# OPTIMIZATION OF A SUSTAINABLE ULTRA-LOW NOISE MICROWAVE AMPLIFIER FOR A PLANETARY SPACE PROBE BASED ON R9-STRATEGIES

Lappeenranta–Lahti University of Technology LUT

Bachelor’s Programme in Mechanical Engineering, Bachelor's thesis

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Examiner(s): Docent Tapio Saarelainen

Professor Xinyu Jia

ABSTRACT

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Mechanical Engineering

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This thesis investigates the environmental impact of three aluminium alloys—AA6082, AA6061, and AA7075—used in the design and production of ultra-low noise amplifiers (LNAs) for planetary space probes. With sustainability becoming a critical criterion in space missions, this study applies a triangulated methodology comprising a Life Cycle Assessment (LCA) via SolidWorks Sustainability software, a systematic literature review, and expert interviews to evaluate and compare the environmental profiles of these alloys. AA6082 emerged as the most sustainable option according to literature due to its high recycled content and low dependence on primary extraction. However, SolidWorks simulations inaccurately ranked it as the least sustainable, likely due to database limitations and manual data entry issues. AA6061 was shown to perform well across multiple impact categories, especially in air acidification potential, while AA7075, although mechanically superior, posed higher environmental burdens unless recycled. The study also examined circular economy principles by analysing R-strategies, identifying "Reduce," "Rethink," and "Reuse" as most applicable to LNA design. Despite the limited scope of the LCA and expert consultation, the convergence of data from multiple sources enhances the reliability of the conclusions. The findings underscore the importance of early-stage material selection, improved simulation tools, and circular design thinking in reducing the environmental footprint of space electronics. Recommendations are made for future research, including enhanced LCA databases and end-of-life modelling for off-planet components.

# SYMBOLS AND ABBREVIATIONS

## Abbreviations

| | |
|---|---|
| EOL | End of Life |
| FET | Field Effect Transistor |
| GaAs | Gallium Arsenide |
| HEMT | High Electron Mobility Transistor |
| ISO | International Organization for Standardization |
| LCA | Life-Cycle Analysis |
| MW/RF | Microwave/Radio Frequency |
| RoHS | Restriction of the Use of Hazardous Substances |
| UWB | Ultra-Wideband |
| WEEE | Waste Electrical and Electronic Equipment |

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# 1. Introduction

Current amplifier designs often rely on materials and manufacturing techniques that have a significant environmental impact, such as the use of rare materials and energy-intensive fabrication processes. These practices contribute to resource depletion, environmental degradation, and increased carbon emissions. The optimal operation of ultra-low noise microwave amplifiers, particularly those used in space applications, requires coolers to maintain temperatures below -150°C, also known as cryogenic temperatures. These cooling systems consume substantial amounts of energy, further exacerbating their environmental footprint.

Sustainability in designs alludes to the use of sustainable theories in engineering and designing devices. To make alterations and make a device sustainable, it is easier to do it in the early stages, before the production phase (Honório et al., 2023). However, changing a material to one that seems to bring less pollution to the environment is not enough to make a product great, it also requires that the new material selected can perform in more than optimal conditions in the device manufactured. Space probes function in challenging conditions, requiring designs that tolerate intense temperatures and radiation. This involves employing space-certified technologies and ensuring that amplifiers are both reliable and consistent (Ciccognani et al., 2018).

Addressing these issues is crucial for the future of space exploration, where sustainability must be considered alongside performance.

Figure 1: Ultra-low noise microwave amplifier for planetary space probes.

## 1.1. Goals

- Assess, based on R-strategies, how well the product meets the principles of sustainable development and circular economy.
- Compiling proposals for mechanical engineering changes that could improve the overall environmental friendliness of ultra-low noise microwave amplifiers, considering both lifecycle thinking and circular economy perspectives.

## 1.2. Background

Previous studies have focused on improving the efficiency and noise performance of LNAs, with significant advancements in material engineering and cooling technologies. The choice of materials and transistor technology plays a critical role. High Electron Mobility Transistors (HEMTs) and Gallium Arsenide (GaAs) are commonly used due to their superior noise performance and reliability. However, these materials also impose design constraints that must be carefully managed. To enhance the sensitivity of receivers, in 1980 it was first proposed GaAs field effect transistor (FET) for radio astronomy (Bei-jun et al., 2022). GaAs is recognized as a carcinogenic material, and its production process produces considerable amounts of hazardous waste. During manufacturing, around 85% of a GaAs boule is wasted, typically being discarded in landfills as toxic material (Torrance, 2009). Thus, the need to find new materials that avoid the contamination of the environment while still manufacturing microwave amplifiers.

In spring 2024, a thesis was completed at LUT University on this MW/RF component, which preliminarily examined the tolerancing and material selection of the part. However, this thesis will focus on aspects of environmental friendliness and circular economy from the viewpoint of mechanical engineering.

## 1.3. Research problem and research question

Despite technological advancements, there remains a critical gap in understanding how LNAs can be designed with sustainable materials and more energy-efficient cooling solutions while maintaining optimal performance. This study aims to address these gaps by evaluating alternative materials and energy-efficient cooling methods that can minimize the environmental footprint of LNAs. The research question that emerges from this problem is then: Why do current ultra-low noise microwave amplifier designs have a significant environmental impact and how can they be optimized to minimize this impact while maintaining performance for planetary space probes?

# 2. Methodology

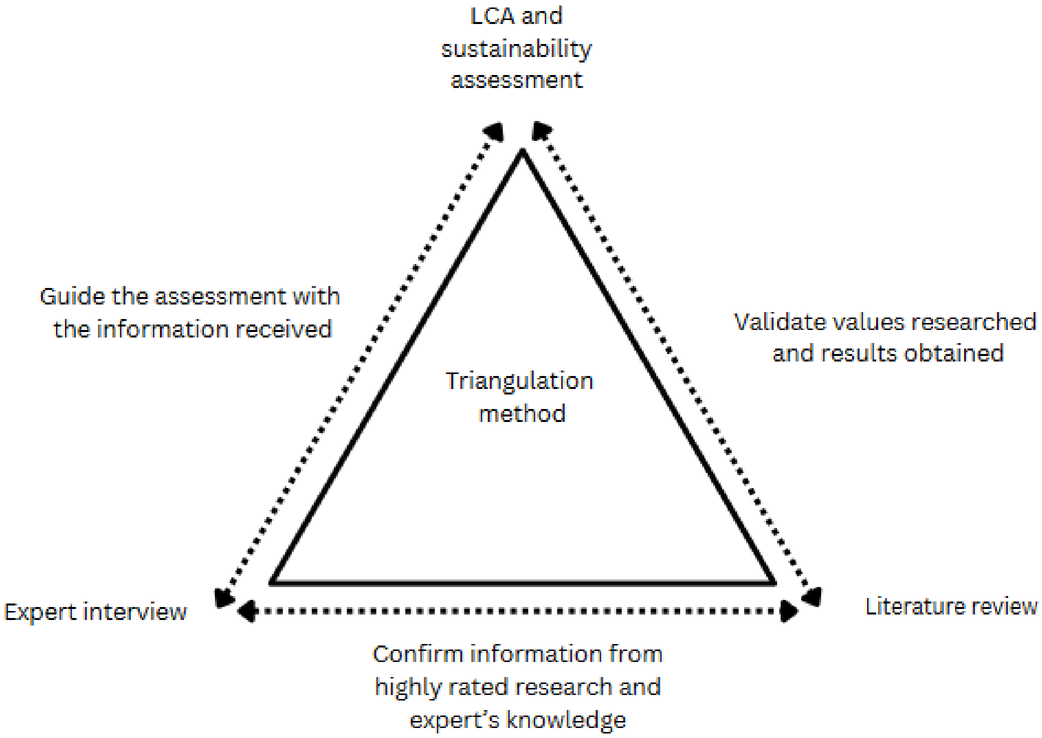
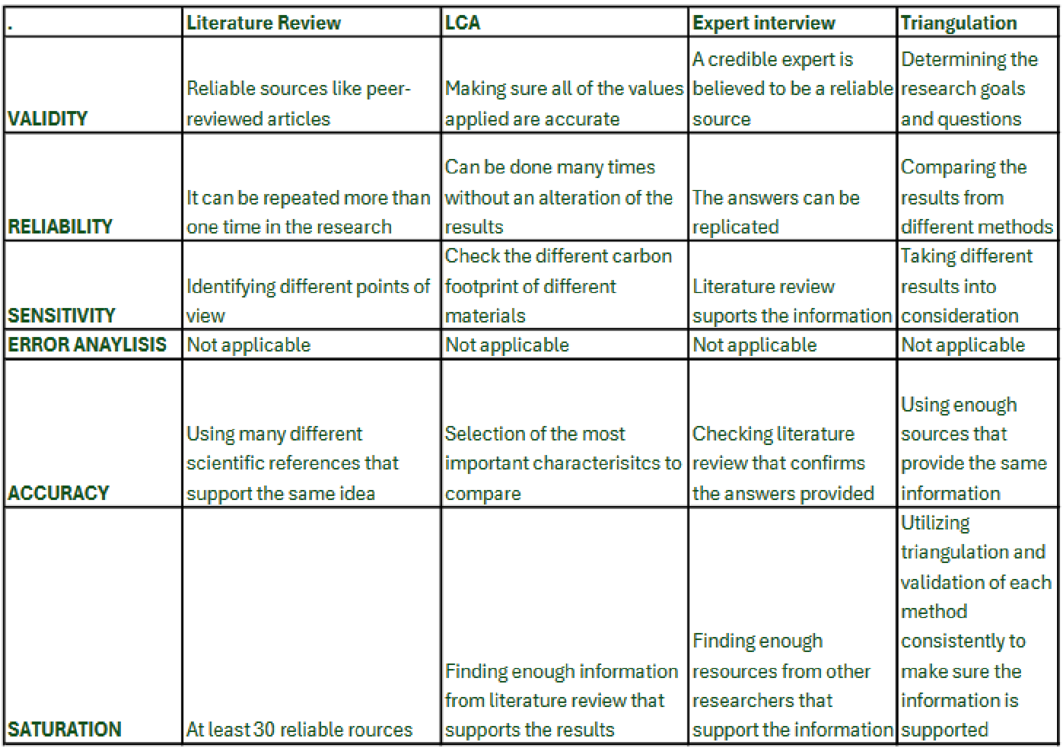


Figure 2: Triangulation method implemented on this research.

This study adopts a mixed-methods approach, combining quantitative and qualitative methods, and utilizes two complementary paradigms: the positivist paradigm and the interpretative paradigm. The positivist paradigm is applied to the design, simulation, and technical performance evaluation of the microwave amplifier, while the interpretative paradigm is used to understand expert perspectives and assess qualitative aspects related to sustainability and the implementation of R9 strategies. During this study, a triangulation in between literature review, Life-Cycle Analysis (LCA), and an expert interview can provide a clear understanding of the research problem and give a suitable answer to the main concern which is the environmental aspect involved in the production, usage and disposal of ultra-low noise microwave amplifiers in planetary space probes.

In this research, it is important to make sure the results found are valid and reliable. Table 1 below shows how each one of the methods is used to ensure the quality of the research.

Table 1. Reliability analysis table.



| . | Literature Review | LCA | Expert interview | Triangulation |
|---|---|---|---|---|
| **VALIDITY** | Reliable sources like peer-reviewed articles | Making sure all of the values applied are accurate | A credible expert is believed to be a reliable source | Determining the research goals and questions |
| **RELIABILITY** | It can be repeated more than one time in the research | Can be done many times without an alteration of the results | The answers can be replicated | Comparing the results from different methods |
| **SENSITIVITY** | Identifying different points of view | Check the different carbon footprint of different materials | Literature review suports the information | Taking different results into consideration |
| **ERROR ANAYLISIS** | Not applicable | Not applicable | Not applicable | Not applicable |
| **ACCURACY** | Using many different scientific references that support the same idea | Selection of the most important characterisitcs to compare | Checking literature review that confirms the answers provided | Using enough sources that provide the same information |
| **SATURATION** | At least 30 reliable rources | Finding enough information from literature review that supports the results | Finding enough resources from other researchers that support the information | Utilizing triangulation and validation of each method consistently to make sure the information is supported |

## 2.1. Literature review

Literature review is the most reliable part of the methodology. During this part of the research, the data collected is data provided by scientific and company databases. The information provided by other authors is considered reliable when the cross-references between authors and the confirmation by other research methods all go along and result in similar conclusions. The way this part of the research is conducted is presented in the diagram below.

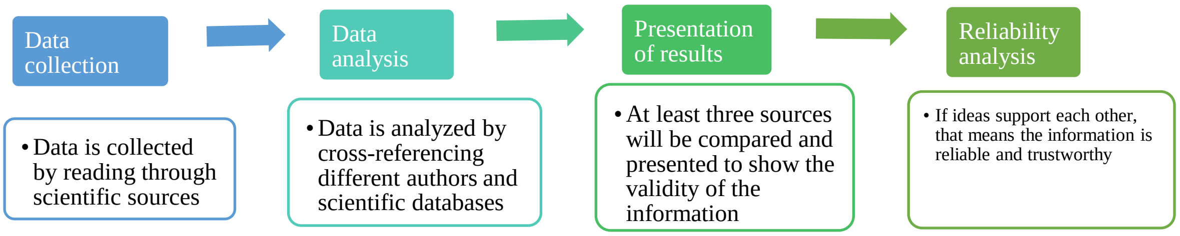


Figure 3: Flowchart for selection of sources for literature research.

Furthermore, the literature review helps to establish reference points for evaluating the environmental footprint and technical viability of alternative designs, forming the baseline against which LCA and expert insights are compared. This iterative process ensures that the study remains within proven scientific principles while allowing for the integration of new solutions.

For this part of the research, many different references were considered to answer the questions that come from the research question and research problem. To make sure these are useful sources the table 2 below was used.

Table 2. Source materials analysis tool.

| Questions Q1-Qn, to which the answers are searched for | Reference #1 | Reference #2 | Reference #3 | Reference #4 | Reference #5 | Reference #6 | Reference #7 | Reference #8 | Reference #9... | Reference #N | Summarized observations to integrate the final answers to each question |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Q1 | | | | | | | | | | | |
| Q2 | | | | | | | | | | | |
| Q3 | | | | | | | | | | | |
| Q4... | | | | | | | | | | | |
| | | | | | | | | | | | |
| Qn | | | | | | | | | | | |
| Summarized observations about the relevance of each reference | | | | | | | | | | | |

One of the main goals of this research is to decrease the carbon footprint of the production of ultra-low noise microwave amplifiers. Knowing that these devices cannot return to Earth due to them remaining in orbit, the selection of materials can be focused on the recycling process since their production process, using recycled materials can reduce the carbon footprint compared to the extraction and manufacture of primary aluminum. However, there is also the possibility to focus on the mechanical properties of each material to ensure the weldability with silver, as it is one of the main goals of this research. This literature review will cross-check the mechanical properties, carbon footprint, and the weldability of the materials chosen.

The materials researched in this literature review are A6061, A7075, and AA6082. The selections of the materials were done based on the materials chosen in the thesis topic researched last year, aluminum alloy A7075, the most common and considered the most affordable material in aluminum alloy, A6061, and AA6082, material found during this research made of 70% of scraps of other alloys. Figure 4 shows the triangulation that will compare the three materials to decide the most suitable one.

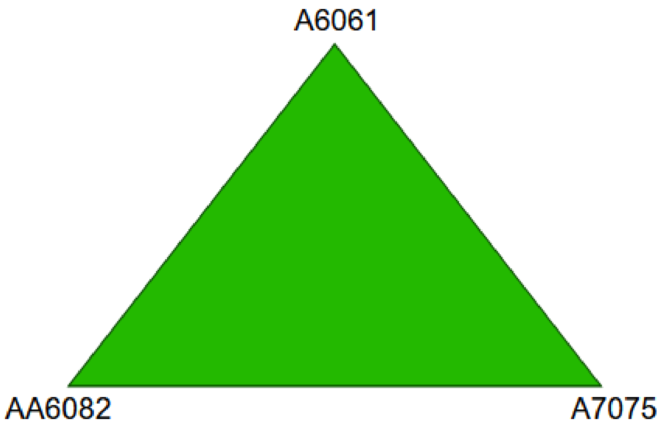


Figure 4: Triangulation on selection of materials.

## 2.2. Life-Cycle Assessment (LCA)

A Life-Cycle Assessment (LCA) is conducted to evaluate the environmental impact of the microwave amplifier from its production through its operational life and eventual disposal. For this part of the research, the use of SolidWorks is required to create a simulation of the ultra-low noise microwave amplifier and get an accurate model that can be worked on and assessed. Inside this software, a sustainability report provides real-time feedback on environmental impact factors and evaluates all the life cycle steps based on the material, manufacturing, and location input. Based on this report, we can obtain the ore extraction from the earth, material processing, part manufacturing, assembly, product usage by the end consumer, and End of Life (EOL) – Landfill, recycling, and incineration. This information is the key to finding the biggest issue with the production and manufacturing of ultra-low noise microwave amplifiers and detecting an optimal solution for this problem following the R-strategies principles.

This quantitative method adheres to ISO (International Organization for Standardization) 14040/14044 standards and examines four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation.

### 2.2.1. ISO 14040/14044

ISO 14040 and ISO 14044 standards are the basic and main principles provided by the International Organization for Standardization for conducting Life cycle assessments. From these key standards, we can also obtain others that explain the carbon footprint calculation for products and the carbon neutrality desired for the life cycle of products.

Define the LCA's goal, scope, and boundaries, as well as which products to assess and the approach (e.g. cradle-to-grave).

Collect and organise all inputs (e.g. raw materials) and outputs (e.g., waste) throughout the product life cycles to create a Life Cycle Inventory (LCI) for accurate environmental impact assessment.

Convert data from the Life Cycle Inventory (LCI) into impact data using environmental impact categories.

Analyse the data and create conclusions, understand the study's limitations and create recommendations to use the LCA results to impact your business positively.

Figure 5: Flowchart for conducting Life-cycle Assessment of products (Walter, 2024).

The goal and scope definition phase outlines the functional unit, system boundaries, and assumptions made during the analysis. For this study, the functional unit is defined as the complete lifecycle of a microwave amplifier used in a planetary space probe, including material extraction, manufacturing, transportation, and use.

The interpretation phase identifies hotspots—stages of the lifecycle with the most significant environmental impact—and explores alternatives to mitigate these effects. By comparing different design scenarios, this analysis supports the identification of more sustainable solutions while maintaining technical performance requirements. This interpretation part of the research is based on R-strategies for circular economy which aim to minimize environmental impacts by promoting sustainable production and consumption.

During this research, the sustainability and life-cycle assessment are defined by the product and its utility. Considering that the ultra-low noise microwave amplifier will be sent to space, we can then avoid the end-of-life part if we suppose the space probe remains in orbit. Which then leads us to the limitations on the evaluation of the device based on the R-strategies.

### 2.2.2. R-strategies for evaluating LCAs

The LCA provides critical insights into energy consumption, material sourcing, greenhouse gas emissions, and end-of-life management. These are also connected to the R-strategies for circular economy, that help picture different stages of resource use and waste management. The framework includes Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, and Recycle as shown in figure 5. However, in this research, the focus is the manufacturing process, where we can find more sustainable ways to manufacture ultra-low noise microwave amplifiers.

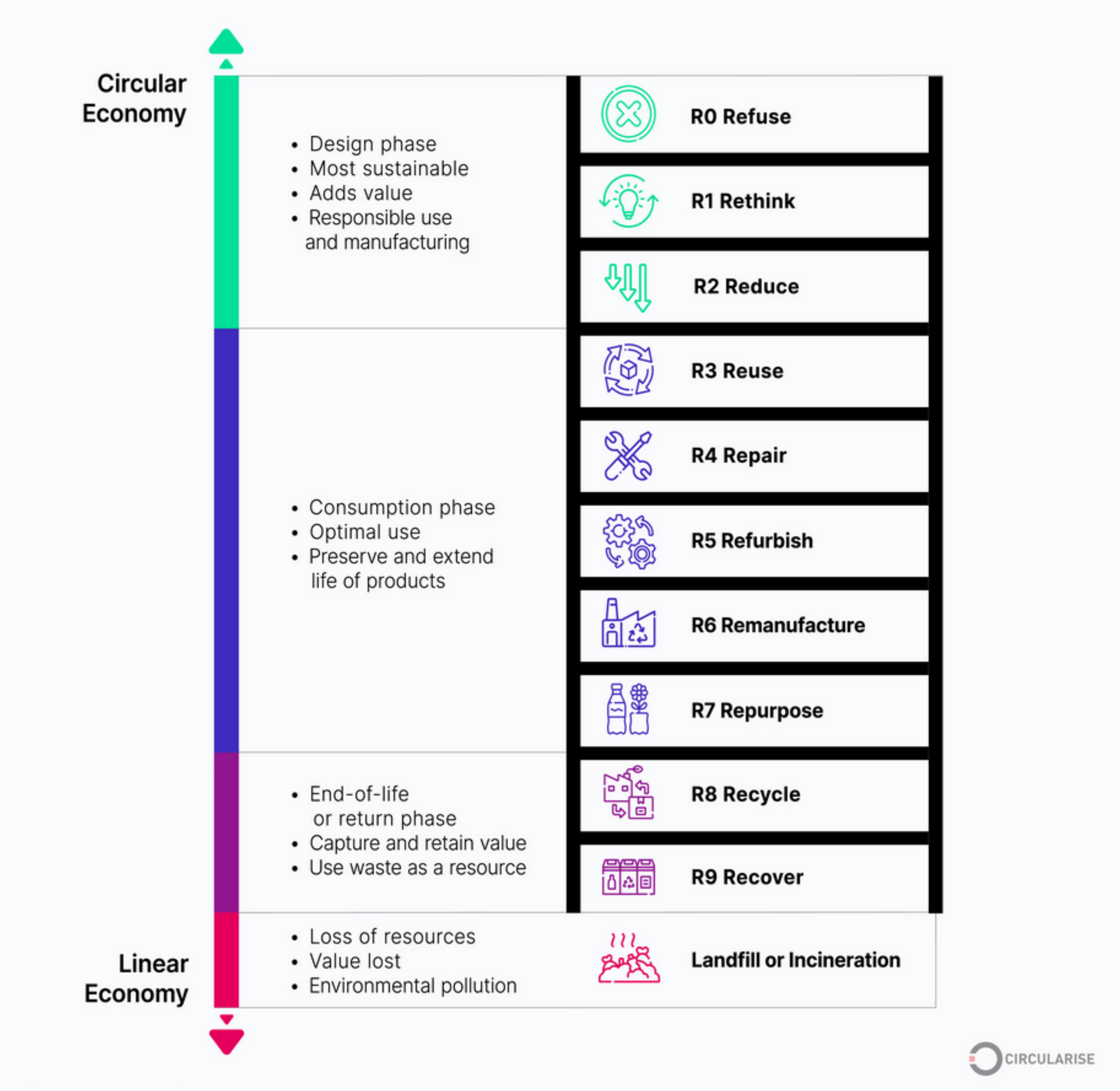
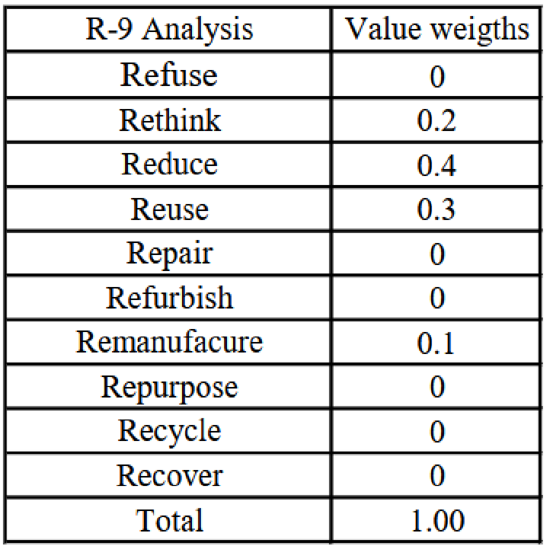


Figure 6: Stages where R-strategies can be applied. (Circularise, 2023).

From table 3 shown below that shows the stages that can be improved, the strategies that will be applied to the optimization of ultra-low noise microwave amplifiers are Rethink, Reduce, Reuse, and Remanufacture. These, have values that indicate how important (weight) they are at the evaluation phase of the device's sustainability. In this case, the most important aspect evaluated is reduce, which indicates the reduction of material and carbon footprint wasted in the manufacturing process of ultra-low noise microwave amplifiers, the next important aspect is the reusability, to evaluate the possibility of utilizing utilized materials or materials that are made of recycled parts. Next, is to rethink the usage of this device, which is why this research takes place, if it has something that needs to be changes, it has something to rethink. Finally, the remanufacture, one of the most concerning points of producing devices that go to space, is the precision and accuracy, so the manufacturability of a device with a new material is important to determine if it is environmentally friendly or, if the methods selected can reduce the carbon footprint compared to the previous utilized.

Table 3. Value analysis of R9-strategies.



| R-9 Analysis | Value weigths |
|---|---|
| Refuse | 0 |
| Rethink | 0.2 |
| Reduce | 0.4 |
| Reuse | 0.3 |
| Repair | 0 |
| Refurbish | 0 |
| Remanufacure | 0.1 |
| Repurpose | 0 |
| Recycle | 0 |
| Recover | 0 |
| Total | 1.00 |

## 2.3. Expert Interview

The expert interview is designed to gather qualitative insights that cannot be easily derived from published literature or technical simulations. This research utilized the email interview method, an asynchronous communication technique that allows the participants to answer at their own time and pace. The selected expert possesses extensive experience in microwave technology and electrical engineering.

The interview process consists of an initial inquiry that focuses on identifying key technical and environmental challenges associated with ultra-low noise microwave amplifiers. Open-ended questions are used to encourage comprehensive responses regarding material selection, cooling techniques, and design considerations for minimizing space debris. In this case, the question asked to the expert was "How can sustainability assessments like LCA be incorporated into the testing phase of amplifier development?"

For email interviews it is not necessary to have feedback rounds where the expert's initial responses are summarized and presented back to them for clarification and elaboration. Instead, we have the opportunity to continue with follow-up questions. However, during this study, time is a limitation where it was only possible to ask the expert one question.

By integrating findings from the literature review, LCA, and expert interview, this study employs methodological triangulation to enhance the reliability, validity, and depth of the research outcomes. This comprehensive approach addresses the environmental challenges associated with ultra-low noise microwave amplifiers and proposes viable pathways toward more sustainable practices in space exploration technologies.

# 3. Results and analysis

This research was conducted utilizing the triangulation method, which combined the results of three instruments to confirm the reliability of the results. These results are first shown separately. For literature review, the three materials are shown in different subchapters to facilitate the understanding of each material composition. Expert interview shows the complete answer, and the picture provided to the expert in which he based his answer. And sustainability assessment which shows the SolidWorks evaluation and a comprehensive table showing the results found.

## 3.1. Literature review

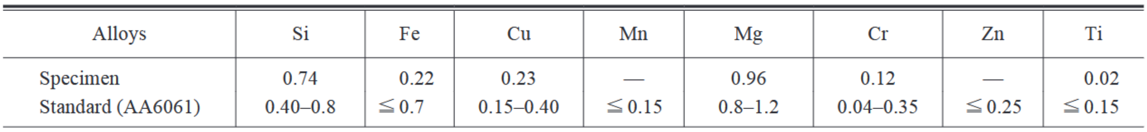
An ultra-low noise microwave amplifier (LNA) is a critical component in microwave receivers, designed to amplify weak signals while minimizing the noise added to the signal. These amplifiers are essential in applications where signal integrity is key, such as in radio astronomy, communication systems, and environmental monitoring. Ultra-low noise amplifiers are designed to operate over specific frequency ranges, which can be narrowband or wideband. For instance, an LNA designed for ultra-wideband (UWB) applications operates from 3.1 to 10.6 GHz, 6 while another LNA covers the 500-1500 MHz band for radio astronomy. Due to these low frequencies, contamination can lead to increased noise temperatures and reduced gain, which are critical parameters for the performance of LNAs, and the presence of contaminants can also cause thermal breakdown and latch-up effects, further degrading the reliability and performance of the amplifiers (Ming et al., 2016).

Because of the necessity to keep contaminants away from the microwave amplifier, there needs to be a hermetic seal in the enclosure. Aluminium alloys are known for their high corrosion resistance due to the formation of a strong, adherent oxide film. This property is crucial for maintaining the integrity of a hermetic seal. Adding silver to solder alloys can enhance mechanical properties such as hardness and tensile strength. These materials have also been shown to interact with microwaves due to their ability to absorb and reflect microwaves, making them suitable for microwave applications. Furthermore, Aluminium is valued for its lightweight properties, which are mandatory in the transportation and aerospace industries. Using aluminium alloys is a good alternative to reduce fuel and gas emissions, making it a more sustainable option for microwave amplifiers.

### 3.1.1. Aluminum alloy AA6061

AA6061 is a medium-strength alloy, it has good conductivity, which is an important property for materials used in microwave amplifiers to ensure signal transmission (Nakai & Itoh, 2015). Talking about the stability of the mechanical properties of AA6061, the fine and stable grain structure enhances the material's mechanical stability, reducing vibrations and noise during operation. Table 4 indicates the chemical composition of AA6061, which shows the incorporation of Zn, that can enhance sound attenuation properties, which is beneficial for reducing noise in microwave amplifiers (Mendoza López et al., 2024).

Table 4. Chemical composition of AA6061 (Nakai & Itoh, 2015).



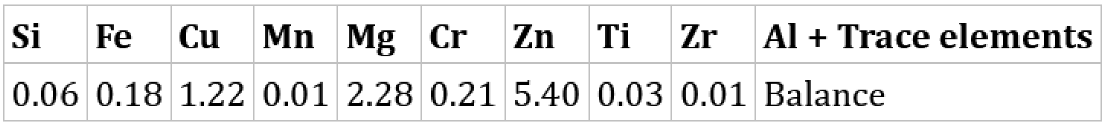
| Alloys | Si | Fe | Cu | Mn | Mg | Cr | Zn | Ti |
|---|---|---|---|---|---|---|---|---|
| Specimen | 0.74 | 0.22 | 0.23 | — | 0.96 | 0.12 | — | 0.02 |
| Standard (AA6061) | 0.40–0.8 | ≦0.7 | 0.15–0.40 | ≦0.15 | 0.8–1.2 | 0.04–0.35 | ≦0.25 | ≦0.15 |

However, when compared to other materials like steel, aluminum alloys generally have a higher environmental impact during the raw material acquisition stage but offer benefits during the usage phase due to their lightweight properties, which improve fuel efficiency in transportation (Peng, 2015). Recycling AA6061 can significantly reduce energy consumption and greenhouse gas emissions, but managing impurities is crucial to maintaining its quality, A study realized by Quan in 2023, suggested that "the excess of Fe impurities is not conducive to efficient recycling of the alloy”.

### 3.1.2. Aluminum alloy AA7075

Microwave amplifiers often require materials with specific electrical properties, such as high electron mobility and low dielectric loss. Common materials include GaN, AlN, and InN, which are known for their high performance. Aluminium alloy 7075 is primarily composed of aluminum, zinc, magnesium, and copper as shwon in table 5. The high thermal conductivity of AA7075 helps in maintaining lower operating temperatures, thereby enhancing the reliability and performance of the amplifiers, but its lower corrosion resistance limits its application without surface treatment (Li et al., 2008). While other aluminum alloys like Al-Si and AlN are also used in high thermal conductivity applications, AA7075's combination of mechanical strength and thermal performance makes it particularly suitable for high-stress environments like microwave amplifiers (Shannon, 2004).

Table 5. Chemical composition of AA7075 (Nasr et al., 2024).



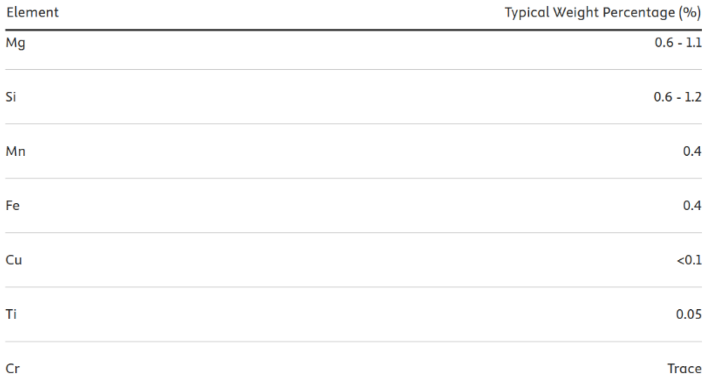
| **Si** | **Fe** | **Cu** | **Mn** | **Mg** | **Cr** | **Zn** | **Ti** | **Zr** | **Al + Trace elements** |
|---|---|---|---|---|---|---|---|---|---|
| 0.06 | 0.18 | 1.22 | 0.01 | 2.28 | 0.21 | 5.40 | 0.03 | 0.01 | Balance |

Talking about its environmental friendliness, the production of AA7075 involves significant energy consumption and emissions, particularly during the aluminum oxide production and electricity consumption stages. However, AA7075 can be effectively recycled, which reduces energy consumption and CO2 emissions. Recycling AA7075 scrap into high-strength castable secondary alloys can achieve energy savings of up to 90% and CO2 emissions reductions of 96% compared to primary aluminum production (Nasr et al., 2024).

### 3.1.3. Aluminum alloy AA6082

AA6082 belongs to the 6000 series and combines good strength, corrosion resistance, and machinability. Because of its chemical composition (shown in table 6), it offers a good balance of heat dissipation and electromagnetic neutrality. The production of aluminum alloy AA8082 involves the use of various recycled scraps. A significant amount of aluminum scrap is generated during machining operations, this scrap is often recycled to produce new aluminum alloys, including AA8082. Adding to this, it is highly recyclable with a relatively low carbon footprint, making it a sustainable option. A Life cycle assessment made in 2012 showed that recycled aluminium alloys have lower environmental impacts compared to primary aluminium. Using aluminium as secondary raw material in aluminium alloy production not only reduces pressure on the environment for waste aluminium disposal but also supplements necessary resources (Hong et al., 2012).

Table 6. Chemical composition of AA6082.



| Element | Typical Weight Percentage (%) |
|---|---|
| Mg | 0.6 - 1.1 |
| Si | 0.6 - 1.2 |
| Mn | 0.4 |
| Fe | 0.4 |
| Cu | <0.1 |
| Ti | 0.05 |
| Cr | Trace |

### 3.1.4. Gold coating

The incorporation of gold nanoparticles significantly improves the sensitivity of RF biosensors for biomolecular detection. Variations in the particles’ morphology, dimensions, and spatial distribution critically influence sensor performance, yielding sensitivity enhancements between 30% and 80% (Mazumder, 2023). This material is chemically stable and extremely resistant to corrosion, making it ideal for space applications where parts must withstand harsh conditions like high humidity and corrosive environments. This durability helps maintain the components' performance and lifespan (Moore, 2023).

Gold coatings improve the corrosion resistance and tribological performance of aluminum alloys, which can extend the lifespan of the coated materials. However, it adds up to the total carbon footprint of the final product. The total carbon footprint of gold-coating an aluminum alloy depends largely on the gold's origin and the coating's thickness. Using recycled gold and minimizing the coating thickness can substantially reduce environmental impact. Gold itself is not considered toxic, but many of the chemicals used in gold plating solutions are potentially hazardous, posing environmental risks (Zhong, 2025).

## 3.2. Expert interview

Ultra-low noise microwave amplifiers have an enclosure that contains connector pins that go through five ceramic and glass bushers and there are two types of feedthrough bushers used in the construction.

Figure 7. Enclosure design picture shown to the expert.

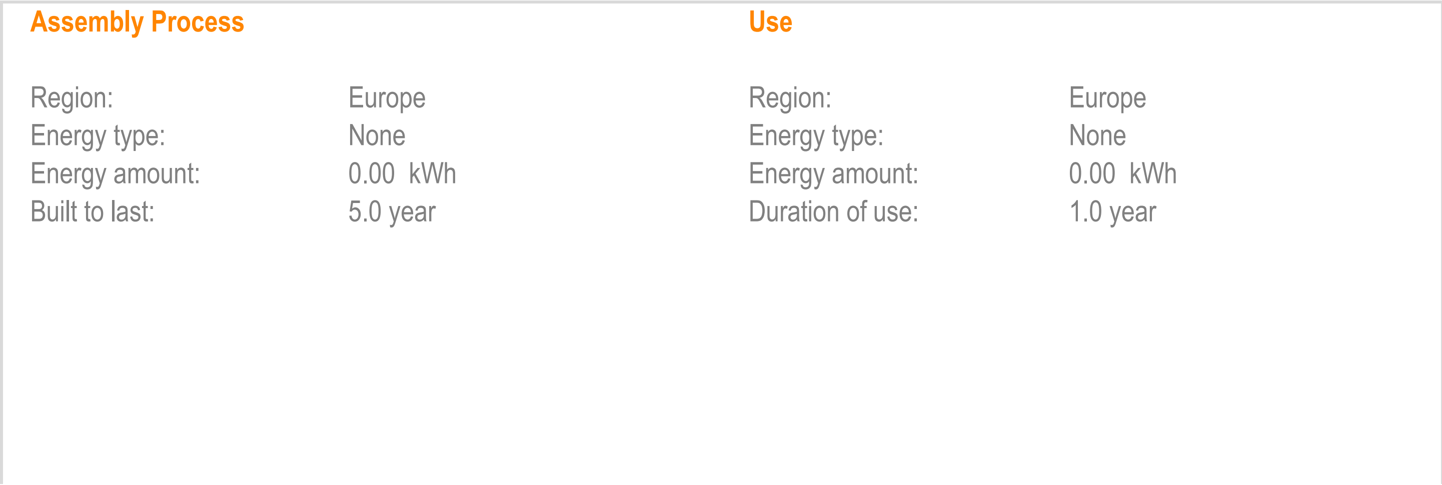
As mentioned in the previous chapter, the expert interview had one question for the expert, asking about the possibility of including the LCA into the manufacturing and testing process of the enclosure to ensure its sustainability. The answer obtained was that this amplifier enclosure is a "one-of-a-kind" product. Only five individual boxes have ever been made: one that went to space, one spare and three engineering models. So, LCA would not be an issue, if only this device is considered. However, as the company which made the amplifier utilizes the very same design and construction principles and almost identical materials regardless of unit's function, there is a general LCA philosophy which aims at reducing e.g. waste of gold by applying "mass production" techniques in the chemical coating process.

Performance targets are, however, continuously near the limits of available methods and so very little can be done. Luckily the production volume is very limited and thus we don't have to take nightmares due to pollution.

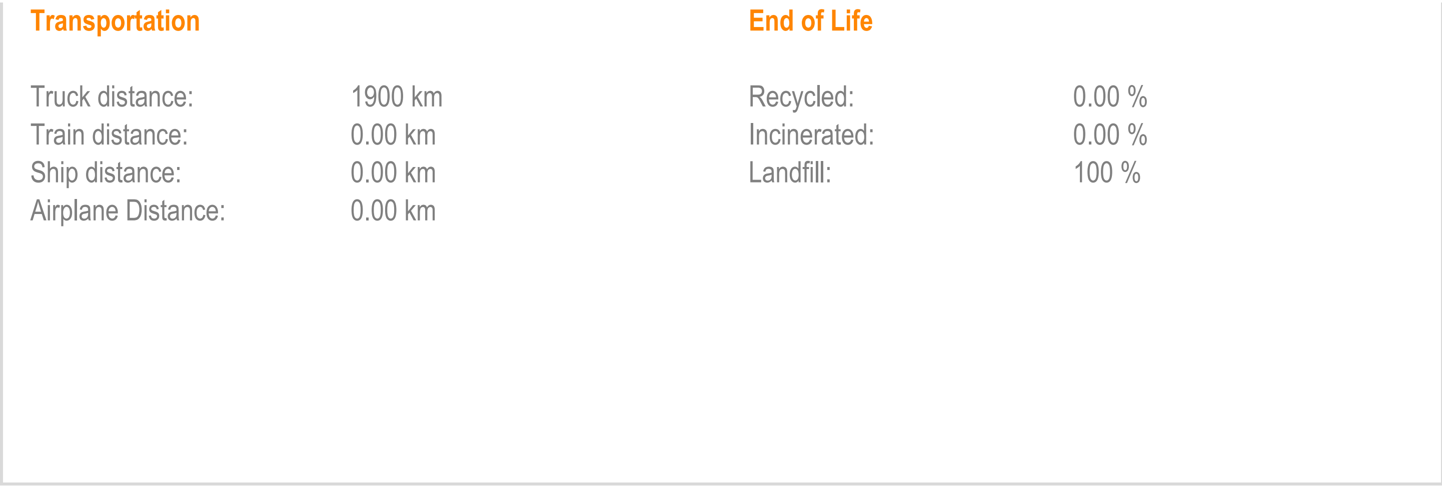
## 3.3. Sustainability assessment (LCA)

Utilizing the Sustainability tool in SolidWorks, it is possible to analyze the influence of materials or manufactured devices has on the environment before, during and after its production. (Honório et al., 2023)

The parameters utilized for the LCA were the following:



| **Assembly Process** | | **Use** | |
|---|---|---|---|
| Region: | Europe | Region: | Europe |
| Energy type: | None | Energy type: | None |
| Energy amount: | 0.00 kWh | Energy amount: | 0.00 kWh |
| Built to last: | 5.0 year | Duration of use: | 1.0 year |



**Transportation**

Truck distance: 1900 km
Train distance: 0.00 km
Ship distance: 0.00 km
Airplane Distance: 0.00 km

**End of Life**

Recycled: 0.00 %
Incinerated: 0.00 %
Landfill: 100 %

This, considering that the device will remain in space, so the end of life will not be taken into account.

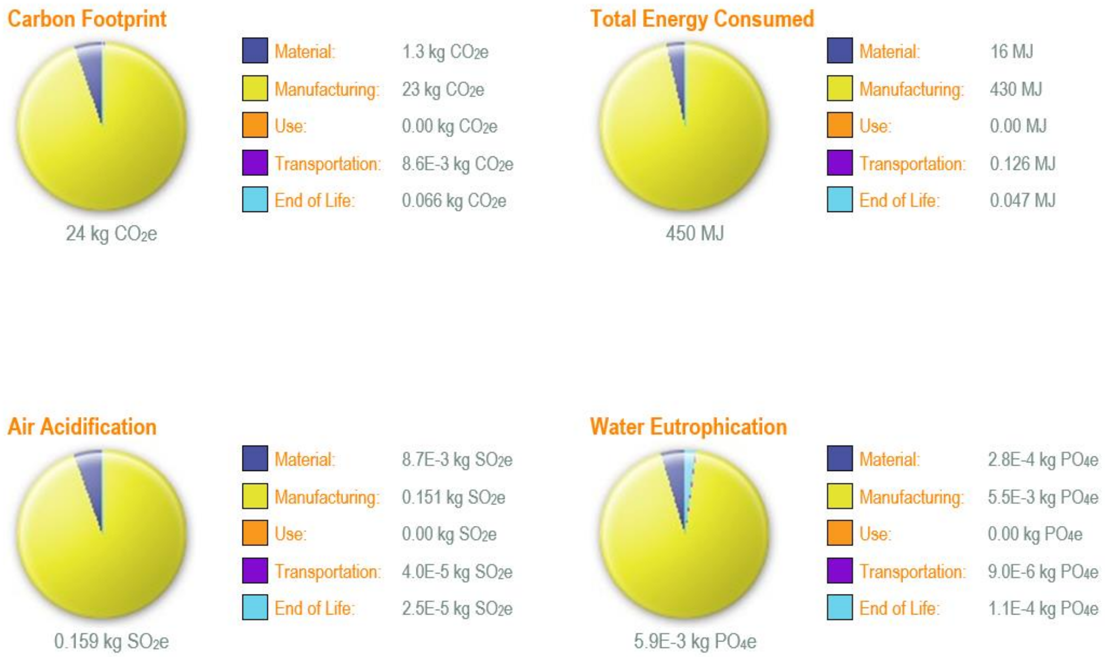


Figure 8. Sustainability assessment for aluminum alloy 6082 in SolidWorks.

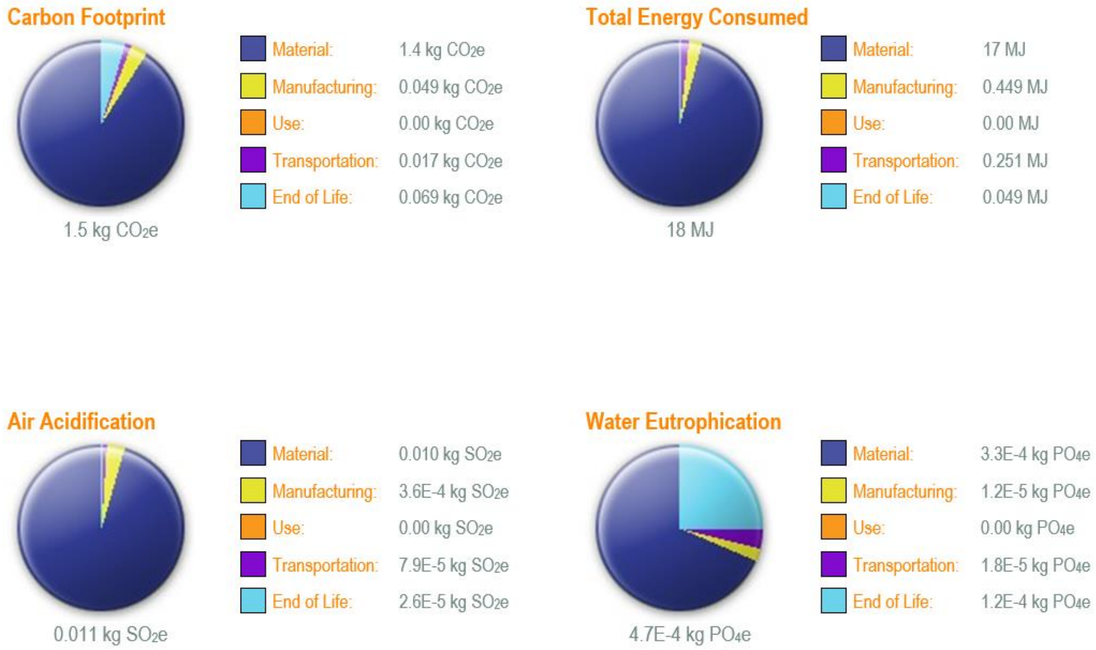


Figure 9. Sustainability assessment for aluminum alloy 7075 in SolidWorks.

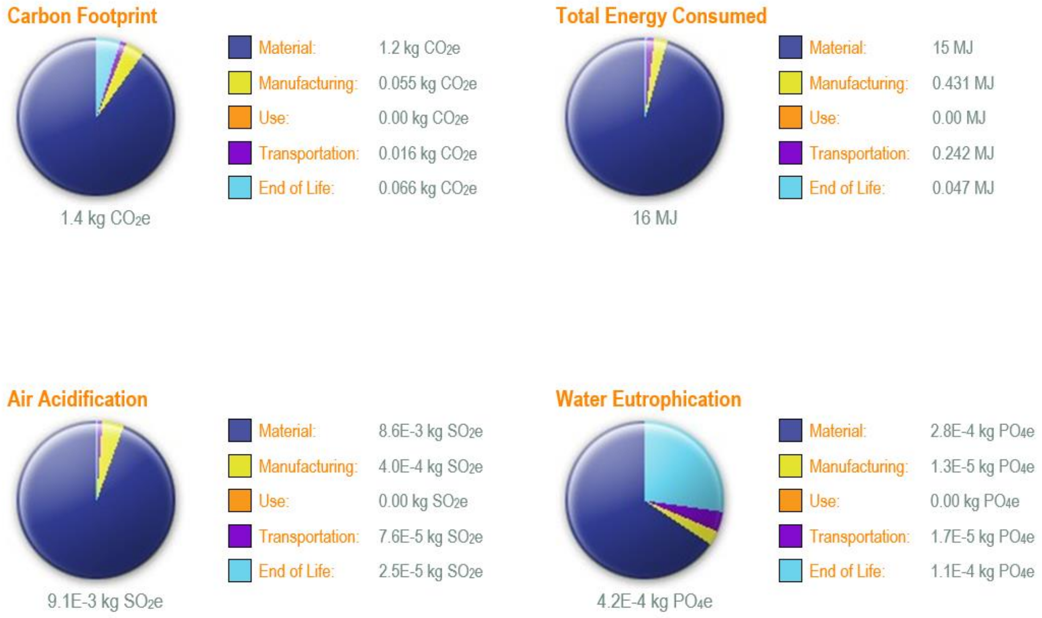
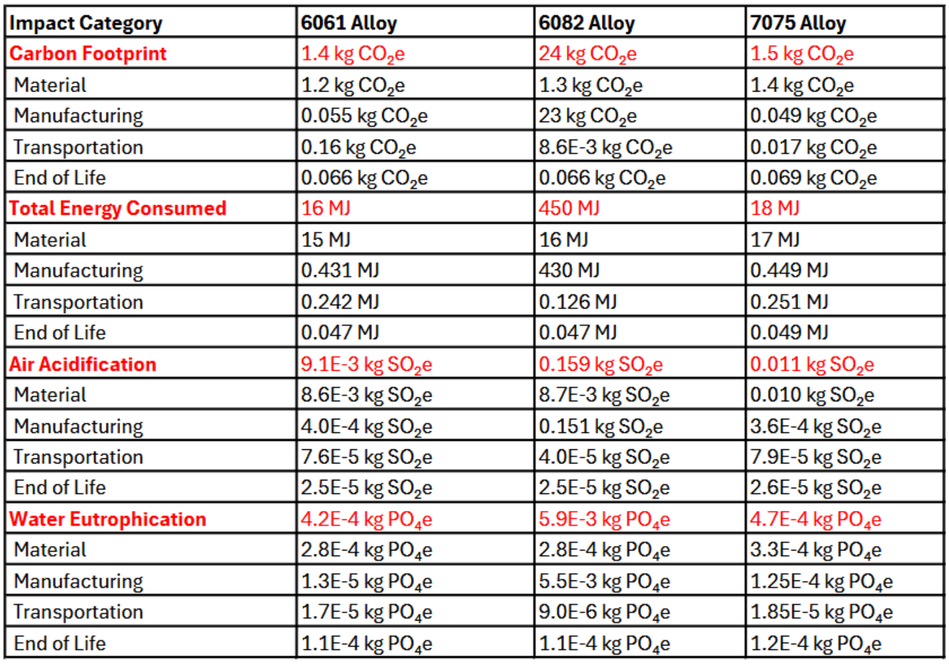


Figure 10. Sustainability assessment for aluminum alloy 6061 in SolidWorks.

The information given by the software was then tabulated to compare the results of each sustainability assessment.

Table 7. Sustainability assessment values.



| **Impact Category** | **6061 Alloy** | **6082 Alloy** | **7075 Alloy** |
|---|---|---|---|
| **Carbon Footprint** | 1.4 kg $CO_2e$ | 24 kg $CO_2e$ | 1.5 kg $CO_2e$ |
| Material | 1.2 kg $CO_2e$ | 1.3 kg $CO_2e$ | 1.4 kg $CO_2e$ |
| Manufacturing | 0.055 kg $CO_2e$ | 23 kg $CO_2e$ | 0.049 kg $CO_2e$ |
| Transportation | 0.16 kg $CO_2e$ | 8.6E-3 kg $CO_2e$ | 0.017 kg $CO_2e$ |
| End of Life | 0.066 kg $CO_2e$ | 0.066 kg $CO_2e$ | 0.069 kg $CO_2e$ |
| **Total Energy Consumed** | 16 MJ | 450 MJ | 18 MJ |
| Material | 15 MJ | 16 MJ | 17 MJ |
| Manufacturing | 0.431 MJ | 430 MJ | 0.449 MJ |
| Transportation | 0.242 MJ | 0.126 MJ | 0.251 MJ |
| End of Life | 0.047 MJ | 0.047 MJ | 0.049 MJ |
| **Air Acidification** | 9.1E-3 kg $SO_2e$ | 0.159 kg $SO_2e$ | 0.011 kg $SO_2e$ |
| Material | 8.6E-3 kg $SO_2e$ | 8.7E-3 kg $SO_2e$ | 0.010 kg $SO_2e$ |
| Manufacturing | 4.0E-4 kg $SO_2e$ | 0.151 kg $SO_2e$ | 3.6E-4 kg $SO_2e$ |
| Transportation | 7.6E-5 kg $SO_2e$ | 4.0E-5 kg $SO_2e$ | 7.9E-5 kg $SO_2e$ |
| End of Life | 2.5E-5 kg $SO_2e$ | 2.5E-5 kg $SO_2e$ | 2.6E-5 kg $SO_2e$ |
| **Water Eutrophication** | 4.2E-4 kg $PO_4e$ | 5.9E-3 kg $PO_4e$ | 4.7E-4 kg $PO_4e$ |
| Material | 2.8E-4 kg $PO_4e$ | 2.8E-4 kg $PO_4e$ | 3.3E-4 kg $PO_4e$ |
| Manufacturing | 1.3E-5 kg $PO_4e$ | 5.5E-3 kg $PO_4e$ | 1.25E-4 kg $PO_4e$ |
| Transportation | 1.7E-5 kg $PO_4e$ | 9.0E-6 kg $PO_4e$ | 1.85E-5 kg $PO_4e$ |
| End of Life | 1.1E-4 kg $PO_4e$ | 1.1E-4 kg $PO_4e$ | 1.2E-4 kg $PO_4e$ |

The results of the Sustainability and Life-cycle assessment show that 6082 Alloy has the highest environmental impact, mainly due to its extremely high manufacturing-related emissions and energy consumption. 6061 Alloy and 7075 Alloy are relatively similar, with 6061 having slightly lower values overall, especially in Air Acidification and Carbon Footprint. 7075 uses a bit more energy for transportation and material processing, but not dramatically more than 6061.

However, we can consider that the values provided by SolidWorks for 6082 are inaccurate due to SolidWorks not having the material in the software. AA6082 was manually added after researching the mechanical properties.

# 4. Discussion

This chapter interprets the results of the literature review, Life Cycle Assessment (LCA), and expert interview, bringing them together to evaluate the environmental sustainability of ultra-low noise microwave amplifier (LNA) designs. The findings are analyzed in light of the research question: "Why do current ultra-low noise microwave amplifier designs have a significant environmental impact, and how can they be optimized to minimize this impact while maintaining performance for planetary space probes?"

## 4.1. Key Findings and Conclusions

AA6082 emerged as the most environmentally sustainable option based on literature, due to its high recycled content and reduced need for primary extraction. However, SolidWorks simulation inaccurately showed it as the least sustainable, likely due to manual data entry limitations. AA6061 performed consistently well across multiple sustainability metrics, particularly in reducing air acidification and carbon footprint. AA7075, while strong and thermally efficient, showed the highest energy usage unless recycled, and proved that it is a material hard to recycle.

R-strategies such as Reduce, Rethink, and Reuse proved especially relevant. Reducing raw material use and emissions through careful design choices had the greatest potential for sustainability gains.

Expert feedback emphasized that while LNAs are low in production volume, standardizing sustainable design principles and using recycled materials can make a meaningful impact.

These findings highlight that sustainable design in high-precision aerospace electronics is not only possible but also beneficial, provided material selection and design principles are carefully optimized.

## 4.2. Comparison and Connections with Former Research

The findings align with previous research emphasizing the environmental impact of aluminum alloys and the importance of recyclability in high-performance components.

Multiple studies have pointed to the superior environmental profile of AA6082 due to its secondary (scrap-based) production. However, its underrepresentation in engineering software databases (like SolidWorks) leads to misinformed sustainability evaluations—an issue echoed in prior studies on CAD-based LCA reliability.

This study also confirms trends in aerospace sustainability literature: low-volume, high-tech manufacturing does not exclude sustainability concerns. Prior works in green electronics and space technology stress design optimization, use of recycled materials, and lifecycle thinking principles that were validated by the results of this research.

## 4.3. Reliability assessment of the results

While the triangulated methodology of LCA, literature and expert input strengthened the overall validity of the conclusions, several reliability concerns must be acknowledged:

- The SolidWorks simulation tool lacked full data for AA6082, which impacted accuracy.
- The expert interview was limited in scope due to time constraints and only one question being addressed.
- The LCA did not include a full end-of-life assessment, as LNAs remain on planetary probes indefinitely.

Despite these limitations, the convergence of results from multiple sources supports the general reliability of the conclusions. Where one method showed weakness (e.g., SolidWorks), others (e.g., literature review and expert opinion) offered correction or clarification.

## 4.4. Topics for Future Research

To further advance sustainable microwave amplifier designs, future research could assess more different materials from SolidWorks, such as AA6082, as some of them were still not available in the software yet. The more materials added and taken into account, the more possibilities exist to have a better and more sustainable design of these devices.

Another point that could be worked on is the possibility of recovering these materials in case they come back from space, which will be based on the regulations by the waste electrical and electronic equipment (WEEE) and restriction of the use of hazardous substances (RoHS).

And finally, further exploration of energy-efficient cooling methods for LNAs, given the thermal importance in space conditions.

# 5. Summary

Ultra-low noise microwave amplifiers are in charge of amplifying the waves received in space. Due to their important role in space probes, the manufacturing of these devices is crucial to be accurate and with a good material to prevent interference in the reception of microwaves. The selection of the materials goes hand to hand with the sustainability aspects for every machine manufactured, following R9-strategies. In this research, the focus was to find a sustainable material that can reduce the carbon footprint during the manufacturing process by checking the life cycle assessment done in SolidWorks while working in optimal conditions. After triangulation, it was found that aluminium alloy AA6082 is the best option to replace other materials while ensuring the weldability with silver and follows the sustainability requirements researched.

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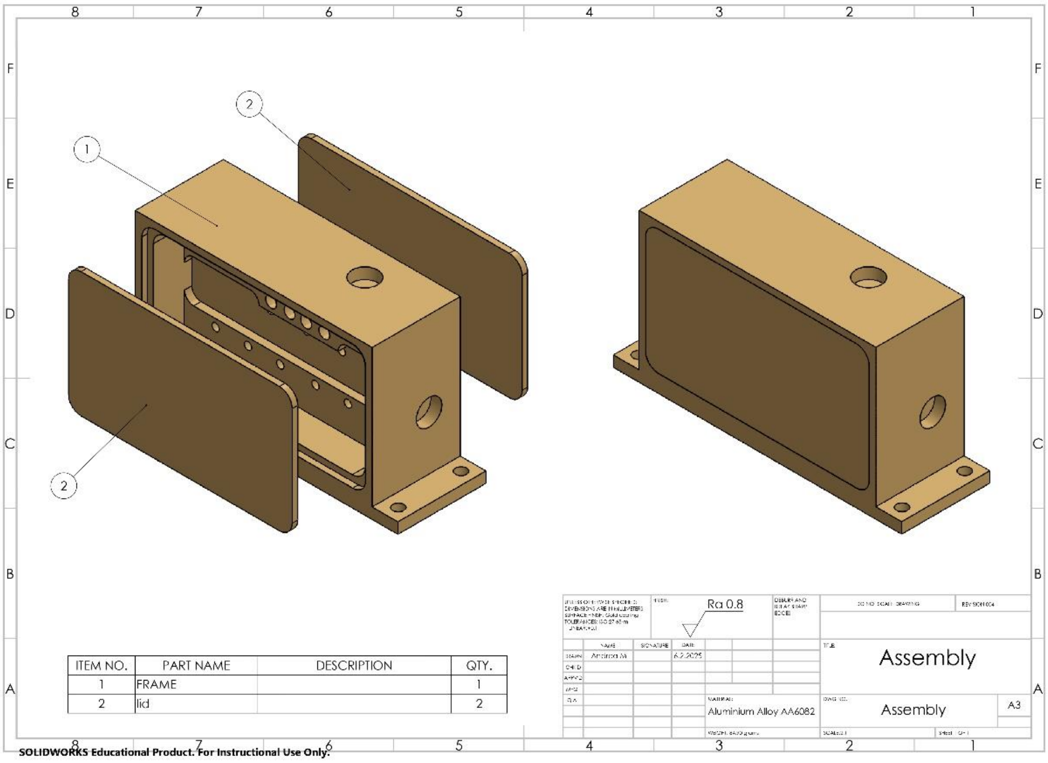
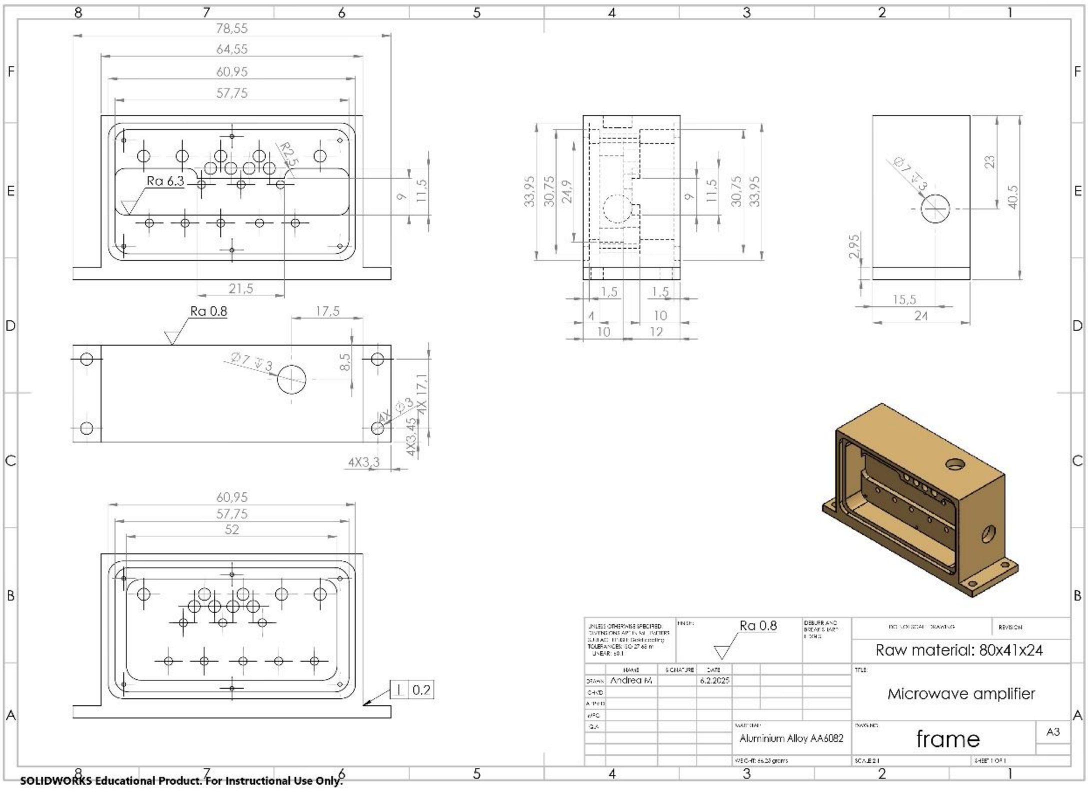
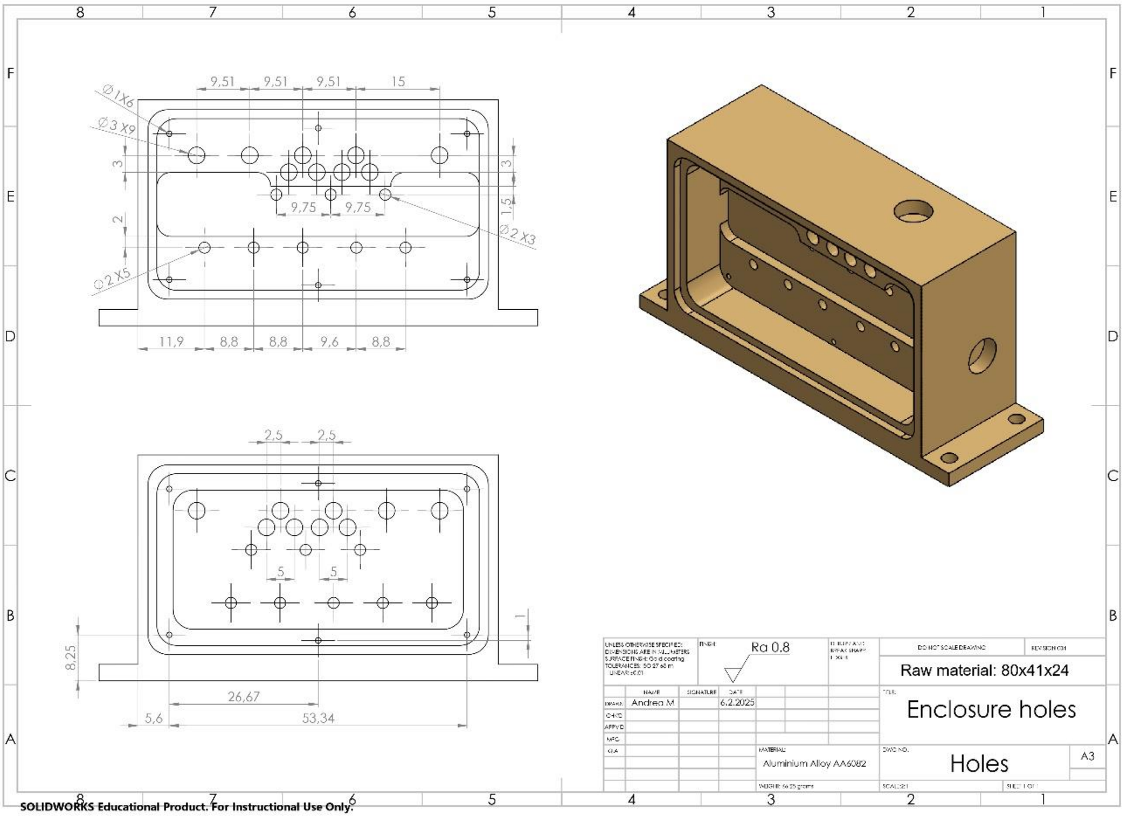
# Appendix 1. Technical drawings



| ITEM NO. | PART NAME | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | FRAME | | 1 |
| 2 | lid | | 2 |





UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH: Gold coating
TOLERANCES: ISO 2768 m
LINEAR: ±0.01

FINISH: Ra 0.8

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION 01

Raw material: 80x41x24

| | NAME | SIGNATURE | DATE |
|---|---|---|---|
| DRAWN | Andrea M | | 6.2.2025 |
| CHK'D | | | |
| APPV'D | | | |
| MFG | | | |
| Q.A | | | |

TITLE: Enclosure holes

MATERIAL: Aluminium Alloy AA6082

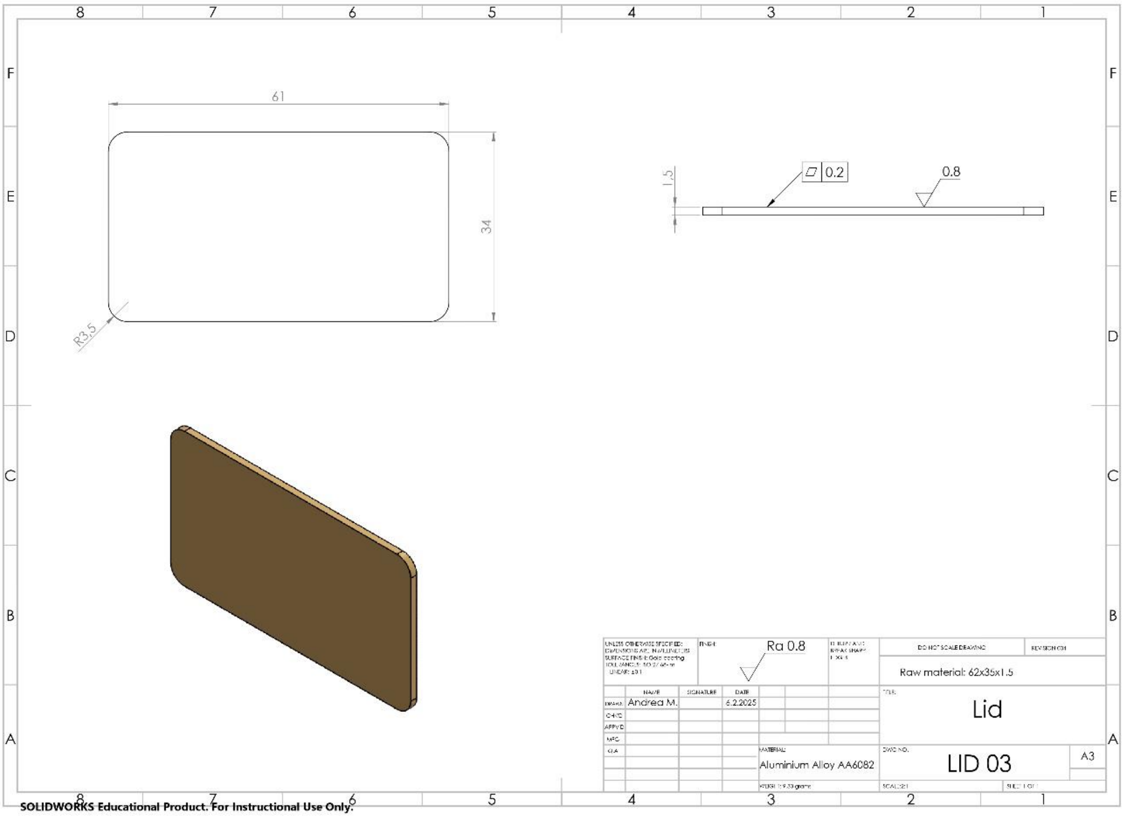
DWG NO. Holes

A3

WEIGHT: 66.25 grams

SCALE:2:1

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH: Gold coating
TOLERANCES: ISO 2768 m
LINEAR: ±0.1

FINISH: Ra 0.8

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION 01

Raw material: 62x35x1.5

| | NAME | SIGNATURE | DATE |
|---|---|---|---|
| DRAWN | Andrea M. | | 6.2.2025 |
| CHK'D | | | |
| APPV'D | | | |
| MFG | | | |
| Q.A | | | |

TITLE: Lid

MATERIAL: Aluminium Alloy AA6082

DWG NO. LID 03

A3

WEIGHT: 9.33 grams

SCALE:2:1

SHEET 1 OF 1