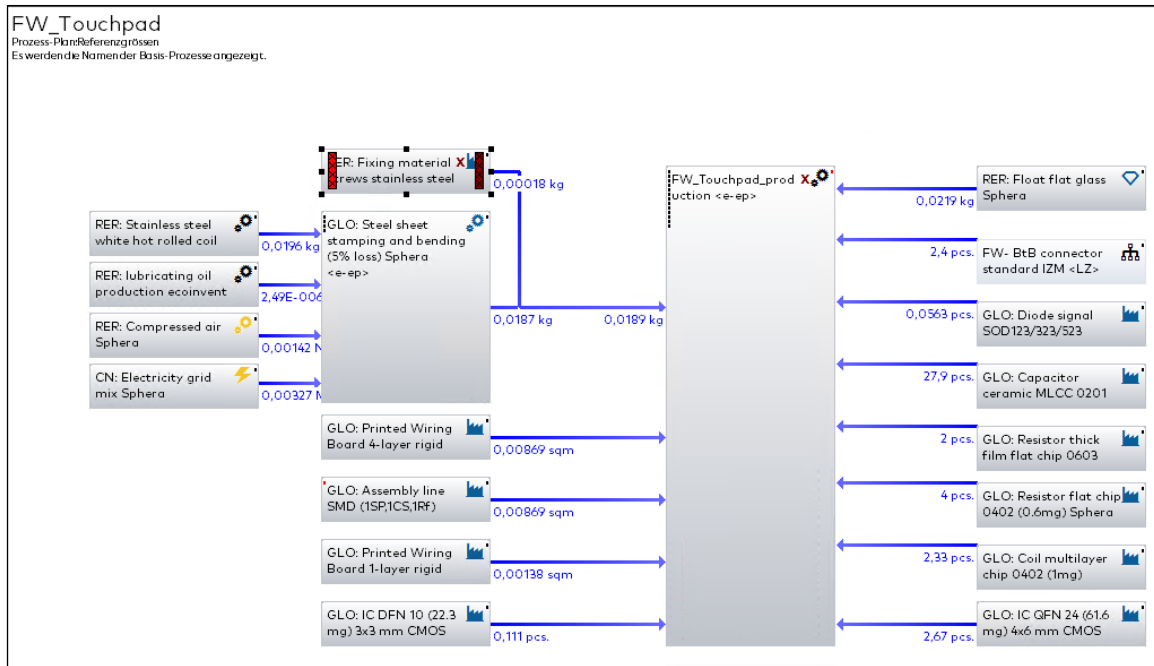
Figure 4-20: Overview of the fingerprint PCB model in LCA FE



#### 4.5.2.5 Touchpad Kit

The touchpad was modelled based on the BOM and the teardown and consists of flex PCBs with electronic components and connector, housing and cover glass as displayed in Figure 4-21.

Figure 4-21: Overview of the touchpad model in LCA FE



#### 4.5.2.6 Display

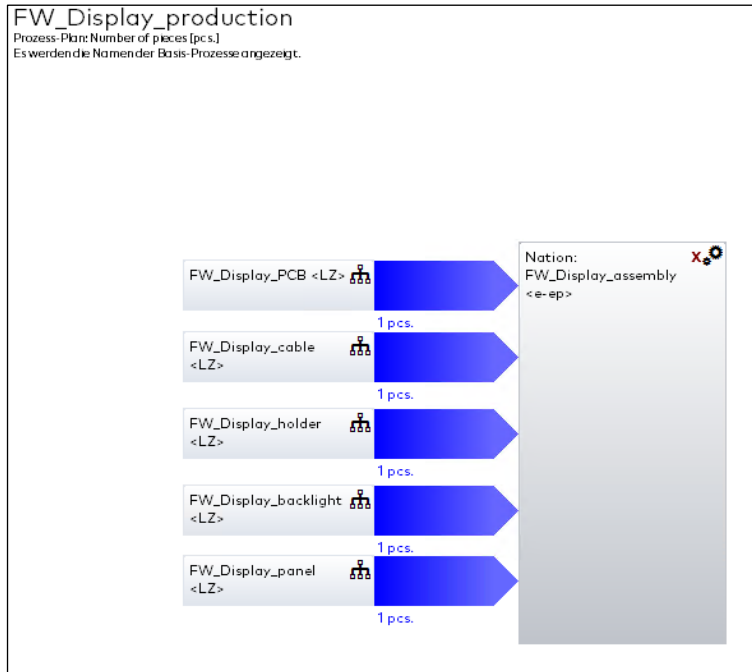
The Display Kit is made up of several submodules, which are stacked on top of each other to form several layers. Each submodule has been modelled separately.

- Display holder
- Display cable and connectors
- Display PCB and components
- Display backlight

- Display panel

The following section describes the display modelling process. Figure 4-22 shows an overview of the display model and top-level plan created in *LCA FE*, including the nested sub-modules from the list above.

Figure 4-22: Overview LCA FE model Display

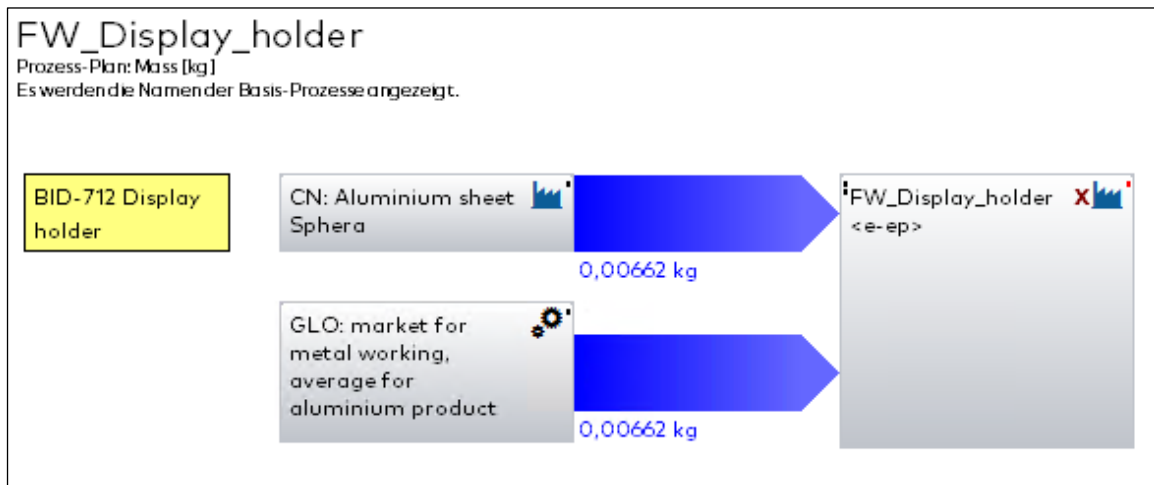


The weight of the complete display including PCB and cable is 182g.

### Display holders

The Display is attached to the case with two display holders. These were modelled using an aluminum sheet process. Figure 4-23 shows the *LCA FE* model of these holders.

Figure 4-23: LCA FE model of Display holders

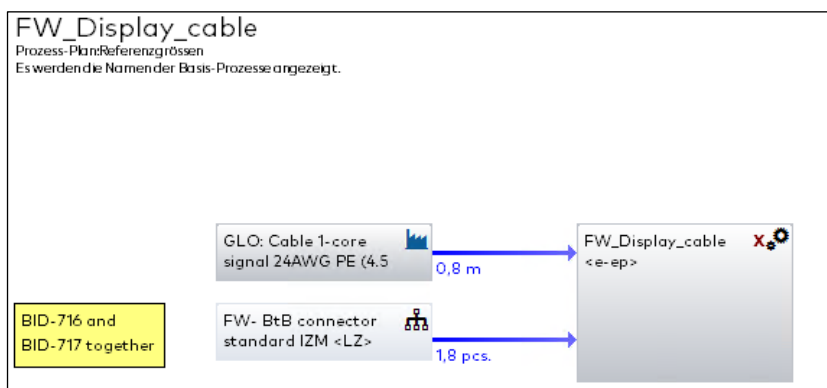


### Display cable and connectors

The Display cable consists of two connectors and one connecting cable and is used to attach the Display PCB to the mainboard. The connecting cable contains 25 individual wires with a diameter of 0.29 mm each. It was modelled using a generic data set from the LCA FE database.

The modelling of the connectors is described in Section 4.5.2.18. Figure 4-24 shows an overview of the LCA FE model for the Display cable, which is further detailed in Figure 4-25.

Figure 4-24: LCA FE model of the Display cable



<sup>17</sup> The following figures display excerpts from our LCA and calculation software which is set to the German standard data format. This means a comma is used instead of a point as a decimal separator.

Figure 4-25: Details of the Display cable modelling

Name	Netlist FW_Display_cable		
<b>Parameter</b>			
Parameter	Formel	Wert	Minimu Maximu Standai Komme
LCA LCC: 0 EUR LCWE Dokumentation			
Vollständigkeit Keine Angabe			
<b>Inputs</b>			
Flüsse	Größen	Menge	Einheit/W/S/F/Kommentar
BTB Framework standard connector (40 pins) [Valuable substances]	Number of pieces	1,8	pcs. X (1 BID-716 and BID-717. Scaled according to number of pins
Cable 1-core signal 24AWG PE (4.5 g/m) D1.4 [Components]	Length	0,8	m X (1 BID-715, scaled according to amount of wires, thickness and length
<b>Outputs</b>			
Flüsse	Größen	Menge	Einheit/W/S/F/Kommentar
FW_display_cable [Valuable subst]	Number of pieces	1	pcs. X 0 0

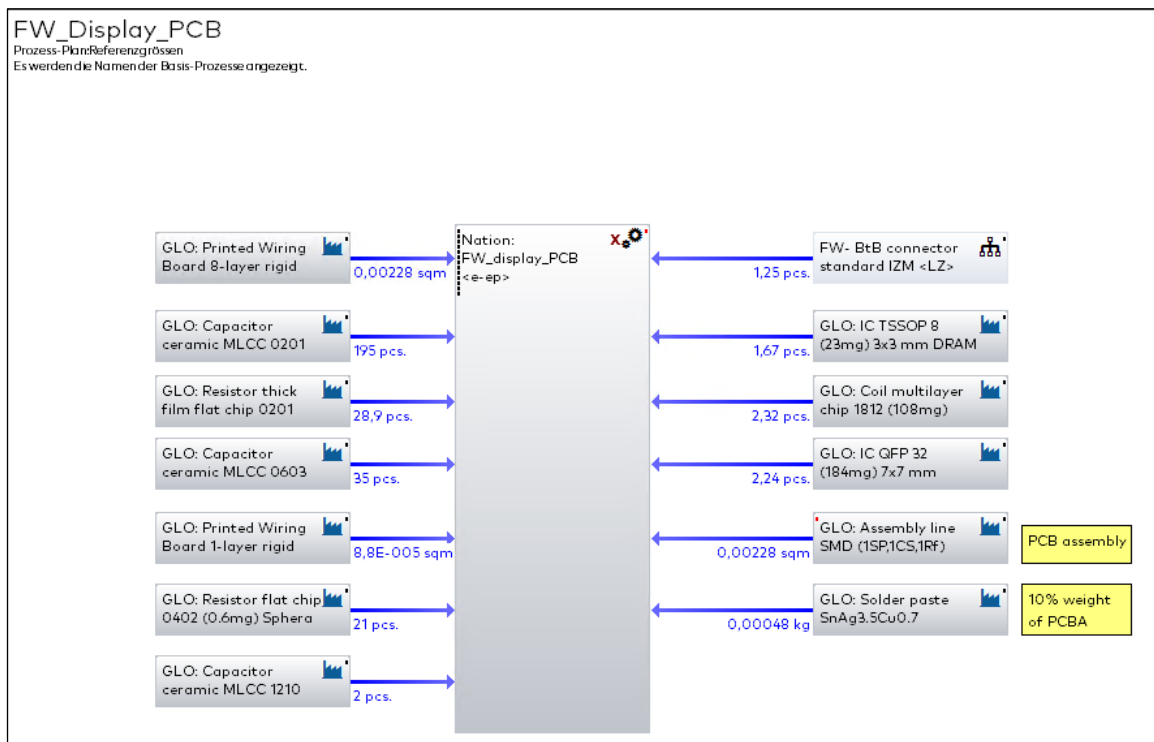
### Display PCB

The display module contains a rectangular PCB. PCBs are conventionally modelled according to the number of layers and outer dimension (smallest rectangular). The PCB has an area of 22.8 cm<sup>2</sup> (22,8x1cm).

In addition, a small flex cable is used to connect the PCB to the display panel, which is modelled using a single layer PCB. The modelling of the passive components is described in section 4.5.2.19, the connectors on the PCB in section 4.5.2.18, the ICs in 4.5.2.20.

An overview of the display PCB modelling is shown in Figure 4-26.

Figure 4-26: Overview of the Display PCB model in LCA FE



## Display Backlight

The display backlight consists of a flex PCB with 54 small SMD-LEDs and 12 capacitors. The flex PCB was modelled using a single layer PCB and has an area of 11.56 cm<sup>2</sup>. The modelling of the capacitors is described in section 4.5.2.19. The LEDs were modelled using an appropriate dataset from the LCA FE.

The overview over the modelling process of the Display Backlight is given in Figure 4-27. Details are listed in Figure 4-28.

Figure 4-27: Overview of Display backlight modelling in LCA FE

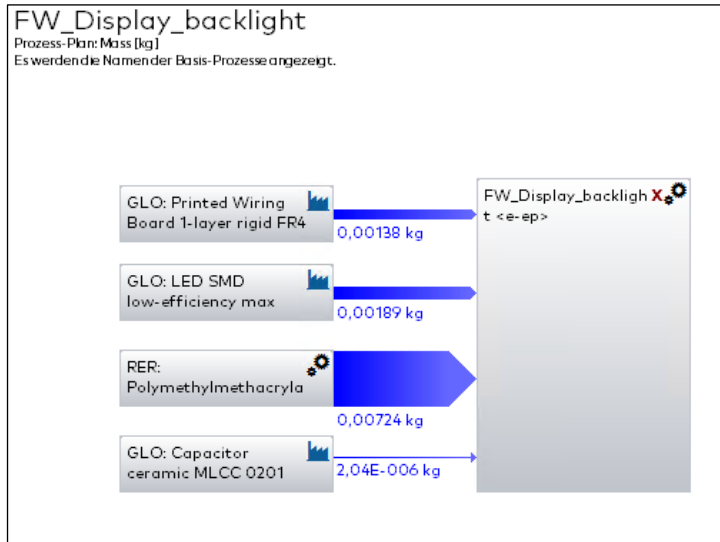


Figure 4-28: Details on the modelling of the Display backlight in LCA FE

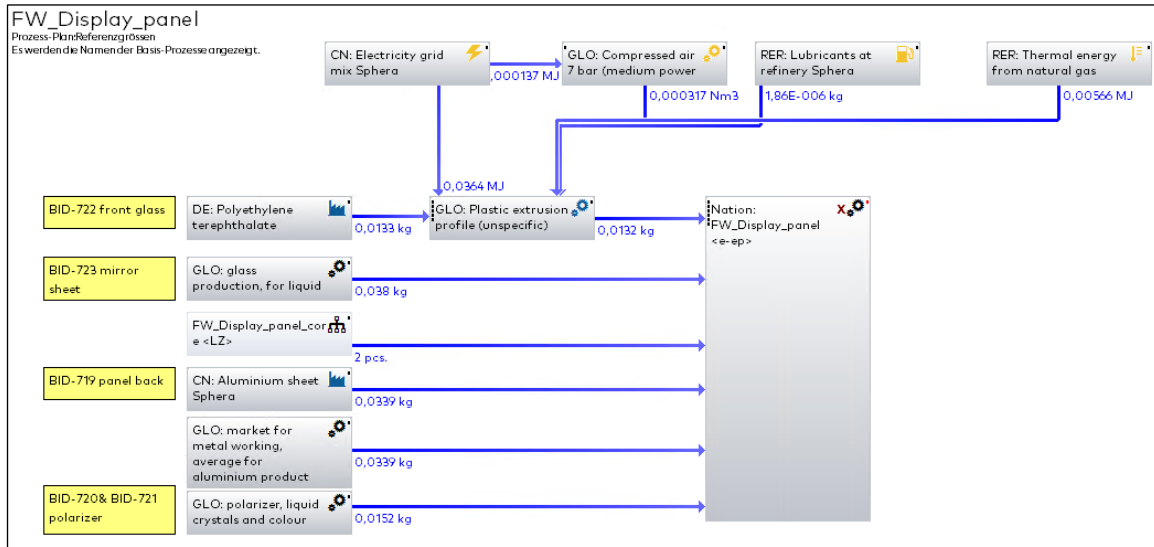
Name	Notizen		FW_Display_backlight		
<b>Parameter</b>					
Parameter	Formel	Wert	Minimum	Maximum	
Parameter					
LCA LCC: 0 EUR LCWE Dokumentation					
Vollständigkeit: Keine Angabe					
<b>Inputs</b>					
Flüsse	Größen	Menge	Einheit	WHS	Kommentar
Capacitor ceramic MLCC 0201 (0.17mg) 0.6x0.3x0.3 (Precious Metals) [Components]	Number of pieces	12	pcs.	X	(K)
LED SMD low-efficiency max 50mA (35mg) without Au 3.2x2.8x1.9 [Components]	Number of pieces	54	pcs.	X	(K)
Polymethylmethacrylate-sheet (PMMA) [Plastic parts]	Mass	0,00724	kg	X	(K BID-739, base of backlight)
Printed Wiring Board 1-layer rigid FR4 with chem-elec AuNi finish (Subtractive method) [Components]	Area	0,00116	sqm	X	(K)
<b>Outputs</b>					
Flüsse	Größen	Menge	Einheit	WHS	Kommentar
FW_display_backlight [Valuable substances]	Number of pieces	1	pcs.	X	(K)

## Display Panel

LCA FE does not contain a suitable LCD data set for a display panel. The ei3.8 dataset for a display is from 2001 and therefore outdated and of limited applicability for a laptop display. Instead, the display is modelled according to a CSR report of the Taiwanese display manufacturer AUO (AUO 2021) in combination with matching datasets from ei3.9.

The data is scaled to the size of the panel, which in the case of the Framework Laptop is 609 cm<sup>2</sup> (29x21cm). An overview of the full display panel model can be found in Figure 4-29.

Figure 4-29: Overview of the Display panel model in LCA FE



The core of the display panel was modelled using AUO data. AUO data covers Scope 1 (direct emissions) and Scope 2 (purchased energy). Scope 3 includes product use, business travel and commuting, but does not include the impact of upstream suppliers and is therefore not considered. Data includes panel manufacturing without backlight and electronics (display board), which were modelled separately.

The data adopted for the LCA model from the AUO CSR report is shown in Table 8-1 in the Appendix of this report. Data points marked blue were transferred, the others were excluded from the model.

An overview over the modelling of the Display panel core is given in Figure 4-30. Details can be found in Figure 4-31.

Figure 4-30: Overview of the model of the Display panel core

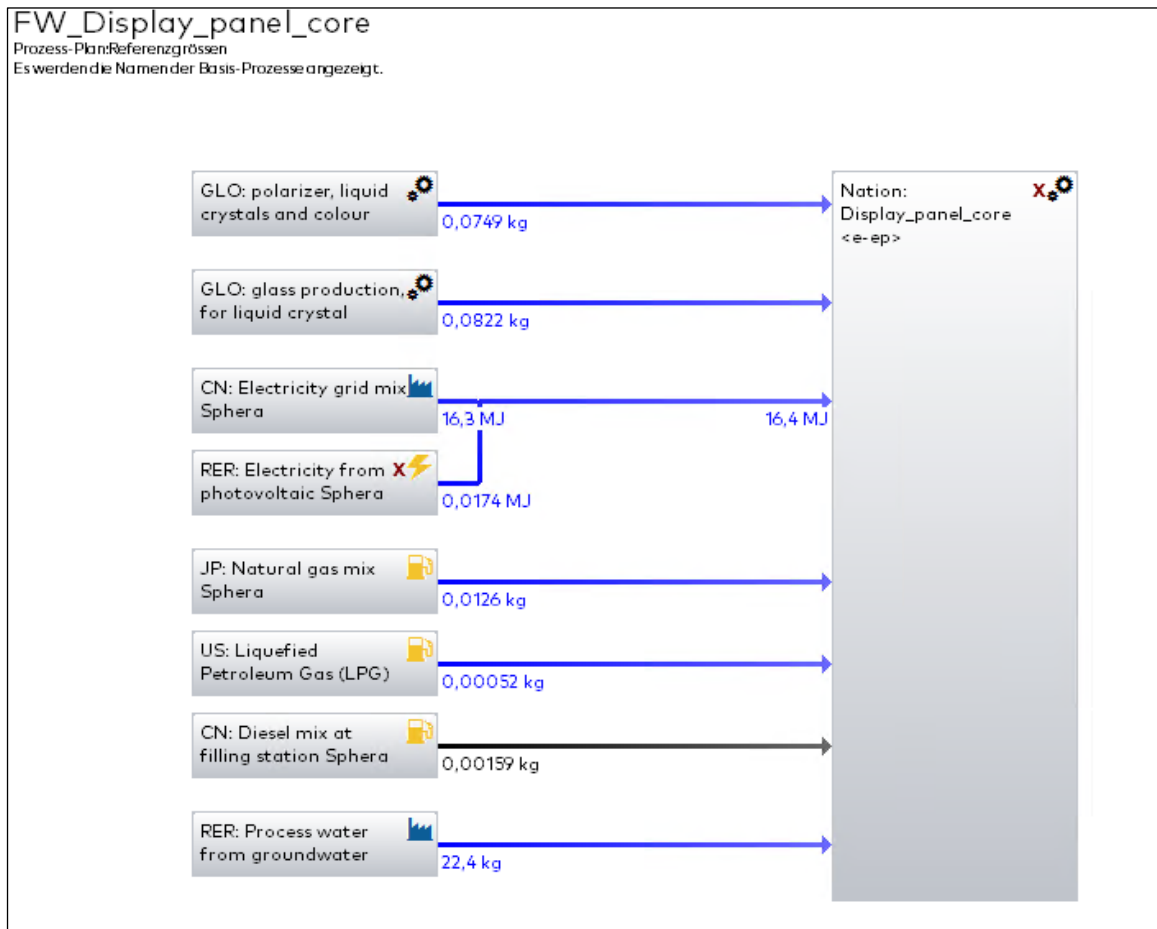


Figure 4-31: Details on the inputs and outputs of the Display panel core model

Name	Natio   Display_panel_core		
Parameter			
Parameter	Formel	Wert	Minimu Maximu Standai Komme
LCA   LCC: 0,568 EUR   LCWE   Dokumentation			
Vollständigkeit: Keine Angabe			
Inputs			
Flüsse	Größen	Menge	Einheit/W/S f Kommentar
Diesel [Refinery products]	Mass	0,00159	kg X 0 (
Electricity [Electric power]	Energy (net calorific value)	16,4	MJ X 0 (
glass, for liquid crystal display [allocatable product]	Mass	0,0822	kg X 0 ( BID-726
Liquefied petroleum gas (LPG; 70% propane; 30% butane) [LPG, at production]	Mass	0,00052	kg X 0 (
Natural gas, at consumer Japan [Natural gas, at consumer]	Mass	0,0126	kg X 0 (
polarizer, liquid crystals and colour filters, for liquid crystal display [allocatable product]	Mass	0,0749	kg X 0 ( BID-727-BID-734 summarized
Water (desalinated; deionised) [Operating materials]	Mass	22,4	kg X 0 (
Outputs			
Flüsse	Größen	Menge	Einheit/W/S f Kommentar
FW_Display_panel_core [Valuable substances]	Number of piece		pcs. X 0 (
BOD in waste water to external WWTP [Production residues in life cycle]	Mass	5,02E-005	kg * 0 ( Emissions from manufacturing (AUO data)
Carbon dioxide [Inorganic emissions to air]	Mass	0,111	kg * 0 ( Scope 1 and additional emission factors
COD, Chemical Oxygen Demand [inconvin long-term to fresh water]	Mass	0,00049	kg * 0 ( Emissions from manufacturing (AUO data)
Hazardous waste (deposited) [Stockpile goods]	Mass	0,0162	kg * 0 ( Emissions from manufacturing (AUO data)
Nitrogen oxides [Inorganic emissions to air]	Mass	6,5E-005	kg * 0 ( Emissions from manufacturing (AUO data)
Non-hazardous waste for further processing [Waste for recovery]	Mass	0,0578	kg * 0 ( Emissions from manufacturing (AUO data)
sulfur dioxide, liquid [allocatable product]	Mass	4,47E-005	kg * 0 ( Emissions from manufacturing (AUO data)
TSS in waste water to external WWTP [Production residues in life cycle]	Mass	0,0001	kg * 0 ( Emissions from manufacturing (AUO data)
VOC (unspecified) [Organic emissions to air (group VOC)]	Mass	0,000151	kg * 0 ( Emissions from manufacturing (AUO data)
Waste water [Production residues in life cycle]	Mass	15,5	kg * 0 ( Emissions from manufacturing (AUO data)

The Scope 2 greenhouse gas (GHG) emissions (from purchased energy) reported by AUO are not directly used, but the energy consumption via the corresponding processes (electricity generation, LPG, gas, diesel) is included to cover other impact categories. Purchased electricity for the manufacturing process is included as electricity from Taiwan.

Scope 1 emissions fed into the model as elementary flows only cover impacts for the GWP category.

This data set forms the core of the display panel. In addition, polarisation filters and the front glass of the display were added using appropriate data from ei3.9 (see Figure 4-29 for an overview).

#### 4.5.2.7 Storage

For the storage module no BOM or material information was available. It was assessed through teardown, microscope images, x-ray and grinding of the main ICs.

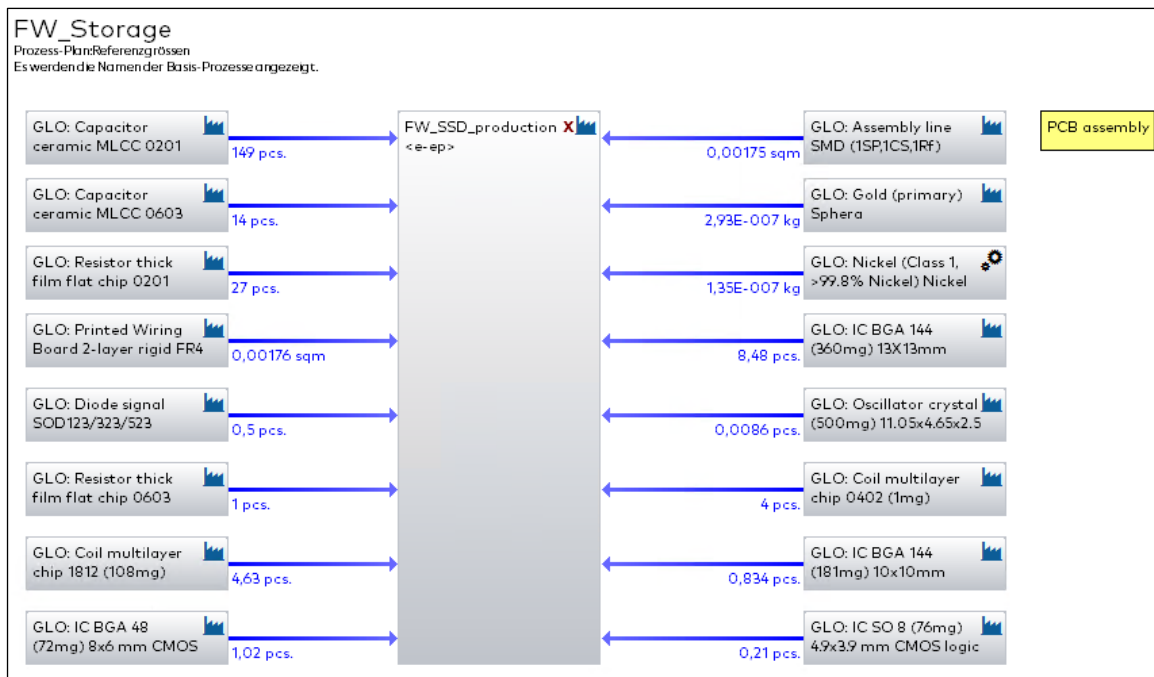
The PCB is as double layer PCB with an area of 17.6 cm<sup>2</sup>. Passive components were identified via microscope and modelled according to section 4.5.2.19. Contact areas on the board were measured via microscope and modelled as nickel-gold plating. The thickness of contacts was based on the results of a literature and market research<sup>18</sup>.

The die size of the main ICs was identified through x-ray and grinding:

- 2 storage ICs: 4.23852 cm<sup>2</sup> die area each
- Controller IC: 0.4671 cm<sup>2</sup>
- DRAM Cache: 0.2046 cm<sup>2</sup>

Additional smaller ICs were scaled by package area.

Figure 4-32: Overview of the storage model



<sup>18</sup> For example: <https://docs.rs-online.com/ba92/A700000008668318.pdf> & <https://www.rutronik.com/pl.html?id=1132&L=11>



#### 4.5.2.8 RAM

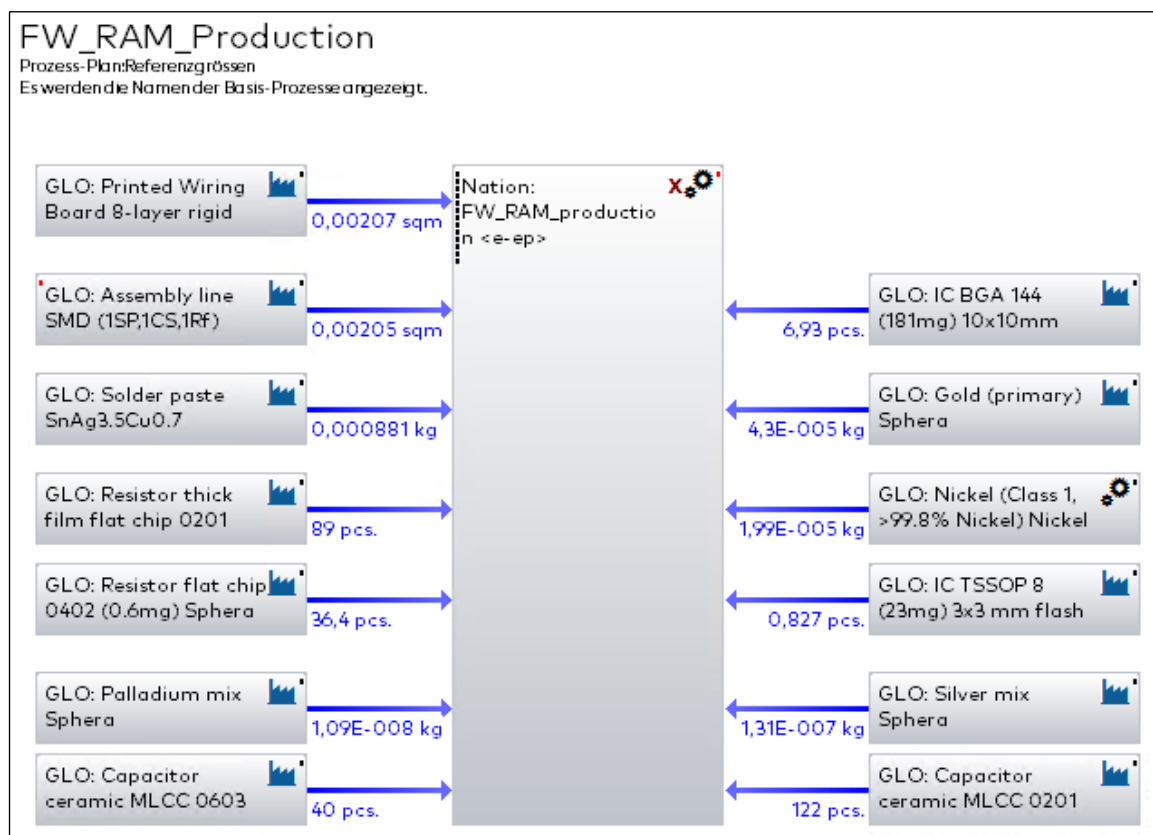
For the RAM module no BOM or material information was available. It was assessed through teardown, microscope images, x-ray and grinding of the main ICs. Two memory modules exist per laptop, so the production plan (Figure 4-33) is set to 2 in the laptop production plan.

The PCB is an 8-layer PCB as determined via grinding with an area of 20.7 cm<sup>2</sup>. Passive components were identified via microscope and modelled according to section 4.5.2.19. Contact areas on the board were measured via microscope and modelled as nickel-gold plating. The thickness of contacts was based on the results of a literature and market research<sup>19</sup>.

The die size of the main ICs was identified through x-ray and grinding:

- 8 Memory ICs: 0.485 cm<sup>2</sup> die area each
- Controller IC: 0.0165 cm<sup>2</sup> die area

Figure 4-33: Overview of the RAM model



#### 4.5.2.9 Webcam

The webcam was modelled based on the BOM and the teardown. It consists of a flex cable (modelled as single layer PCB), connector and PCB with image sensor.

<sup>19</sup> For example: <https://www.futurlec.com/Memory/62256.shtml> ; <https://www.westercom.eu/en/ddr4-memory/6338/advantech-aqd-d4u4gn32-sp.html> & [https://www.simms.co.uk/PDFS/Products/dram/Innodisk\\_DRAM\\_At-a-Glance.pdf](https://www.simms.co.uk/PDFS/Products/dram/Innodisk_DRAM_At-a-Glance.pdf)

The 6-layer PCB was modelled as 8 layer PCB (as no 6-layer PCB data set was available). The connector was scaled by the number of pins, ICs were scaled according to the package area. The image sensor was modelled according to the die area assuming two stacked dies (sensor and logic). The two microphones in the camera were modelled with existing Sphera data sets for SMD microphones. LEDs were scaled by area. The lens is modelled as borosilic glass. The ambient light sensor is based on a 2-layer sub-board.

Figure 4-34: Overview of the webcam model

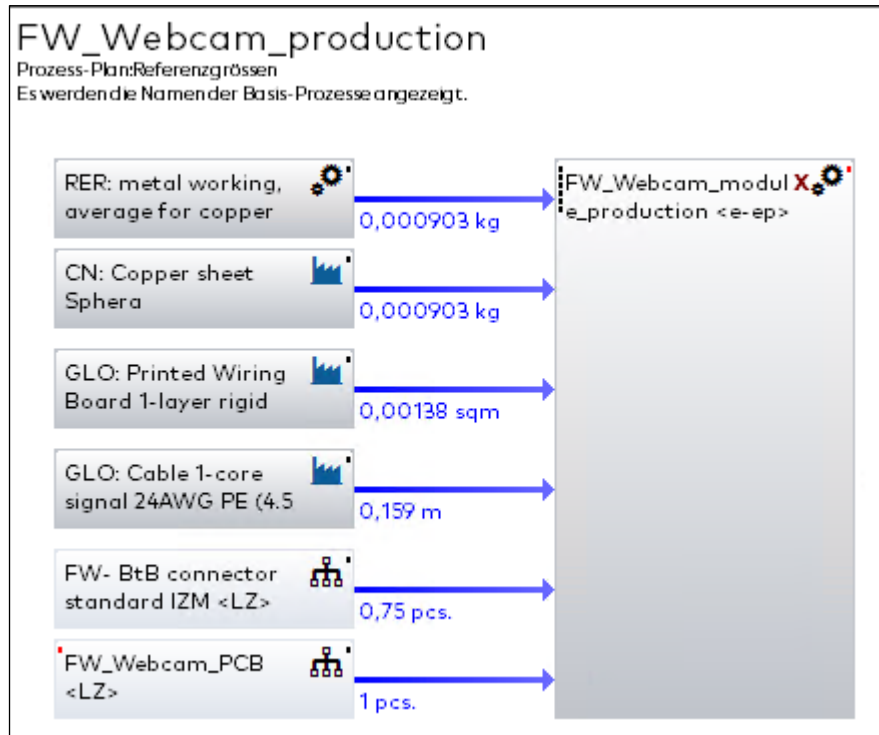
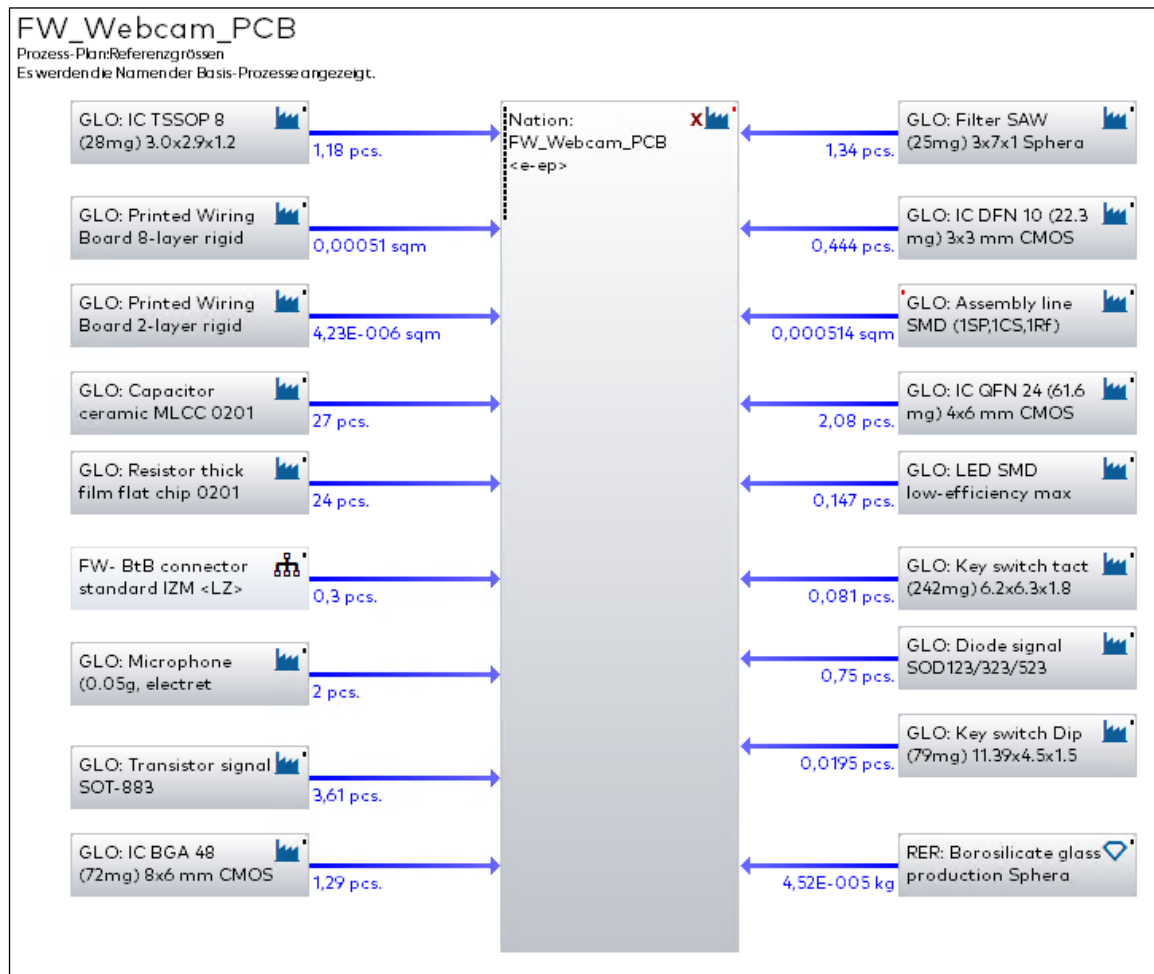


Figure 4-35: Overview of the webcam PCB model



#### 4.5.2.10 Speaker kit

The speaker kit consists of two identical speakers connected with a cable. The individual speaker consists of a polycarbonate case, a coil, metal casing and vibration damper.

Figure 4-36: Overview of the single speaker

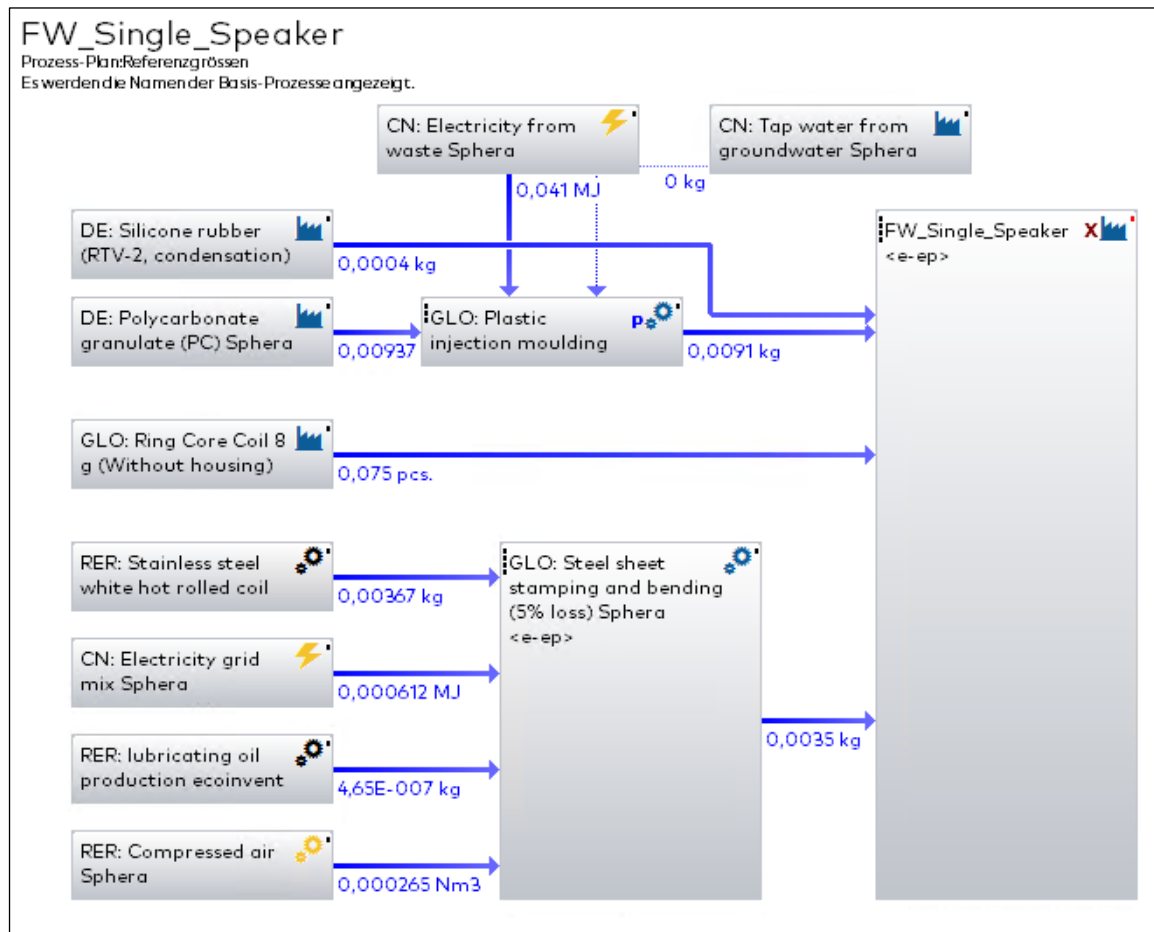
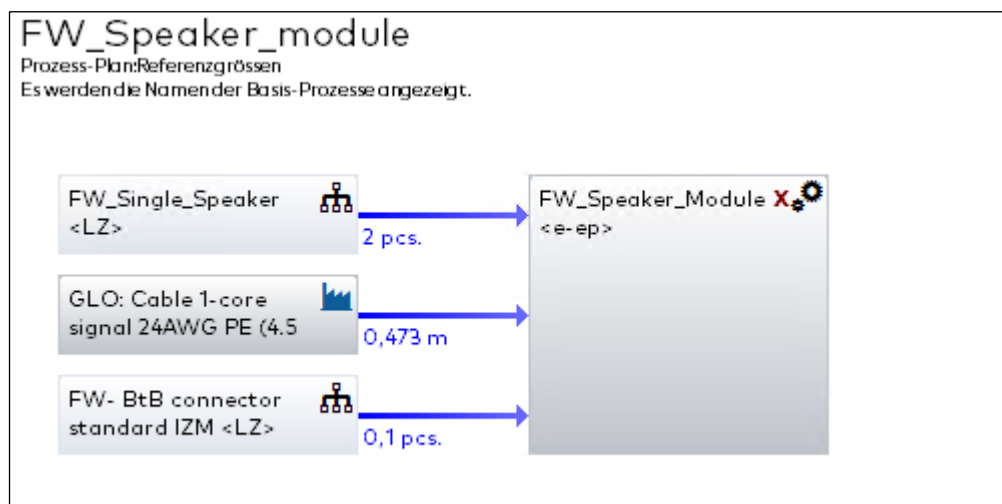


Figure 4-37: Overview of the speaker module



#### 4.5.2.11 WiFi module

The model was based on the tear down and x-ray of the WiFi module. No BOM or further material and manufacturing data were available. The holder is modelled as stainless steel sheet. Screws are modelled with generic Sphera datasets for fixing material. Both are scaled per weight

The WiFi PCB is modelled as 8-layer PCB. Contact areas were measured via microscope and modelled as nickel-gold contacts. The ICs were modelled based on package area as no information on the die size was available.

Figure 4-38: Overview of the WiFi module

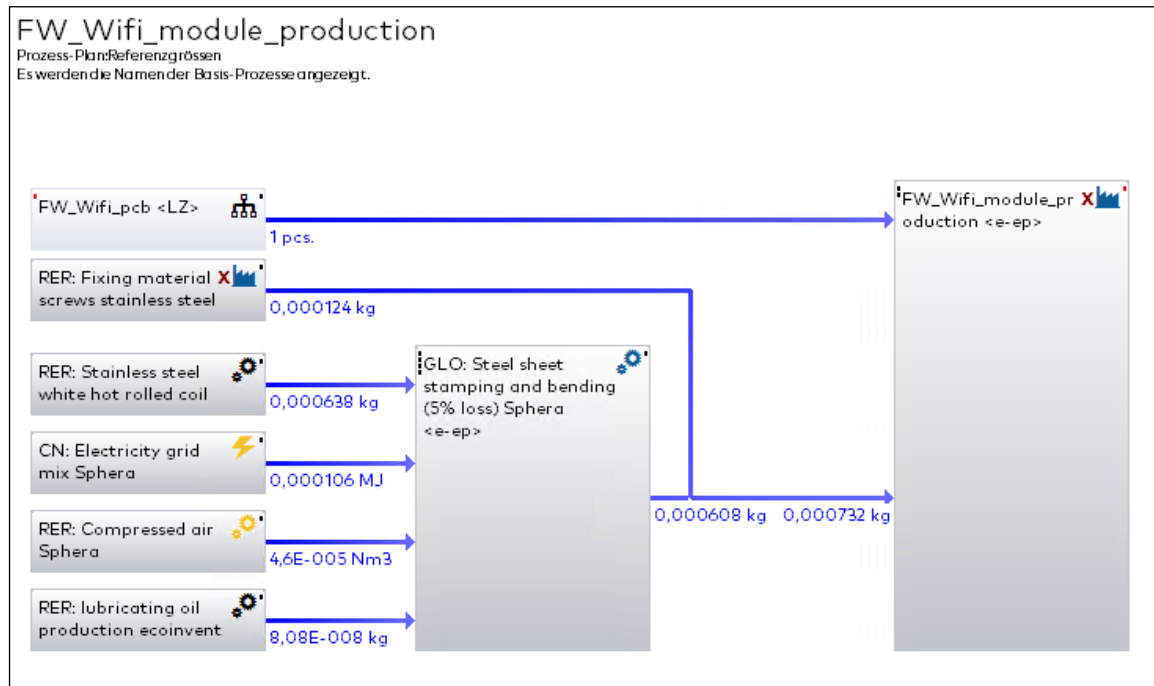
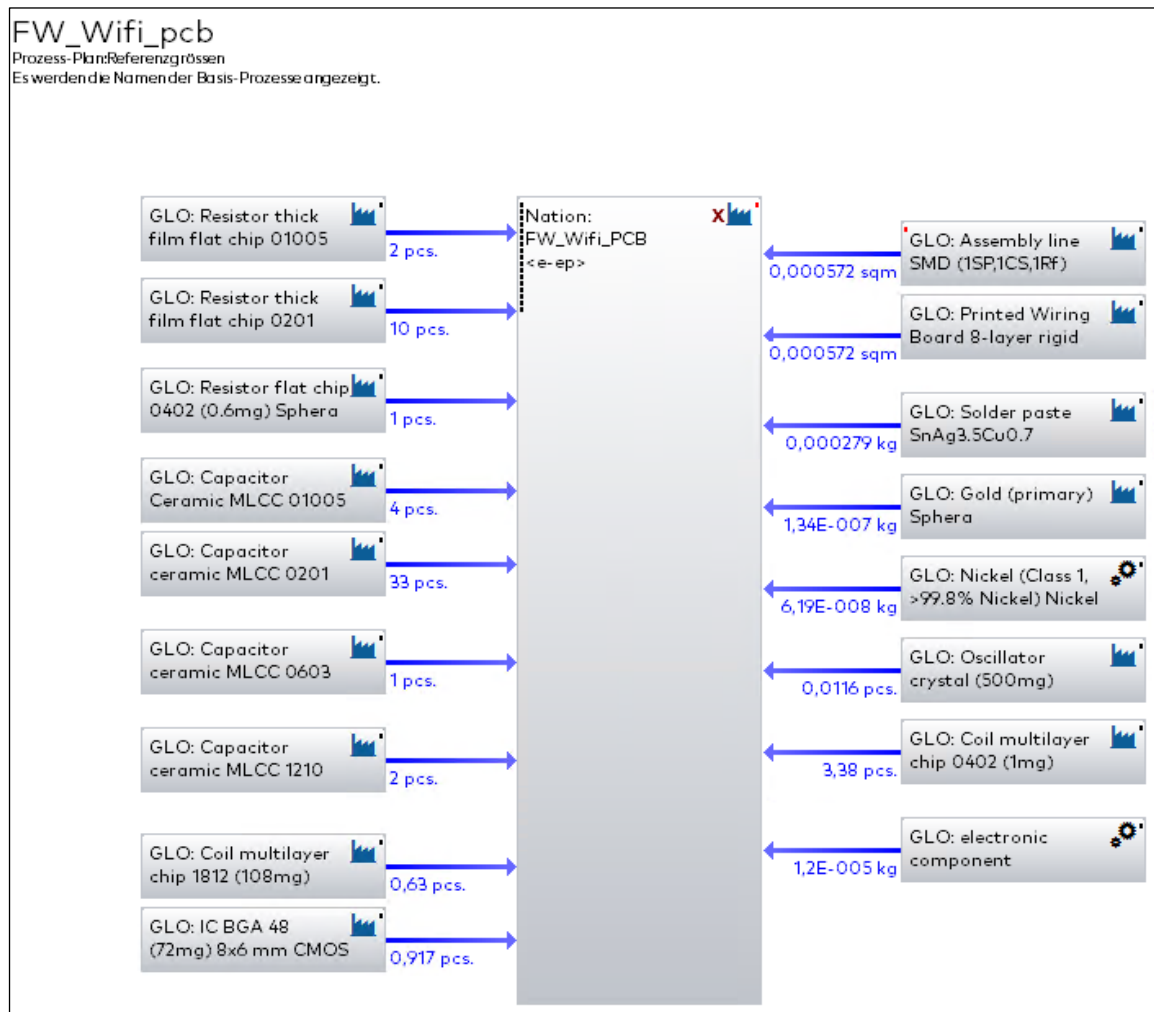


Figure 4-39: Overview of the WiFi PCB model



#### 4.5.2.12 Audio jack

The audio jack was modelled based on a tear down, microscopic images and x-rays. It consists of a rigid and a flex PCB, screws, connectors and the actual audio jack (plug). Screws were modelled with Sphera datasets for fixing material. The rigid PCB is modelled as 8-layer PCB based on x-rays. The flex PCB is modelled as single layer PCB. The audio jack itself is based on material composition from literature (Sanchez, Proske & Baur, 2022).

Figure 4-40: Overview of the audio jack model

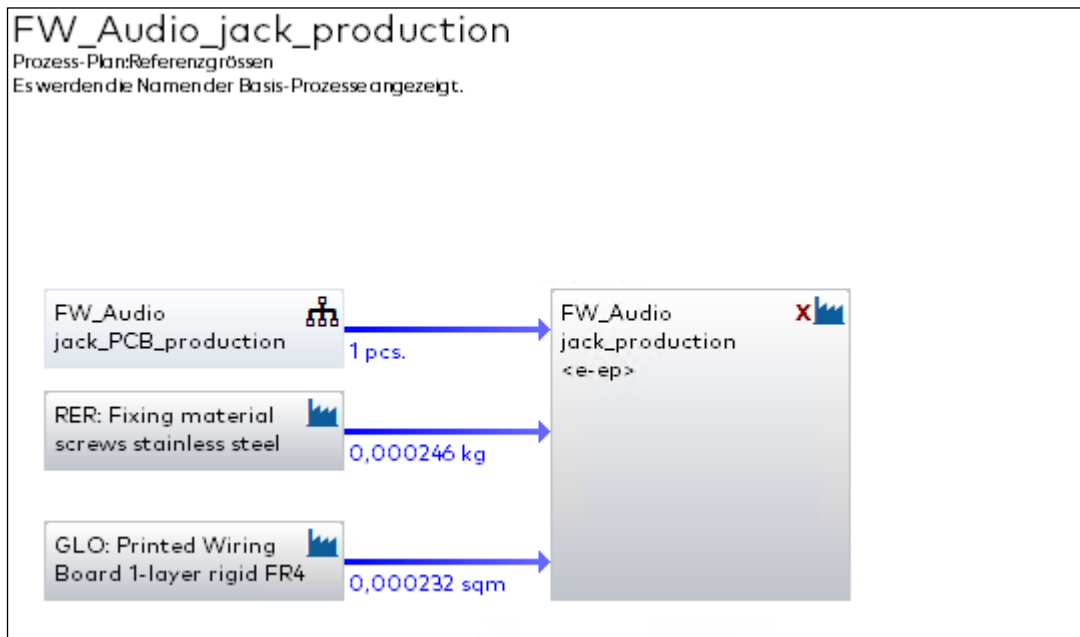
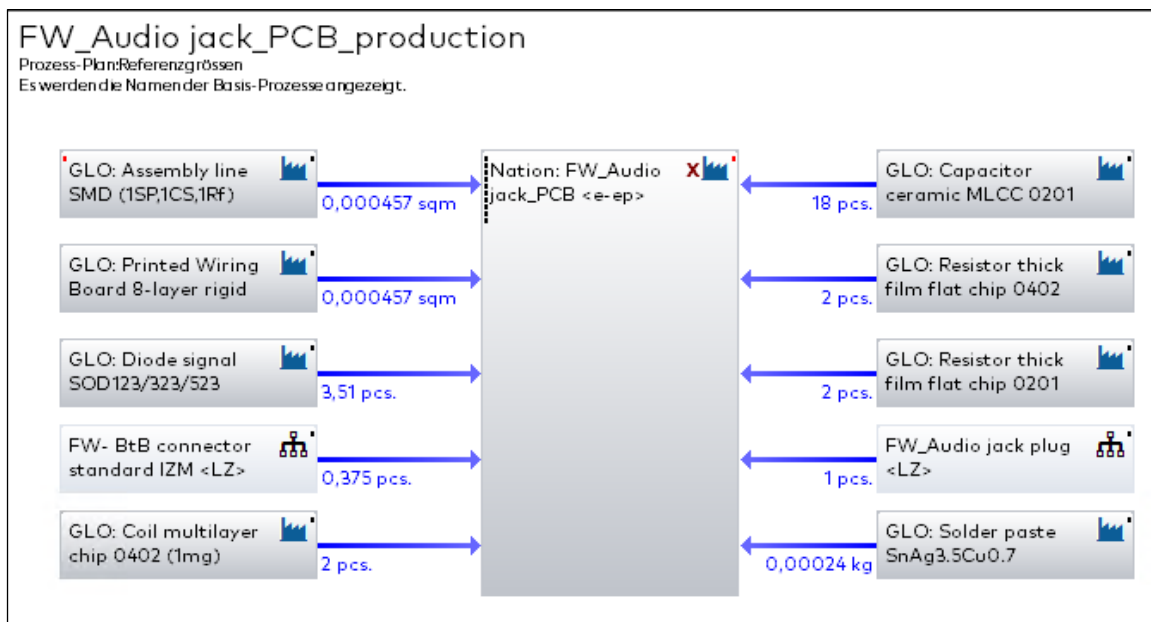


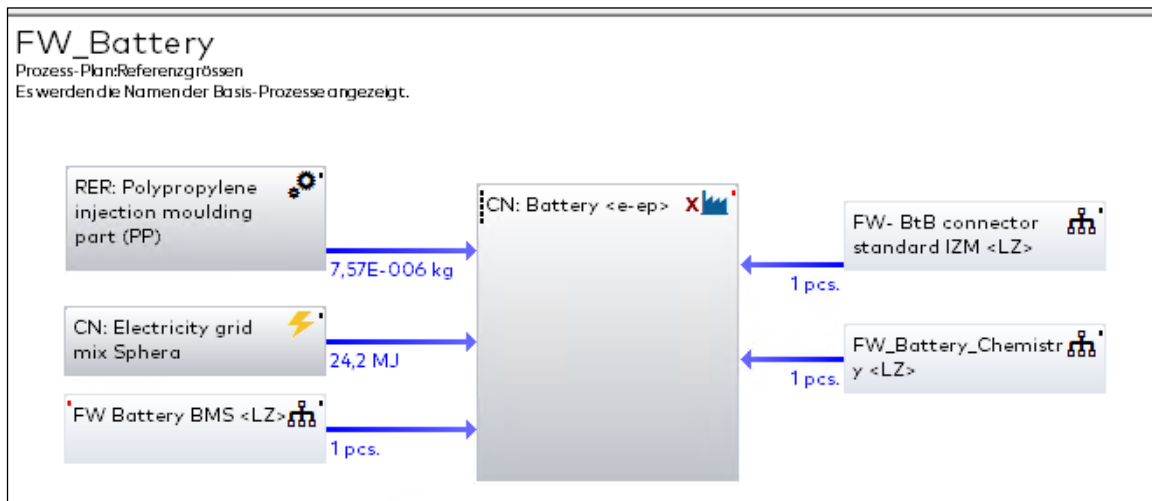
Figure 4-41: Overview of the audio jack PCB model



#### 4.5.2.13 Battery

The battery was modelled based on literature data on chemical composition plus energy consumption for manufacturing scaled by weight of the battery (Sanchez, Proske & Baur, 2022). Additionally, a connector and battery management system was added as two pieces based on Sanchez, Proske & Baur, 2022. Production takes place in China.

Figure 4-42: Overview of the battery model



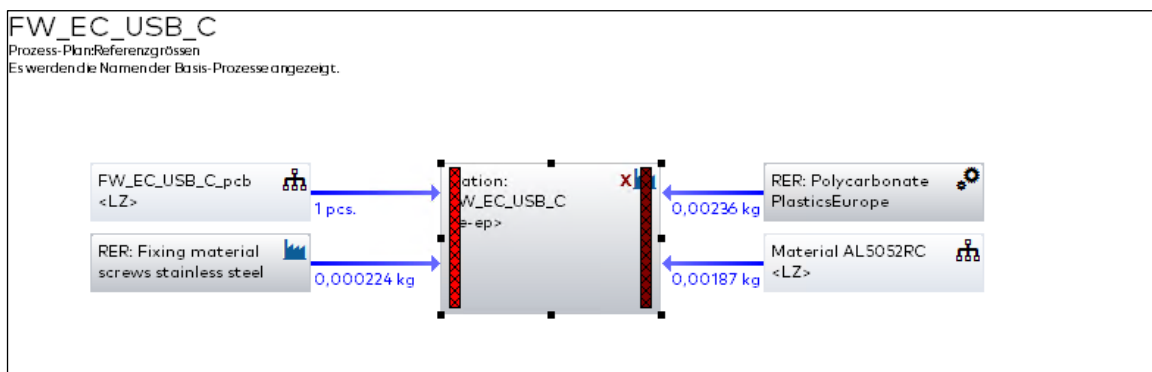
#### 4.5.2.14 Expansion Cards (EC)

Two different expansion cards with an USB-A and USB-C connector were included in the modelling for the laptop.

The ECs are modelled based on tear down, microscopic images and x-rays. No BOM or further material and manufacturing information was available.

The casing of the expansion cards is assumed to be the same material as of the whole laptop. The PCBs are modelled as 4-layer boards based on the x-ray images. The card-to-board connectors are modelled as USB-C plugs based on literature material composition (Sanchez, Proske & Baur, 2022). The USB-A connector is modelled based on material composition by TE connectivity<sup>20</sup>.

Figure 4-43: Overview of the expansion card model – USB-C



<sup>20</sup> Full material composition:

[https://www.te.com/commerce/DocumentDelivery/DDEController?Action=showdoc&DocId=Product+Compliance%7FMD\\_292303-2%7FD%7Fpdf%7FEnglish%7FENG\\_PC\\_MD\\_292303-2\\_D.pdf%7F292303-2](https://www.te.com/commerce/DocumentDelivery/DDEController?Action=showdoc&DocId=Product+Compliance%7FMD_292303-2%7FD%7Fpdf%7FEnglish%7FENG_PC_MD_292303-2_D.pdf%7F292303-2)



Figure 4-44: Overview of the expansion card PCB model – USB-C

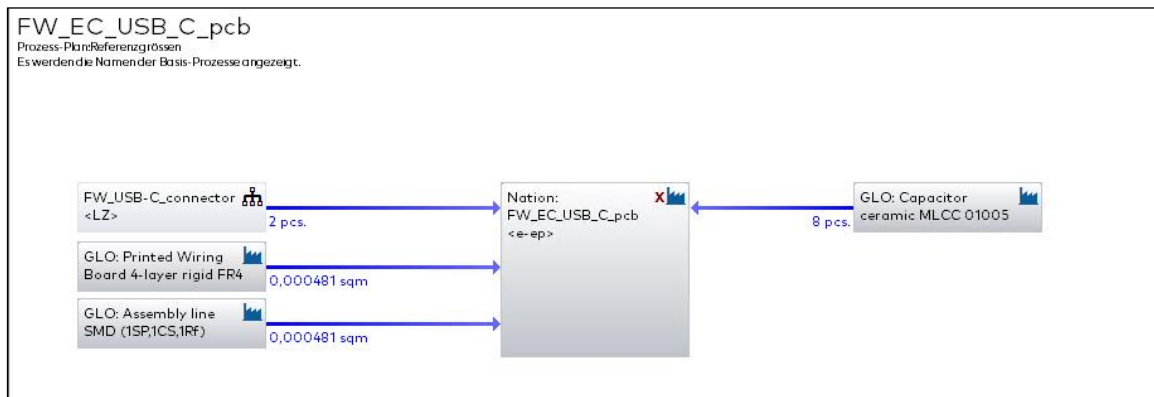


Figure 4-45: Overview of the expansion card model – USB-A

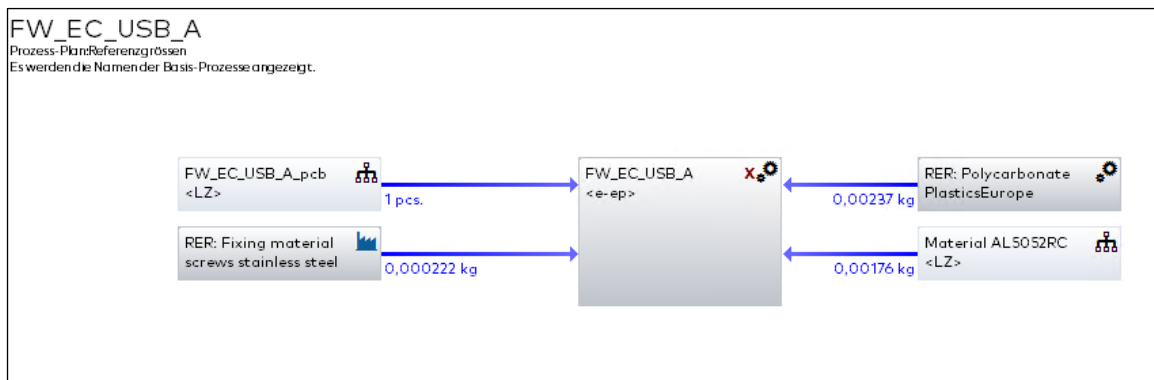


Figure 4-46: Overview of the expansion card PCB model – USB-A

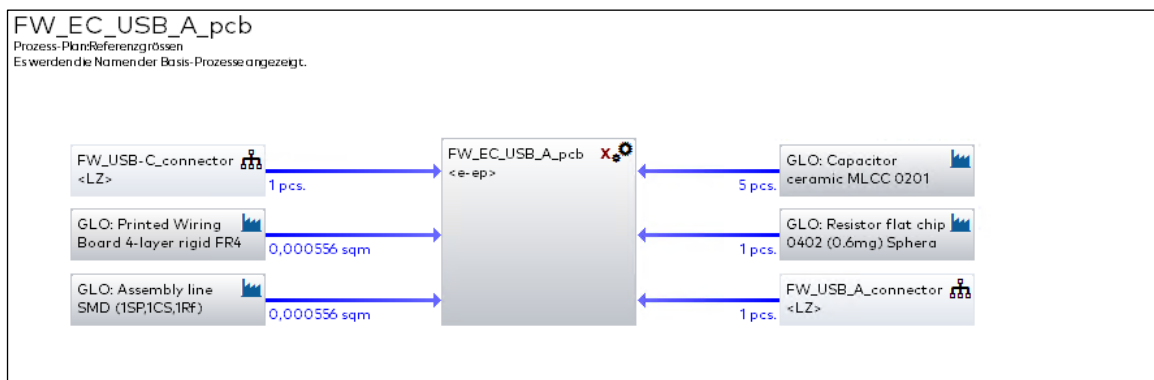
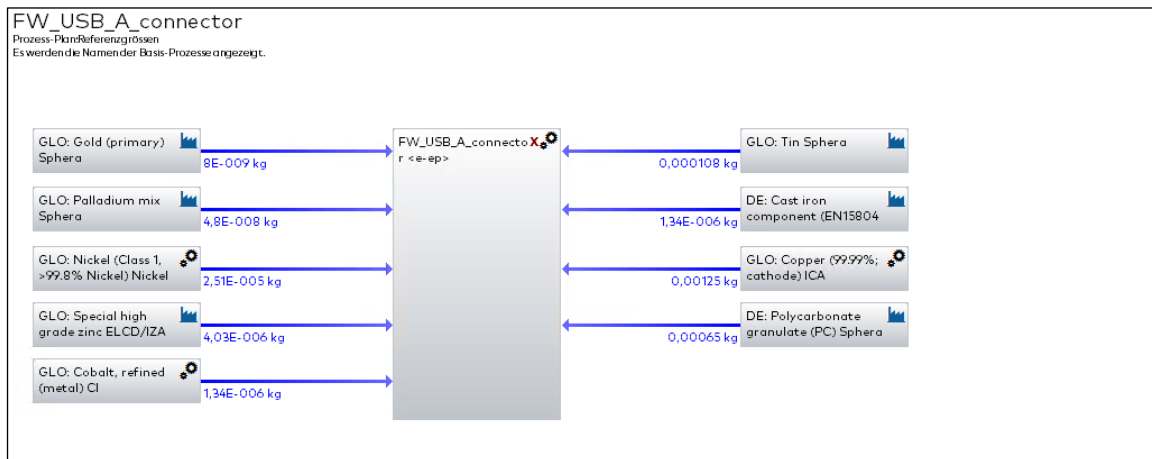


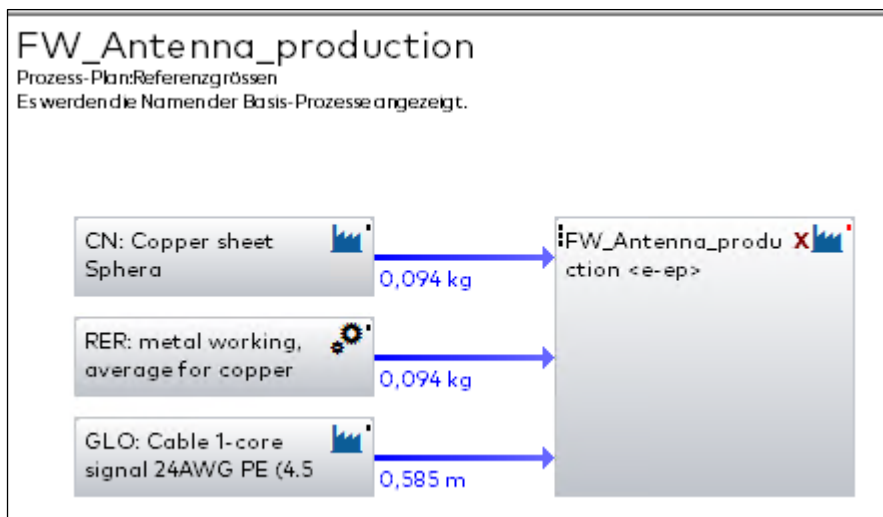
Figure 4-47: Overview of the expansion card model – USB-A connector



#### 4.5.2.15 Antenna module

The antenna module consists of copper adhesive foil and two cables as displayed in Figure 4-48.

Figure 4-48: Overview of the antenna model



#### 4.5.2.16 External Power Supply

The modelling of the external power supply (EPS) is based on a tear down. No further material or manufacturing information were available.

The EPS consists of a plastic housing with additional steel plates inside, one major PCB with several electronic components, a small PCB with the USB-C connector, some cables and a power plug. The PCB was potted with a flexible plastic compound, which is modelled as TPU.

Figure 4-49: Overview of the EPS model

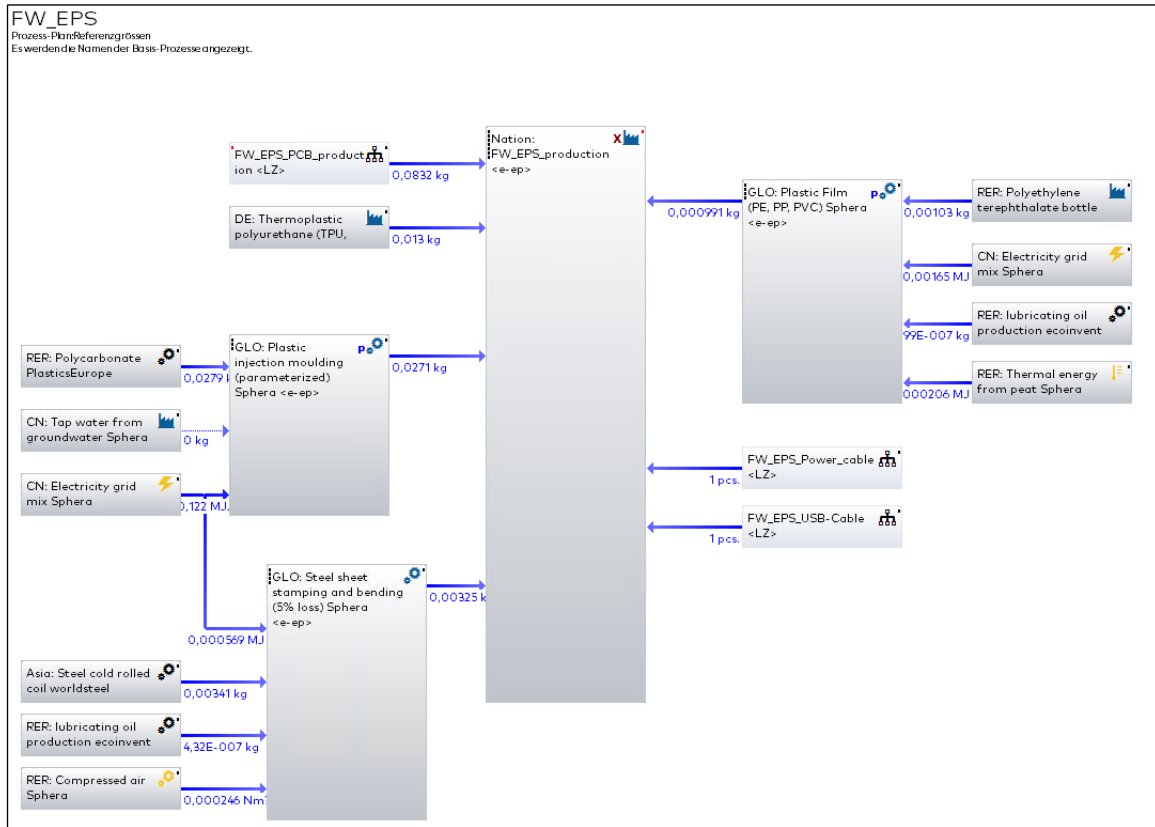
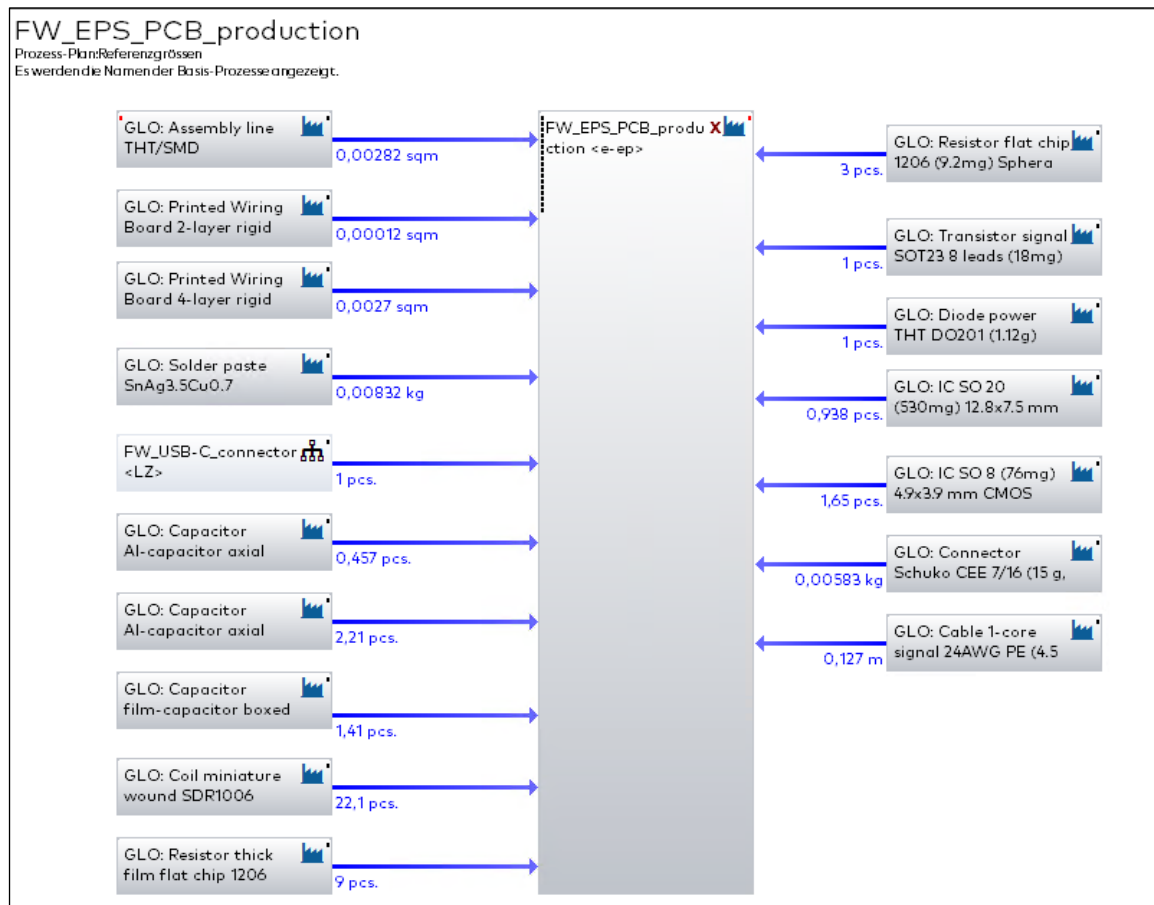


Figure 4-50: Overview of the EPS PCB model



#### 4.5.2.17 Printed circuits boards

Some general approaches are applied across the modules. Printed circuit boards are modelled according to the number of layers and produced board area based on Sphera datasets. As no specific production layout were available for the Framework laptop boards, the smallest rectangular of irregular shapes was considered for the impact of the board production.

Additionally, assembly processes were modelled with a generic Sphera dataset. That process is also modelled per board area. Here, only the specific final board area (without cut-offs) is modelled. Solder (SnAgCu) is added to all printed circuit boards. As no specific information is available on the amount of solder paste used, 10% weight based on the populated printed circuit board assembly is added.

#### 4.5.2.18 Connectors

Due to a lack of manufacturer’s data, connectors are modelled according to a standard board-to-board connector defined based on literature data (Sanchez, Proske & Baur, 2022). These connectors were assumed to be 40-pin press-fit connectors, mainly consisting of copper for the contacts and nickel or tin for the plating. The different connectors were then scaled by pin number.

Most modules are connected to the mainboard by flex cables, which have been modelled separately as one-layered PCBs.

USB plugs were also modelled according to material compositions from literature (Sanchez, Proske & Baur, 2022).

#### 4.5.2.19 Passive components

Passive components were modelled using suitable generic datasets from the LCA FE electronics extension and scaled by the number of pieces. If necessary, components were rescaled based on weight and size:

- Diodes, oscillators: scaled by volume
- Inductors, filters and switches: scaled by area
- Resistors, capacitors: scaled per weight

Chip resistors were modelled according to FMD of a chip resistor. In lack of suitable dataset, it was modelled as a normal resistor (size 0402, scaled by weight) and the amounts of silver and palladium used were added manually to account for the increase in ADP by these precious metals.

#### 4.5.2.20 Integrated Circuits (ICs)

The environmental impact of integrated circuits is mainly driven by the processed die area within the package. However, identifying the die size is time-consuming. Therefore different approaches are applied, depending on the available information:

- "Average" ICs: PCBs were x-rayed. If die size could be measured via x-ray, suitable datasets from the LCA FE electronics extension were selected and rescaled by die area. If die size could not be identified via x-ray, ICs were modelled based on type and package area.
- Main ICs (mainly on RAM and storage, plus selected ICs from the mainboard) were x-rayed and grinded if necessary to determine the die size. The die size of the processor were based on public technical information.<sup>21</sup> Suitable datasets from the LCA FE electronics extension were selected and rescaled by die area.

Not all package types were available in the Sphera LCA FE data base, so similar types were used as proxys.

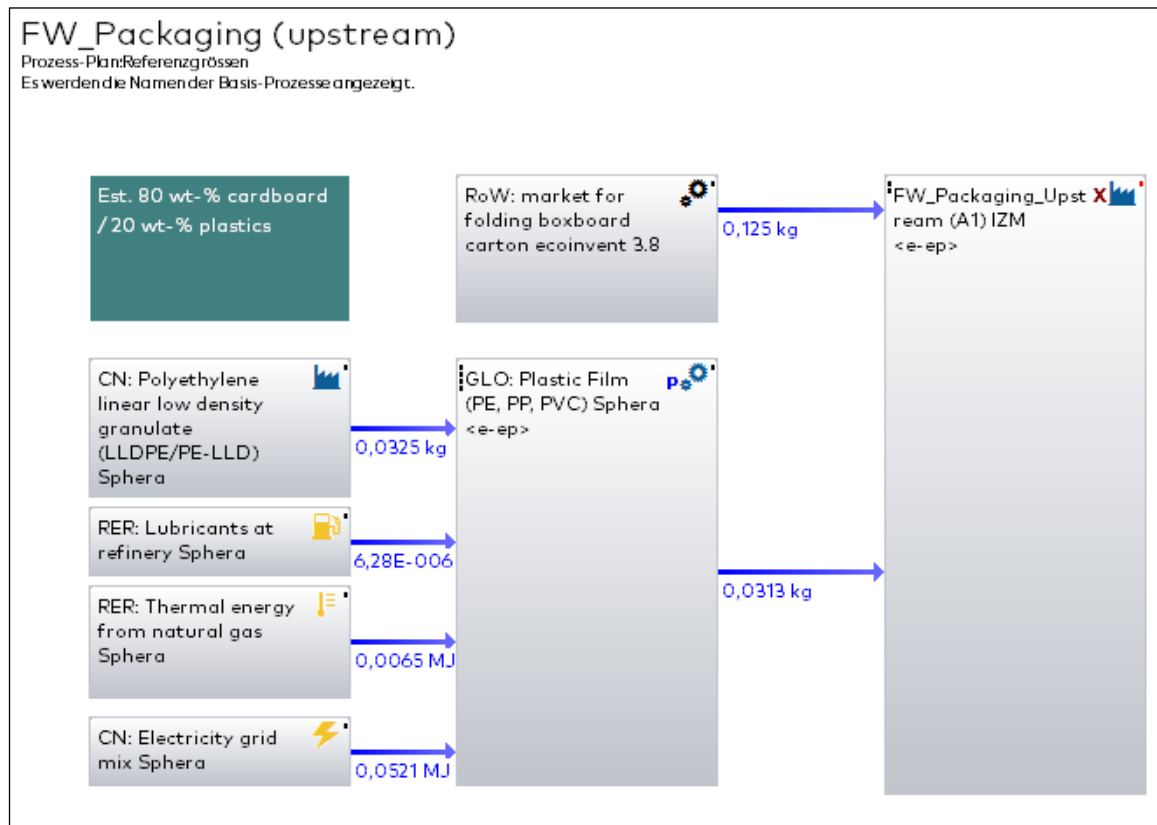
#### 4.5.3 Product Packaging and accessories (A1)

All associated packaging materials from up- and downstream processes have been included.

For the upstream components no primary data was available. The estimated weight of the packaging material was calculated as approximately 12% of the aggregate weight of the laptop, its accessories, and related extension cards. The composition of this estimated packaging was determined to be 80% cardboard and 20% PE foil (see Figure 4-51).

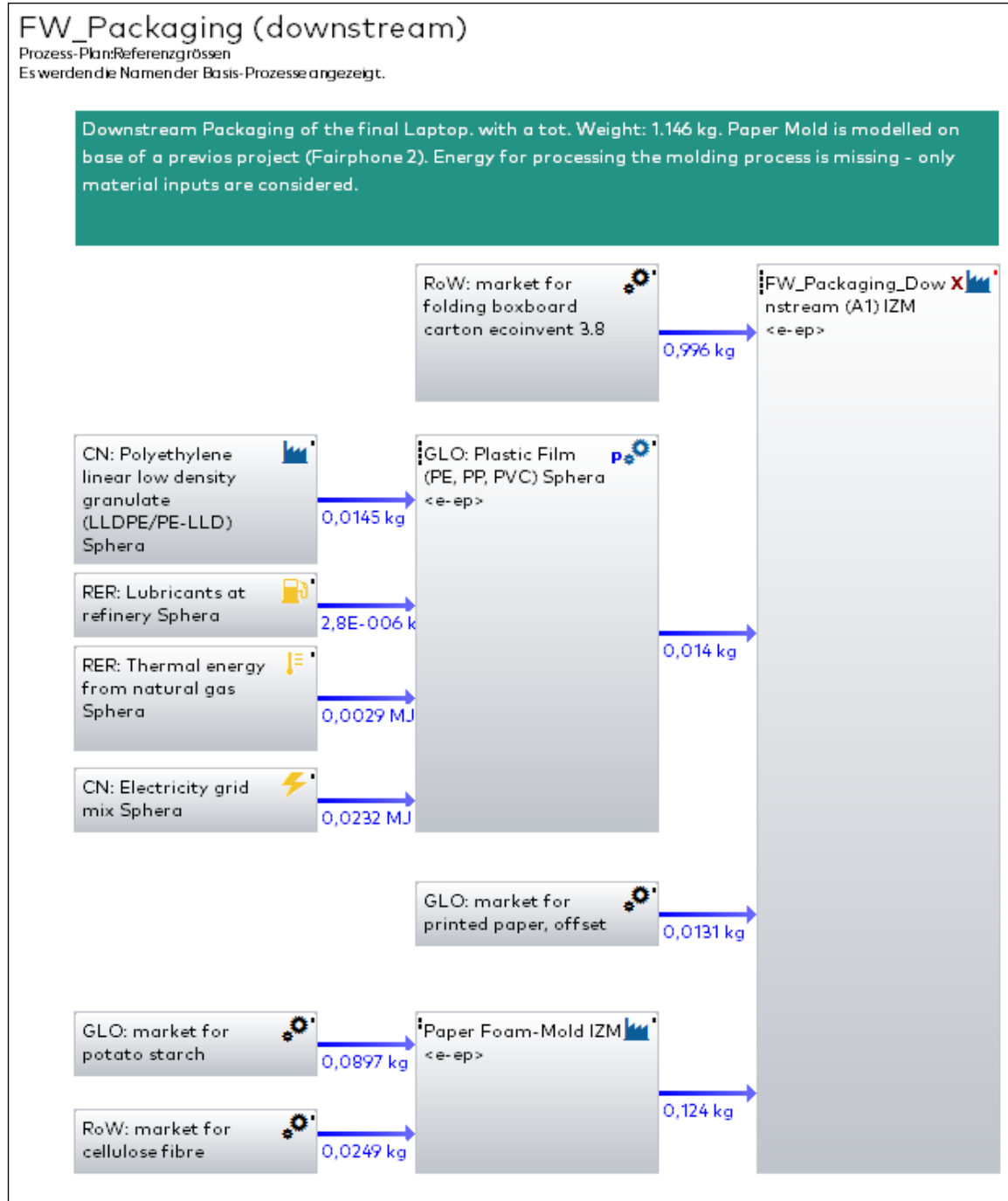
<sup>21</sup> <https://www.techpowerup.com/cpu-specs/core-i5-1240p.c2583>

Figure 4-51: Model for packaging materials for the upstream components



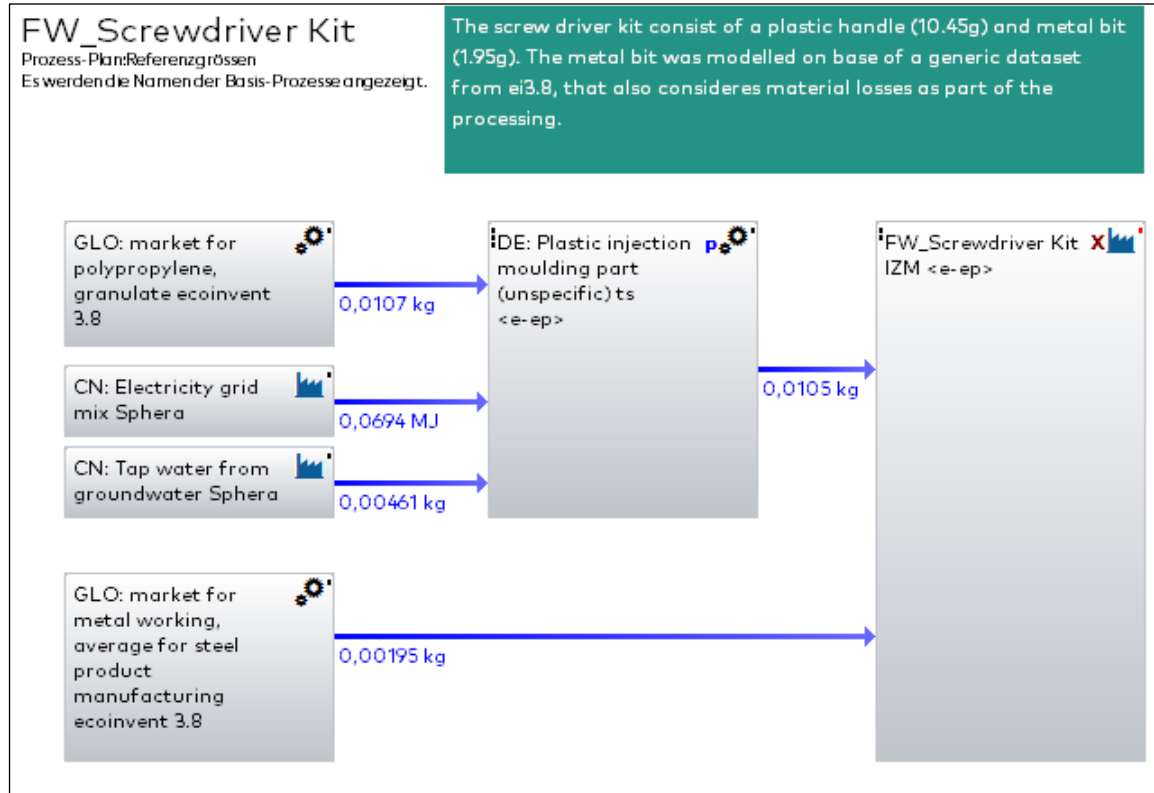
The material specifications for the final device, including its accessories (downstream packaging) and related extension card, were derived from measurements taken during the teardown and aggregated in a single process (see Figure 4-52).

Figure 4-52: Model for downstream packaging materials for the final Laptop



The Framework Laptop comes with a screwdriver kit to open and replace individual modules. Due to the lack of primary data, the modelling was done with generic data sets from the background databases based on the material fractions.

Figure 4-53: Overview of the model for the production of the screw driver kit



#### 4.5.4 Transports of intermediary product (A2)

The modelling scenarios of upstream transports are described in detail in Chapter 3.4.1.2 and are as follows:

- Components (A1): Generic transport scenario and mix is assumed (see Figure 4-54)
- Screwdriver Kit (A1): Generic intracontinental transport (see Figure 4-55)
- Downstream packaging (A1): Generic local transport (see Figure 4-56)

No specific distances are known for the transport of intermediate products (components from A1), so an aggregated transport mix based on the components from the USA and other countries (Global Transports) [CPU and main ICs, memory, RAM] and Asia (Intercontinental Transports) is assumed, based on the approximate weight percentage of the components as part of the final device (see Figure 4-54).

All modes of transportation are modelled according to the assumptions in Chapter 3.4.1.2, and background data sets are adjusted accordingly (e.g. payload, distance).



Figure 4-54: Overview of the transport model for upstream components

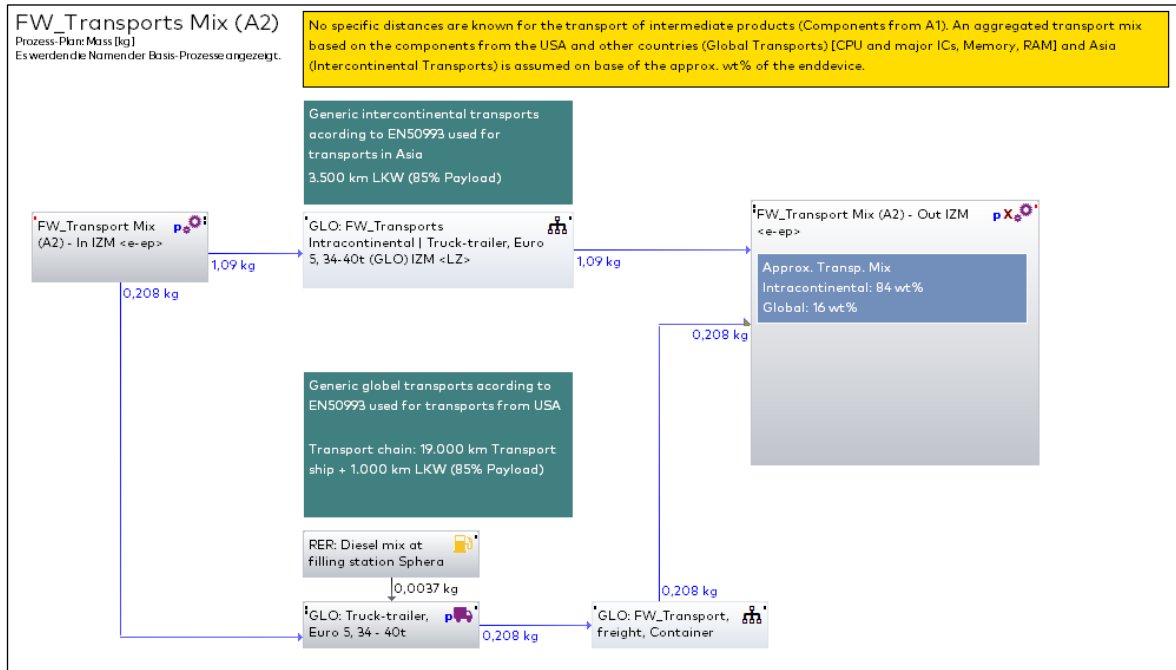


Figure 4-55: Overview of the model for intracontinental transports

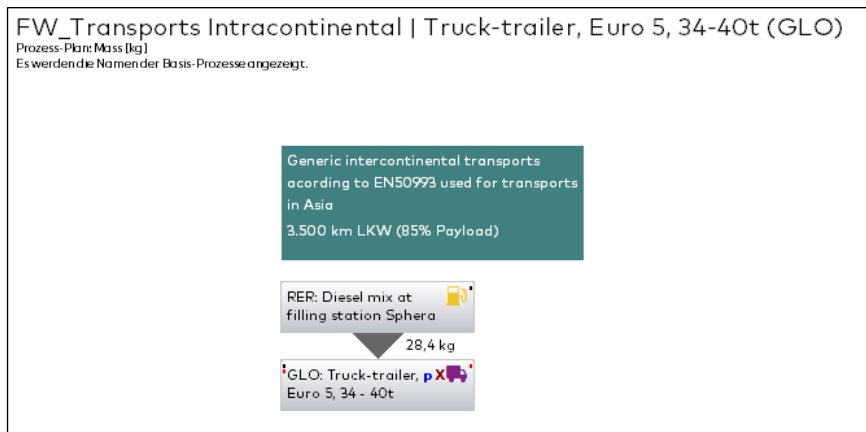
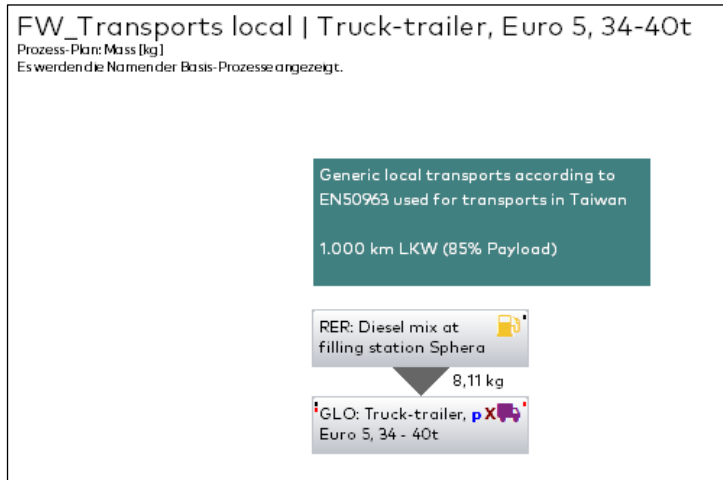


Figure 4-56: Overview of the model for local transports

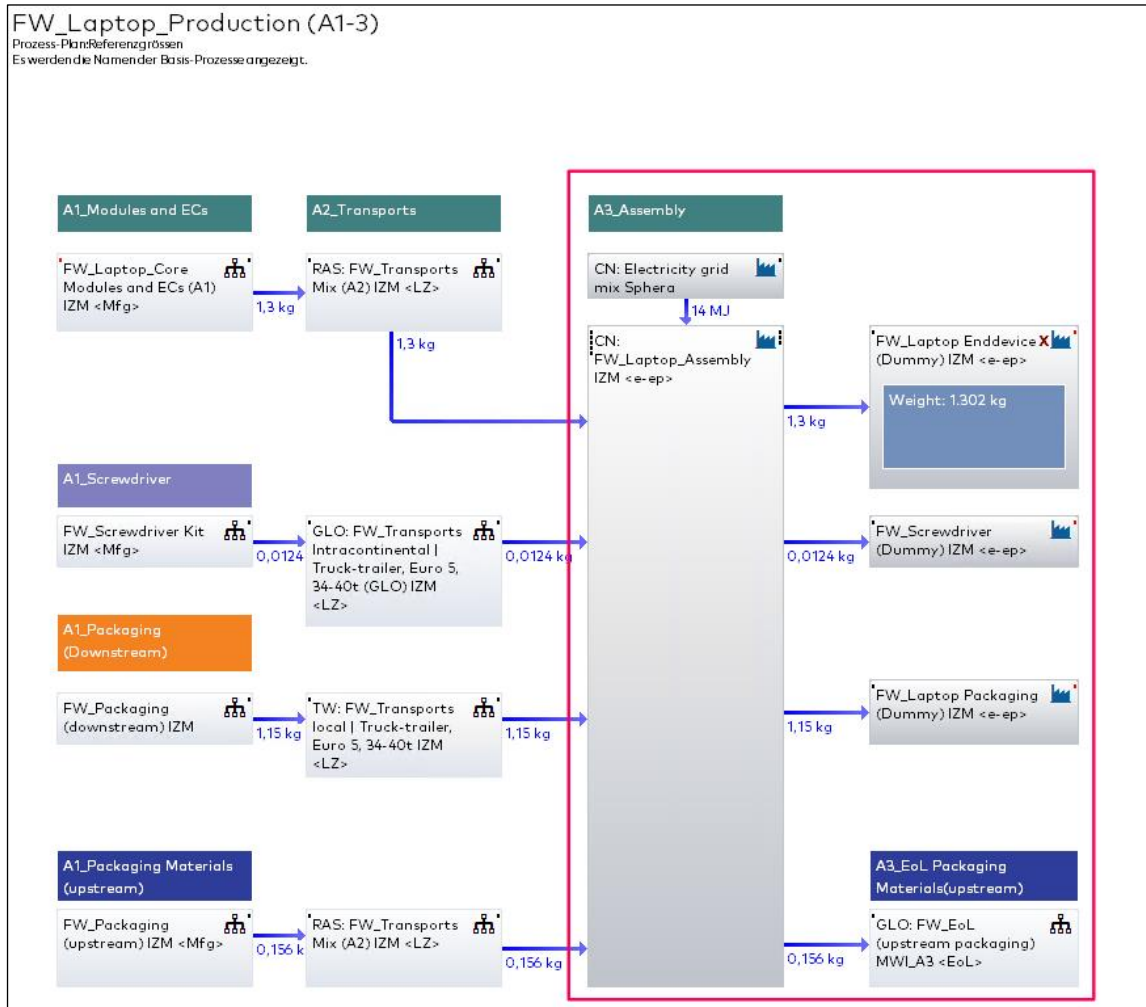


#### 4.5.5 Assembly and shipping preparation (A3)

The assembly stage and shipping preparation (A) are modelled according to the assumptions in Chapter 3.4.1.3).

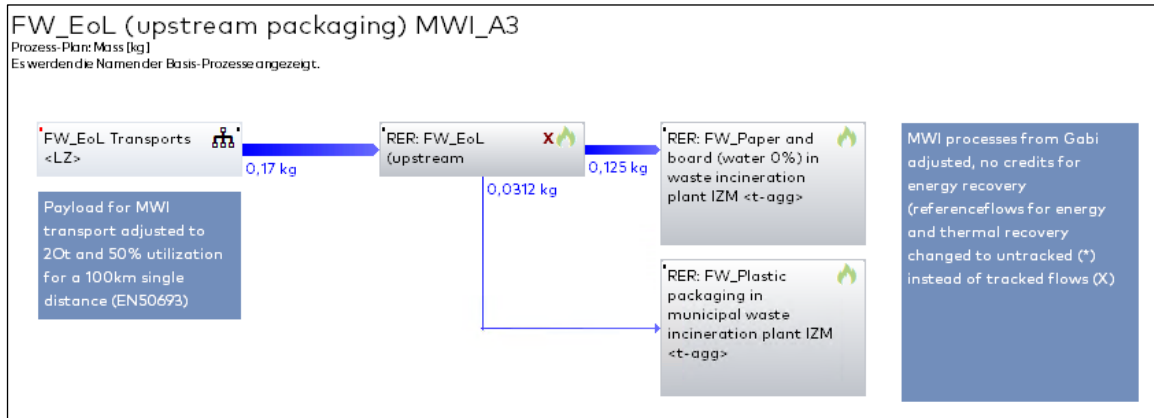
No primary data for the assembly process was available. A literature research was therefore conducted to estimate the energy used during the assembly process. Energy consumption during assembly seems to be fairly constant throughout several different ICT-product categories and was therefore estimated at 3.89 kWh (14 MJ) for the Framework laptop, which was the literature average [e.g. Proske et al. (2016; 2020), O'Connell & Stutz (2010), Huawei (2016; 2018-a; 2018-b; 2018-c; 2019-a; 2019-b; 2020-a; 2020-b)].

Figure 4-57: Overview of the model for assembly of Laptop (red frame)



For the disposal of upstream packaging waste in the manufacturing stage (see Figure below), a generic municipal waste incineration process was assumed, which is the common treatment practice in Taiwan for packaging waste. According to the reverse cut-off approach (waste content), no credits are given for energy recovery. Transports of upstream packaging waste from the assembly stage to waste facility were estimated by the LCA practitioner as 80 wt-% cardboard/ 20 wt-% plastics. According to EN50693 Chapter 4.3.2 waste Transports include a full outward journey and empty return journey by truck and thus modelled with a utilization of payload of 50% over a single distance. The transport distance of 100 km is estimated by the LCA practitioner based on the area coverage and number of MWIs in Taiwan.

Figure 4-58: EoL model for the upstream packaging as part of the assembly stage (A3)

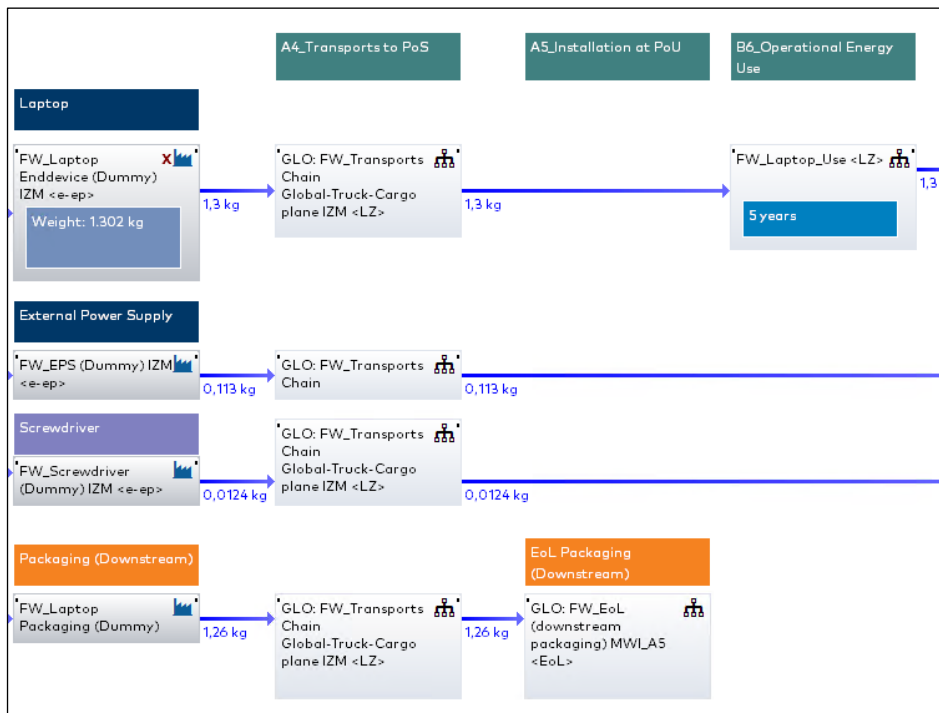


#### 4.5.6 Distribution and use phase (A4-B7)

The modelling scenarios for the distribution and utilization phase includes:

- The transports (A4) of the final Laptop device, the external power supply (EPS), screwdriver kit and all packaging material from Taiwan to the point of sale (PoS) in the USA where modelled as global transport chain according the assumptions in Chapter 3.4.1.4.
- The packaging was modelled to become waste at the point of usage (PoU) (A5) and for the recycling a generic municipal waste incineration process was assumed.
- The operational energy usage (B6) was modelled on base of the typical energy consumption (TEC) for the device over a period of 5 years (see further details on Chapter 3.4.1.5)

Figure 4-59: Overview of the distribution model and use phase



#### 4.5.7 End of Life (C2-C4)

For the EoL of the device a generic treatment for electronic equipment and products was assumed and adjusted to the approximated material fraction determined in Chapter 3.4.1.7. The energy intensity for shredding and sorting the device was adopted from a generic ecoinvent dataset. A 100% collection and recycling rate is assumed.

All burdens for the incineration of plastic fractions are assigned to the product system and no credits for energy recovery are given (cut-off, "polluter pays" principle). Shredded and sorted metal waste is valuable good that will lose its waste status after the sorting process and no additional waste processing is needed (e.g. melting) and no credits for material recovery are given.

Figure 4-60: Overview of the EoL of the Laptop

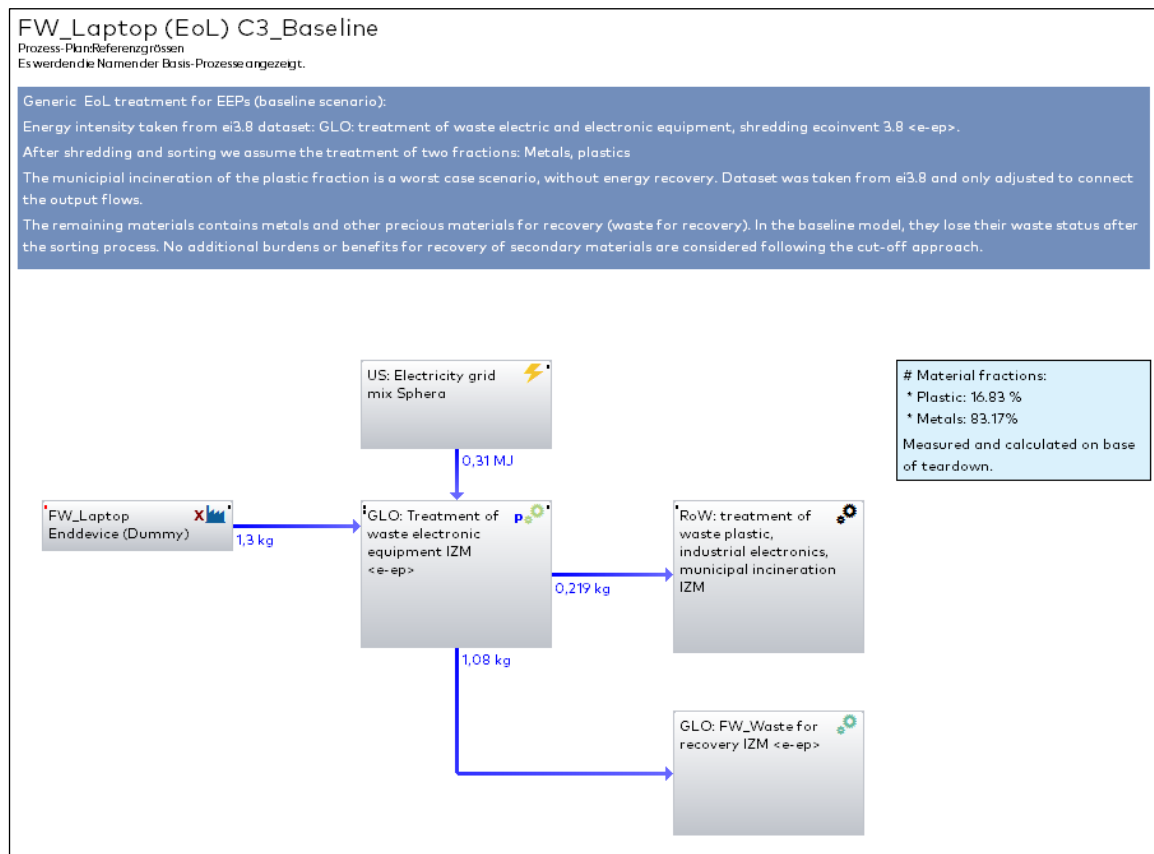
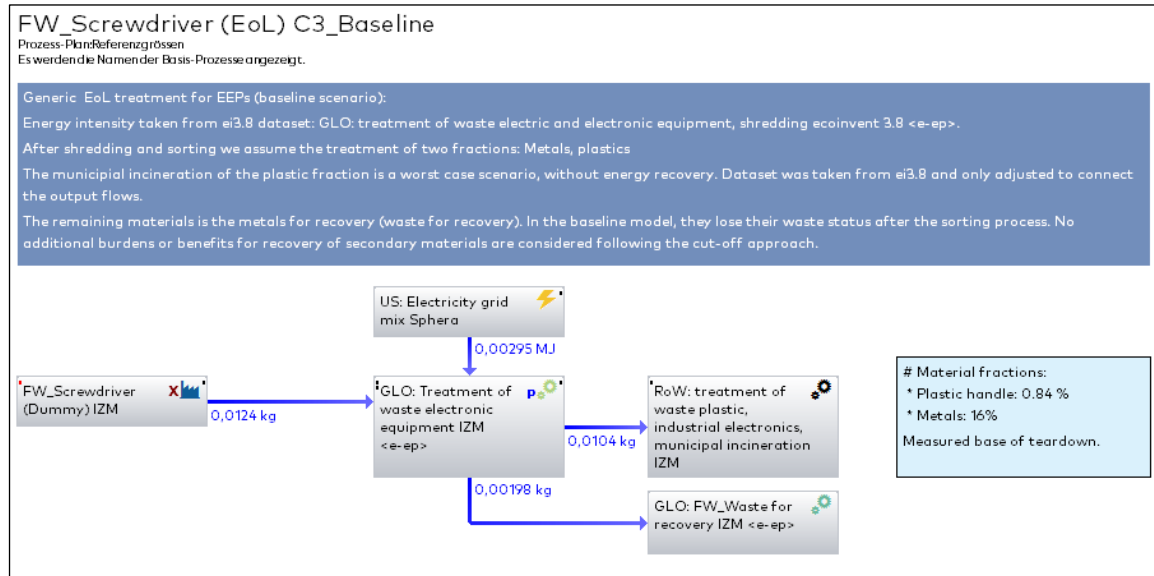


Figure 4-61: Overview of the EoL of the Screwdriver



## 5 Lifecycle impact assessment

The following impact assessment is based on the characterization factors of the Environmental Footprint Reference Package 3.1 (abbreviated as EF 3.1) as implemented in the LCA Software LCA FE by Sphera. The results of the impact assessment are relative expressions, and the impact estimate results do not predict impacts on category endpoints or the transgression of thresholds, safety margins or risks.

For the following impact categories, the results will be displayed and discussed in detail:

- Climate change:
  - Global Warming Potential, 100 years (GWP100) in kg CO<sub>2</sub>-equivalents
- Resource depletion:
  - Abiotic resource depletion (ADP) elements in kg Sb equivalents

Normalization, grouping, and weighting of the results (optional steps in the impact assessment of an LCA) will not be applied.

The results will be presented as follows:

- Chapter 5.1 gives an overview of the aggregated LCA results per lifecycle stage
- Chapter 5.2 gives a detailed view of disaggregated LCA results for single modules and components.

### 5.1 Indicators for Impact Assessment per Lifecycle Stage

This section provides the aggregated results for each lifecycle stage as described in Section 3.4.1 and the following table.

*Table 5-1: Lifecycle stages and corresponding modules codes considered in the LCA*

PRODUCT STAGE				DISTRIBUTION		USE PHASE	END OF LIFE STAGE			
Raw materials and intermediary	Transport	Manufacturing/ Fulfillment center	Cradle to gate total.	Transport to PoS	Installation at PoU	Operational energy use	De-installation at PoU	Transport	Waste processing	Disposal
<b>A1</b>	<b>A2</b>	<b>A3</b>	<b>A1-3</b>	<b>A4</b>	<b>A5</b>	<b>B6</b>	<b>C1</b>	<b>C2</b>	<b>C3</b>	<b>C4</b>

The following Table 5-1 provides the aggregated results for each life cycle phase and sub-phases/modules for the target impact categories of GWP and ADPe.

The total impact for the Framework Laptop is estimated to be a GWP of 200 kg CO<sub>2</sub>e and an ADPe of 1.7E-02 kg Sb-e.

Table 5-2: Impact contribution per lifecycle stage and process

Lifecycle Stage	GWP	ADPe
	[kg CO2 eq.]	[kg Sb eq.]
A1 - Preproducts	128.74	1.73E-02
A1, Laptop	123.60	1.66E-02
A1, EPS	2.06	7.02E-04
A1, Packaging Downstream	2.65	1.46E-05
A1, Packaging Upstream	0.39	1.35E-06
A1, Screwdriver	0.04	1.73E-07
A2, Transports	0.44	2.61E-08
A3 - Assembly	3.19	1.35E-07
A3, Electricity	3.11	1.34E-07
A3, EoL Upstream Packaging	0.08	4.18E-10
A1-3 -Cradle to gate	132.37	1.73E-02
A4 - Transport to PoS*	18.93	1.16E-06
A5 - Installation at PoU*	0.05	2,42E-09
B6 - Usage	47.42	3,05E-0,6
C2 - Transport to EoL	0.01	7,24E-10
C3 - EoL	0.97	5,01E-08
A-C - Cradle to grave	199.75	1,73E-02

\* PoS = Point of Sale; PoU = Point of Use

The cradle-to-gate, meaning the manufacturing and raw material acquisition phase has the highest impact in both impact categories. Separating in the phases production, use, transport (over the whole life cycle) and end-of-life, the results are displayed in Figure 5-1 showing that especially the resource use is almost exclusively caused by the production phase. Use phase follows in its relative contribution, although this is only a relevant order of magnitude for GWP. For EoL, only impacts were considered and no credits for recycling were given, so this phase also has a small contribution. Transport has a smaller impact, mainly caused by the distribution (A4) and less by transports during the manufacturing phase (A2) or to EoL treatment (C2).



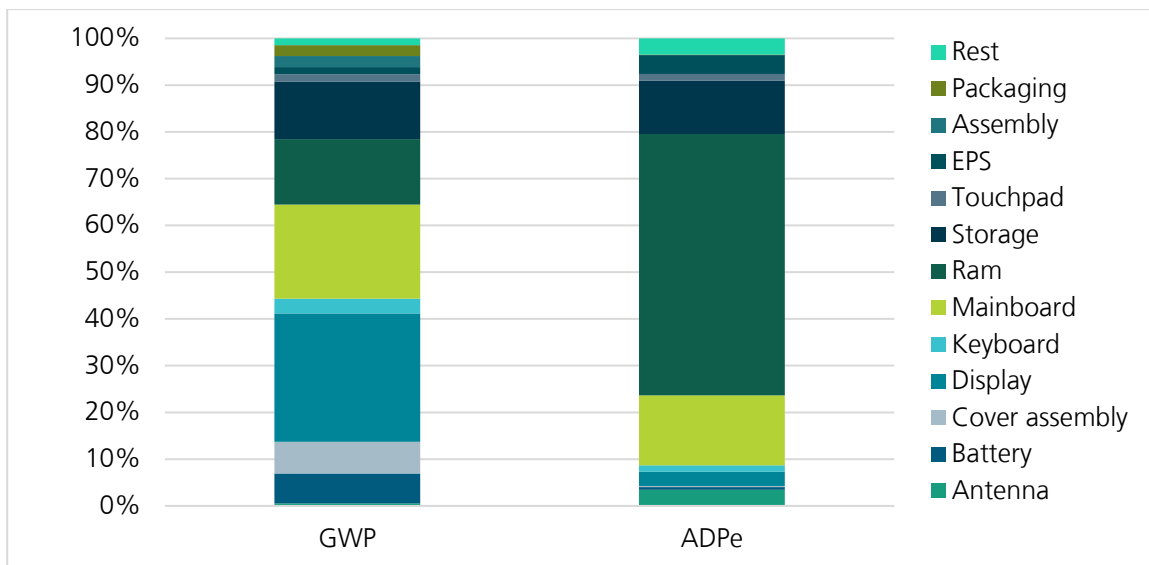
Figure 5-1: Relative impact of life cycle phase to the total impact per impact category



## 5.2 Indicators for Impact Assessment per components and modules

The relative impact of the production (A1, A3) is displayed in the following Figure 5-2 (rest includes all modules with an individual contribution <1.5% in both impact categories). The highest contribution to the GWP has the display module, whereas the ADPe is mainly influenced by the RAM (and thereby by the assumed amount of gold on the connector of the RAM bar). Mainboard and storage have also a significant impact in both impact categories.

Figure 5-2: Relative impact per module to the production phase



The absolute impact per module is displayed in Table 5-3.

Table 5-3: Absolute impact per module

Module	GWP [kg CO <sub>2</sub> e]	ADPe [kg Sb-e]
Antenna	0.69	5.96E-04
Audio jack	0.22	7.24E-05
Battery	8.46	1.06E-04
Cover assembly	8.93	3.74E-05
Display	36.20	5.30E-04
EC USB-A	0.19	1.09E-04
EC USB-C	0.21	1.91E-04
Fingerprint module	0.17	2.87E-05
Keyboard	4.14	2,36E-04
Mainboard	26.57	2.60E-03
Ram	18.44	9,69E-03
Speaker	0,15	7.54E-06
Storage	16.28	1.98E-03
Touchpad	2.01	2.44E-04
WiFi module	0.93	1.93E-04
EPS	2.06	7.02E-04
Assembly	3.11	1.34E-07
Packaging	3.04	1.59E-05
Screwdriver	0.04	1.73E-07

### 5.2.1 Display

The LCIA shows that the final global warming emissions of the raw material acquisition and production of the display amount to 35.91 kg CO<sub>2</sub>-eq. Of these, a total of 32.65 kg CO<sub>2</sub>-eq. can be attributed to the display panel. Detailed results for the different impact categories and components of the display are shown in Table 5-4.

Table 5-4: LCA Results of the Display

Impact category	Production total	Display backlight	Display cable	Display holder	Display panel	Display PCB
GWP 100 years [kg CO2 eq.]	35.91	1.46	0.02	0.15	32.65	1.64
ADP elements [kg Sb eq.]	5.29E-04	6.20E-05	1.61E-05	1.52E-08	1.51E-04	3.00E-04

Figure 5-3 shows the distribution of impact on the GWP-category across the Display module. As can be seen, the Display panel contributes by far the most to the GWP-category with a share of over 90%. The PCB and the backlight of the display make up around 4% each, the other components are negligible.

Figure 5-3: Contributions to GWP impact during the production phase of the display

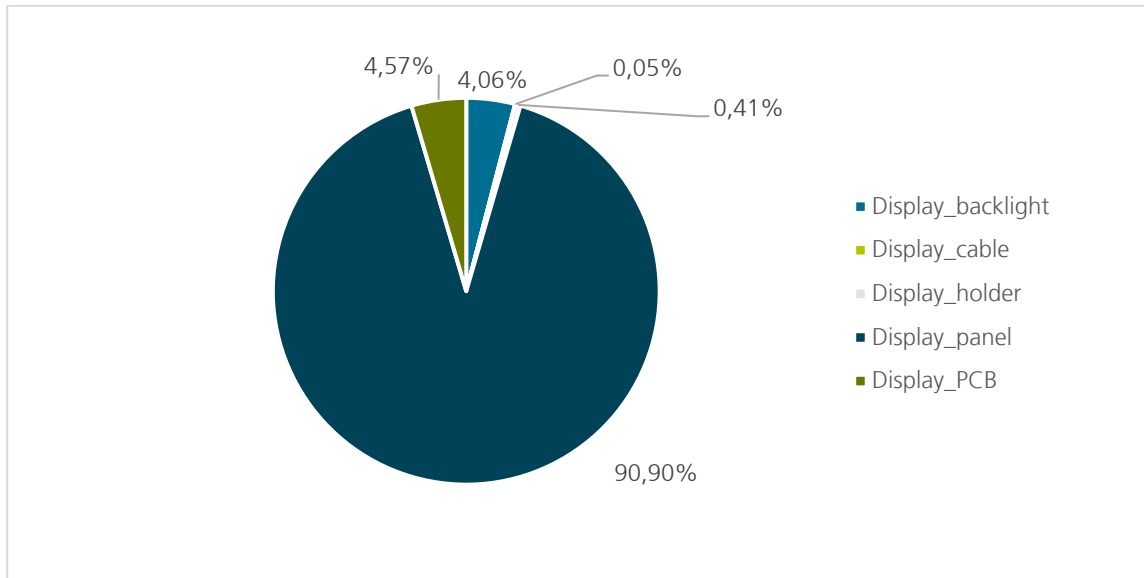
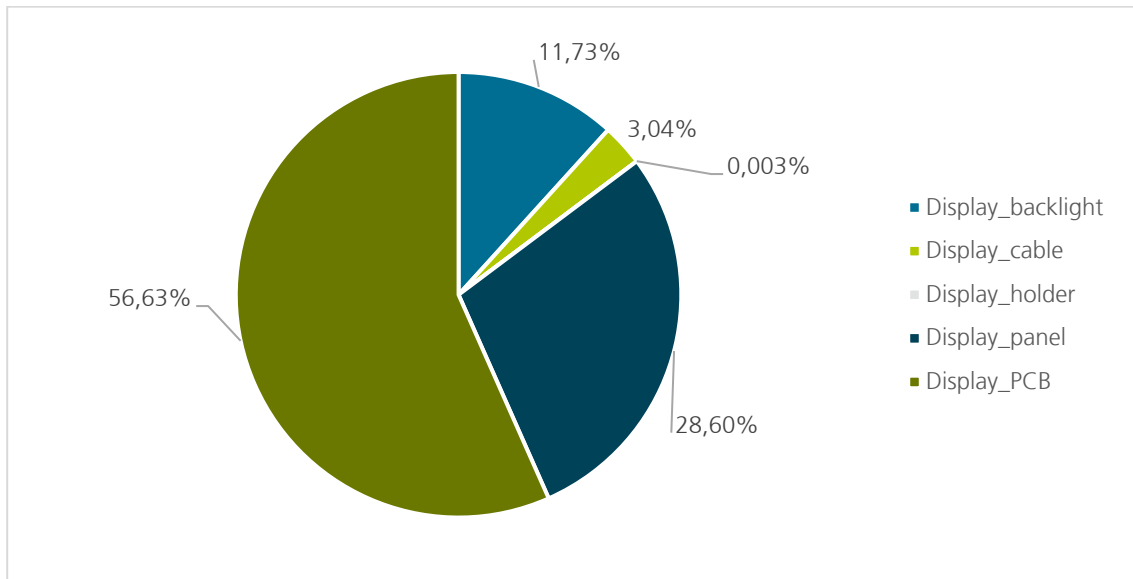


Figure 5-4 shows the distribution of impact on the GWP-category across the Display module. The PCB is the main contributor for the ADPe category with a share of 56%. The panel is the second-largest contributor with a share of 28.5%, followed by the backlight (11.7%).

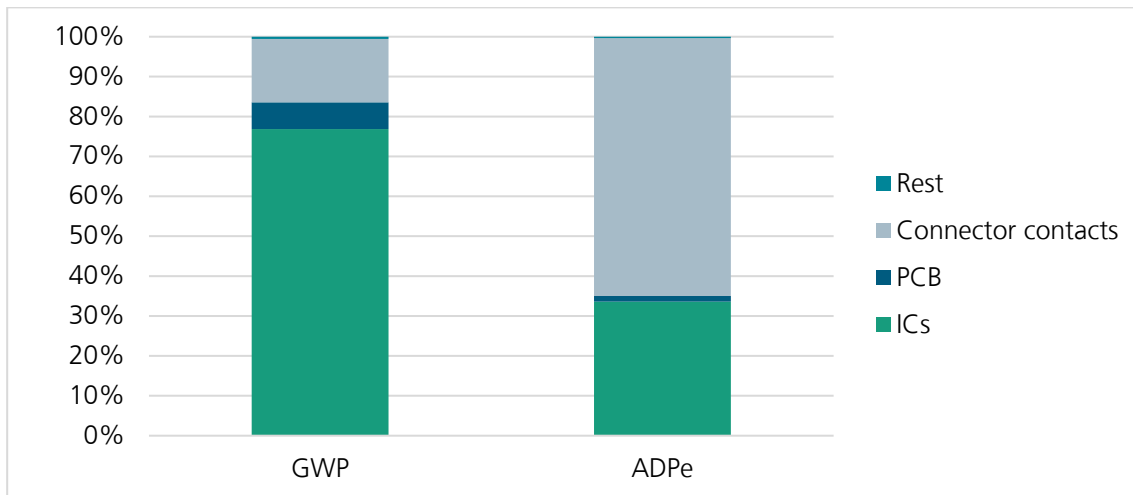
Figure 5-4: Contributions to ADPe impact during the production phase of the display



### 5.2.2 RAM

The RAM bar has the highest contribution to the ADPe with more than 58% of the overall production impact and about 14% contribution to the GWP production impact. The ADPe impact is thereby mostly caused by the connector material, mainly the gold on the edge of the RAM bar. The GWP impact is determined by the memory ICs themselves (see Figure 5-5).

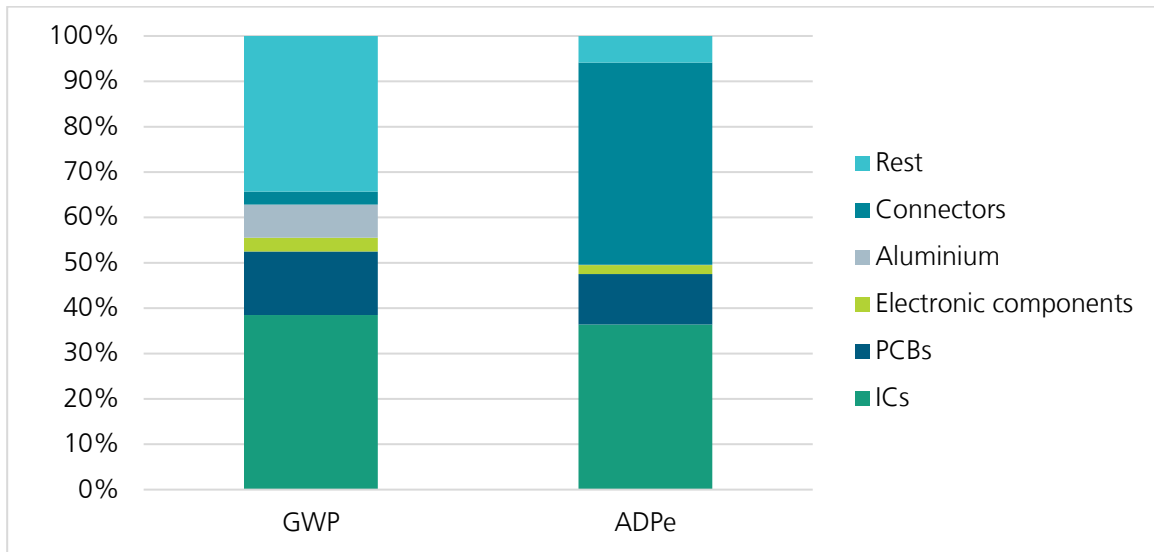
Figure 5-5: Relative impact to the RAM module



### 5.2.3 Cross module impacts

The impact of individual component and material types across modules are displayed in Figure 5-6 (electronic components refers to passive and active components on the printed circuit boards excl. ICs), ICs cause the highest contribution to GWP, followed by the PCBs. The ADPe is mainly caused by the connectors, followed by the ICs. Other electronic components have a small impact below 3% in both impact categories.

Figure 5-6: Relative impact of component types across modules



## 6 Life cycle interpretation and sensitivity analysis

Due to variations in the methodological approaches and data (assumptions, dataset choice, etc.), direct comparison between LCA results should be done with care. Nevertheless, comparison is still a valuable tool to review the methodology and modelling assumptions used. At 199 kg CO<sub>2</sub>e, the absolute impact of the Framework Laptop, as well as the distribution across lifecycle stages, is comparable to other laptop LCAs with similar memory and display sizes (Apple 2022; ASUS 2021 & 2022). Some LCAs do, however, yield significantly higher impact values (Dell 2023; HP 2021; Lenovo 2022). It has to be noted, though, that all of these assessments use a streamlined LCA-approach called “Product Attribute to Impact Algorithm” (PAIA). Larger differences in the overall impact results are therefore most likely due to differences in methodology and data sources rather than differences in the products themselves. PAIA-estimations include an uncertainty range for their results and the absolute impact of the Framework laptop is within, or very close to, the lower bound of this range for all LCAs considered. PAIA appears to attribute a larger overall impact to the production of electronic components than other methodologies, but no further conclusions can be drawn without deeper insight into the algorithm.

Impact categories other than GWP are more difficult to compare as they are not addressed in many other studies.

The results and contribution analysis show that the display module, mainboard, RAM and storage cause the main environmental impact. This is in line with the other laptop LCAs, though the proportions differ slightly from case to case.

### 6.1 Differences between LCA indicators

Impact hotspots for different LCA indicators may vary due to the different impact areas they illustrate. In this LCA, ICs are a large contributor for both, GWP and ADPe indicator. The gold connectors for RAM and storage module, on the other hand, contribute largely to the ADPe due to their high precious metal content, but contribute very little to the GWP value.

Regarding data quality, both analysed impact categories are fully covered by the used Sphera LCA FE and ecoinvent datasets. An exemption here is the display panel. As no suitable display data was available, the display was modelled based on environmental reporting by AUO as described in section 4.5.2.6. The corporate environmental reporting is very much focused on greenhouse gas (GHG) reporting and therefore does not specifically address the use and consumption of metals and other resources relevant to the ADPe impact category. The modeling has attempted to address and cover ADPe as best as possible, e.g. by including Scope 2 emissions not only as GHG emissions, but via Sphera LCA FE data sets for the corresponding energy and electricity generation, which covers ADPe as well. However, ADPe for the display panel (but not the other parts of the display) may be under-represented by this approach.

### 6.2 Integrated Circuits

ICs are the largest contributor to the overall GWP impact of the laptop and the second largest contributor to its ADPe. Modelling of the ICs therefore needs to be carefully evaluated. ICs are, however, also an area where up-to-date LCA data is scarce and technology advances fast.

The die size is an important determinant of the life cycle impact of an IC, so modelling the IC based on the die size is the method of choice. X-ray and grinding methods have been used to determine die size. Modelling results are most accurate when an appropriate data set is selected and the die size is adjusted. However, in many cases this was not possible, which affects the reliability of the results.

### 6.2.1 Storage ICs

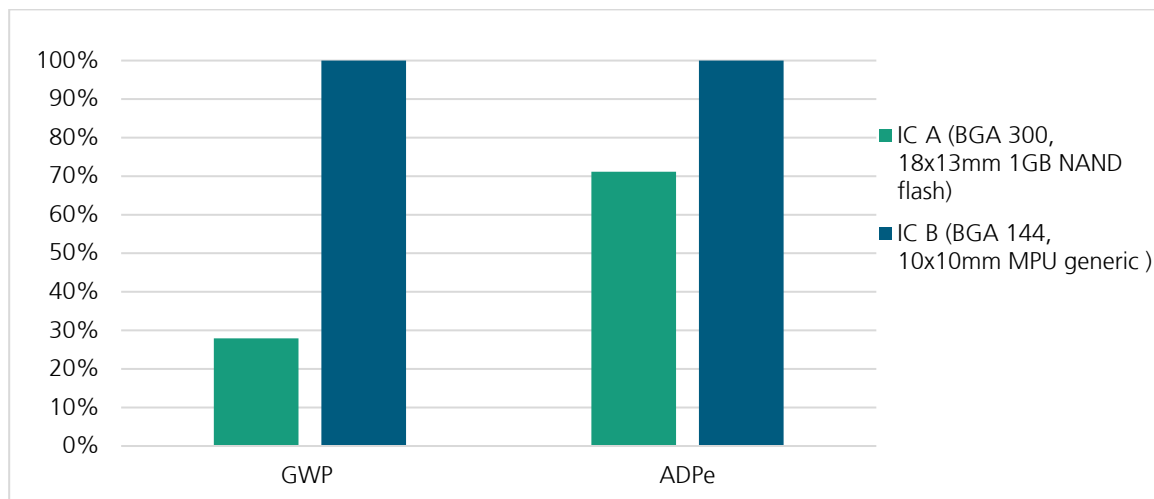
As mentioned above, in this study, the die size of the main ICs such as the memory ICs of the RAM bar and the memory module were identified to model them accordingly. However, the die size is not documented for all LCA FE IC datasets. Thus, these datasets could only be applied based on package size (or weight, which is not applicable for ICs).

Therefore, there were two options for the memory module: model the flash IC with a NAND flash IC dataset, which scales less accurately with package size, or use a more generic chip type (MPU<sup>22</sup>) which scales specifically with the measured die size. The latter approach was chosen for the overall LCA result.

In Figure 6-1 a comparison is given for two methods of modelling the main storage flash ICs. Dataset *IC B* was used in this model for the storage ICs. It is less suitable in type, but the die size was scaled according to the grinding measurements and it is suitable in package type. *IC A* is more suitable in type for the storage module, but since no die size was given for the data set, scaling was only possible according to package size. As can be seen, the differences in result are significant. As there is often, especially in highly complex BGAs, little correlation between package and die size, it seems best to scale datasets according to die size (Billaud et al. 2023). Other sources also state die-to-package-ratios of 30% to 80% to be on the market and found in lab testing for NAND flash chips in 2019, significantly impacting the final results (Thinkstep, 2019).

Some packages may, however, have specific characteristics that make them less suitable for substitutions (see section 6.2.2).

Figure 6-1: GWP and ADPe comparison of two different IC datasets from the LCA FE database for the storage module



### 6.2.2 RAM ICs

Another problem with the limited availability of IC datasets is that the most appropriate dataset for the function may be in a different package type. This was the case for the RAM bar. There were also

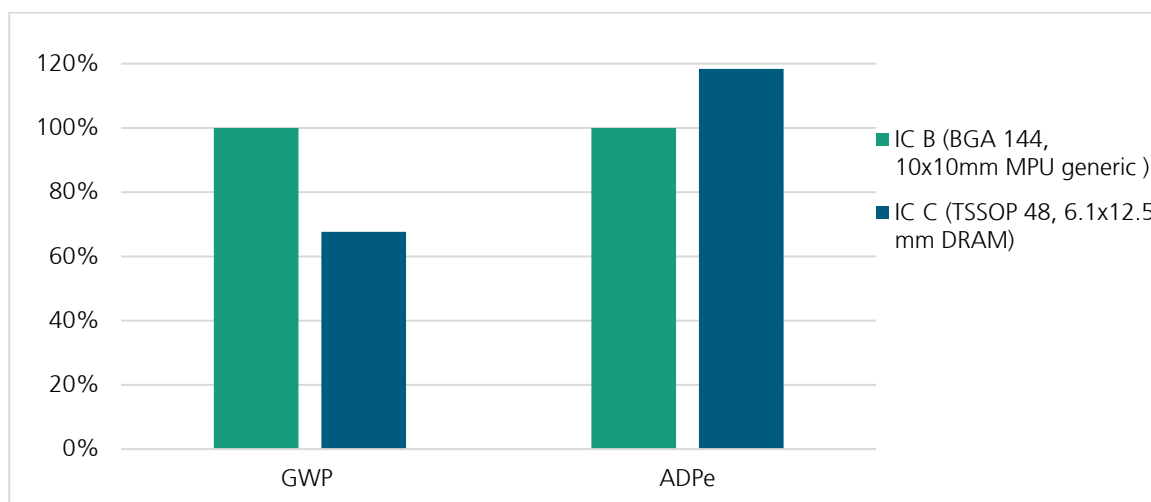
<sup>22</sup> Sphera data set documentation: „The MPU process technology reflects a device at the 130 nm CMOS generation with both logic and on-chip memory, which is representative of a generic microprocessor unit.“, online: <https://sphera.com/2023/xml-data/processes/e83c9bb2-85b9-4d3a-a19f-3d47f400b1e4.xml>

two options: model the RAM with a DRAM IC dataset of a different package type (TSSOP<sup>23</sup>), scaled by die size, or applying a more generic chip type (MPU) scaling specifically by measured die size. For the overall result of the LCA, the latter approach was chosen.

In Figure 6-2 a comparison is given for two methods of modelling the RAM ICs. The values given are for the total die/package size of this IC on the RAM module. Dataset *IC B* was used in this model. It is of the correct package type, but less suitable in type. But die size could be scaled according to the grinding measurements. *IC C* was scaled according to die size. It is most suitable in function for the RAM bar, but of a different package type.

As can be seen in Figure 6-2 the ADPe-values are much higher for the TSSOP package, possibly due to a larger gold-content in the package. The generic BGA-dataset was therefore chosen instead of the DRAM TSSOP dataset for the RAM ICs.

Figure 6-2: GWP and ADPe comparison of two different IC datasets from the LCA FE database for the RAM bar



### 6.2.3 Processor modelling

The GWP of the processor is estimated to be 5.19 kg CO<sub>2</sub>e based on modelling with Sphera LCA FE. However, due to innovation pace and complex processes up-to-date IC data is crucial but scarce. Imec publishes carbon footprint data for newer technology nodes compared to Sphera LCA FE. However, this data is not directly applicable in LCAs as it covers on only the impact category GWP and (more importantly) does not address the whole packaged IC, but only front-end processes of the IC manufacturing. Nevertheless, the data is used for qualitative comparison.

Data from this IC modelling tool (imec.netzero) is shown in Figure 6-3 for a die of the size of 225 mm<sup>2</sup> manufactured in different technology nodes. The energy mix assumed is for Taiwan<sup>24</sup>. The data is modeling data that is not based on a specific product, but the tool is used by manufacturers to assess their environmental impact. The yield for the data points in Figure 6-3 was set to 70% to portray a worst-case-scenario.

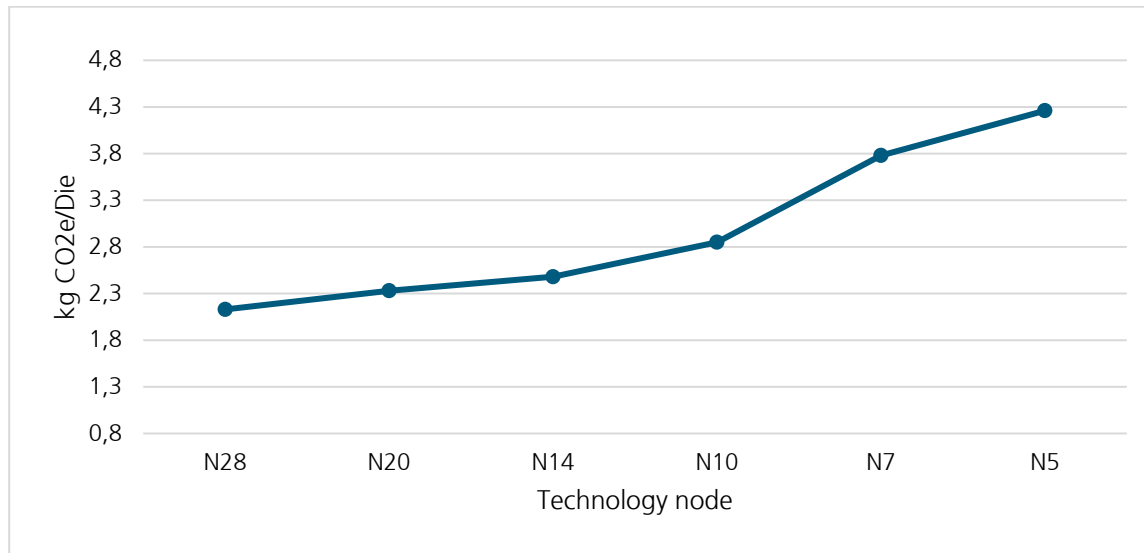
<sup>23</sup> Sphera data set documentation: „IC TSSOP 48 (187mg) 6.1x12.5 mm DRAM (57 nm node).“, online: [Process data set: IC TSSOP 48 \(187mg\) 6.1x12.5 mm DRAM \(57 nm node\); front-end and back-end processing of the wafer, including Czochralski method of silicon growing; production mix, at plant; \(187mg\) 6.1x12.5 mm DRAM \(57 nm node\)\(en\) \(sphera.com\)](https://www.sphera.com/process-data-set-ic-tssop-48-187mg-6.1x12.5-mm-dram-57-nm-node-front-end-and-back-end-processing-of-the-wafer-including-czochralski-method-of-silicon-growing-production-mix-at-plant-187mg-6.1x12.5-mm-dram-57-nm-node-en)

<sup>24</sup> <https://netzero.imec-int.com/>



The processor of the Framework Laptop was manufactured with a 10 nm node, which IMEC lists as having a GWP of 2.85 kg CO<sub>2</sub>e. Assuming an overhead of 30 to 50% for packaging, the IMEC data is still lower than the LCA FE data for the IC in question<sup>25</sup>.

Figure 6-3: GWP of a die (225mm<sup>2</sup>) for different technology nodes<sup>26</sup>



Additionally it is interesting to see the differences in GWP of different technology nodes for the manufacturing of a die of the same size. Newer technologies need additional process steps causing higher GWP per produced area (with more transistors on the same area). Pirson et al. conducted a comprehensive literature research of 27 different studies on this topic. The results of their analysis “highlight a clear increasing trend of the environmental footprint with CMOS technology downscaling below 0.13 μm, despite a significant variation between the sources mainly due to scope mismatch.” Additionally, they “show that environmental impacts per cm<sup>2</sup> did not significantly decrease compared to historical values from 1980–2010 [...]” (Pirson, 2022; p.1). This highlights the need for up-to-date lifecycle data on ICs is to produce accurate LCA results.

### 6.3 Display

The display module has a large effect on the overall GWP value of the laptop with a total of 36.2 kg CO<sub>2</sub>e. Due to a lack of primary data and datasets in the database, the display panel was modelled based on AUO environmental data.

When comparing the results of the display modelling for the Framework Laptop to other laptop LCAs the same effect as for the absolute environmental impact can be observed. The results are in line with some other LCAs, but are much lower than the results for display modules assessed via the PAIA method: LCAs of the ASUS laptops under consideration state a GWP value of 25.8 and 30.6 kg CO<sub>2</sub>e for the respective displays (ASUS 2021 & 2022). The LCA of the Lenovo and Dell laptop under consideration, which were conducted using PAIA, state a value of 67 and 118.8 kg CO<sub>2</sub>e respectively for the displays (Lenovo 2022; Dell 2023). Larger differences in the results are therefore again most likely due to differences in methodology rather than differences in the products themselves.

All laptops mentioned contain a 13.5- or 14-inch display.

<sup>25</sup> 30% overhead would lead to a total GWP of 3,705 kgCO<sub>2</sub>e/die, 50% to 4,275 kgCO<sub>2</sub>e/die.

<sup>26</sup> Data retrieved from <https://netzero.imec-int.com/> on 13.09.2023

## 6.4 Connectors

The RAM and storage connectors largely influence the overall ADPe results due to the rather large amount of gold used in the contacts. Due to a lack of primary data, the area of the gold contacts was measured using a microscope and assumptions on the coating thickness was taken from literature. These gold contacts are, however, rather standard in these modules and coating thickness is well documented. The assumptions the model was based on therefore seem plausible. However, the overall ADPe result is sensitive to the assumed coating thickness. Varying the assumed coating thickness (and thereby assumed amount of gold and nickel) by 20%, changes the overall ADP of the production phase by about 8%, but the GWP only by about 0.5% (see Figure 6-4 and Figure 6-5).

Figure 6-4: Impact of the assumed contact thickness of the RAM bar on the overall production phase - GWP

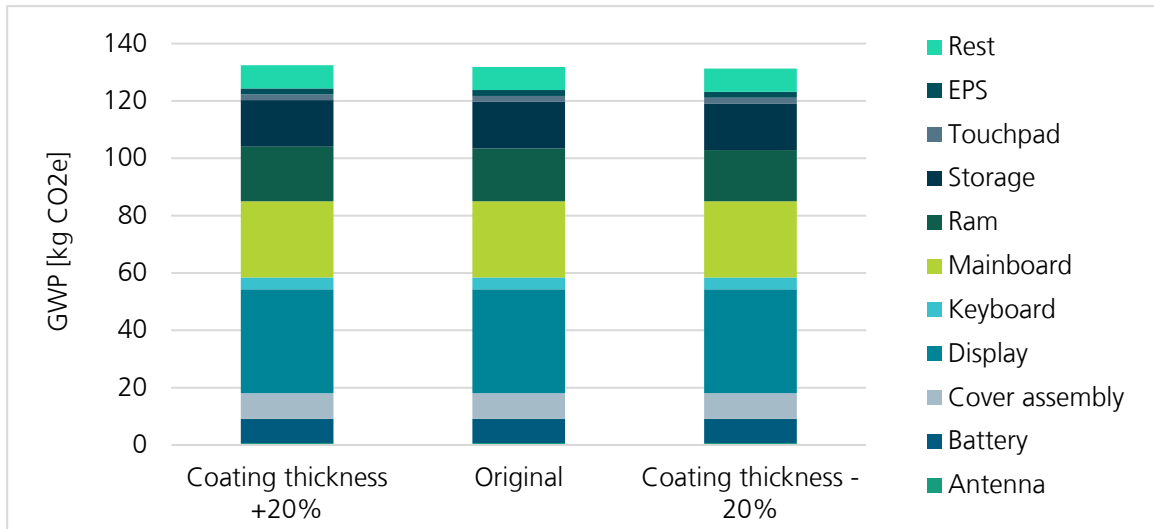
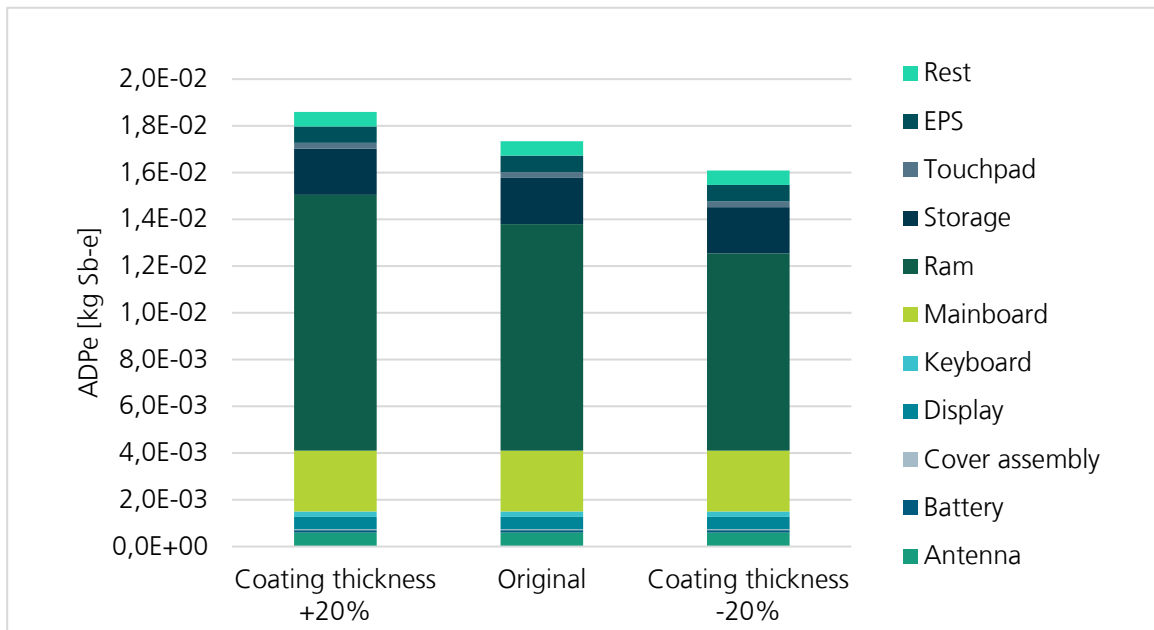


Figure 6-5: Impact of the assumed contact thickness of the RAM bar on the overall production phase - ADPe



## 7 Conclusions

The results of the LCA show that electronics and thereby the ICs as such cause the main global warming potential. Therefore, the functionality and performance parameter determine the overall impact much more strongly than the overall design. Although, of course (display) size and housing material also influence the impact, but to a smaller degree.

For ADPe, it was shown that the connector material is very important as it is a critical factor in the modular design. A direct comparison between directly soldered memory and storage compared to exchangeable modules was not carried out in this study, but might be interesting regarding ADPe. However, good need-fitting customization and possible repair and especially upgradability of functionality through the modular design is likely to be beneficial in term of service life extension.

It was shown, that up-to-date lifecycle data for electronics are crucial but scarce. Further (industry wide) data collection on semiconductors would help to improve the quality of LCA for electronics. On the specific level of the Framework Laptop, more primary data e.g. regarding electricity consumption of assembly, production layouts of PCBs or specific data from battery or display suppliers could help to improve data quality of the LCA and identify product specific eco-design options.

## 8 Appendix

### 8.1 Life cycle inventory

#### 8.1.1 Bill of material

Due to its scope and confidentiality, the bill of materials (BOM) is not publicly available as part of this report. The bill of materials contains important data for the LCI of the laptop and is provided as Appendix II. The BOM is for internal use only. Interested third parties can request further information directly from the contractor of this study.

Annex II Version number: [A2-FW-NB2022/IZM2023-1.0](#)

#### 8.1.2 Materials for component modelling

Table 8-1: Display panel manufacturing data by AuO [2021]

Input	Total	per m <sup>2</sup>
<b>Material</b>		
Glass substrate	91,769.86 tonnes	1.35E+00 kg/m <sup>2</sup>
liquid crystal	88.60 tonnes	1.30E-03 kg/m <sup>2</sup>
Photoresist	30,120.00 kiloliters	4.43E-02 l/m <sup>2</sup>
Array stripper Usage	57,758.00 tonnes	8.49E-01 kg/m <sup>2</sup>
CF Thinner	1,957.00 tonnes	2.88E-02 kg/m <sup>2</sup>
Developer	11,385.00 tonnes	1.67E-01 kg/m <sup>2</sup>
Aluminium Etchant	8,251.00 kiloliters	1.21E-01 l/m <sup>2</sup>
PFC Usage	1,185.91 tonnes	1.74E-02 kg/m <sup>2</sup>
<b>Energy</b>		
total consumed	19,056,414.56 GJ	2.80E+05 kJ/m <sup>2</sup>
Purchased Electricity	18,264,773.14 GJ	2.69E+05 kJ/m <sup>2</sup>
Natural Gas	668,187.88 GJ	9.83E+03 kJ/m <sup>2</sup>
LPG	26,717.99 GJ	3.93E+02 kJ/m <sup>2</sup>
Diesel	76,490.01 GJ	1.12E+03 kJ/m <sup>2</sup>
Gasoline	774,01 GJ	1.14E+01 kJ/m <sup>2</sup>
self-generated solar power	19,471.54 GJ	2.86E+02 kJ/m <sup>2</sup>
Wind power	0.00 GJ	0.00E+00 kJ/m <sup>2</sup>
<b>Water</b>		
total	24,991.78 megaliters	3.68E+02 l/m <sup>2</sup>

Input	Total	per m <sup>2</sup>
<b>Emissions</b>		
scope 1	79,200.00 tonnes CO <sub>2</sub>	1.16E+00 kg CO <sub>2</sub> /m <sup>2</sup>
scope 2	2,841,200.00 tonnes CO <sub>2</sub>	4.18E+01 kg CO <sub>2</sub> /m <sup>2</sup>
scope 3	1,286,100.00 tonnes CO <sub>2</sub>	1.89E+01 kg CO <sub>2</sub> /m <sup>2</sup>
ODS emissions	0.07 tonnes	1.00E-06 kg/m <sup>2</sup>
SO <sub>x</sub>	49.96 tonnes	7.35E-04 kg/m <sup>2</sup>
NO <sub>x</sub>	72.52 tonnes	1.07E-03 kg/m <sup>2</sup>
Fluorides	0 tonnes	0 kg/m <sup>2</sup>
HCl <sub>4</sub>	0 tonnes	0 kg/m <sup>2</sup>
Volatile organic compounds (VOC)	168.46 tonnes	2.48E-03 kg/m <sup>2</sup>
Wastewater	17,280.86 megaliters	2.54E+02 l/m <sup>2</sup>
COD	574.25 tonnes	8.05E-03 kg/m <sup>2</sup>
Biochemical oxygen demand (BOD)	56.04 tonnes	8.24E-04 kg/m <sup>2</sup>
total suspended solids	111.66 tonnes	1.64E-03 kg/m <sup>2</sup>
hazardous waste	18,099.85 tonnes	2.66E-01 kg/m <sup>2</sup>
non-hazardous waste	64,554.67 tonnes	9.49E-01 kg/m <sup>2</sup>

### 8.1.3 Foreground processes and mapped background datasets

Due to its scope the mapped foreground processes and used background datasets can be found in a separate Annex I: Background data on LCA-processes and background data, which displays the nested LCA models per column and used datasets.

Annex I Version number: [A1-FW-NB2022/IZM2023-1.0](#)

## 8.2 Life cycle impact assessment

### 8.2.1 Indicators according to PEF

Table 8-2 gives an overview of the LCA results aggregated for each lifecycle module and for all core LCA impact categories required for reporting according to the latest recommendation on the use of the Environmental Footprint methods by the European Commission in December 2021.<sup>27</sup> The LCA model uses background data from different LCIA databases, which may lead to inconsistencies and influence the impact indicators (Pauer et al., 2020).

<sup>27</sup> <https://environment.ec.europa.eu/system/files/2021-12/Annexes%201%20to%202.pdf>

Table 8-2: Results of the LCA - Indicators according to PEF

LCA Impact Assessment Framework Laptop 2022   EF 3.1												
Indicator	Unit	A1	A2	A3	A1-A3	A4	A5	B6	C1	C2	C3	C4
<b>GWP Total</b>	[kg CO <sub>2</sub> -Äq.]	1.29E+02	4.39E-01	3.19E+00	1.32E+02	1.89E+01	5.02E-02	4.74E+01	0.00E+00	1.11E-02	9.74E-01	0.00E+00
<b>GWP-fossil</b>	[kg CO <sub>2</sub> -Äq.]	1.28E+02	4.35E-01	3.19E+00	1.32E+02	1.89E+01	4.99E-02	4.74E+01	0.00E+00	1.10E-02	9.74E-01	0.00E+00
<b>GWP-biogenic</b>	[kg CO <sub>2</sub> -Äq.]	3.26E-01	1.08E-03	2.90E-04	3.27E-01	4.14E-03	1.53E-04	2.75E-02	0.00E+00	2.93E-05	4.74E-05	0.00E+00
<b>GWP-luluc</b>	[kg CO <sub>2</sub> -Äq.]	1.14E-01	3.60E-03	1.96E-03	1.20E-01	2.43E-03	9.79E-05	3.00E-03	0.00E+00	1.01E-04	8.27E-06	0.00E+00
<b>ODP</b>	[kg CFC11-Äq.]	3.46E-06	5.36E-14	1.42E-11	3.46E-06	1.62E-12	1.97E-13	2.34E-10	0.00E+00	1.42E-15	1.49E-09	0.00E+00
<b>AP</b>	[kg SO <sub>2</sub> -Äq.]	8.63E-01	3.18E-03	1.51E-02	8.81E-01	7.39E-02	5.43E-04	9.10E-02	0.00E+00	6.39E-05	3.09E-04	0.00E+00
<b>EP-freshwater</b>	[kg PO <sub>4</sub> -Eq.]	1.46E-02	1.43E-06	1.37E-06	1.47E-02	3.41E-06	9.64E-08	2.85E-05	0.00E+00	3.99E-08	7.53E-06	0.00E+00
<b>EP-marine</b>	[kg N-Eq.]	1.23E-01	1.39E-03	2.40E-03	1.26E-01	3.24E-02	1.86E-04	1.50E-02	0.00E+00	2.98E-05	1.73E-04	0.00E+00
<b>EP-terrestrial</b>	[mol N-Eq.]	1.33E+00	1.54E-02	2.61E-02	1.38E+00	3.54E-01	2.29E-03	1.62E-01	0.00E+00	3.31E-04	1.39E-03	0.00E+00
<b>EcoTox</b>	[CTUe]	1.00E+03	4.18E+00	4.64E+00	1.01E+03	2.12E+02	3.04E-01	2.21E+02	1.00E+00	1.07E-01	9.43E+00	1.00E+00
<b>HT-c</b>	[CTUh]	1.98E-07	8.40E-11	6.33E-10	1.98E-07	3.24E-09	1.51E-11	6.32E-09	2.00E+00	2.16E-12	1.23E-10	2.00E+00
<b>HT-nc</b>	[CTUh]	1.57E-06	3.65E-09	1.07E-08	1.58E-06	6.22E-08	4.12E-10	1.12E-07	3.00E+00	9.62E-11	2.13E-08	3.00E+00
<b>IR</b>	[kBq U235 eq.]	9.65E+00	1.57E-03	4.98E-02	9.71E+00	4.53E-02	4.27E-03	6.58E+00	4.00E+00	4.17E-05	6.52E-03	4.00E+00
<b>PM</b>	[Disease incidences]	9.18E-06	3.17E-08	1.52E-07	9.36E-06	2.23E-07	2.62E-09	6.25E-07	5.00E+00	2.46E-10	1.51E-09	5.00E+00
<b>POCP</b>	[kg Ethen Äq.]	3.54E-01	3.01E-03	7.10E-03	3.64E-01	8.78E-02	4.75E-04	4.28E-02	0.00E+00	5.83E-05	3.38E-04	0.00E+00
<b>ADPF</b>	[MJ]	1.56E+03	5.81E+00	3.10E+01	1.60E+03	2.49E+02	5.59E-01	5.86E+02	0.00E+00	1.48E-01	7.31E-01	0.00E+00
<b>ADPE</b>	[kg Sb Äq.]	1.73E-02	2.61E-08	1.35E-07	1.73E-02	1.16E-06	2.42E-09	3.05E-06	0.00E+00	7.24E-10	5.01E-08	0.00E+00
<b>Land use</b>	[Pt]	4.31E+02	2.21E+00	4.16E+00	4.37E+02	2.16E+00	2.01E-01	7.90E+01	1.00E+00	6.21E-02	1.24E-01	1.00E+00
<b>WDP</b>	[m <sup>3</sup> world-Eq]	3.93E+01	4.76E-03	1.01E+00	4.03E+01	7.24E-02	1.98E-01	1.08E+01	0.00E+00	1.32E-04	3.27E-02	0.00E+00
<b>Caption</b>	GWP = Global warming potential; ODP = Depletion potential of the stratospheric ozone layer; AP = Acidification potential of land and water; EP = Eutrophication potential; EcoTox = Ecotoxicity; HT-c = Human toxicity, cancer; HT-nc = Human toxicity, non-cancer; IR = Ionising radiation; PM = Particulate matter; POCP = Formation potential of tropospheric ozone photochemical oxidants; ADPE = Abiotic depletion potential for non-fossil resources; ADPF = Abiotic depletion potential for fossil resources; WDP = Water (user) deprivation potential											

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