ENVIRONMENTAL IMPACT REDUCTION IN W-BAND DIRECTIONAL COUPLERS FOR 92 GHZ DOCKING RADAR VIA R9 STRATEGIES

Lappeenranta–Lahti University of Technology LUT

Bachelor's Programme of Mechanical Engineering, Bachelor's thesis

2025

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Examiner(s): Professor Tapio Saarelainen

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ABSTRACT

Lappeenranta–Lahti University of Technology LUT
LUT School of Energy Systems / LUT School of Engineering Sciences
Mechanical Engineering
Double Degree, in co-operation with partner university: Hebei University of Technology

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Environmental impact reduction in W-Band directional couplers for 92 GHz docking radar via R9 strategies

Bachelor's thesis
2025
49 pages, 10 figures, 7 tables, and 8 appendices

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Keywords: W-Band directional coupler, environmental aspect, R9 strategies, gold-plating, brass alloys, graphene, sustainability.

Due to rapid space exploration, W-Band directional coupler development continues. As an important component in a deep space probe, the directional coupler is used to separate the input 92 GHz signal into the two waveguides. The component's dimensions are 120*20*20 mm^3. The article presents environmentally friendly solutions for material selection and sustainable gold-plating alternatives. The main part of the paper concentrates on ecological brass selection. The triangulation method was applied as a research method, including expert interviews, literature review, and SolidWorks 3D model observation. At the same time, R9 strategies were utilized to ensure the accuracy of the research.

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Acknowledgements

I would like to thank my family, my girlfriend Anna, my friends, and professors Tapio Saarelainen and Harri Eskelinen for the great support throughout my thesis.

Note: I used the Grammarly tool [https://app.grammarly.com/] to improve the grammar, style, and composition of the article.

1 Introduction

W-band directional couplers are important parts of 92 GHz docking radar systems, helping ensure reliable signal transmission. However, making these components is not environmentally friendly. The use of gold plating creates a lot of CO_2 emissions and makes recycling difficult.

The production process also consumes a lot of energy and leads to unnecessary waste. This research looks for better, more sustainable ways to produce these couplers without losing performance. The focus is on finding eco-friendly materials, improving manufacturing processes, and making the parts easier to recycle**.**

To achieve this, the study will use three research methods: reviewing existing studies, interviewing experts, and analyzing designs in SolidWorks. The goal is to suggest new ways to manufacture these couplers with less environmental impact, making them more efficient, recyclable, and sustainable for future aerospace and satellite applications. The component is represented in Figure 1.

Figure 1. The W-Band directional coupler structure.

1.1 Goal of the research

The main goal of the thesis is the analysis of W-Band directional coupler production and utilization, to determine suitable metal materials and manufacturing aspects, to improve the environmental aspect of component production and application.

1.2 Background and motivation

“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 questions

The directional coupler is a detail on the satellite, which is why it should withstand vast amounts of radiation. For this reason, the part is gold-plated. This solution is highly effective; however, the gold plating process is not eco-friendly. During that process, the amount of CO2 emission is huge. Additionally, soldered and gold-plated components are not easily separated during recycling, leading to inefficiencies in material recovery and reuse. Together with that, the production of the directional coupler requires significant energy, since the manufacturing involves multiple stages (plating, bending, soldering), which are derived from non-renewable sources. On top of that, a lack of modularity and repairability means that the entire coupler is often discarded when a small component fails, increasing the waste amount. Find a way to improve the sustainability factor in directional coupler production, allowing the reduction of the carbon footprint during production.

After analysing the research problem, this part production has two questions that need to be answered:

Are there more sustainable material and process alternatives, and how do we implement them?

What are the best strategies to improve manufacturing efficiency and sustainability?

1.4 Research methods

The method used for the research is triangulation, which includes three different methods. The literature review, expert interview, and observation of the SolidWorks model. These are three independent methods, and each implemented method is shown in Figure 2. By applying the triangulation method, the precision, validity, and reliability of the research increase, allowing the improvement of the manufacturing process.

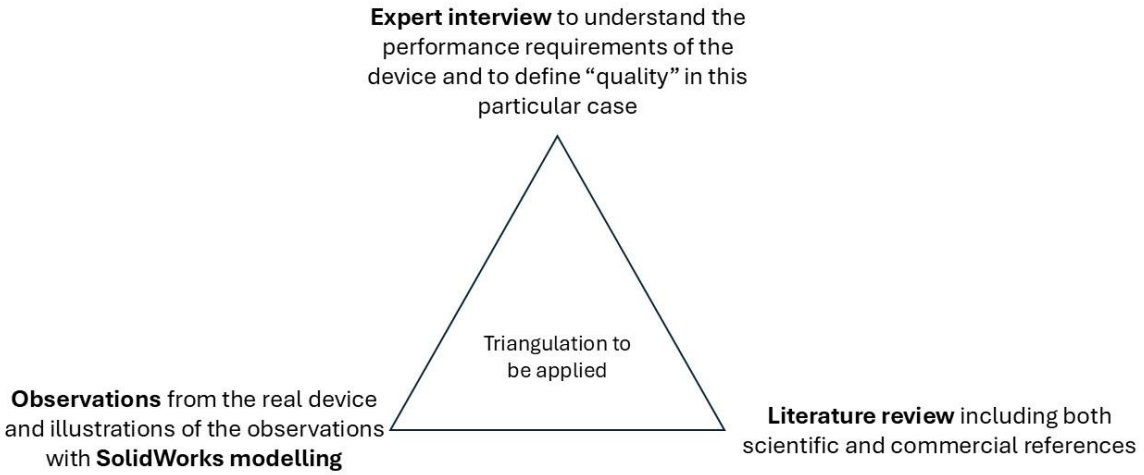

Figure 2. The triangulation's relationship.

1.5 Expected contribution

The expected outcome of this research is to determine environmentally friendly manufacturing methods that match the accuracy of manufacturing without affecting the mechanical properties. Choose a suitable material to ensure the part can withstand radiation and a rough outer space environment.

1.6 Applied methodology

Triangulation is used as the main method. This method consists of three main sections: literature review, expert interview, and 3-D model utilization.

2 Research methods

The research method for evolving the manufacturing plan of the W-Band directional coupler using the triangulation method. Each of the three elements of the triangulation supports the other and augments the overall view of the sustainability aspect of the component production. This chapter will explain how this method is used in researching this device, covering the process and key details of its application. These methods aim to change the perspective of part production in a more environmentally friendly direction.

2.1 Overall component information

The W-Band Directional coupler is a device that is used to separate input signals. The most common applications of this component are docking radars or communication systems, which require high frequency to operate, particularly 92 GHz. It functions by coupling part of the signal to another circuit, which allows for direct power transfer while marginally affecting the original signal. The component comprises two waveguides, standardized IEC R900 waveguides, the straight waveguide and the bent waveguide, the gateway for the input and output signal (Everything RF 2025). For structural stability and mounting precision, standardized UG-387 rounded flanges and steel pins are applied (Fairview Microwave n.d.). Together with that, a copper perforated plate is used for the input signal separation. The plate is perforated with 0.6 mm holes. The role of holes is to separate the signal with the required precision (Micouin 2014). The coupler is gold-plated and silver soldered to ensure high conductivity, reduce signal losses, and protect the component from space radiation. The material selection and different manufacturing techniques are key aspects of the component's sustainability.

2.2 Applied triangulation

The triangulation application involves bringing together information from the expert interview, literature review, SolidWorks analysis, and material selection methods**.** Every aspect of the triangulation seeks to give more information about the environmental aspect of the parts' production, and to provide new potential solutions for sustainability improvements. However, during the research, information from different sources might be controversial. For this reason, only new findings supported by different research aspects are going to be taken into further consideration and deeper research. Each part of the research is essential. The expert interview focuses on answering questions via expert experience; though conversation time is limited, it is necessary to extract the technically most complicated questions. With the interviewee's help, it is possible to find answers to the toughest questions. Literature review, on the other hand, aims to provide a vast amount of important data related to the topic that was published by numerous scientists. This is the most significant part of the research, since it could provide all the important findings. The utilization of the SolidWorks 3-D model is the last component of the triangulation. It provides carbon footprint and water waste statistics, as well as total energy consumption and material financial impact, for different production raw materials. The goal is to evaluate the device's performance and explore possible improvements to the original W-Band directional coupler design.

2.3 Expert interview

2.3.1 Arrangements for the Expert Interview

This method contains an interview between me, as a student writing my bachelor's, and a scientist, provided by LUT University. Critical aspects of the interview are defining interview objectives and identifying the right expert in the field that is relevant to my thesis. It is necessary to develop questions for the structured interview. Questions should be based on R9 strategies and SolidWorks sustainability analysis. For a better understanding of answers, it is going to be useful to write down answers or record the conversation, to ensure the validity of the given information. An interview is going to be held in the LUT University classroom. The group of 10 students is going to be presenting in the interview. During the interview, it is necessary to listen to other students' questions and expert responses, to capture the information that might be related to the topic. Since a number of thesis topics capture the environmental aspect of different component production, the answers given to other students can explain several elements of the W-Band directional coupler production. The next step is data analysis. First of all, the transcription of the answers is important, as well as the categorization of the responses. After the transcription, it is necessary to analyze expert feedback in relation to key aspects, such as material selection and environmental impact during the production process. For the last step of the data analysis, a comparison of the existing literature is crucial. For the representation of the results, it is preferable to show charts and tables for answers, as well as numerical data, and then compare the expert insights with the sustainability module outputs. The goal of the interview is to enhance the knowledge of current W-Band directional coupler production, especially the solid material used for the manufacturing, soldering, and gold plating specifications, and the techniques used for the production. Detailed step-by-step expert interview implementation is shown in Figure 4.

2.3.2 Questions the expert interview aims to answer

What is the function of the central plate of the W-Band Directional Coupler?

What are the mechanical and material properties of this component?

What are the holes' purposes?

The component mentioned in the questions is shown in Figure 3.

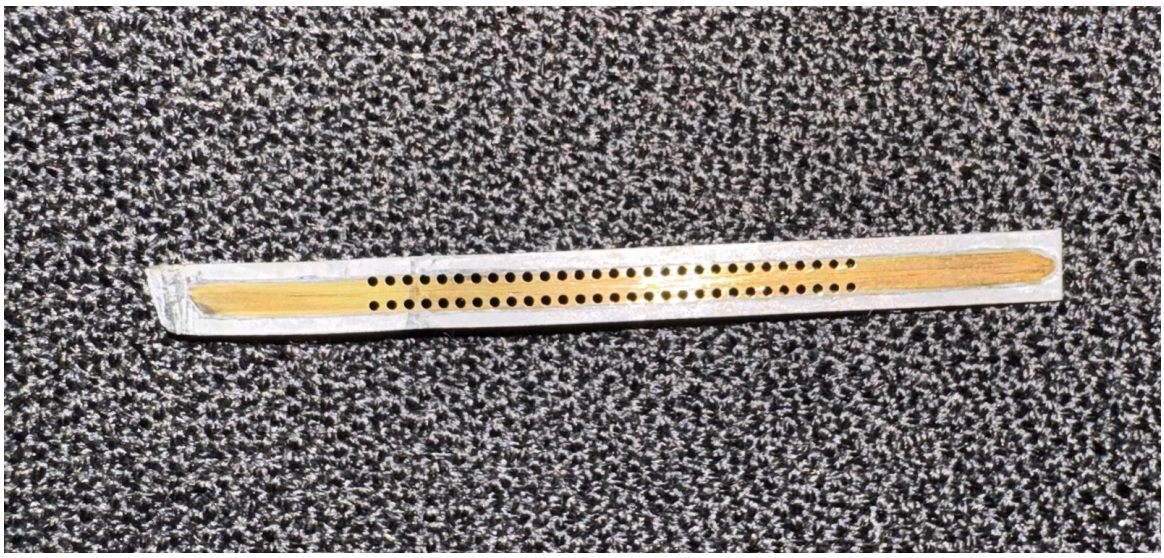

Figure 3. The central plate of the W-Band Directional coupler.

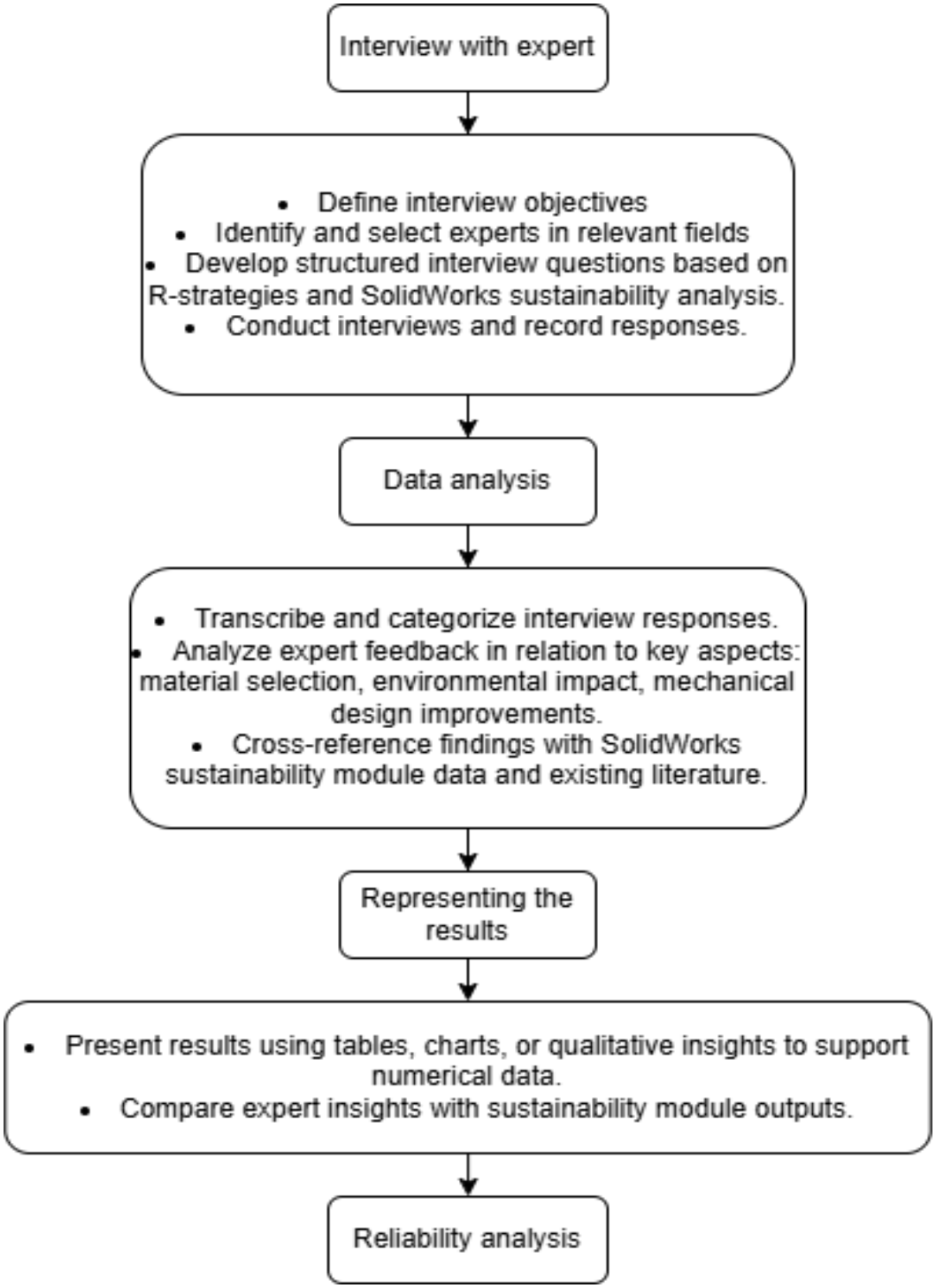

Figure 4. Interview with an expert on implementation.

2.4 Literature review

2.4.1 Flowcharts presentation of literature search and review

The method of collecting literature sources for the thesis is shown in Figure 5. For the literature review, two parallel source paths are available, scientific and commercial. The knowledge from the literature aims to answer different aspects of W-Band directional coupler manufacturing. The basic information can be divided into two categories. The first category is the description of the part, manufacturing techniques, used materials, and an explanation of different component production. One of these components is the middle plate of the directional coupler, shown in Figure 3. This component production contains high precision, to ensure proper displacement and roundness of every hole, each of which is 0.6 mm in diameter. The second category is potential environmental improvements. A central aspect of the research is detecting more sustainable alternatives for the material selection. In addition, production techniques and waste material reduction are taken into consideration. To be more precise, the scientific data needs to be taken from the IEEE databases, and the data needs to be no more than 5 years old; otherwise, due to constant progress in engineering technology, the information given might not be reliable. On the other hand, commercial sources can be used. Using those, it is important to pay attention to the information in the article that is related to the thesis topic. Likewise, it is critical to be confident about the article's veracity and authenticity. An effective way to verify the trustworthiness of the website is by checking other articles written by the same author or reviewing whether the article was written by well-known global companies. To eliminate any disinformation, it is preferable to go through at least three comparable references, written about the same issue. The results of the literature review should be systematically analyzed and documented. The goal of the literature research is to find sustainable alternatives for the directional coupler material selection and manufacturing improvements.

2.4.2 Questions literature research aims to answer

How does gold plating affect the environment?

How to recycle the components of the part?

What are the most suitable materials for the part?

What is the time and energy consumption for the production?

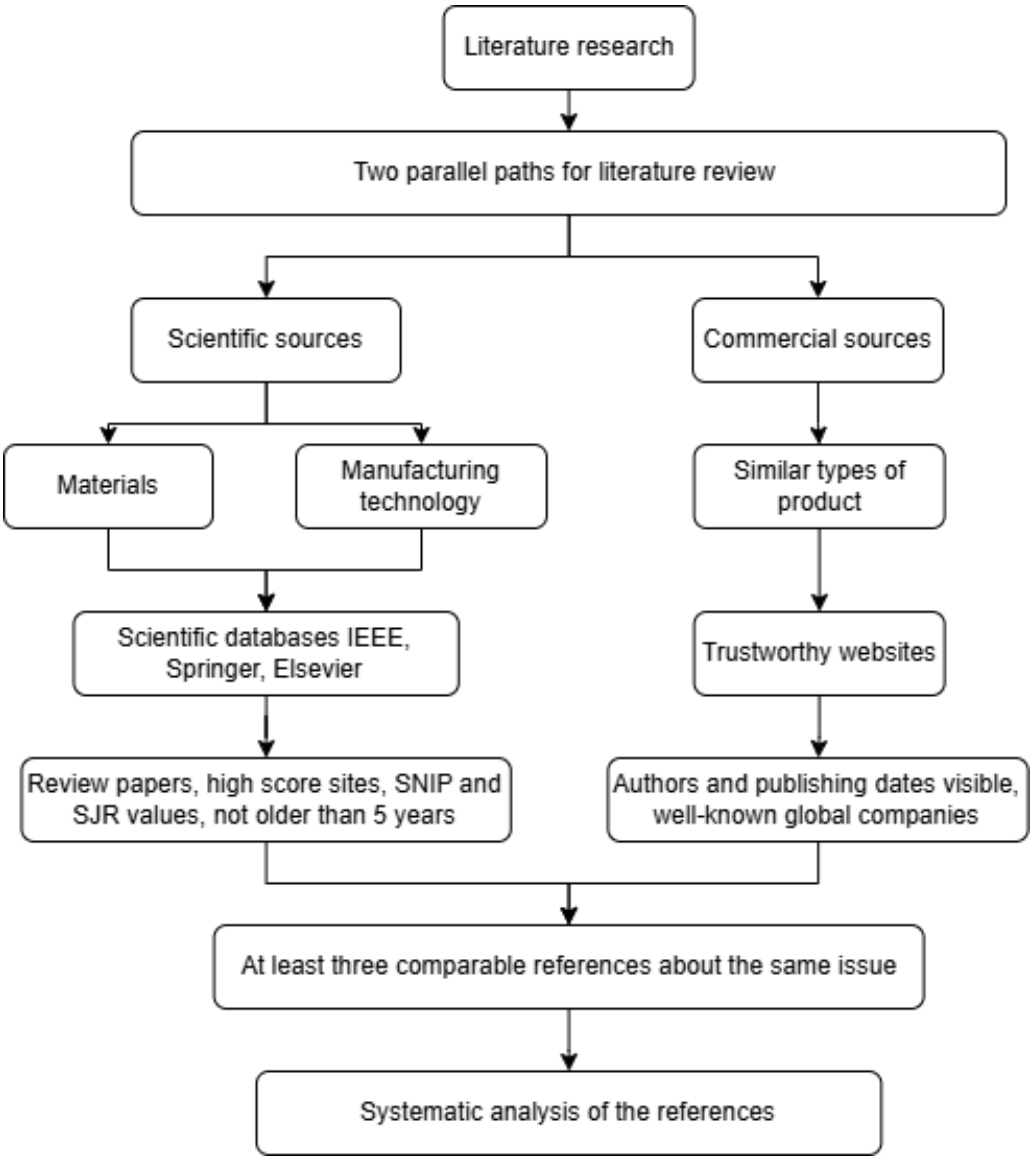

Figure 5. Flowchart of literature review implementation.

2.5 Utilization of the 3D SolidWorks model

2.5.1 Utilization of R9-principle and SolidWorks Sustainability module

The method of 3D model observation is shown in Figure 6. To assemble a valid 3-D model, the precision of the component measurements is vital. Multiple measurement attempts are allowed to secure a precise 3-D model. The first drawing after the measurements is shown in Figure 7. After the part is measured, material selection should be completed. These steps are going to ensure an accurate final model, which is going to provide a precise sustainability analysis of the component. It is necessary to identify the 3D model components and establish them using SolidWorks software. Then, to double-check the model, a visual inspection is needed, comparing the 3D model and the part. To finish the 3D model, all dimensions and tolerances need to be specified, together with material properties. The next step is data analysis. Firstly, it is important to specify the design of the model and compare it to the real part. Then, assess the mechanical properties, sustainability aspects, and circular economy criteria. Together with that, the 3D model observed features with technical documentation and industry standards. After the comparison, identify potential design improvements or issues. To represent the results, first, it is necessary to create a structured report with annotated screenshots of the 3D model. After that, summarize key observations in tables and charts. Additionally, providing visual comparisons with the original design specifications. The last step is suggesting improvements based on the analysis. The analysis is going to be based on the SolidWorks sustainability module. The representation is going to contain Carbon Footprint, Total Energy Consumption, Water Acidification, and Water Eutrophication.

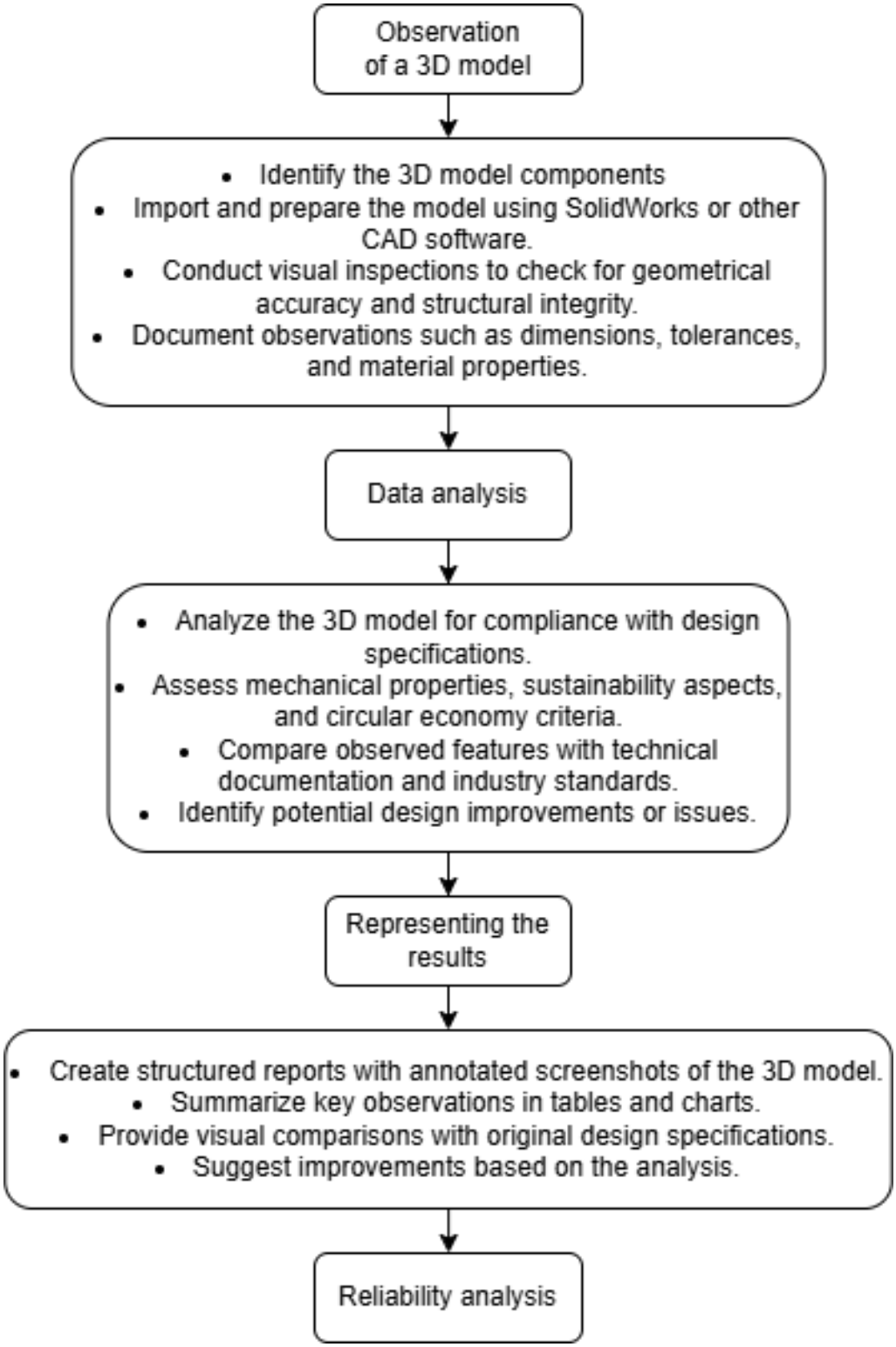

Figure 6. Observation of a 3D model implementation.

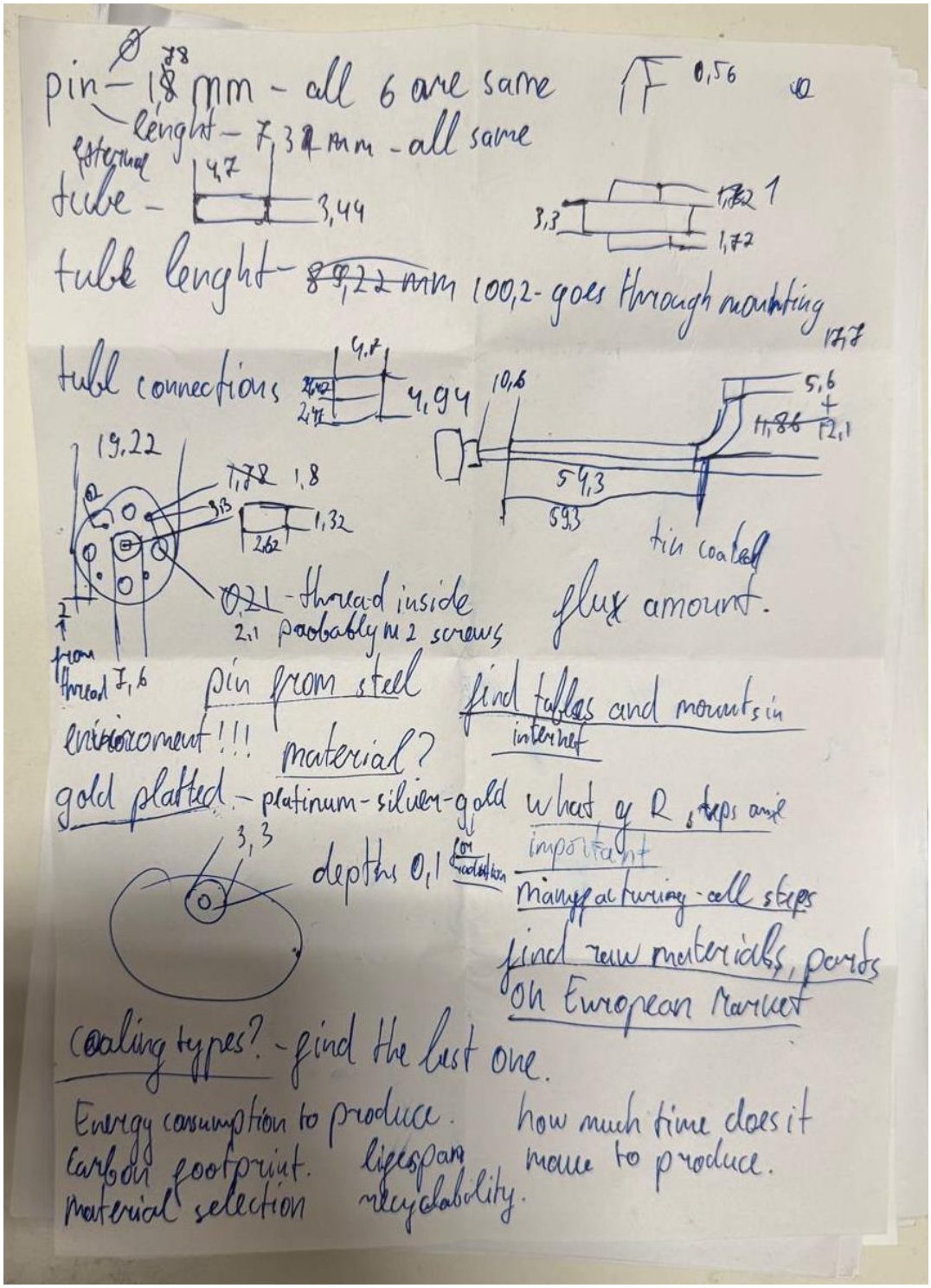

Figure 7. Hand-drawn parts of the component with measurements and notes for further investigation

2.6 Means to carry out reliability analysis

	Expert Interview	Literature analysis	Observation of the SolidWorks model	Triangulation
Validity	Checking the competence	Checking if the source is valid, not Wikipedia, and the sources should be no more than 5 years old	Checking the precision of the measurements and material selection	Checking if all three methods give the same results
Reliability	Double-checking (ask if it is allowed to record)	Mark important parts, take notes	Measurement tools need to be calibrated	At least 2 methods should be reliable
Sensitivity	Listen to all answers to all questions, as from other students	Read carefully, sometimes read twice	Compare the model to the part	Compare your results with your groupmates
Error analysis	Only one professor was interviewed	Compare different sources, and see if the information is similar	Remeasuring all the components	Errors should be considered
Accuracy	Get the answers you need (precise questions)	Read the text properly, and precisely understand the given information	Use precise tools for measurements	Compare your results with your groupmates to see if the precision is on the same level
Saturation	Listen to all questions and answers, and see if they are the same	Check if the abstract is valid, and if the abstract gives the answer to the question	Only one 3-D model was produced	Methods need to be saturated.

Table 1. Reliability analysis of the triangulation.

3 Results

The results of this chapter will show the potential improvements of the W-Band directional coupler manufacturing environmental aspect, using R9 strategies. The improvements contain new material selection and manufacturing techniques, the goal of which is to improve the sustainability of the component production. The expected outcome is to select new, environmentally friendly materials and implement sustainable manufacturing technologies.

3.1 Implementing R9 strategies

The environmental aspect of the W-Band Directional Coupler production can be explored through R9 strategies to understand which stage of the manufacturing process can be improved. Since the component is manufactured for aerospace purposes, aspects R3-R9 cannot be applied due to the location of the component. Phases of R9 strategies are represented in Figure 8. The component cannot return to Earth. For this reason, it is not possible to improve the consumption phase and the end-of-life phase. This means that the focus moves to the design and manufacturing phase.

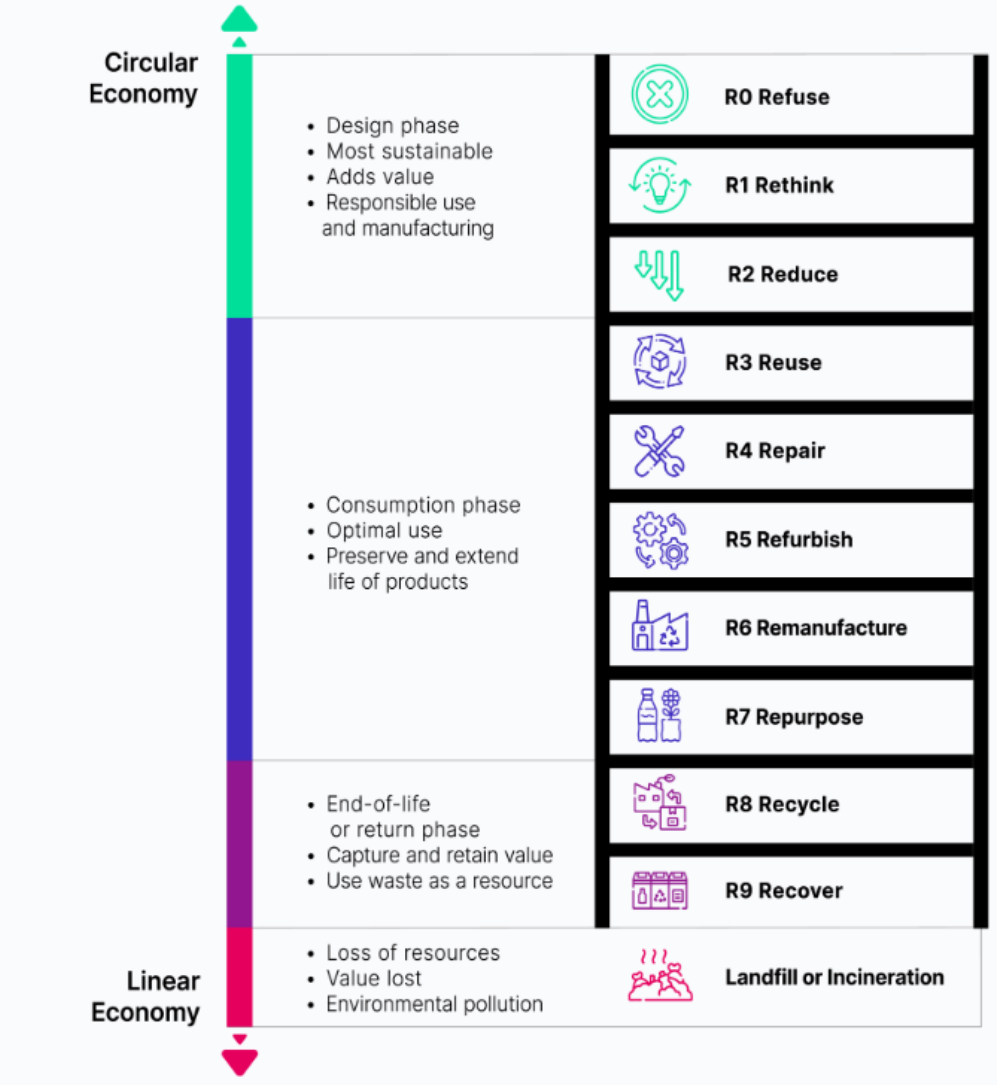

Figure 8. R9 strategies flowchart (Malooly 2023)

3.2 Expert Interview

From the expert interview (Expert 2025), it was discovered that the middle plate of the directional coupler is produced out of copper, a non-magnetic material, to ensure high conductivity. Copper conductivity is 5.96*10^7 S/m at 20 °C. For comparison, silver conductivity is 6.3*10^7 S/m at 20 °C. Silver is the best conductor of all metal alloys. For the same reason, the whole part is also produced out of non-magnetic material, especially for the high-frequency device. The most common material for the directional coupler is C28000 brass alloy (Yufeng & Xuequan 2012, 166).

To ensure high conductivity and reflect heat and radiation, the directional coupler is gold-plated. In addition to ensuring high conductivity, all components of the directional coupler are soldered together with silver. It was also discovered that there are no widespread alternatives for gold plating and silver soldering. The electrical and engineering properties of copper are displayed in Table 2.

Property	Value/Description
Atomic Symbol	Cu
Atomic Number	29
Atomic Mass	63.546 u
Density	8.96 g/cm³ at 20°C
Electrical Conductivity	~5.96 × 10^7 S/m at 20 °C
Young's Module	~110–130 GPa
Melting Point	1084.62 °C

Table 2. The electrical and engineering properties of copper

3.3 Literature review

The biggest amount of information is found during the literature review. For this reason, the decision was to separate the results into 2 different groups.

3.3.1 Material selection

During the exploration of commercial literature sources, the UNS C28000 (Muntz metal) brass alloy was spotted as the most often applied material (Fairview Microwave n.d.; Yufeng & Xuequan 2012, 166; AZoM 2013; Rathi et al. 2008, 590). This material is widely implemented in aerospace engineering; however, modern research provides two additional materials, UNS C69300 ECO brass alloy and a new, innovative composite named graphene.

The UNS C28000 brass alloy was primarily chosen by manufacturers due to its good conductivity and no lead in material compound (Wu et al. 2024), however, UNS C28000 brass alloys have moderate machinability. Comparing the machinability of the UNS C36000

brass alloy (Sequoia Brass & Copper n.d.), the reference standard for brass machining with a 100 score, with UNS C28000, the Muntz metal has a 40 score for machining (Copper Development Association Inc. 2020). The UNS C69300 ECO brass alloy has a machining score of 85, which leads to a 40% decrease in energy consumption for the components manufacturing. The difference in alloys' compounds is 2-3% silicone implementation in UNS C69300 brass alloy, to improve the sustainability of material production (Shahnawaz & Muhammad 2022, 1103), as well as the difference in copper and zinc ratio (London Metal Exchange 2025). The comparison of UNS C28000 and UNS C69300 alloy compounds is displayed in Table 3.

Component	C69300	C28000
Copper Content	73-77%	59-63%
Zinc Content	20-22%	40%
Silicone Content	2.7-3.4%	-
Lead Content	0% - Lead free	≤0.09%
Other Metals	Fe ≤ 0.1%, Ni, Sn	Fe ≤ 0.07%, Ni, Sn

Table 3. C69300 and C28000 alloys compound table.

The UNS C69300 material is environmentally friendly for several reasons (Blankey-Milner et al. 2021). Lead-free alloy composition that the RoHS and REACH approve is the main aspect of sustainability. According to RoHS, lead was banned from exploitation in 2006 to ensure sustainable improvements, due to the hazardous vapor and extraction complexities (Menon 2015, 4021). Another reason for the alloy's sustainability is good machinability (Stavroulakis 2022, 246). The improved machining of the UNS C69300 brass alloy is achieved due to the higher yield and tensile strength. This allows for cutting and rolling the material to produce the part without affecting mechanical properties. In comparison, the widely used UNS C28000 brass alloy is suitable only for rolling, however, cutting affects the structural durability of the component. In terms of electrical and thermal conductivity, both alloys have similar characteristics. The UNS C28000 alloy has 10% higher electrical and 9% higher thermal conductivity (Sulitsin et al. 2020), although both alloys' values are suitable for aerospace engineering, particularly for W-Band directional coupler production.

Mechanical and electrical properties of materials are displayed in Table 4 (Concast Metal Products Co. 2023).

Property	C69300	C28000
Electrical conductivity	14,5 MS/m	16MS/m
Thermal conductivity	110W/mK	120W/mK
Machinability	85	40
Tensile strength	585MPa	360MPa
Yield strength	310MPa	140MPa

Table 4. Mechanical and electrical properties of C28000 and C69300 brass alloys.

Another crucial aspect that needs to be taken into consideration during material selection is gold-plating exposure. The beneficiary of UNS C69300 brass alloy combines two significant factors. The comparison of the gold-plating process between alloys was identified for the chemical gold-plating, the most commonly used gold-plating technique in aerospace engineering. The first aspect is the pre-treatment of the component before gold-plating. Due to the lower proportion of zinc and silicone implementation in the UNS C69300 alloy, the surface is less reactive, due to Zn rapid oxidation in the air. Furthermore, UNS C28000 brass activation requires higher acid concentration. The UNS C28000 brass alloy requires 10-20% HCl concentrated acid, while the UNS C69300 requires 5-10% HCl concentrated acid (He et al. 2024). These factors and machining complexities require deeper and more detailed pre-treatment for components produced from UNS C28000 brass alloy. For the C28000 brass alloy, machining lube is required to ensure structural stability of the future part. The lube stays on the component and requires additional treatment to secure sterility of the surface before gold layer implementation. The UNS C69300 ECO brass requires simpler pre-treatment, light brushing, or blasting if the oxide layer is visible (Shishkovsky 2018). The second factor is the gold-plating process. The higher Zn concentration in UNS C28000 brass alloy, in comparison with the UNS C69300 brass alloy, affects gold-plating. Rapid Zn oxidation can affect gold-plating by creating a thin oxide layer between the material and the gold layer, causing low-quality plating and complications with product finish. In addition, due to the unstable UNS C28000 alloy properties, the gold-plating process demands higher

precision and a restricted time frame for each layer of the plating. In contrast, the UNS C69300 brass alloy, owing to lower Zn concentration and Si application, provides precise and high-quality gold-plating with less sensitivity to timing between steps (Egorova & Ananikov 2016). This aspect reduces the control level during production, reducing energy consumption. These aspects provide environmental benefits of UNS C69300 brass alloys over the UNS C28000 brass alloy.

Another sustainable option for the material selection is graphene (Kogan 2022). Graphene is an innovative material and is not fully explored; however, it is already showing the potential to become the future of engineering (Torres et al. 2021), including aerospace engineering (Graphenea 2022). Graphene is a 2-dimensional material composed of carbon atoms aligned in a hexagonal structure. The simplicity of material structure provides extraordinary properties (Sellathurai 2023). A single layer of graphene is 99.7% transparent and is ~0.34 nm thick (one atom thick). In terms of mechanical and electrical properties of the material, the data is prominent. Graphene is the stiffest, stiffer than diamonds, and the strongest material in modern material selection. The theoretical electrical conductivity of graphene is 2 times higher than the conductivity of copper. However, in practice, nowadays, the highest value of graphene's electrical conductivity is 10^3 times smaller than the theoretical values. The material is still in the development phase; for this reason, theoretical and practical values vary greatly. Mechanical and electrical conductivity values are presented in Table 5.

Property	Graphene (mono layer)
Young's Module	1 TPa
Tensile Strength	130 GPa
Electrical Conductivity (theoretical)	10^8 S/m
Electrical Conductivity (practical)	10^5 S/m

Table 5. Mechanical and electrical properties of graphene.

In terms of sustainability, graphene is identified as a sustainable brass replacement. There are at least 6 different ways of graphene production, however, the most sustainable option is the Liquid-Phase Exfoliation method (Hernandez 2008, 563). The necessary raw material

for production is graphite powder. The most sustainable ways of graphite powder production are extraction from the physical waste, from coconut shells, sugarcane bagasse, wood chips, coffee grounds, or from CO_2 and methane. These methods help to recycle the waste to produce high-performance material for aerospace engineering. The production process consists of 5 steps: graphite dispersion, sonication, exfoliation, centrifugation, and collection (Awada 2023, 1897). The final product of this method is a few-layer graphene, sometimes even a monolayer of graphene, usually a 1–5-layer structure. As a solvent, a usually ethanol-water mixture, to separate graphene layers from each other. This method of production does not require acids and does not release harmful vapor into the atmosphere, which makes it environmentally friendly.

Due to graphene's high conductivity, there is no reason to gold-plate the component, since the theoretical electrical conductivity is more than 2 times higher than the conductivity of gold. In comparison, graphene's theoretical conductivity is 10^8 S/m, and gold's conductivity is $4.1*10^7$ S/m. To ensure the conductivity of 92 GHz frequency, 10-20 layers of graphene are required with a total thickness of 3-7 nm. In terms of space radiation resistance, 3-10 layers of graphene are necessary to withstand Atomic Oxygen, Ultraviolet radiation, and trapped electrons or protons. Due to the complexities of graphene production nowadays, it isn't easy to implement it in mass production.

3.3.2 Sustainable gold plating equivalent

Gold-plating is necessary in aerospace engineering. Perhaps gold is not the best electrical conductor, but it can withstand space radiation without material structure changes (Okinaka & Hoshino 1998, 3). For example, silver is a better electrical conductor than gold, however, it cannot be implemented as a coating due to oxidation, which causes loss of conductivity. Traditionally, chemical gold-plating is used with a gold layer thickness of 5 µm. This method allows for gold plating with high precision and small-time consumption (Ma et al. 2024; Menon 2015, 4021). However, this method requires cyanide acid to ensure stability and control of the process. The acid vaporizes during the manufacturing process, releasing hydrogen cyanide gas, a flammable and hazardous gas (He et al. 2024). The sustainable alternative to chemical gold-plating is electroless laser powder-bed gold-plating (Gezerman & Çorbacıoğlu 2015, 641; Inberg 2020, 395). This method does not require cyanide or any

other acid (Li 2024, 1; Pu et al. 2022). However, this method requires advanced machinery. The first step of the gold-plating, after the component is prepared, is placing the component into the provisional bath filled with gold powder. For the second step, a laser is required. The laser has a significant role in the gold-plating process. It heats the gold powder until it melts and connects to the component (Hansen & Pawlewicz 1982, 2064; Wu 2021). Nowadays, the limitation of this method is component dimensions; however, this method is suitable for the W-Band directional coupler. This gold-plating method does not require additional acids; however, energy consumption is higher, and primary investment in the machinery is 5 times higher than for the chemical gold-plating. The value analysis of different design options is represented in Table 6.

		Grade for material and design options	Grade for material and design options	Grade for material and design options	Scores for material and design options	Scores for material and design options	Scores for material and design options	
	Weightening							#1- sustainable material #2 - different brass alloy
R9 criteria	of the criterium	#1	#2	#3	#1	#2	#3	#3 - different gold plating
Refuse	0.3	2		2	0.6		0.6	
Rethink	0.5	4	3	1	2	1.5	0.5	
Reduce	0.2		1	3		0.2	0.6	
Reuse	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
Repair	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
Refurbish	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
Remanufacture	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
Repurpose	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
Recycle	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
Recover	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
Total	1			Total scores (TS)	2.6	1.7	1.7	
				Total price (TP) €		7900.93	250000	
				Costs/score (C) €		4647.605882	147058.8235	

Table 6. Value analysis for different design options.

3.4 Utilization of a SolidWorks 3D model

The SolidWorks sustainability module is the main tool for 3D model research. Using this tool, it is possible to capture the difference in environmental impact when different raw materials are used. In this section, the comparison is set between different brass alloys. The first alloy is high-leaded brass UNS C34200 and Free-Cutting brass UNS C36000. The second alloy is recommended as one of the most sustainable brass alloys since the lead alloy percentage in the material is very low. According to the SolidWorks Sustainability Module, UNS C36000 alloy has 45% less Carbon Footprint, 52% less Total Energy Consumption, 28% less Air Acidification, and 36% less Water Eutrophication than the UNS C34200 high-leaded alloy. This study represents the effect of the brass alloys and manufacturing complexities on the environment, especially machinability. ISO 2768 mK and Ra 6.3 standards were chosen for the tolerances and surface finish (Electronic Design. 2024;

Anselmetti & Louati 2005, 1124). Higher tolerance precision is not required in the production and would require extra energy for manufacturing. This would increase the total environmental impact of component production. More precise numerical data of sustainability analysis is shown in Figures 9 and 10. Due to the limitations of the material selection in the software, deeper analysis was not possible.

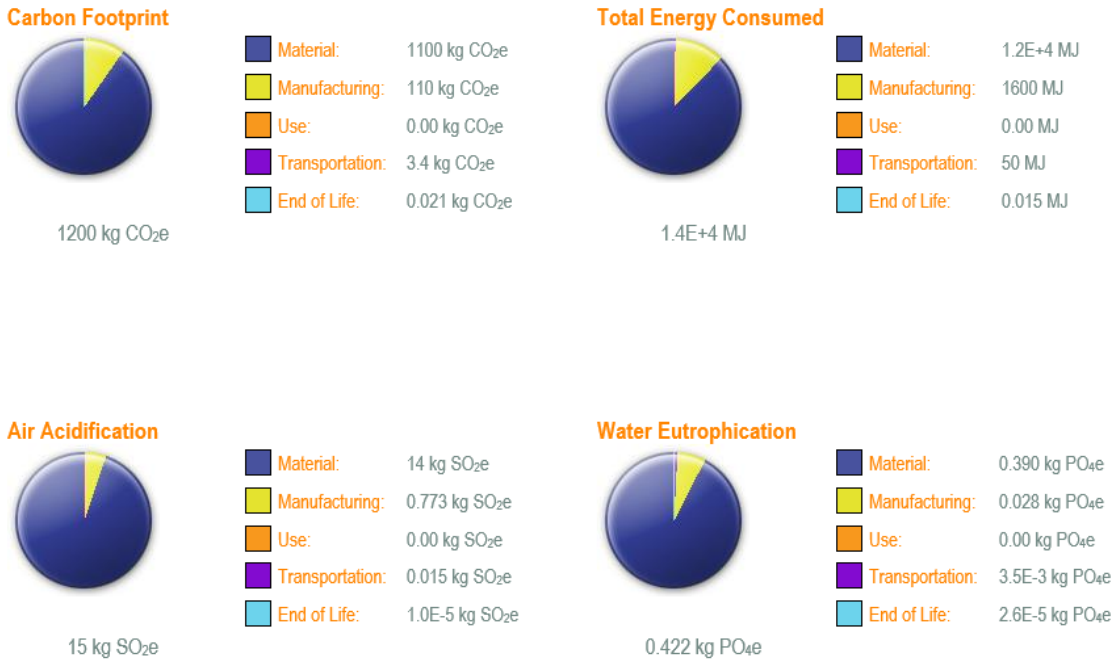

Figure 9. Energy and resource consumption for C36000 brass alloy production

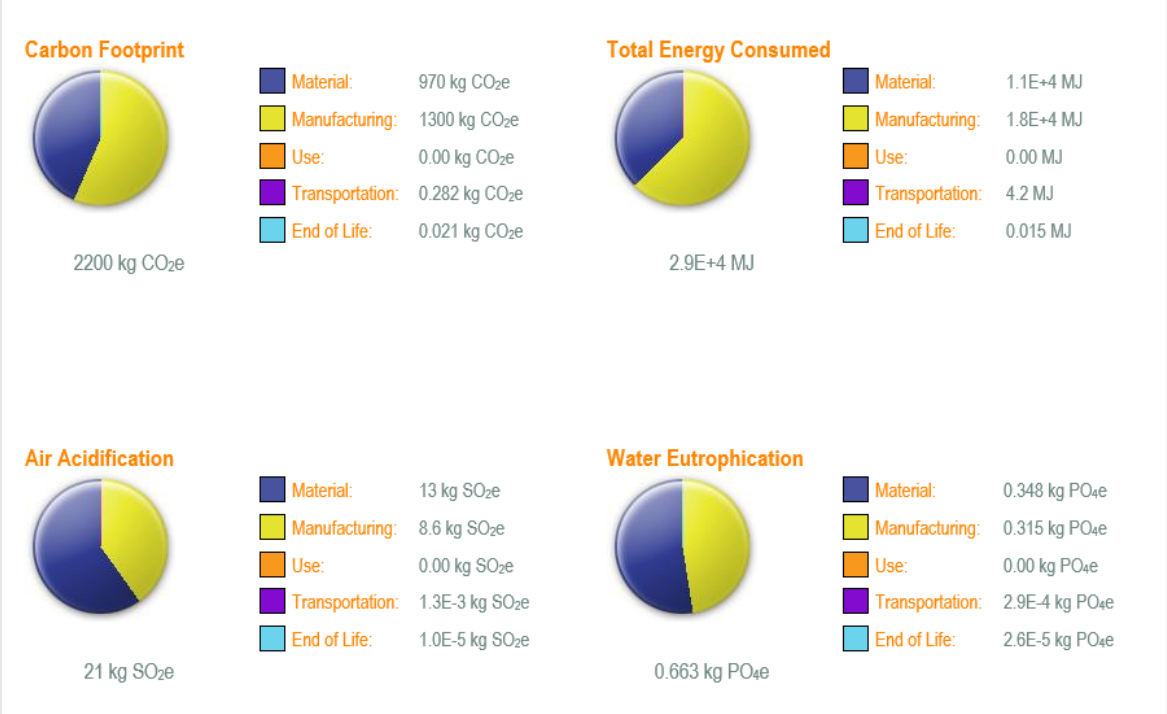

Figure 10. Energy and resource consumption for C34200 brass alloy production

3.5 Applied triangulation

The triangulation method allowed for combining, fulfilling, and comparing the analysis from each triangulation section. After the comparison of the results, the validity of the found information was confirmed. During the expert interview, the professor from Aalto University explained the material selection of the middle plate of the directional coupler, see Figure 3. Copper was the chosen material. To support this selection, a literature review provided a conductivity table, see Table 7. The table provides the numerical data, which shows a high conductivity value of copper material, 5.96×10^7 S/m at 20 °C, conceding only to silver, with 6.3×10^7 S/m at 20 °C. Although the difference is only 0.34×10^7 S/m at 20 °C, compared with the gold, the third best conductor, with the 1.86×10^7 S/m at 20 °C distinction. This shows relative similarity between copper and silver as conductors, thus, the environmental impact and material costs for copper are lower.

Another combination of the results came by comparing the SolidWorks sustainability analysis and the literature review at the raw material selection phase. The primary literature

research revealed that the most widely implemented material for different aerospace engineering components, including the W-Band directional coupler, is UNS C28000 brass alloy (Muntz metal). This material was chosen previously due to its good machinability and lack of lead in the compound. After deeper research, more sustainable material, UNS C69300 brass alloy, was spotted. This material is called the ECO brass. The sustainability analysis in SolidWorks between UNS C36000 and UNS C34200 brass alloys, the material limitation in the software did not allow for full exploration of other brass alloys. The analysis proved sustainable benefit for the UNS C36000 brass alloy, see Figures 9 and 10. Combining both the literature review and the SolidWorks sustainability analysis the most suitable material for the components production.

Metal	Conductivity, 20°C, S/m X10^7
Silver	6.3
Copper	5.96
Gold	4.1
Aluminum	3.5
Tungsten	1.79
Zinc	1.69
Nickel	1.43
Iron	1
Platinum	0.943
Tin	0.917

Table 7. Different metals' electrical conductivities (Electronic Design 2024).

4 Discussion

After the analysis, these are the primary results for the components' sustainability improvement. In this section, key findings and conclusions will be discussed, along with the comparison and connections with former research, the reliability assessment of the results, and topics for future research will be considered.

4.1 Key findings and conclusions

Two aspects of the parts component’s selection were studied. The first and most important was raw material selection for manufacturing. Due to the sustainability aspect of the parts production, the raw material selection is very important to lessen the overall environmental impact. During the research, 4 different materials were discovered; however, after the sustainability analysis, only 3 of them were taken into further consideration. The innovative, however not completely scientifically explored, material for W-Band directional coupler production is graphene. This material can replace both brass and gold, which are used for gold plating, through graphene's incredible mechanical and electrical properties. Although this material is not produced at industrial levels, all research showed the advantage of the composite compared to the most used metals, copper, gold, silver, and brass. To ensure the least environmental impact during the material generation, the green reduction of the graphene oxide is the most suitable option. During this process, the utilization of the plant extracts as a reducing agent is the most eco-friendly option to replace the traditional chemical method of graphene production, leading to sustainable and high-quality graphene manufacturing. However, graphene is not a mass production material. For this reason, most competent material from the existing metal alloys was discovered. During the studies, the best brass alloy for the directional coupler production is UNS C69300 brass alloy. This alloy ensures not only high enough conductivity and mechanical properties, but also a smaller ecological footprint. For comparison, the widely used UNS C28000 brass alloy and high-leaded UNS C34200 brass alloy were taken. The sustainable material option has the lowest environmental impact. This represents that the most suitable option for the material selection

without a great financial impact is the UNS C69300 brass alloy. Another great option is to use the recycled brass that was utilized in industrial factories.

The second objective of the research was to identify sustainable gold-plating options. The standard and most widespread option of the gold-plating option is chemical gold plating; however, this method requires a hazardous chemical called cyanide to ensure the quality and thickness of the gold layer. To improve the eco-friendliness of the gold-plating, the electroless laser powder-bed gold plating is used. This method does not require any chemical additives, only gold and silver powder and a laser to melt the metal powder and produce high quality and controlled layer of gold plating. The laser gold-plating is not suitable for the gold-plating over the big components; however, for the W-Band directional coupler with dimensions 12*2*2 cm^3, this method can be applied. The machinery for this method is complicated and expensive, although the manufacturing does not release cyanide vapour. For the manufacturing workers, this plays a key role in long-term medical conditions. Human health is one of the most important sustainability aspects, which should be taken into consideration for the factory construction.

4.2 Comparison and connections with former research

In the thesis component's description, the gold-plating presence and manufacturing aspects are introduced. In the material selection stage, due to the SolidWorks sustainability module and literature research widespread application, errors were specified. In former research, material was not specified, and this fact provided freedom in primary material selection. The literature research provided a specific brass alloy, UNS C28000 brass alloy. It was possible to discover the used material online, since the W-Band Directional Coupler is mass produced component that is widely used in aerospace engineering. This discovery gave primary awareness about the ecology of the component manufacturing. Further investigation with literature review and the SolidWorks sustainability module implementation allowed for finding more sustainable material alternatives and enhancing the manufacturing technology. After the implementation of the sustainability module, the appropriate brass alloy was specified. The UNS C69300 brass alloy was selected after the sustainability analysis. Without affecting the performance of the component and manufacturing costs, thus reducing carbon footprint, energy consumption, air acidification, and water eutrophication, the chosen

material provides the most suitable option. During the manufacturing process, gold-plating was applied. According to the reviewed data, the most used gold-plating method was chemical gold-plating. The prevalence of this method is explained by the simplicity and effectiveness, as well as the quality of the final product. However, the cyanide used is a harmful acid, and its utilization is damaging human health, together with releasing cyanide vapour into the atmosphere. For the sustainable option, the choice landed on electroless gold-plating. This method does not require any acids, using only a laser and gold dust. This leads to a harmful vapour decrease, keeping the high quality of the gold layer.

4.3 Reliability assessment of the results

The research method for this thesis was triangulation: expert interview, literature review, and observation of the sustainability module SolidWorks 3D model. The comparison and combination of results and R9 strategies implementation are the fourth and fifth aspects of the research.

R9 strategies implementation: The R9 strategies are strategies for improving the environmental aspect of the components at every life stage. The W-Band directional coupler is utilized in space. This aspect limits the potential sustainability improvements only to the production stage of the component.

Expert interview: The interview with a respected professor with over a quarter of a century of experience in radio engineering from Aalto University. The experience includes working with different types of microwave and frequency devices.

Literature review: The information was taken from scientific, peer-reviewed journals. The main information sources were sites such as the LUT Library and IEEE. Sources should be no older than 5 years, with rare exceptions, for example, the basics of mechanics. The commercial sources should be reliable and cited in peer-reviewed papers.

Utilization of SolidWorks 3D model: The software for the modeling and analysis was SolidWorks. The sustainability module was implemented to secure valid material analysis. During the sustainability analysis, the best of the presented material was selected, and important data was captured.

Applied Triangulation: The triangulation aims to combine the and fulfill the results found in every section.

4.4 Topics for Future Research

The material selection and gold-plating solutions are critical aspects of the component's eco-friendliness.

Modern engineering is developing new, innovative composite materials to replace widely implemented metals and alloys to provide more sustainable production processes. Graphene is the future of aerospace engineering; however, today, mass production of this material is complicated due to technological limitations. For this reason, deeper research, as well as testing and analysis, are required to implement this sustainable material in practice.

The gold-plating operation has room for improvement, to implement gold layering without harming the world.

The machinery of the W-Band directional requires in-depth research using high precision and high-quality equipment. This process aims to improve the quality of production and reduce the energy used, and reduce the environmental impact during manufacturing.

5 Summary

The thesis provides the environmental analysis and R9 strategies analysis of the W-Band directional coupler for 92 GHz docking radar. The research method contains triangulation. During the literature review, scientific and commercial information sources were examined. Material selection, gold-plating specifications, material properties, and mechanical and chemical basics were considered. After the literature review, graphene, a sustainable and innovative material, was discovered. In addition, a new gold-plating option was discovered, the electroless laser powder-bed gold-plating. The literature helped to fill the exploration table for the structured study. In terms of the expert interview, the experienced professor in the radio-engineering field from Aalto University answered all given questions, expanded, and provided knowledge of the chosen component's material selection, as well as explained the reason behind the choice. As for the SolidWorks 3D model utilization, the sustainability module was used to compare 4 elements of the environmental aspect to ensure the best possible material option. High-leaded brass alloy UNS C34200 and free-cutting brass alloy UNS C36000 were compared. After the comparison of materials, UNS C69300 was chosen as the most sustainable option. Another potential brass replacement is graphene, which is an innovation. For this reason, it was not possible to fully analyze the potential of this material.

Through the results section, it was found that if the material selection and the sustainable gold-plating option are going to be implemented, it may lead to a rapid decrease in environmental impact and a gradual increase in costs. However, it is recommended to have a team of scientists further provide deeper sustainability and material cost analysis.

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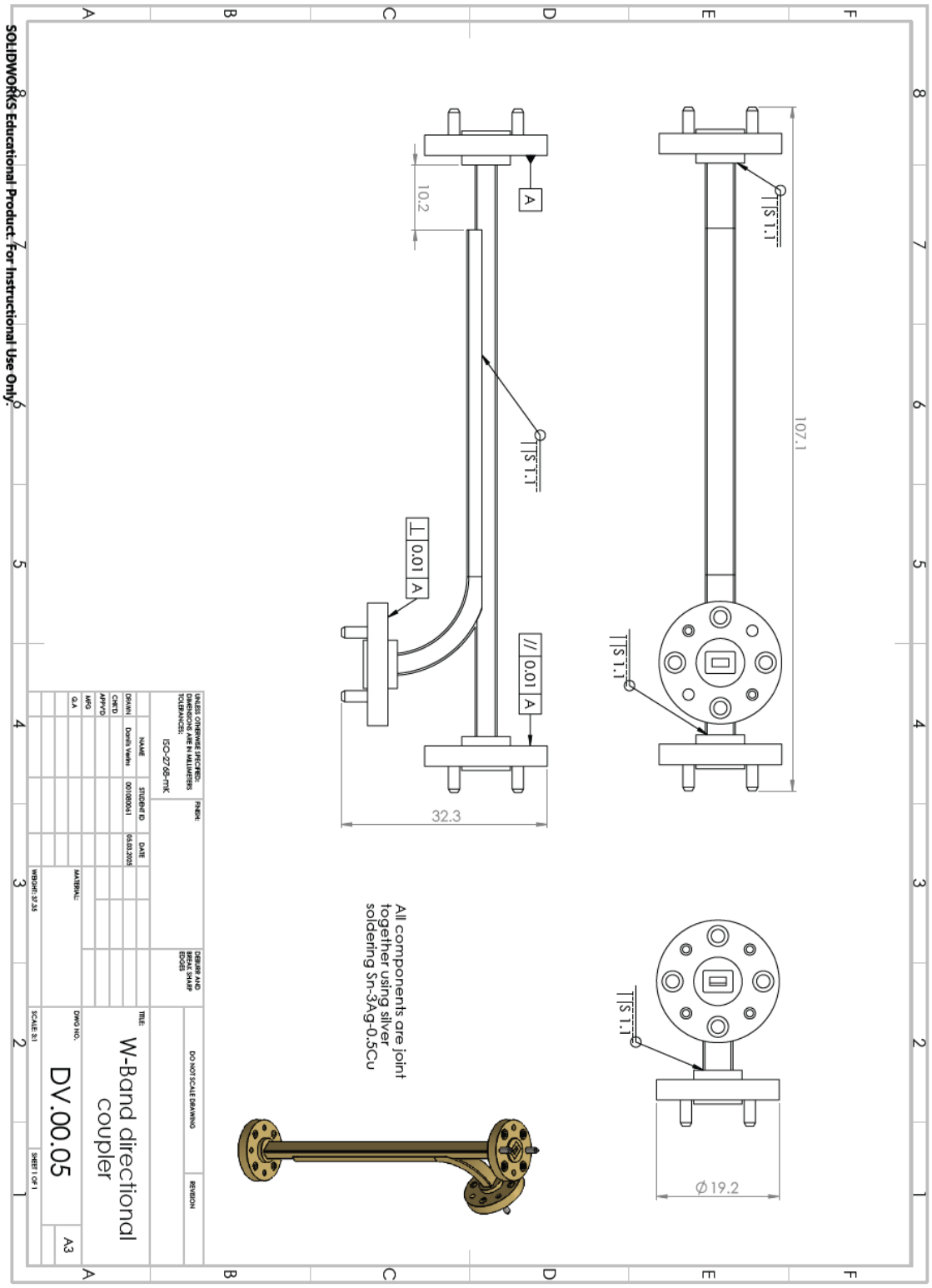
Appendix 1. Literature review table.

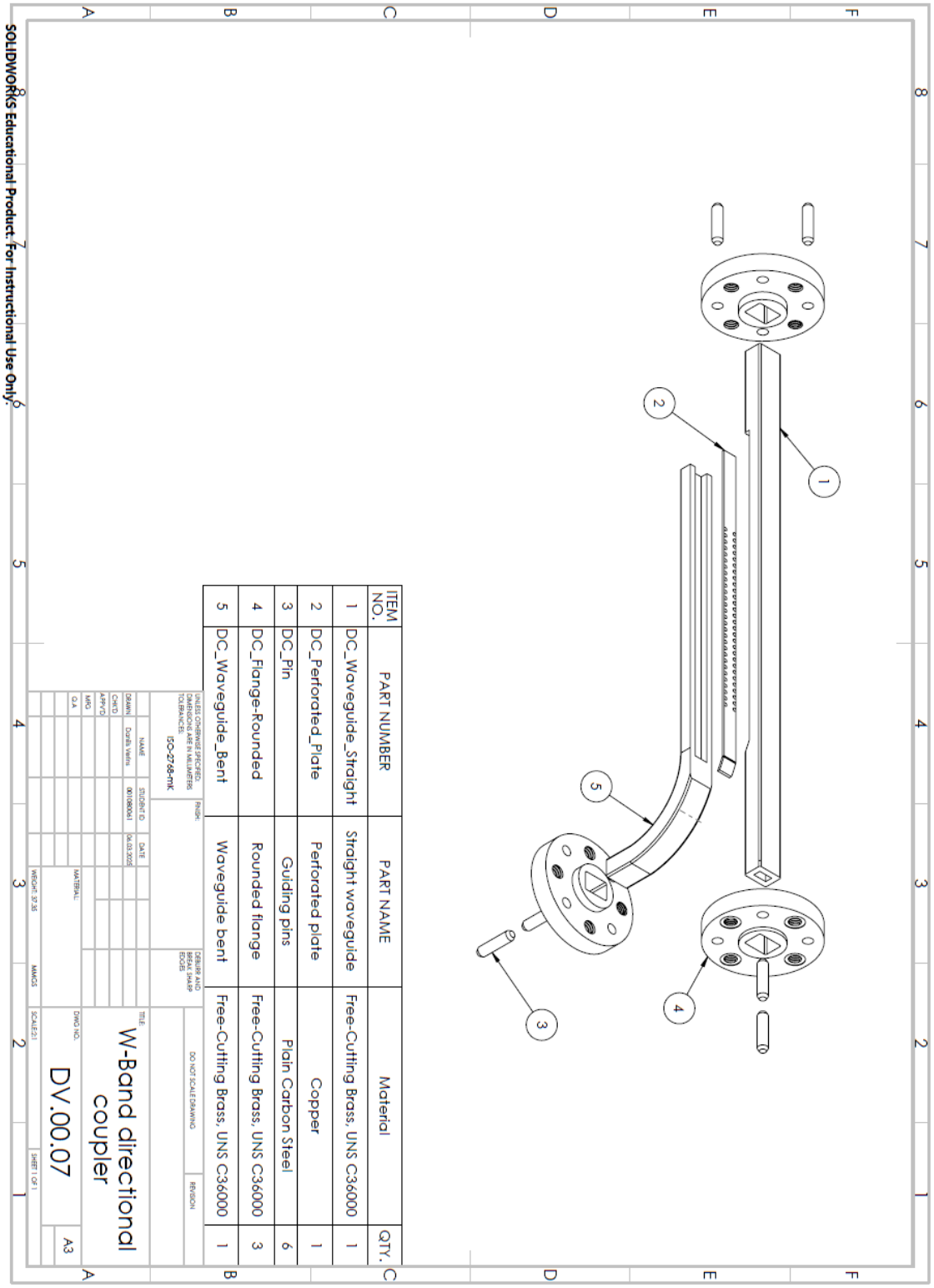
	Q1	Q2	Q3	Q4	Q5
Ref #1			The part is produced from brass, also applying gold plating.		
Ref #2				The technique is a method of thinking that is applied to itself and is improved after trials and errors.	
Ref #3					For the new, experimental, and more eco-friendly gold-plating solution, the solution was heated for around 1 hour.
Ref #4					The gold is heated for an hour to secure the correct coating process.
Ref #5	The article gives a solution to decrease the amount of used gold by mixing it with the silver before plating.				

				The 3-D printing technology might be applied to several components of production.	Gold plating is a time and energy-consuming process, however, new research gives another, more environmentally friendly solution.
					One of the techniques for the production is simply improving the basic technique until the best possible result is reached, however, another option is to apply the 3-D printing technique.
			The material should be non-magnetic, since the part is small and thin, it should not be affected by a magnetic field.		The material should be non-magnetic, and the optimal solution for that is brass, together with gold plating.
	The brass can be chemically separated into the key components, zinc and copper, after which the components are chemically recycled, with an efficiency of over 95%.	Copper and gold can be recycled using a loop strategy.			Solution for the part recycling is the chemical separation of the material into key components, after which the material can be reused.
The gold parts will be exposed to the air for the next 400 days, which may cause major health problems for the employees.					The gold dust will be exposed to the air for a long time, and to decrease the amount of gold parts, one solution is to mix the gold with the silver.
Ref #6	Ref #7	Ref #8	Ref #9	Ref #10	**Summarized observations to integrate the final answers to each question**

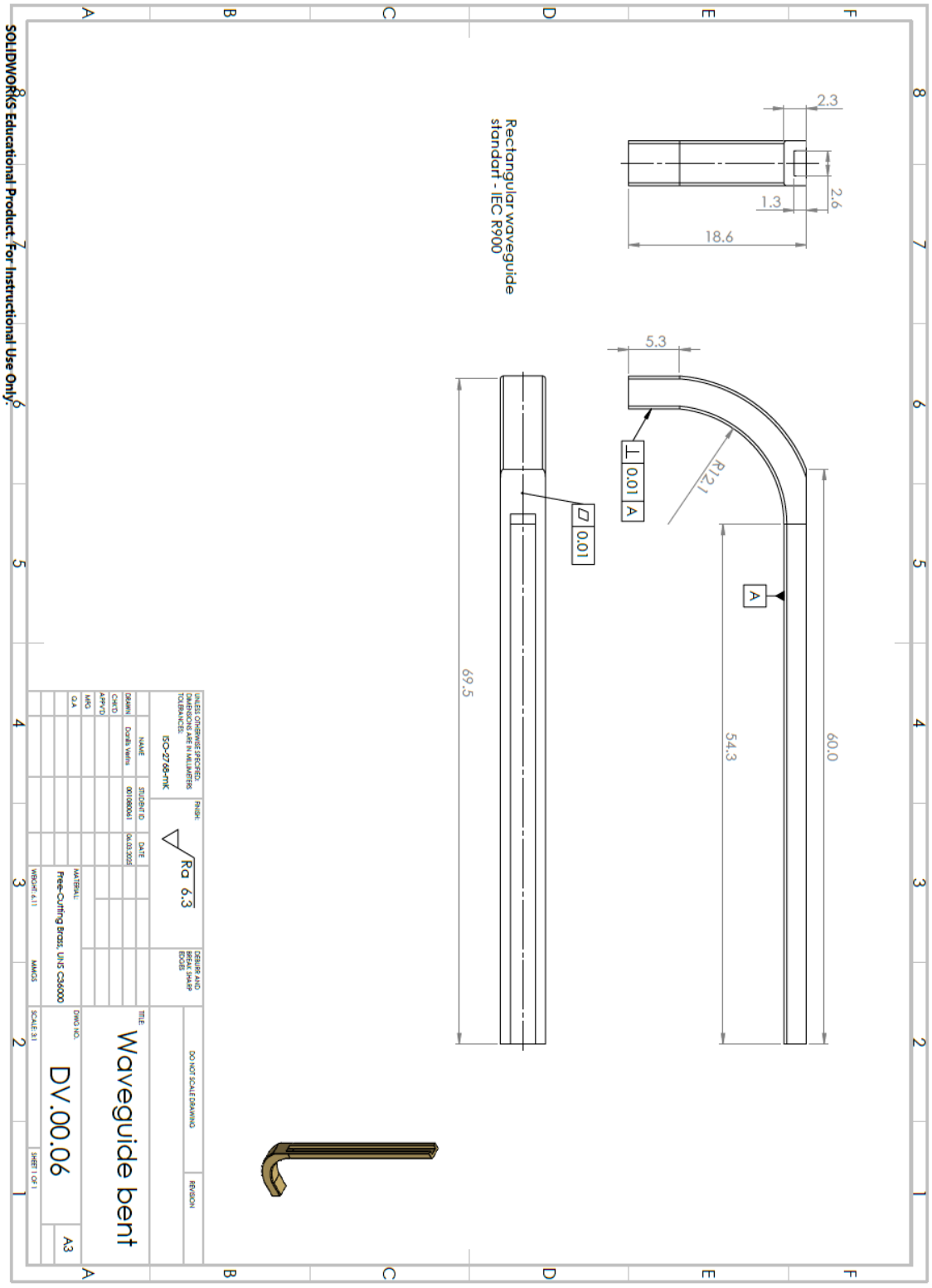
Appendix 2. Assembly drawing of a 3D model.



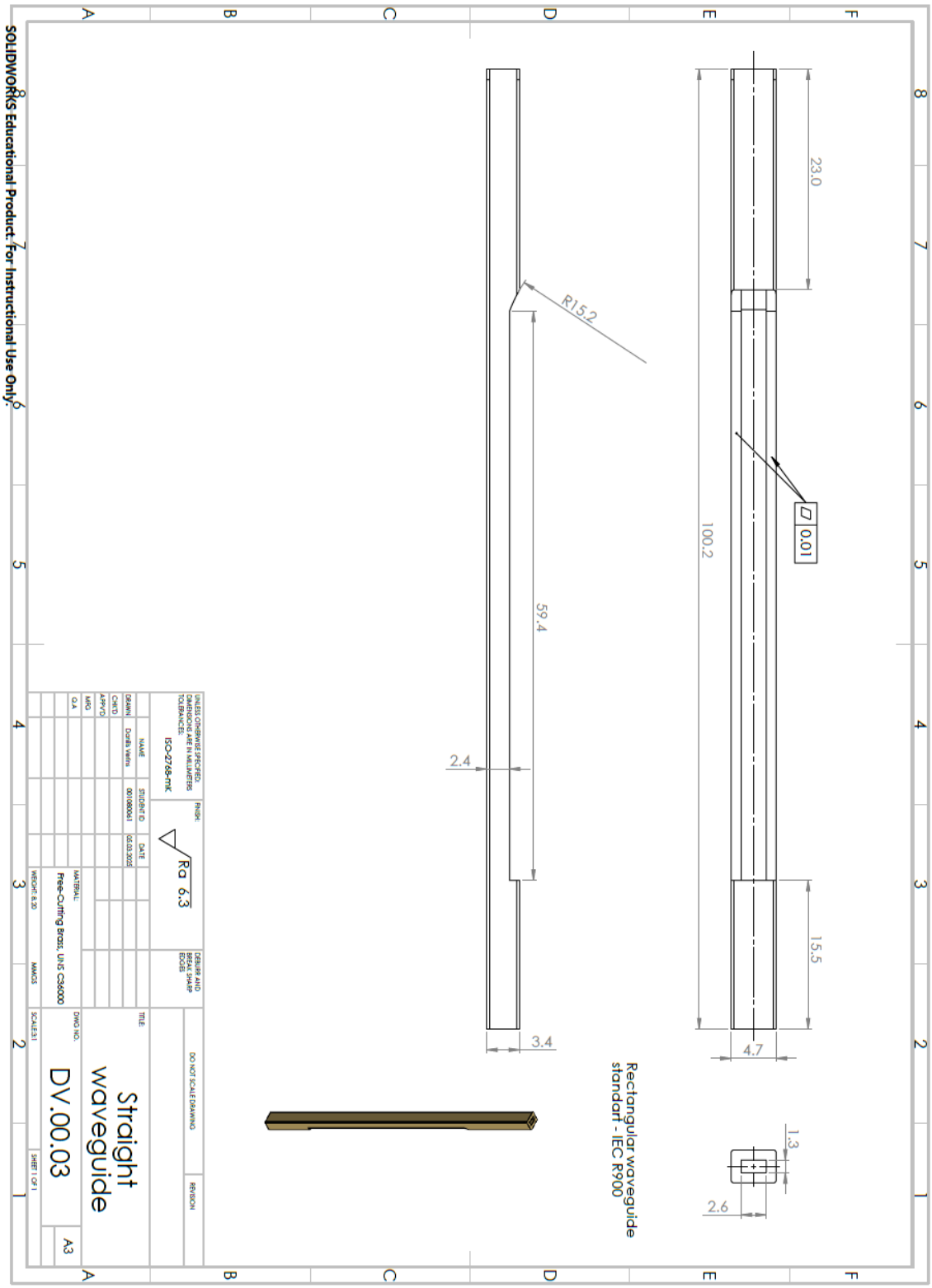
Appendix 3. Exploded view of a 3D model.



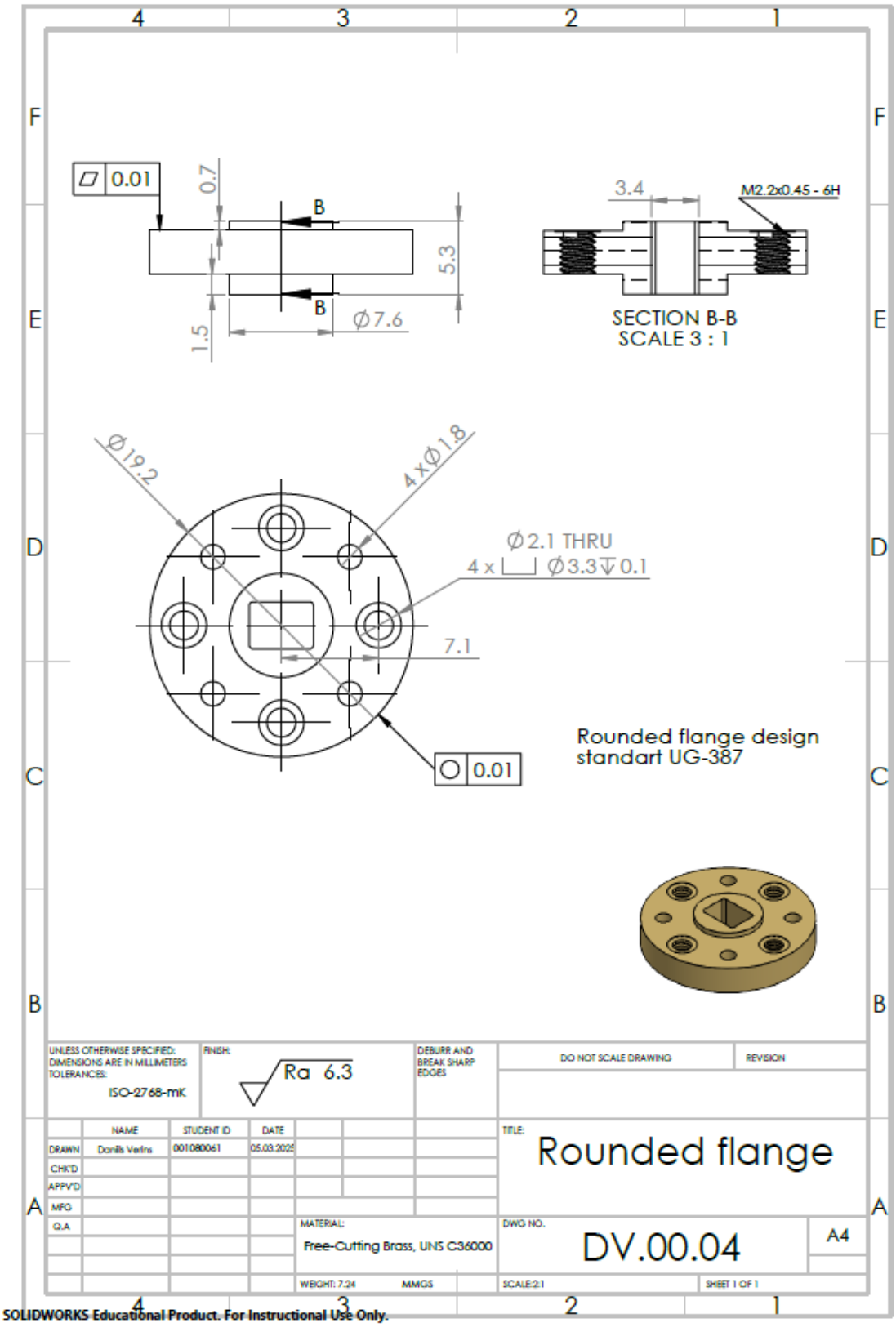
Appendix 4. Drawing of a bent waveguide.



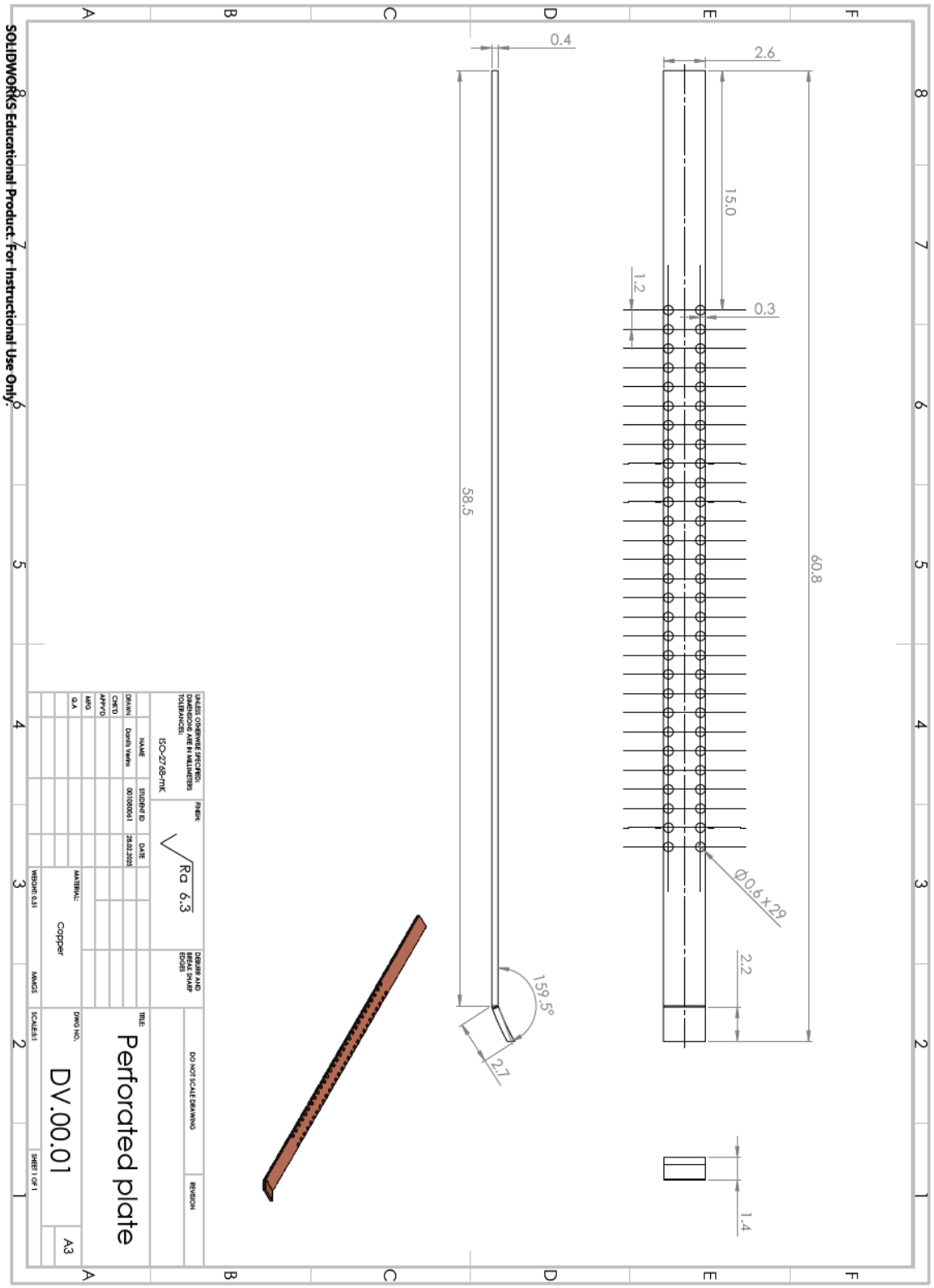
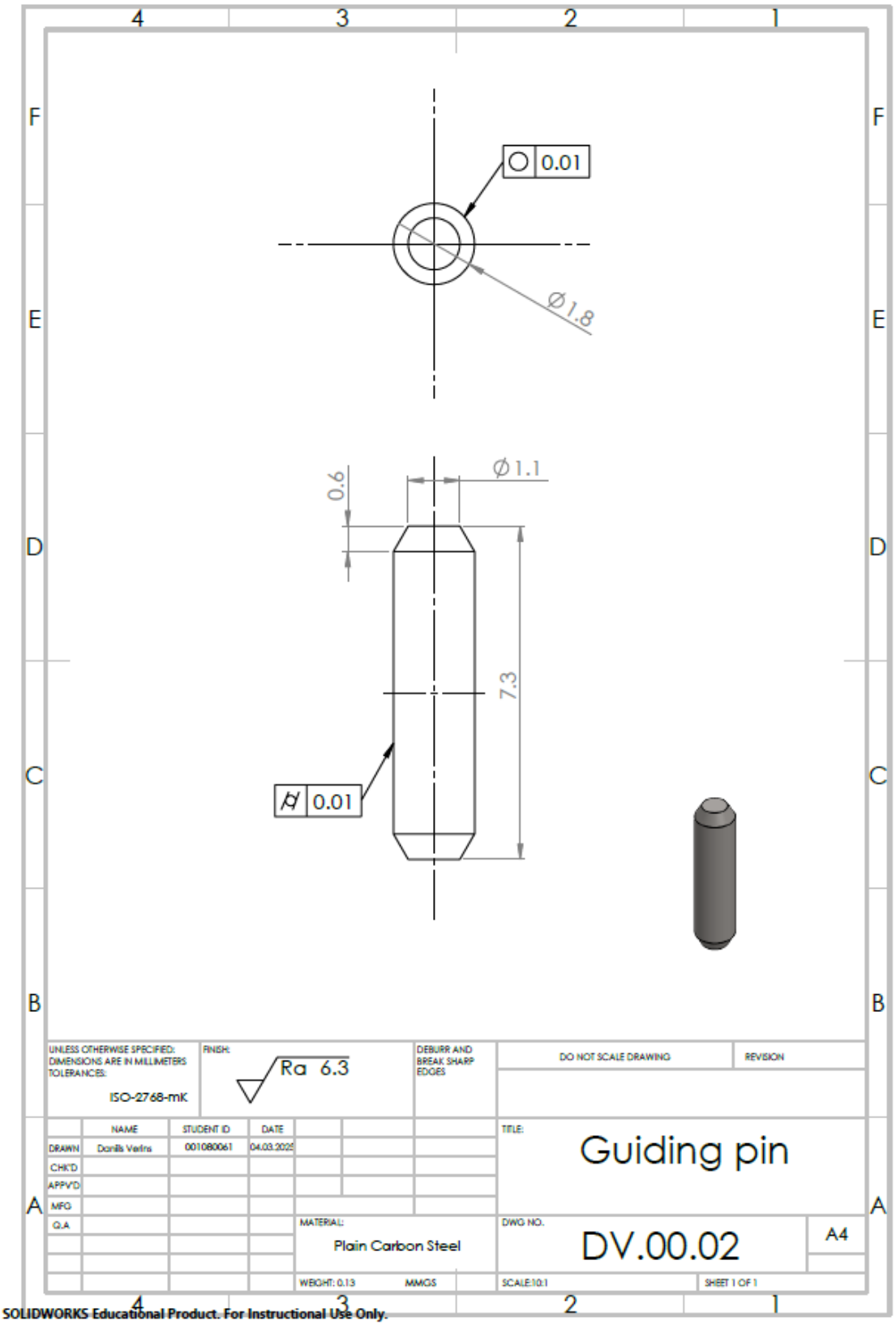
Appendix 5. Drawing of a straight waveguide.



Appendix 6. Drawing of a rounded flange.



Appendix 7. Drawing of a perforated plate.



Appendix 8. Drawing of a guiding pin.