



**DETAILED ANALYSIS OF QUALITY ASSURANCE ASPECTS CONCERNING
THE MECHANICALLY ADJUSTABLE PRECISION MICROWAVE PASSIVE
PHASE SHIFTER**

Lappeenranta–Lahti University of Technology LUT

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

2025

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Examiners: Associate Professor Harri Eskelinen

ABSTRACT

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Detailed analysis of quality assurance aspects concerning the mechanically adjustable precision microwave passive phase shifter

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The conducted research includes a complete set of quality assurance considerations needed to produce the mechanically adjustable microwave precision passive phase shifter. As the detailed and complete discussion of the device quality assurance aspects was missing, the question of what are the most influential quality assurance aspects of the discussed device responsible for the correct operation under various operating conditions was answered in the work. Furthermore, the utilized triangulation method has provided the results from three unique viewpoints, including the literature review, expert interview as well as CAD modelling. The novel approach regarding the quality assurance allowed for a detailed description of the QA actions not only after but also before and during the manufacturing stages of the device and its components. Moreover, combined with expert interview data, it enabled the creation of a digital twin of the real device. Consequently, the research question was answered successfully by deriving the conclusion from the combination and comparison of the triangulation method results. Hence, the most important quality aspects were identified, leading with the geometry and shape of PTFE element at the same time including the copper strip zone, dimensioning and tolerances as well as proper material selection, were discussed in the conclusions. Additionally, research has addressed the gap in existing literature regarding the quality assurance aspect of the examined phase shifter, at the same time introducing new possibilities for further study in the discussed area. Eventually, the work utilized a reliability analysis tool, which led to verified conclusions. Hence, it poses as a great base for further investigation of the topic.

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SYMBOLS AND ABBREVIATIONS

Symbols

d	total height of cavity	mm
h	height	mm
t	thickness	mm
w	width	mm
Z	impedance	Ohms
\mathcal{E}	strain	-

Abbreviations

CAD	Computer-Aided Design
DC	Direct Current
DOI	Digital Object Identifier
FWCI	Field-Weighted Citation Impact
GD&T	Geometric Dimensioning and Tolerancing
MW	Microwave
NA	Not Applicable
PTFE	Polytetrafluoroethylene
QA	Quality Assurance
RF	Radiofrequency
SMA	SubMiniature version A
VA	Value Analysis
3D	Three Dimensional

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Abstract

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1 Introduction

The following chapter will focus on presenting the titular topic as well as brought up the necessary consideration at the beginning of the research. The section of this chapter include goal of the research, background and motivation, research problem and question as well as applied methodology and expected contribution.

1.1 Goal of the research

The work aims to provide a detailed study on quality assurance (QA) strategies for mechanically adjustable precision microwave passive phase shifter. Moreover, the paper addresses the need for more comprehensive literature regarding the discussed microelectronic component considering the lack of such research in nowadays world. This particular issue is addressed in the following subsection at the same time indicating that the primary goal of the research is to solve the research problem and answer the research question.

1.2 Background and motivation

The microwave phase shifters are widely used microwave electronic components which are popularized in various industries, especially those relying on antenna systems such as adaptive and phased-array ones. (Wang and Yan, 2023; Zhang, Yuan and Liu, 2016) The device is primarily used in adjusting the radio frequency which enables the smooth signal steering. Hence, the microwave passive phase shifters are essential in nowadays world which still heavily relies on radio wave signals. The distinctive feature above the regarded type of phase shifter is the mechanical steering characteristics. Due to this attribute the device has the advantage of no direct current (DC) power required to shift the phase making the process energy-efficient as well as opening new possibilities to use the device in remote applications. (Wang and Yan, 2023; Zhang, Yuan and Liu, 2016) The microelectronic component is responsible for changing the phase of the signal due to the movement of double finned insulating polytetrafluoroethylene (PTFE) element towards and away the copper strip. The

phase is changed, because the signal propagation is slower in PTFE element than in air. Since the mechanism of regarded device is mechanically adjustable it means that the linear movement of PTFE element is converted from rotary movement of the tuning screw steered by operators hand. Having considered all of the above, the research regarding the quality assurance of such a device is necessary for ensuring satisfactory performance under various operating conditions.

To ensure the correctness of the research it is necessary to define some of the terms which will be frequently used across the paper. First, such a word is a quality of the discussed device. In this paper the quality is defined as the ability of the device to perform its work satisfying all the requirements with no flaws or errors outside of the margin (Gill, Xenitidou and Gilbert, 2010; Murugavel, 2017). Also, another definition used is “the requirements necessary to satisfy the needs and expectations of the consumer” (Careche and Sánchez-Alonso, 2017). Thus, the quality of microwave passive phase shifter will be considered across the paper with compliance to the two clarifications given above.

Another frequent word used across the work is the performance of the phase shifter. Regarded term is defined as satisfying the key metrics which include the appropriate range of shifting with having in mind the relation: the wider the range the more high performing phase shifter can be. Also, low insertion loss and applicability in the expected bandwidth are essential features in performance considerations (Alkaraki, Qu and Kelly, 2024; Rahimian Omam et al., 2020). Eventually, performance of precision phase shifter is based on accuracy, thus, minimalizing phase error as well as proper integrability with desired systems is key objective regarding the functionality (Microwave Journal, 2006; Wang et al., 2015). Hence, the expected performance metrics will be used in defining the device operation.

Moreover, the research will discuss the functional, structural and other technical requirements of the microwave (MW) phase shifter from the microelectronic mechanics point of view. It is necessary to provide the detailed quality assurance actions for the mechanical or structural components of the phase shifter before the important electrical and radio-technical performance measurements. By doing so, it is assured that the quality of the device will be achieved in cost-effective way, which consequently sets up the environment for mass production of the component. Thus, the verified aspects will include the dimensional and geometrical accuracy of individual parts, surface finish, raw material properties considerations, joining methods as well as every other specific requirements

necessary to ensure high quality. Consequently, appropriate measurement techniques should be also revised to draw attention on necessary setups and tooling. Also, all the measuring inaccuracies should be compensated by various adjustment methods. Furthermore, another challenge to be addressed lays in the geometrical tolerances required from the assembly while datum is found on various components. This issue should be addressed by properly adjusting the tolerances for each component to precisely restrict the dimensional variability for the components and as a consequence for the entire assembly. Similarly to structural requirements, all the functional constraints need to be covered in the work as well to ensure the high quality of the research paper. Eventually, it is beneficial to portray the device which is a backbone of the research to better visualize all the requirements regarding its operation. Hence, the device which will be studied is visible in the Figure 1.



Figure 1. The photo of the discussed phase shifter

The model visible in the figure above will serve as a base and inspiration for a digital model to be created and investigated during this research. The base model is crucial in obtaining the satisfactory results of the quality assurance studies pursued in the research since it provides valuable insight into the actual solutions used in the real world.

Furthermore, while considering the background of this study, it is important to note that the work is a part of a wider ongoing research conducted at LUT University regarding microelectronic components. In the study more than 40 devices were analysed from three

distinct perspectives including design for manufacturing and assembly (DFMA) approach, Quality Assurance, and Environmental aspects. Moreover, a thesis work on this particular microwave/radiofrequency (MW/RF) component was completed at LUT University in spring 2024. That paper preliminarily examined the tolerancing and material selection of the part. (Ma, 2024) However, current work is aimed at the quality assurance measures for the manufacturing of the part in the workshop, along with performance instructions.

1.3 Research problem and research questions

The research problem touches on the analysis of the quality assurance aspects for mechanically adjustable precision microwave passive phase shifter. Even though the regarded device was discussed from various perspectives recurrently, the detailed and complete analysis of its quality assurance aspects is missing. In this work, the explanation of quality assurance aspects, instead of taking into account only the production process as previously done, will involve the entire life-cycle of the product including the stages before, during and after the manufacturing process. The challenge of the research is connected to finding the trustworthy experimental data on which reliable and repeatable quality assurance methodology could lay its fundamentals. Also, the information used in the research need to be carefully revised to ensure accurate and valid results. Consequently, properly conducted research should lead to obtaining new, broad as well as multi-dimensional compilation of the quality assurance aspects which has not yet been connected in complex and thorough enough manner. Furthermore, the work will lead to finding the key and most influential quality assurance aspects at every product stage. Moreover, it will point out the most important setups and equipment for different types of measurements of dimensions, tolerances, and surface properties which has not yet been marked. Finally, the work will be enhanced by implementing the gathered knowledge into practice by employing illustrative three dimensional (3D) pictures prepared with computer-aided design (CAD) modelling software together with necessary components and the model itself. Having considered all of the above, it is clear that the work will answer the question of what are the most influential quality assurance aspects of the discussed device responsible for the correct operation and how to ensure that the phase shifter meets rigid performance standards under various operating conditions.

1.4 Research methods

To succeed in achieving research goal the work will use the comprehensive triangulation method approach which enables the wide yet precise analysis. It is a novel method which includes the usage of various perspectives to enhance the research quality. (Godfroid and Spino, 2015; Sciberras and Dingli, 2023) It focuses on 3 focal points which combined together will present the satisfying solution to the research problem. The usage of triangulation method has diverse advantages including enhancing validity, improving the depth of the research as well as combining various understanding of the same research problem. (Nightingale, 2019) Each of the triangulation method components is thoroughly portrayed in the Methods section.

1.5 Expected contribution

The expected outcome of the research is rather a guide which navigates through complex issues of quality assurance aspect for mechanically adjustable microwave passive phase shifters. A detailed description of quality assurance actions not only after, but also before and during manufacturing process of the device will be provided in the work. Furthermore, it will include the presentations of the required setups and tooling for various measuring processes of dimensions, tolerances and surface which are considered as influential in quality assurance for microwave devices. In addition, the practical implementation of the tolerance requirement with illustrative visuals created by using CAD modelling software shown with the help of 3D modelled components of the phase shifter will be provided in the work. Therefore, this work will contribute to the world of discussing microwave components by filling the gap created by the lack of existing literature regarding the titular device. Further, the knowledge gathered in the work will allow for ensuring the decent performance of the device through its operating life and expanding the discussed life itself. Considering the information above, the research will provide contribution taken into account both aspects, the theoretical considerations as well as practical implementations.

2 Research methods

The following chapter will focus on portraying the methods used in the research to achieve the described research goal. The information contained in this chapter includes the detailed triangulation methodology description as well as means to carry out reliability analysis.

2.1 Applied triangulation

The method used in the research lays its fundamentals on three main pillars visible on the Figure 2 below. Each of the triangulation corners is a separate method of conducting research, yet only used together they will provide correct and reliable results. Namely, the triangulation method used in the work contain the literature review, expert interview and CAD modelling of the components which combined together are believed to provide satisfactory results. Hence, it is important to note the possible connections and differences between the distinct triangulation methods which will be further discussed in the subsections below.

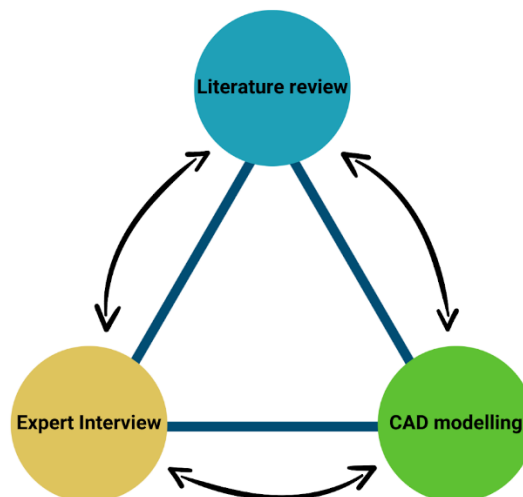


Figure 2. Illustrative visual of the triangulation method

Valid results will be guaranteed by finding the proper relations between the triangulation method components. The connection flow chart of the three triangulation methods is illustrated below on Figure 3. Firstly, the comparison of the knowledge found during the

literature review phase with the one obtained from the expert interview need to be conducted. From the comparison table the accurate and constructive conclusions ought to be derived regarding found similarities and differences. Then, each of the discussed approaches need to be validated with the CAD software method application. Here, the conclusions about the implementation of the literature review and expert interview into the 3D model should be obtained. Additionally, the missing aspects of the work which were omitted or not discussed should be found and implied in the work. Eventually, after all three pillars are compared, finding key conclusions is essential for the success of the work.

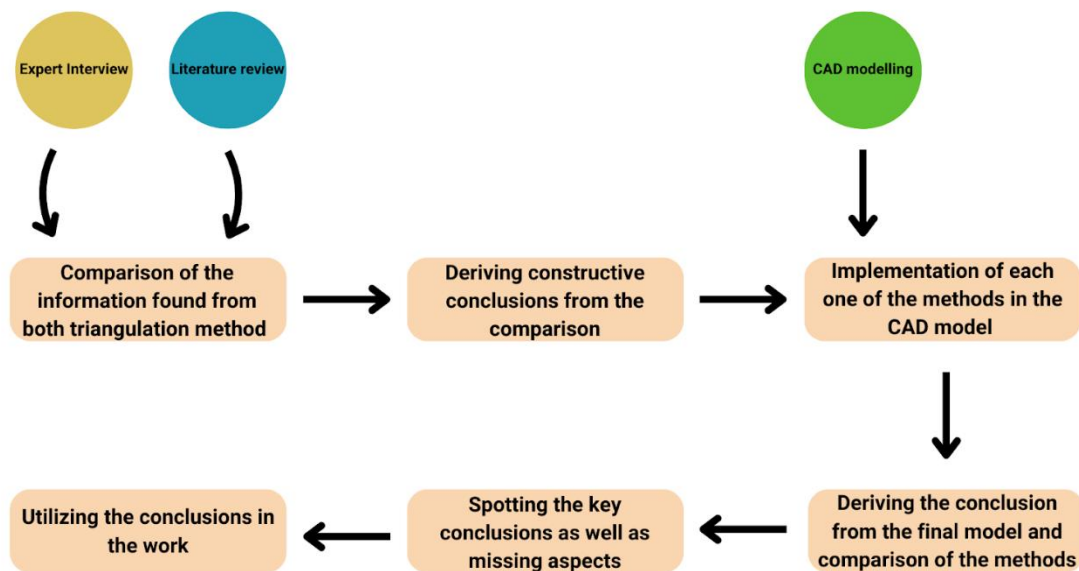


Figure 3. The triangulation method connections flow chart

Figure 3 above portrays the exact relationships between all 3 triangulation methodologies. Additionally, it contains the step-wise process of methods comparison which assist in understanding the flow of the study. Hence, the discussed flowchart can be easily applied into the discussed research.

2.1.1 Flowchart presentation of literature search and review

First of the triangulation method corners is literature review, which is critical element of the research which summarizes the existing information on the titular issues as well as provides a thorough base for implicating further results (Farrukh and Sajjad, 2023). Moreover, deep and diverse literature review allows for gaining comprehensive understanding of the field and developing a theoretical and conceptual framework essential for the success of the work (Brendel et al., 2020; Le et al., 2024). Its stepwise instruction is portrayed as a visual on Figure 4. It starts from considering what is known and what topics need to be further addressed. After the identification of the missing knowledge, the appropriate questions should be created to fill the gap in the knowledge. Further, the list of the questions to be answered should be created to keep the order of the found answers. Next, the information search should be conducted by first, looking directly at the scientific papers in online scientific papers libraries and then, by utilizing the most popular search engines. In particular the LUT Primo library, Scopus library and Google Scholar will be used to find necessary information. The keywords used to find the answer are based on the combinations of ‘quality assurance’, ‘microelectronics’, and ‘phase shifters’ phrases. Due to the limited number of existing publications the age limit will not be set for the search and all the information will be carefully revised. If the information will not be found by previously mentioned search optimization processes, the answers should be searched in scientific books regarding the discussed topic at the university’s library. The goal of the information search is to find at least three legitimate sources for each question if possible. Moreover, all the references will be read in a systematic way to ensure the smooth flow of the research. This approach will provide the researcher with the necessary multi-dimensional view and broad knowledge from diverse sources which will enable to sort out the true claims from wrong opinions. It is worth noting here that the information search should touch both the analyzed device and its quality assurance aspects in the case of the discussed work. After the information is found it should be placed in the correct location in the information list as well as in the work if necessary. The information about the device itself can be used in introduction and about its quality assurance in the entire work. Consequently, to complete the literature review method the information found in the internet needs to be utilized in the work in an appropriate manner. After the information is used the suitable references need to be produced to ensure

the authenticity of the paper. Eventually, results verification described in the 2.2 section will be conducted.

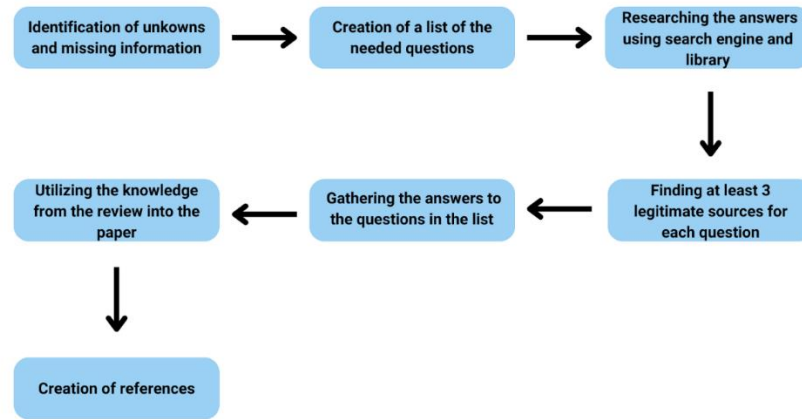


Figure 4. The literature review method flow chart

As mentioned in the title Figure 4 depicts the relation between each step of the literature review process. It can easily help in understanding the elements of literature review used in the discussed study.

Furthermore, in the research the portrayed approach will be incorporated with the help of popular research tools. In particular, after the identification of missing knowledge, the table of question will be created in spreadsheets software to keep track of all the needed information. Such a procedure allows for great organization of data as well as easy knowledge sharing (Alonso-Arroyo et al., 2012; Amat, 2009). Moreover, this advanced reference managing tool enhances the functionality of the research and allows for systematic work with the identified issues and unknowns (Ghisi et al., 2012; Ruiz et al., 2021). Such a systematic review is a well-known tool widely used across researches to ensure high quality of results as well as sources. Also, it leads to high performing and easily replicable methods, which other researches can repeat on their own (Noordzij et al., 2009; Siddaway, Wood and Hedges, 2019). The empty table which will be filled during literature review process is portrayed as Table 1 below.

Table 1. Management tool for identification of unknowns as well as reference analysis

Number of question (Q1-QN)	Questions to which the answers are searched for	Reference #1	Reference #2	Reference #3	Reference #4	Reference #5	Reference #6	Reference #7	Reference #8	Reference #N	Summarized observations to integrate the final answers to each question
Q1											
Q2											
Q3											
Q4											
Q5											
Q6											
Q7											
Q8											
Q9											
Q10											
Q11											
Q12											
Q13											
Q14											
Q15											
QN											
Summarized observations about the relevance of each reference											

This brilliant yet simple tool allows for keeping the track of all the questions which needs to be addressed as well as answers found to them in a clear and consistent manner. Herein, the first column contains numerical identificatory of the question to which the answer should be found, whereas the second column will contain the question itself. Next columns, will include the references used in the research implying to which question a particular reference is considered as the one containing the answer. Eventually, in the last column, the additional observations regarding each question together with location of the used reference in the research will be added. On the other hand, each row except the first and the last one, contains a relation between a numbered question with an appropriate reference. In contrary, first row is responsible for depicting each column, meanwhile, the last row will include the information regarding the quality checks for each answer.

To keep clear the numerical characteristics of the referencing used in the tool above, a list of references will be created with the corresponding number used in the analysis tool, appropriate Digital Object Identifier (DOI) number, Field-Weighted Citation Impact (FWCI) factor as well as reference itself. Such a list is visible in Table 2 below.

Table 2. List of references used in the management tool

Reference number	Reference	DOI number	FWCI
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
N			

This list will strictly cooperate with the management tool as they will be filled at the same time providing clear, consistent and thus high quality notation of the answers found during this stage of the methodology. Later both Table 1 (Appendix 1) and Table 2 (Appendix 2) will be filled and attached to the work as appendices.

Eventually, ensuring the quality of the resources will be done by double checking the DOI number and FWCI score of the reference as well as setting the origin of the reference to be only scientifically approved. Thus, only the references coming from high-quality sources and databases such as Scopus, LUT Primo or Google Scholar will be used in the work.

2.1.2 Arrangements for expert interview

Next triangulation method segment in the discussed research is expert interview illustrated on Figure 5. This method is equally salient as both other component of triangulation due to its unique benefits which include obtaining the knowledge which could have been not recorded into any work or paper before as well as the information which is based on the years of continuous work and experience. Also, expert interview assists in solving complex issues which could not have been addressed using other methods such as literature review and sources including database libraries (Chernova, 2023; Rose and Grosvenor, 2013). At the beginning, the process should look similar to the one before as the first step is spotting

unknowns which could be addressed by the expert in the appropriate field. In consequence, all questions which one wants to ask from the expert should be composed and gathered in a single place. After scheduling and arranging the expert interview the researcher should prepare by coming up with preliminary answers to the questions. By doing so, one will be able to better understand the received answers and even come up with possible new important questions still during the conversation. Next, the interview should be carried out in a responsible as well as respectful manner and all the answers need to be noted down which will enable returning to them later if necessary. Eventually, the answers should be further analyzed from various perspectives and utilized in the work where needed. Also, while concluding the results of expert interview one should use the cross-referencing tool to validate the obtained data and enhance the comprehensiveness of the research. The validity and reliability of the conducted problem-centered interview (PCI) will be checked by cross-referencing the obtained data with the information found during the literature review phase. (Beyers et al., 2014; Döringer, 2021)

In this particular research, the expert interview will be conducted on 10th of February 2025 at the LUT University campus. The connection with the expert will be established on the Microsoft Teams platform and the answers will be acquired from the Retired Professor of Radio Engineering at Aalto University, Pekka Eskelinen, who is an expert in the field of microelectronic components which is proven by decades of research in the discussed field. Moreover, the meeting with other participants of the Bachelor's Thesis Seminar course organized at LUT will be arranged to verify and compare the results of the expert interview. It is hoped that the meeting will provide the unorthodox and unnoticed conclusions derived from other students' expert interviews. Herein, again, all the newly derived conclusions applicable for the phase shifter case will be noted down and then used in the work.

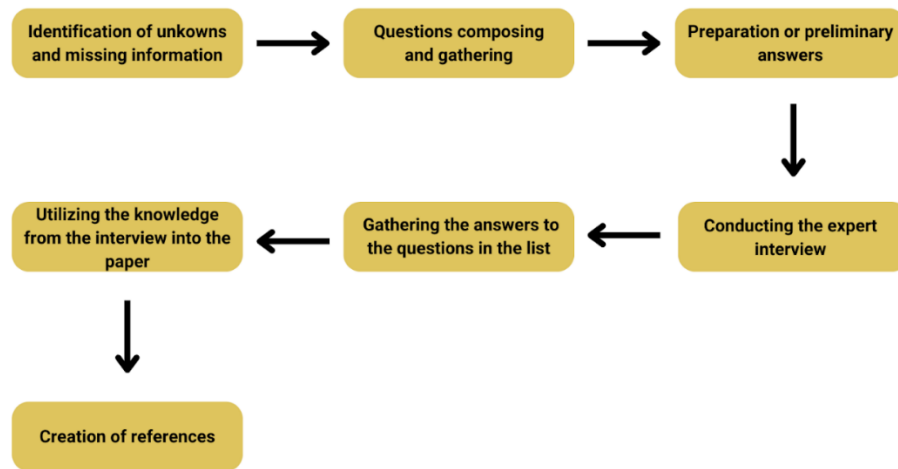


Figure 5. The expert interview method flow chart

Similarly to previous visuals, Figure 5 portrays a flow chart which is responsible for portraying the triangulation method component. This time the method described step by step is the expert interview. Once again the chart provides a valuable insight into the discussed methodology by describing each step of the procedure.

2.1.3 Utilization of stepwise quality assurance procedure and SolidWorks illustrations

Finally, the third and last fragment of the triangulation method is the 3D model creation. Step by step implementation of this method is visible on Figure 6. Although this process requires the utilization of the 3D modelling software the work itself starts a way ahead of the software opening. First, the researcher needs to identify all the dimensions which are needed to completely model the discussed device for each of the part as well as for the entire final assembly. Consequently, the device should be taken apart step by step in an ordered manner to recognize all the necessary components and to be able to assemble it again. When the proper dimensions are spotted the detailed measurements of the device and its components should be carried out. It is important that all of the dimensions measured are written down in the clear and ordered manner. This procedure will enable coming back to them later in the modelling phase itself as well as it will simplify the double-checking process. Then, the suitable CAD software must be chosen in order to proceed with the

modelling itself. After the software is ready, all the parts need to be modelled one by one with regards to dimensions taken from the real-life sample. Before assembling all the components should be double-checked in search for any mistakes done during the modelling phase. When the parts are ready and accurate the assembly should be created if possible in the same CAD software. Again, in case of any misalignments resulting from the mistakes in the modelling or dimensioning the issue should be checked individually and possible errors in the modelling stage should be fixed. Furthermore, with the assembly ready the general dimensions of the model should have been checked to verify the modelling results with the dimensioned device. Eventually, the suitable visuals of the model need to be created in the software as they will be used in the final paper.

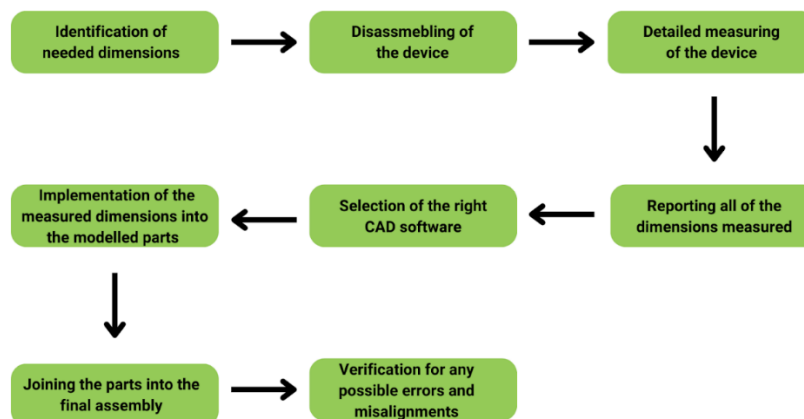


Figure 6. The CAD modelling method flow chart

Figure 6 portrays a stepwise procedure of creating a CAD model based on a real-life example. Moreover, it abbreviates all the essential point stated in the paragraph above for the reader to be able to decode the triangulation methodology with comprehensive understanding of the regarded topic.

2.2 Means to carry out reliability analysis

The reliability analysis will be conducted in regards with the Table 3 visible below. The NA abbreviation used in the table means ‘not applicable’, whereas ‘yes’ signifies that the following criteria will be investigated.

Table 3. The applicability of results verification aspects in the discussed research

Reliability factor	Literature review	Expert interview	CAD modelling	Triangulation method
Validity	Yes	Yes	Yes	Yes
Sensitivity	NA	NA	Yes	NA
Reliability	Yes	Yes	Yes	Yes
Error	NA	NA	NA	NA
Accuracy	NA	NA	Yes	NA
Saturation	Yes	NA	NA	Yes

As it can be noticed from the table the validity analysis is essential part of each component of the work since all information obtained must be based on valid sources or as in the case of CAD on a valid model. The applicability of the reliability analysis remains the same as the one of validity since all the results must be reliable for further usage in both theoretical and practical applications. The situation looks different with sensitivity where it is only possible to apply for CAD modelling since it touches on the issue of lack of results change with increasing the number of input samples. Similarly, the accuracy must be checked for the model only as it is not applicable for other methods. However, regarding saturation of information it will be only used for literature review and triangulation method. It is key aspect of the literature review to ensure the appropriate number of references stating the same point to ensure the correctness of the regarded claim. Likewise, in the triangulation method the saturation will be verified by cross referencing the answers given by the expert during interview, literature review and 3D modelling. Eventually, since there is only one device, the saturation is not applicable for 3D model. For the same reason it is not applicable for expert interview since during the research only one expert will be interviewed.

3 Results

While accessing the quality assurance of the mechanically adjustable precision microwave passive phase shifter it is important to highlight the complexity at which it must be considered. Only comprehensive enough consideration of obtained results will allow for satisfying the demanding performance as well as the environment requirements. Hence, the first subchapter of the 3rd chapter will ubiquitously address this issue from various perspectives.

3.1 Literature review

This section will focus on reviewing the existing literature in order to assist in deriving meaningful conclusion in quality assurance of mechanically adjustable precision microwave passive phase shifter. The section will focus on 3 stages, namely, before, during and after manufacturing.

3.1.1 Before manufacturing

The careful consideration of the existing literature allowed for the meticulously studied conclusions to be drawn. From the viewpoint of mechanical design, it is important to consider the design constraints, limitation and performance factors as the most influential quality assurance aspect of the discussed device. The factors were derived through careful literature review process as well as systematic consultations regarding the found results with the supervisor. This process allowed for deriving eight most influential factors which should be considered at the designs stage, Those factors are portrayed in Table 4 below.

Table 4. The list of the most influential factors regarding QA of the discussed phase shifter

Number	Factor	Why it is crucial
1	Dimensional and geometrical accuracies	Satisfactory performance, tightness, fit
2	Impedance at the level of 50 Ohms (Ω)	Satisfactory optimal performance
3	The appropriate height of the cavity on both sides of the copper strip	Satisfactory impedance and performance
4	Position and the size of the copper strip	Satisfactory impedance and performance
5	The right geometry of the PTFE element	Satisfactory phase shifting range
6	Electrically tight cavity	Satisfactory performance in varying, demanding conditions
7	Coaxiality of the SMA connector and centricity of the copper strip between them	Satisfactory performance for the input and output considerations
8	Material selection	Satisfactory performance

When considering microelectronic mechanics in the design strategy, it is clear that dimensional and geometrical accuracy are key quality establishing factors. The tolerance and dimensioning for each individual component influence the overall performance of the device, hence, they must be clearly specified in the work (Umaras and Tsuzuki, 2011). Geometric Dimensioning and Tolerancing (GD&T) is essential designing feature which is determining the quality of the produced component by effectively and efficiently modifying design specifications (Pathak et al., 2018). Thus, it must be ensured that the required standards and accuracies are not only clearly stated in the technical documentation of each component, but also checked in detail after the manufacturing process to ensure the satisfactory performance of the device.

As visible in row 2, another key performance defining factor is the impedance. As derived from the existing literature, the impedance for the discussed device should be reaching the

value of 50Ω (Eskelinen, Lätti and Silventoinen, 2004). To ensure this magnitude one should consider the following equation for impedance obtained by comparing electric and magnetic fields derived from Eskelinen H. and Eskelinen P. (2003) work:

$$Z = \frac{60}{\sqrt{\epsilon}} \ln\left(\frac{1.9(2h+t)}{0.8w+t}\right) \quad (1)$$

In the equation (1), the impedance Z depends on the parameters w , t and h , which are the width (w) and thickness (t) of the copper strip and the distance (h) from the copper strip surface to the surface of the cavity. Then, the strain ϵ depends on the chosen material. The research has shown that the material which yields a satisfactory performance is PTFE, for which the value of ϵ is approximately 2.05 ± 0.01 (Eskelinen, Lätti and Silventoinen, 2004). This mathematical relation between the parameters is crucial for the performance of the device, hence, it should be carefully considered in the design phase.

The 3rd factor in the table is straightforwardly derived from the 2nd factor as it portrays the importance of ensuring the right height of the cavity on both sides of the copper strip. This value is obtained with the help of the collars, which should be placed on the main cavity bottom as well as the cover to enhance the controllability of the inner space height as shown in Figure 7.

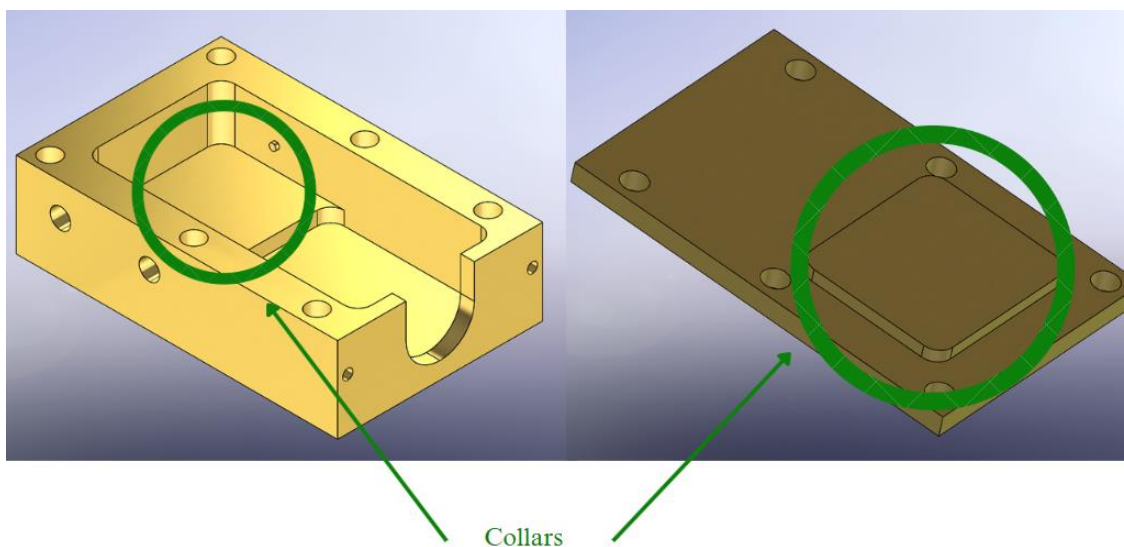


Figure 7. The visualization of the collars placed at the cover plate and in the main cavity

Now, having analysed the placement of the collars, the distance between them will allow for further calculation of the parameter h which is needed in the required impedance calculation. It can be calculated by equation 2 pictured below:

$$h = \frac{d-t}{2} \quad (2)$$

In equation 2, the h is the height from the surface of the copper strip to the collar stated previously, d is the total height of the space and t is the thickness of the copper strip. This equation can be used only under the assumption that the copper strip is placed ideally in the middle of the d , which needs to be ensured through the dimensional tolerances in the technical drawings. Copper strip and the zone surrounding it is as an essential component in microelectronic devices. Hence, there is a need to satisfy high thermal and, more importantly, electrical requirements while dealing with such component (Liu et al., 2024). Thus, special attention should be paid to that structure.

Consequently, the 4th row of the table includes the position and size of the copper strip since those factors influence the impedance of the device. As stated before regarding the position of the copper strip, it should be centred between the collars of the main cavity and the cover. The engineer behind the design must achieve this placement, even considering the challenges which result from the fact that the datum cannot be placed on the other component in the assembly technical drawing. This is due to the fact that it is impossible for the manufacturer of the single component to apply the tolerance on the height between the collars only as it is an imaginary value derived from two other components (the distance between the components). Instead, the designer should apply this requirement through appropriate linear tolerances applied onto the cover and the main cavity separately. By doing so, it will be ensured that the regarded distance will satisfy the requirement as well as that the allowed production error will not be summed up from the standardized general tolerance value only, but will be limited inside the allowable range.

Furthermore, the size of the copper strip matters as well as the parameters w and t are essential in the impedance equation 1. Thus, selecting the right values for the parameters will result in satisfactory performance of the device (Eskelinen and Eskelinen, 2003). In the following research, it was calculated that for the discussed phase shifter, the appropriate values are 4 mm and 0.5 mm for width and thickness respectively. Moreover, the parameter

d was designed to be 6.5 mm which results in the magnitude of parameter h achieving 3 mm. After substituting the values of h , w , and t it is possible to calculate that the impedance of the phase shifter reaches 50 Ohms as required to achieve the desired quality level.

The 5th row underlines that the special attention should be paid to the correct geometry of the insulating PTFE element since this component is directly connected to the phase shifting operation. The PTFE elements are widely used as a structural sealing device (Ni et al., 2023). Thus, it is regarded as essential component in quality considerations of the phase shifter. After the tuning screw is rotated, the angular movement is converted by the screw into linear movement which moves the PTFE element forward onto the copper strip to cover the space around the strip or backward to come back to initial condition depending on the desired level of the phase shift. Thus, the regarded component is crucial for the satisfactory level of the phase shifting. Furthermore, the asymmetry of the component plays a crucial role in the functionality, thus it must be ensured through the set of tolerances in the design phase. To reach the desired level of phase shift one side of the groove has a stepwise decreasing cross-sectional geometry, while the other side incorporates a linear decrease. Even the smallest deviation in the shape or the dimensioning of the component can affect negatively the performance by limiting the range of the phase shift. The satisfactory level of phase shift for the discussed phase shifter expressed in degrees is 180.

Row number 6 examines the need for an electrically tight cavity. As stated in the work of Eskelinen H. and Eskelinen P. (2003) this is the crucial factor while operating in various as well as demanding conditions. This factor should be achieved by a set of geometrical tolerances on the surfaces of the main cavity and cover as well as the surface roughness consideration. The surface finish is key in ensuring the tightness of the device. As it is established the level of Ra 1.6 is enough for the satisfactory tightness performance in space environment. (Eskelinen and Eskelinen, 2003)

Furthermore, the SubMiniature version A (SMA) connector placed on the sides of the main cavity should be coaxial in order to ensure the proper performance. Moreover, the copper strip should be centred between them to ensure the satisfactory performance regarding the input-output relation for the device. Since the SMA connectors are considered as the input and output ports, it is crucial to ensure that the processed values are not changed due to the inappropriate alignment of the connector or the strip. However, the concentricity of the SMA connector as well as the centring of the copper strip once again stands a challenge since all

the datums are in four distinct components, both the SMA connector, the copper strip and the main cavity which connects them. Here, the solution is similar as the linear tolerance must be included in all parts separately. The key component is the cavity, which needs to incorporate limited tolerance on the mounting holes for connectors and the strip. Also, the connector needs to satisfy the tolerance regarding the placement of the mounting holes to ensure the best fit with the main cavity. Once again, the summation error during the usage of general tolerancing only is a great threat to the fit of the components, thus, it needs to be properly addressed through the usage of the appropriate linear tolerances on the required dimensions. Only the consideration for all of those fits and allowable deviations will result in satisfactory quality of the regarded phase shifter. (Eskelinen, Lätti and Silventoinen, 2004)

The last factor taken into account in the design phase is the material choice for each component. The material choice is the key factor in quality assurance of microelectronic devices and their components (Gupta and Kandpal, 2020). Hence, through the careful literature review process, the materials with satisfactory properties were chosen in the research as visualized in the Table 5 below.

Table 5. The materials chosen in the project

Best material chosen	Grade/Class	Key characteristics and properties	Component(s)
Polytetrafluoroethylene	PTFE	Superior insulation properties, Chemical Resistance, High thermal stability, Low flammability, Low dielectric constant	Double-finned insulating element
Free Machining Brass (FMB)	CuZn39Pb3	Excellent machinability. Easily improvable corrosion resistance, Great mechanical strength	Main cavity, Cover of the main cavity, Tuning screw adaptor, Tuning screw head plate
Oxygen-Free Copper	Cu-OF-OK	Superior electrical and heat conductivity	Copper strip
Stainless Steel	X8CrNiS18-9	Acceptable machinability, Decent corrosion and wear resistance, Satisfying mechanical strength	Tuning screw, SMA connectors

As can be observed from the table, the materials considerations of the research resulted in the choice of 4 favourable materials which are portrayed together with various traits and respective applications in the components in the table above. The first material considered for the insulating double-finned element is chosen. Herein, the best choice is polytetrafluoroethylene (PTFE) due to its superior insulating capabilities in microelectronics applications. Due to the superior thermal stability, outstanding mechanical properties, as well as excellent dielectric properties, the PTFE is perfect for microelectronic, insulating applications (Zhu et al., 2023). Additionally, according to the studies, PTFE is highly non-reactive, non-flammable and has a low friction coefficient (Radulovic and Wojcinski, 2023). The second trait makes it perfect for various operating conditions, and the low coefficient of friction will enable smooth movement inside the phase shifter. Another research has repeated that PTFE is excellent insulating material with high thermal stability and contributed by claiming that it has a decent chemical corrosion resistant as well (Lizotte, 2008). Moreover, low modulus of elasticity which summed up with decent dielectric properties making it a great insulator. Namely, due to the low dielectric constant of magnitude 2.79, PTFE is capable of minimising energy loss and signal distortion even in high-frequency applications (Zhu et al., 2023). Therefore, this material is a responsible choice for double-finned elements in the regarded phase shifter considering the quality assurance perspective.

The second and the most commonly used in the device material is brass. It is the best raw material chosen for the group of components including the main cavity, the main cavity cover, the tuning screw adapter as well as screw head plate. However, due to the varying nature of properties of diverse types of brass, it is necessary to specify which grade of brass is the best for the discussed application as the chosen metal should be easily machinable as well as be able to withstand demanding operating conditions. Hence, the best type of brass for the application was chosen to be Free Machining Brass (FMB) with European encoding CuZn39Pb3 which has not only exemplary machining capabilities but also it has easily improvable corrosion resistance which is crucial in the space environment. Due to the presence of lead this material is efficient as well as precise in production and processing, especially using machining techniques (Pantazopoulos and Toulfatzis, 2012). Moreover, it can be easily gold or silver coated to improve corrosion resistance and make it more stable in diverse environmental conditions (Zor, Ünal and Gökergil, 2011). Eventually, this type of brass was chosen due to durability and reliability which are resulting from decent mechanical

strength and hardness (Toufatzis et al., 2016). Those properties are key in achieving the necessary performance in space conditions. Consequently, brass CuZn39Pb3 material would ensure satisfying quality of the discussed device.

The 3rd material was copper, which was chosen for the strip due to its superior properties in form of the great conductivity. Those properties result in the fact that copper is frequently used as a raw material for the functionality of a majority of microelectronic devices (Platzman et al., 2010). The type of copper chosen to be used in the research is Oxygen-Free Copper (Cu-OF-OK) due to its superior properties of both high electrical and thermal conductivity, which is caused by extremely small oxygen rates in the alloy, as well as high strength and wear resistance (Ladani, Razmi and Lowe, 2023). Moreover, due to the fact that it is oxygen free it has great oxidation resistance in comparison to other types of copper. (Knych, Smyrak and Walkowicz, 2011). Nevertheless, the most important aspect, conductivity, makes Cu-OF-OK a great material for the copper strip used in discussed phase shifter.

The last material considered in the work was stainless steel which is chosen for the SMA connectors and the tuning screw. In detail, stainless steel X8CrNiS18-9, which is a widely used material for SMA connectors, will be used in the work due to its decent wear resistance as well as superior mechanical strength (Brnic et al., 2012). Those properties are crucial for the part which will be further connected with outer components such as SMA connectors and the part which is exposed to highly frequent stress such as the tuning screw. However, the tuning screw is a spare part of a micrometre taken from Mitutoyo manufacturer who provides the information about the raw material of the tuning screw being stainless steel (Mitutoyo, 2015). Moreover, the discussed grade of stainless steel has high oxidation resistance and has relatively low electrical conductivity (Pereira, Candido and de Malafaia, 2021). Hence, the grade X8CrNiS18-9 it is considered an appropriate material which will assist in achieving high quality as well as serve well in various operating conditions.

The materials described above should fulfil the requirements of international standards. In this research it is advised that the used standards are based on European standardization. Hence, brass should fulfil the EN 12164:2024 standard, Stainless Steel should meet the requirements of EN 10088-1:2023 standard and copper of EN 13599. Next, for PTFE the required standard is EN ISO 13000-1:2021. The usage of material specified by other standardization such as American or Japanese ones can result in achieving different results

regarding performance and operation of the discussed phase shifter. While the copper standardization is largely equivalent across the various locations, the standards used for brass and stainless steel may differ in tolerancing and composition, which lead to varying mechanical properties and in consequence possibly worse performance. Meanwhile, having accurate mechanical properties is one of the major aspects regarding material considerations from the quality assurance perspective of the discussed phase shifter. Hence, the recommended materials should be strictly followed during the manufacturing stage.

Eventually, it is possible to conclude that Table 4 displayed the crucial factor for the performance of the discussed device. Hence, it becomes a key tool in assessing the quality assurance of the mechanically adjustable precision microwave passive phase shifter at the design stage of the device. The responsible engineer should take into account also the stated factors to properly address the quality of the phase shifter and achieve the highest performance.

3.1.2 During manufacturing

It is equally important to consider the quality after the design phase in the production process. Here, the quality lays its foundation on the process of enforcing the necessary requirement given in the design phase to the product itself during the manufacturing stage. Consequently, it is crucial to select suitable technology which is capable of manufacturing the components with the satisfactory quality. However, in this work, the manufacturing processes will not be discussed in detail as the DFMA approach should be considered separately from Quality Assurance viewpoint to underline the importance of all the consideration connected to manufacturing itself. This work will rather focus on briefly outlining how the quality should be ensured in the manufacturing process which may be chosen for the discussed phase shifter.

First and foremost, it is important to state the previously mentioned key aspect of quality control during the manufacturing stage. As machine tool selection is crucial it needs to be performed carefully. The tooling should be capable of operating with precision and position accuracy mentioned in the drawings. Otherwise, it is impossible to achieve the desired quality and performance requirements with low-precision tooling. Also, the selected machine should have great vibration-damping properties and rigidity. Moreover, the tooling

should be well maintained as well as sharp to avoid burrs and micro-tears. Thus, to avoid the usage of malfunctioning tooling it is important to use the machines which have been regularly inspected. Moreover, in processes endangered with overheating, appropriate coolant and lubrication fluids are necessary for the satisfactory performance of the producing device. Before using a machine, it should be properly set up and calibrated according to its individual instructions. Herein, a warmup session for the machine before the start of production will exert a beneficial influence on the product quality. After considering all the machine requirements it is needed to ensure satisfactory environmental conditions. Hence, confirming stable temperature as well as humidity and isolation from vibrations will yield a properly operating production environment. Eventually, it is salient to pursue an adequate manufacturing strategy to achieve high-quality results. Therefore, Table 6 not only shows the detailed manufacturing methods chosen for the discussed phase shifter components, but also it opens a possibility of further discussion regarding the required manufacturing approach and strategy.

Table 6. Components with chosen manufacturing methods

Manufacturing method	Type	Component	Required machines
Machining	Milling	Main cavity, Cover of the main cavity, Tuning screw adaptor, Tuning screw head plate,	CNC milling machine
	Drilling	Main cavity, Cover of the main cavity, Tuning screw adaptor, Tuning screw head plate,	CNC Drill
	Cutting	Connector pins, Copper strip	CNC laser cutting machine
	Sawing + milling	Insulating PTFE element	CNC precise and automatized saw

As visible in Table 6, the most frequently used methods for the components are milling and drilling, which are highly popular methods while dealing with brass. Milling was found to

be the best manufacturing technique for the regarded application, considering its high accuracy and achievable low surface roughness (Kannan et al., 2015). In the meantime, drilling as a manufacturing method is a technique which is capable of efficient creation of high-quality holes (Zoghipour, Atay and Kaynak, 2021). Thus, it should be used to create all the mounting holes present on the phase shifter. It is highly important to use CNC drilling and milling machines with the required dimensional accuracy and appropriate surface roughness. Moreover, in case of a geometry with multiple holes such as the main cavity or the cavity cover, the usage of a multi-axial drilling machine could yield certain advantages limiting the unnecessary movement of the component and consequently limiting the possibility of a dimensional error occurrence.

For the efficient manufacturing of the copper strip from the raw material form of rod, cutting was chosen as a suitable method, considering the high speed at which it can be manufactured (Shinozuka, 2013). The copper strip can be bought in the form of a thin bar and then further cut to the desired dimensions. Since the material chosen Cu-OF-OK is not alloyed it has relatively poor machinability, hence ensuring the appropriately high machining speed, and small feeding ratio together with small cutting depth is key for the success of the process. Hence, after carefully selecting raw material manufacturers it is necessary from a quality perspective to ensure a satisfactory performing cutting machine, which will be capable of cutting such small components.

The insulating element cannot be treated by the manufacturing methods of injection moulding, pressing or extrusion because of the high viscosity of PTFE as well as the low precision of the discussed processes. The necessary precision of geometrical tolerances would be challenging to achieve with the abovementioned methods. Due to its poor machinability, PTFE poses a challenge for manufacturing with enough precision. However, with optimized parameters, it is possible to use cutting as a manufacturing method for the components made from this material (Ni et al., 2024). Thus, to produce the PTFE element it is necessary to use a particular combination of sawing and milling, where a circular saw cuts into the component repetitively ensuring the appropriate perpendicularity tolerances. The usage of this process will assist in abiding depressing the geometry which would definitely occur in other processes. Hence, the combination of sawing and milling together is the best manufacturing method for the double-finned element.

Further, it is necessary to ensure that each component complies with the demanding surface roughness requirements. This can be done using various techniques, however, in this research, the machining and sanding will be further discussed. The best surface roughness used in the work is similar to the ones used in slider roller bearings due to the fact that the PTFE element needs to smoothly move while being in contact with the cover and the cavity with no further obstacles. Thus, the best surface roughness used with the Ra magnitude of 0.8 can be achieved by turning, milling and grinding processes. Among those 3 the best one will be milling since turning is not suitable to the geometries of the cavity and the cover. Moreover, to ensure the tight fit of the cavity cover to the main cavity, a surface roughness of RA factor equal to 1.6 should be sufficient. Lastly, the surface roughness of 6.4 should be achieved by using the location given by the technical drawings (Appendix 3) to ensure the correct fit of the various components. Both roughness values can be achieved by operating with appropriate milling tooling.

Not every component used in the phase shifter should be manufactured as several of the parts undergo the standardisation process, which makes it easier to choose the appropriate part from the existing standards provided by the manufacturers. The tuning screw should be used from the existing micrometres. The research has shown that it is possible to choose the tuning screw as a spare part of a commercial micrometre and order the part from the manufacturer, e.g. Mitutoyo. It has been proven that it is possible to adjust the tuning screw to the phase shifter's needs using the customizable created tuning screw adaptor and tuning screw head adaptors for satisfactory connection. Moreover, the choice of SMA connectors is strictly limited to achieving the required standards. Hence, it was found that the standard describing the SMA connector for various operating conditions including space is EN IEC 61169-15. The usage of this European standard will allow for the selection of appropriate for the discussed phase shifter SMA connectors.

3.1.3 After manufacturing

Eventually, to fully support the quality assurance process, it is salient to verify the quality after the manufacturing. Here, various tests can be conducted to check the quality of each component. This subchapter will focus on quality assurance at the testing stage. Consequently, the tests chosen in the research were described below.

There are four various tests needed to properly assess the quality after the manufacturing stage. The most frequently used measuring setup included the general measurement setup which needs to be used on every component. Here the simple dimensions could be measured by tooling including micrometre or vernier calliper, however, much more recommended from the quality assurance viewpoint is digital measuring gauge which is portrayed in Figure 8 below.

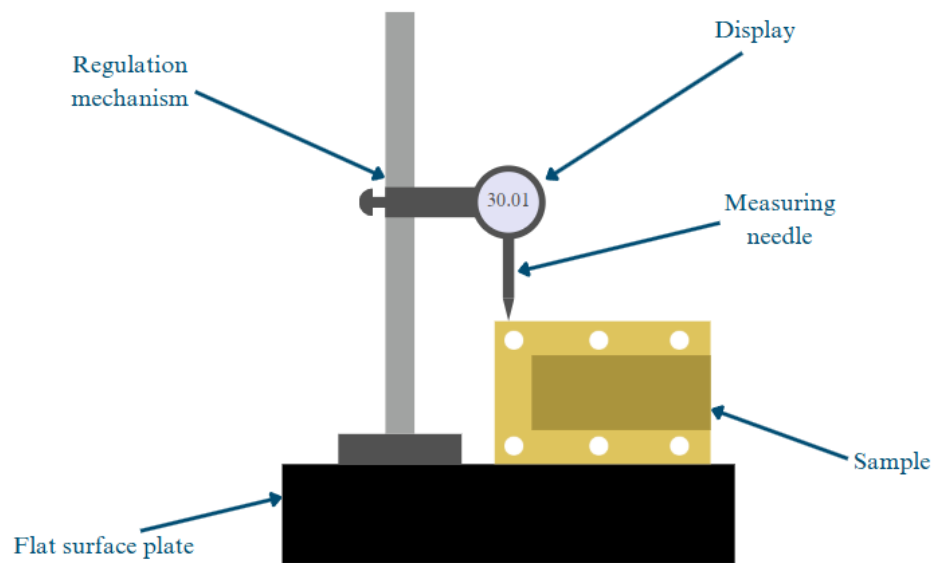


Figure 8. Digital height measuring gauge

Digital measuring gauge is capable of providing a high accuracy, precision, degree of repeatability and it is easy to use (Robins, 2006). Thus, it makes it the perfect device for quality control of the discussed phase shifter. As it can be observed the device includes the surface which serves as a datum for the measurements as well as component and measuring device. Moreover, the flat surface plate of the device is a location where the sample should be placed. Further height regulating mechanism should be used to place the measuring needle right at the spot of the sample's dimension to be measured. Now, each required dimension of the component should be checked by lowering the measuring needle as much as possible onto the component. When the needle touches the component a measure should be taken and noted down. As it can be observed from the description what the machine is

measuring in reality is the distance of the needle tip to the datum, thus it is highly important to place the sample in the correct configuration under the needle. Later, the measurements should be verified with the required dimensional tolerancing. Failure to comply with the tolerancing requirements will result in rejecting the part from the consideration and need for the creation of another component to be tested. Additionally, the real photo of the device is portrayed in Figure 9 below for better visualization.



Figure 9. Photo of the digital measuring gauge (INSIZE, 2025)

Nevertheless, when it comes to measuring the diameter of holes the vernier caliper is recommended as a tool since the two jaws on the back of the caliper are capable of measuring the circular dimensional with high precision. Another feature measured in the work are geometrical tolerances including parallelism, perpendicularity and flatness. Even though simple perpendicular geometries could be measured by precision meter square, it is recommended from the quality assurance viewpoint that both of geometrical tolerances discussed in this paragraph should be measured by coordinate measuring machine (CMM). CMM are key aspects of quality control in various applications requiring high precision requirements. Moreover, they enable automation of the process as well as repeatability equal to the one of gauges (Kurfess and Campbell Jr., 2006). Furthermore, the use of CMM reduces the time and price of the quality control process as well as provides versatile solution needed

in various tolerance measurements (Machado et al., 2019). The bridge type version of this machine is portrayed in the Figure 10 below.

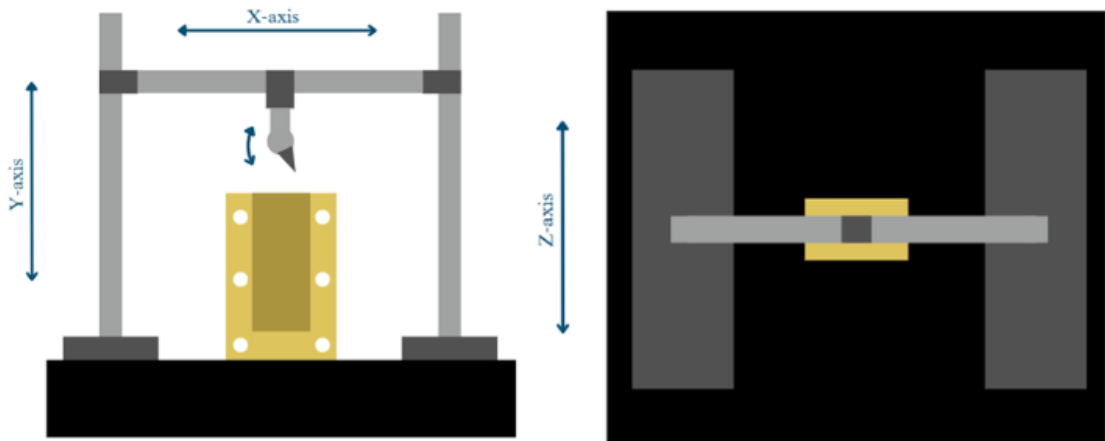


Figure 10. The setup of coordinate measuring machine (CMM) - side and top view

As visible in Figure above the equipment involves bridge like structure which is capable of operation in three dimensions using just 5 beams. Moreover, due to the usage of circular joint with the middle beam, the needle at the end of the joint gain additional DOF which is necessary in precision dimensioning of the required geometrical tolerances. Again, in this case sample should be placed on the under the bridge, on the bed which serves as a datum for the measurements. In reality, the needle touches the sample and coordinates of the needle end are taken into account as measurements. Processed later by the machine, the coordinates allow for various geometrical tolerance measuring, Because of high DOF this machine is capable of measuring with high accuracy which is required from the quality assurance perspective. The real photo of the device is shown in Figure 11 below.



Figure 11. The real photo of the device (Mitutoyo, 2025)

Eventually, it is needed for multiple components to measure the surface properties, thus, the surface roughness measuring machine should be taken into account. The surface roughness measurements should be conducted with a profilometer, as it is excellent regarding reliability and accuracy of the obtained measurements (Grochalski et al., 2021). Additionally, a diamond stylus used to take the measurements is advised from the QA viewpoint to achieve the necessary precision and accuracy. An exemplary machine is visible in the Figure 12 below.

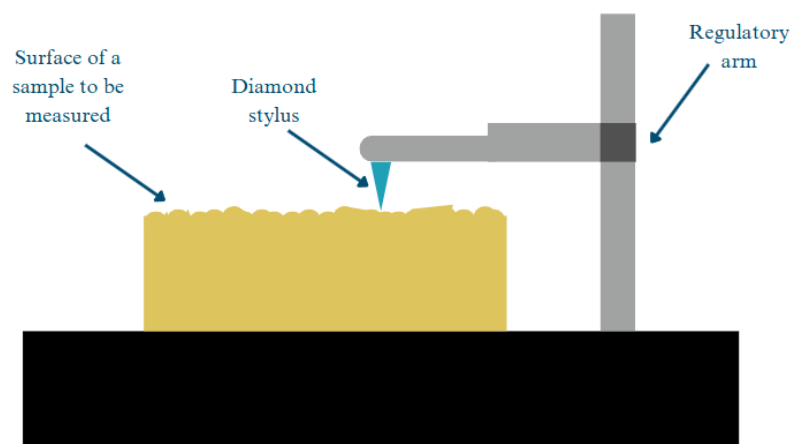


Figure 12. The surface roughness measuring setup

Once again the setup requires a surface at which the sample could be positioned. Further, the regulatory arm should be adjusted so that arm with diamond stylus attached could be placed right on the top of the required sample surface. After the stylus touches the sample it should be moved across the surface to take measurement of complete side of the component. What is actually measured is similarly to measuring gauge the distance from the datum, which is the bottom flat surface, to the end of the needle. By measuring this distance, it is possible to derive surface roughness which is highly required from the quality assurance viewpoint. Eventually, a real photo of such a device is visible Figure 13 below.

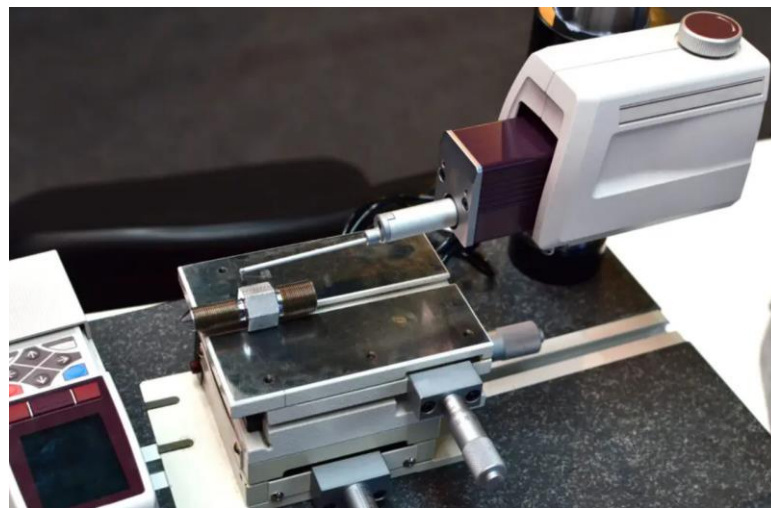


Figure 13. Real photo of profilometer with diamond stylus (REM, 2025)

The necessary accuracy of the tolerancing measured by the device mentioned in this subsection varies depending on the component. However, all the components are properly described with tolerances and surfaces finish on the technical drawing which can be found in the attached documentation in Appendix 3. In general the required accuracy is given by the standard used ISO-2768-mK or ISO-2768-fH, however, for some of the components more strict tolerancing is used. For geometrical tolerances the values vary between 0.01 and 0.05. Similarly, surface roughness values used in the work include 0.8, 1.6 and 6.4.

Nevertheless, after the measuring and checking is finalized it is necessary to identify all the malmanufactured component. Any deviation from the allowed tolerancing should be taken into account. Thus, if the feature is below the lower limit the component should be rejected.

However, if the measured feature is above the upper limit, it is always possible to correct the mistake and machine the appropriate feature using the same technique as given in subsection 3.1.2. Consequently, the manufacturing inaccuracies should be compensated, and the whole measuring process should start again from the beginning. Those adjustments are necessary to achieve satisfactory manufacturing quality of the discussed phase shifter.

Eventually, it is important to remember that after all the components comply with the rules separately, it is a key consideration to choose an appropriate joining method for the components. Also, the order of joining is heavily important for the operation of the device. Consequently, the first method is soldering as the copper strip needs to be connected to the main cavity with a method that allows for the flow of electricity in an efficient manner. Soldering is ideal considering its benefits which includes the reliable electrical connection, cost-effectiveness, mechanical stability and the most important great electrical conductivity performance (Eskelinen and Eskelinen, 2003). Thus, for high strength and best conductivity the soldering standard specified by EN ISO 17672 should be used to achieve the best performance of the discussed device.

On the other hand, the second joining process is mechanical joining, which is used to connect all the other components with each other. The mechanical joining will be conducted using fasteners, especially standardized screws which will allow for easing the accessibility and lowering the costs of the project. As wrong choice of screws can lead to disassembling of the device, a proper choice of fasteners is crucial from quality assurance perspective. The recommended standards while choosing the fasteners include EN ISO 898-1 for mechanical properties and EN ISO 965-1 for thread standardization.

Having considered all of the above it is possible to conclude the first subchapter of the results section with the proved statement that the quality assurance of the microelectronic component such as phase shifter is not only limited to the design phase but conversely, it is key aspect in all the phases, from design, through production to finally the post-processing. The quality must be ensured at all of those stages to ensure the satisfactory performance under various operating conditions.

3.2 Expert interview

The result of the second triangulation method component is equally salient as the one obtained in the literature review section. The primary question which was asked to the expert was what are the key quality assurance aspects of the phase shifter responsible for the best performance, and what are the strategies in ensuring that the device meets standards under various operating conditions. As advised in the methods section, all the answers that were obtained were noted and submitted for further analysis. Both, the question and answers asked during the interview can be found in attached documentation (Appendix 5).

During the interview, it was said that the precision is key in obtaining the high performance operating device. Moreover, the regarded phase shifter was described as one of the few radio modules which is entirely mechanical. Thus, the dimensioning of the module is salient to ensure proper fit and the correct operation. Also, considering the operation mode of the device in which the dielectric fin is moving closer or further away from the copper strip, it was concluded that the features placed around the copper strip are essential for the operation. Hence, the most crucial quality assurance aspect for the correct performance of the device from the microwave mechanics point of view is the geometry and dimensioning of the double finned, insulating PTFE element. Then, only the appropriate materials chosen for the element will allow for the best performance of tuning in the range of 180 degrees. Also, special attention should be paid to the asymmetry of the element. However, the information which was previously unnoticed regarding the fin element stated that the orientation of the fin in top-bottom (upright or upside down) does not matter, as long as it is asymmetric. Herein, the challenge lies in the uncertainty of the precision of the regarded double fin when it is already assembled inside the phase shifter. Thus, all the necessary quality checks on that component should be conducted before the assembly since a wrongly shaped or dimensioned fin affects the operation of the phase shifter. Failing to satisfy the requirements will result in poor performance by limiting its operating shifting range to significantly lower than 180 degrees value. Thus, the dependency of the device on that particular element is tremendous. Nevertheless, the expert pointed out the importance of the distance between the copper strip and both the main cavity and cover as a key parameter of the device which influences the operation deeply as well. To address this issue, the milling and surface treatment to ensure

the flatness and smoothness were recommended as the manufacturing technique for the main box body, so the finned element will fit into the cavity neatly. (Eskelinen P., 2025)

Worth noticing is the fact that all the expert answers are not only non-contradictory but also match the ones obtained from the previous literature review section, which underlines the validity of the obtained data. Moreover, the meeting with the other participants of the Bachelor's Thesis Seminar course for Mechanical Engineering students with Thesis on microelectronic components at LUT was conducted to check and cross-reference the obtained data to ensure high quality of the research paper. The comparison has yielded additional insights applicable to the microelectronic in general, thus, the regarded phase shifter as well. (Eskelinen P., 2025)

The expert emphasized multiple times that while working with machines operating at a low frequency (a couple of gigahertz), brass is an appropriate material to choose for the main cavity and the cover. Also, another key aspect was aligning the tuning screws which is crucial for the performance of the device. In the case of a phase shifter, this transfers to the SMA connectors with the connector pins, which need to be aligned for the best operation. Here, the precision is the key, therefore, the required tolerances need to be considered in the model and work. Once again it was expressed that the geometrical tolerances must be met so that there is no occurrence of bending and twisting where it negatively affects the operation. While generalizing the obtained results, it was also stated that for all the regarded microelectronic components, the dimensioning is crucial for the satisfying performance of the device. However, not only the proper dimensioning but also correct material selection is essential for the quality assurance of all the discussed devices. Nevertheless, how strict the material selection process becomes depends on the operating frequency of the device, yet, for the low frequency devices, almost any conductive and metallic will yield satisfactory results. Another relevant comment was touching on the connection surface of the cover with the main cavity or the main housing, as they need to be planar and smooth with precise dimensioning of holes in x, y, z directions to ensure the proper fit and avoid mechanical stresses. Moreover, this procedure ensures the proper fit and tightness level of the discussed components, which results in the capability to work in various operating conditions. Sealing is important to have in mind as the phase shifter is required to work in demanding space conditions. Also, it was mentioned that for the devices, which include the box, instead of the cavity, most of the materials will work well as long as the dimensioning of the box fits the

component inside nicely and leaves the required level of space above and below the inner components. Next criteria brought to attention was that perfect electrical performance is impossible to achieve, but it should still be the main objective to manufacture the part to perform on the best possible level. On the other hand, it is important to watch out for overdesigning in less important parts such as mounting screws of the cover which usually can be simplified in manufacturing to lower the cost without decreasing the performance. Hence it was recommended to avoid complicated manufacturing processes and not overengineer the device in the modelling phase. The most important insight regarding microelectronic components in general, provided by the expert was a frequently appearing statement that wrong dimensions result in poor performance. Eventually, the cross-referencing processes have shown the comprehensiveness of the research as well as the reliability of the answers obtained from PCI phase. (Eskelinen P., 2025)

3.3 CAD modelling

The last subchapter of the Results section will focus on the 3rd element of the triangulation method, CAD modelling. The subchapter is divided into three corresponding subsections, each describing the results of a separate phase of the 3rd triangulation component.

3.3.1 Measurements

The first subsection touches on measurements conducted on a real model of the discussed device. The real phase shifter was disassembled, so that precise measurement could be conducted on each part separately. The measurements conducted with a precise micrometer were then written down so that it was easier to come back to them if needed. Also, all the precautions given in the methods section regarding this stage were taken into account, which resulted in the creation of photos which helped in assembling the device back. An exemplary photo of the disassembled phase shifter and its components is visible below in Figure 14.

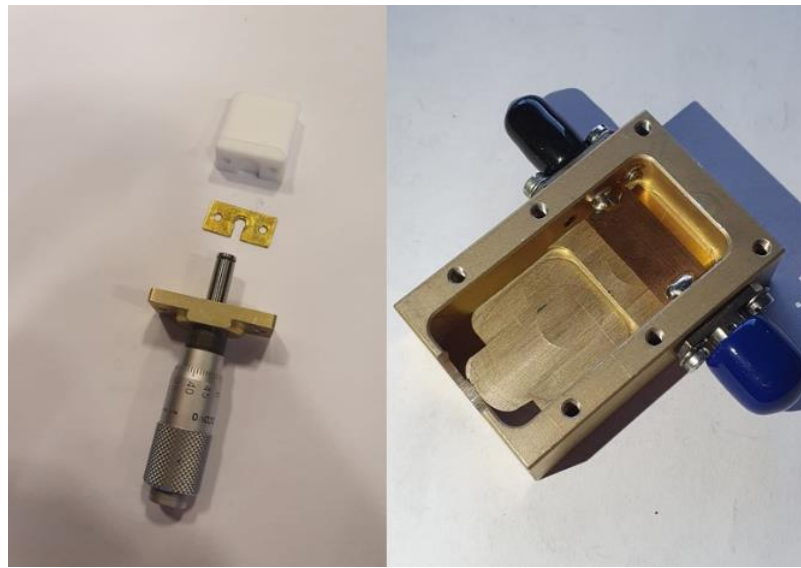


Figure 14. Photo of taken-apart device

The only component which raised issues during the measuring stage was component no 7., the Copper strip which was soldered to the main cavity. Due to this fact, it was challenging to take measurements of the part without exposing the soldered connection to mechanical stress and breakage. However, the dimensions of this part are strictly related to impedance 'Z', thus, they need to be calculated separately based on initial less precise measurements which posed as an initial guess. Similarly, the geometry and size of the PTFE element did not allow for ideally precise measurements, hence, the same process was applied to PTFE. The less precise measurements were then confronted with the dimensional and performance requirements of the PTFE element location and standardized to achieve optimal dimensioning. The rest of the dimensions taken from the real device were strictly transferred into the 3D model. Since the table of measurement was created using pen and paper by hand during the session it is available on request only.

3.3.2 Modelling

The results of a second subsection, modelling, were completed as the creation of a digital twin model to the real device. The software used to model the device was DS SolidWorks. First, each part was modelled separately, as later on the parts were joined into the assembly file. The visualization-created assembly is visible in Figure 15 below.

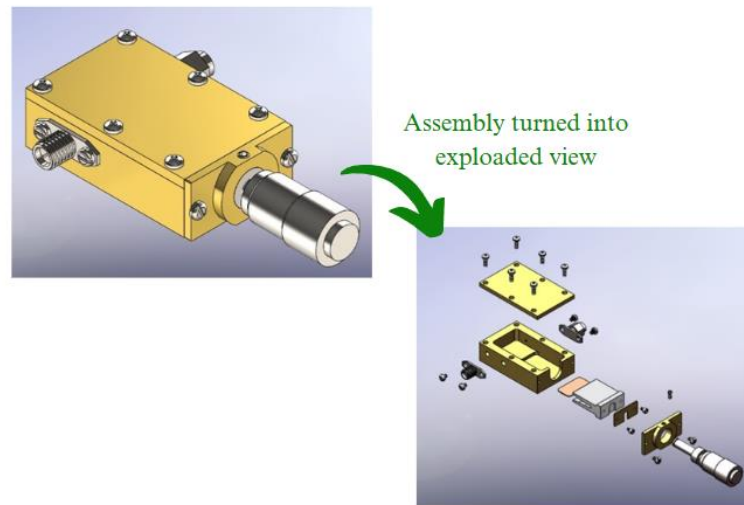


Figure 15. The assembly as well as the exploded view of the regarded phase shifter

However, since the device is characterized by the closed box structure, even though the outer layer clearly displays some of the components, the inner components are hidden inside. Thus, the exploded view showing all the components used was created and included in Figure 17 portrayed on the right. The majority of the parts are an ideal representation of the real component. Nevertheless, some of the components such as the copper strip and internal hex screw adaptor were adjusted from initial values to ensure satisfactory quality and high performance. Herein, to simplify the model the tuning screw was modelled as an ‘empty’ blank so that it does not include all the inner parts which are restricted by the company Mitutoyo. Eventually, it can be concluded that the modelled components were not only the precise adaptation of the real model but also an ideal base for the next step, the creation of technical documentation. All the model files are available on request and all the visualization of the created model are attached to the document (Appendix 4).

3.3.3 Documentation

Eventually, with the model ready, the technical documentation regarding each component as well as the entire assembly was produced. All the drawing sheets are attached to the paper as Appendix 3. In each part documentation, the general standardization was included. Considering all the components it varies between two values ISO-2768-mK and ISO-2768-

fH, among which the second one is more strict. This is the reason why it is used for the PTFE element as visible in drawings number PS-IPE-2.1 and PS-IPE-2.2. The other components need to comply with less strict dimensional accuracies, this is why the other standards were assigned to their drawings.

Moreover, each component drawing not only includes general tolerance, specified in detail material, surface roughness, but also dimensional and geometrical tolerances. However, even though those two terms are widely used the understanding of what they actually mean is less understood. Hence, the next paragraphs will focus on clarifying what the tolerancing used in the drawings means. Namely, Figure 16 portrays a visualisation of parallelism geometrical tolerance, which is particularly used in drawing number PS-IPE-2.2. This geometrical tolerance has a salient influence on the performance of the insulating double-finned element. Moreover, complying with this tolerance allows the PTFE element to fit inside the cavity-cover assembly, thus, the highest attention should be paid to achieving the desired value.

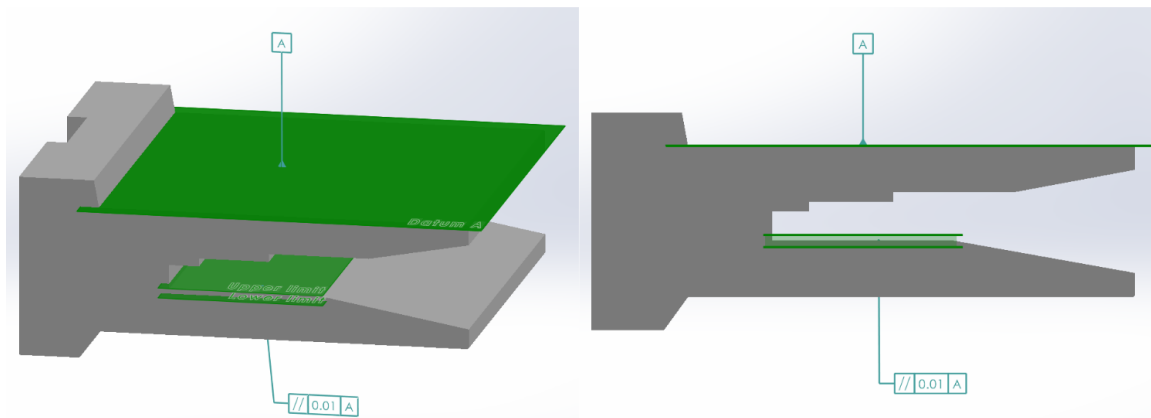


Figure 16. Visualization of parallelism geometrical tolerance

As visible in the figure above, the parallelism tolerance requires datum. In the visualization the datum is marked with letter A. Then, the parallelism tolerance focuses on the area between limits established by the two smaller planes which is called a tolerance zone. For instance, 0.1 mm of tolerance means that two each plane is 0.05 mm deviated from the original one. Herein, all the points of the surface between the lower and upper limit must lie

inside zone. Otherwise, the sample is not fulfilling its requirements of being parallel. Parallelism allows for specifying the limits in mm to which feature's orientation may vary as it is used to constrain the alignment of features for a proper function. Another geometrical tolerance used in the drawing PS-IPE-2.2 is perpendicularity which is visualized in Figure 17. Similarly to parallelism, perpendicularity requires a datum which is marked on the drawing with the letter A. The perpendicularity constraints that chosen feature should lay in 90 degrees orientation to the selected datum. Here, the upper limit is constrained by the plane placed outside of the sample and lower limit by the plane placed slightly into the sample on the photo. Again, those two planes create a tolerance zone which restricts the location of all the possible points of the constrained feature. In other words, perpendicularity is controlling the location where the surfaces have to lie and considering the creation of the tolerance zones the unit of the tolerance is again mm.

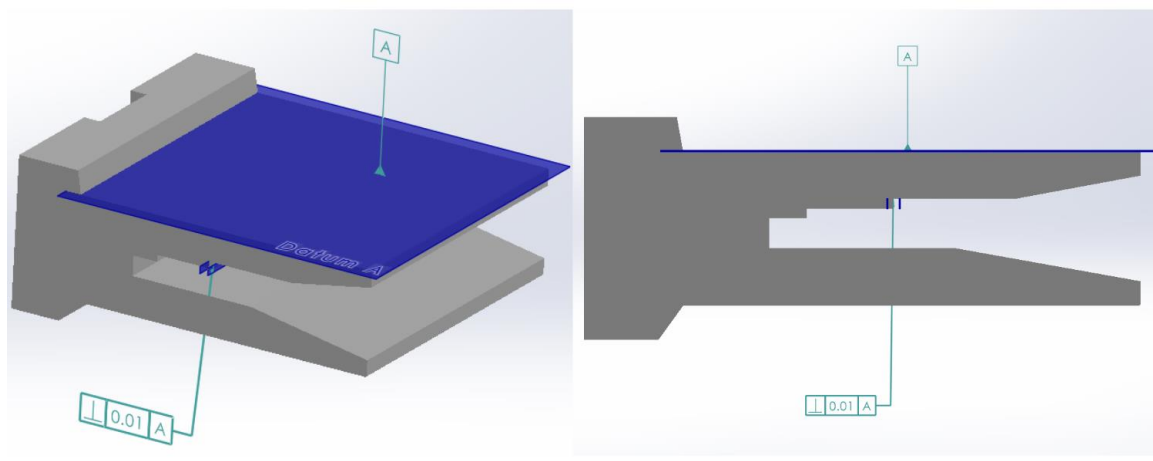


Figure 17. Visualization of perpendicularity geometrical tolerance

Meeting the appropriate values of this tolerance will allow for an appropriate stepwise decrease on one side of the asymmetric double-finned element. It is critical since the range of phase shifting is strictly related to the geometry of the PTFE element. Even the smallest deviation in the geometry could cause a significant decrease of operating range or even lead to the failure in proper operation at all. The next geometrical tolerance used in the drawing is flatness. It is used not only in the drawing number PS-IPE-2.2 but also in e.g. PS-MC-1 and PS-CCP-5. This geometrical tolerance is responsible for ensuring that the required

surface is flat enough according to the assigned deviation value regardless of any other datum or feature. Flatness is visualized on the Figure 18 below.

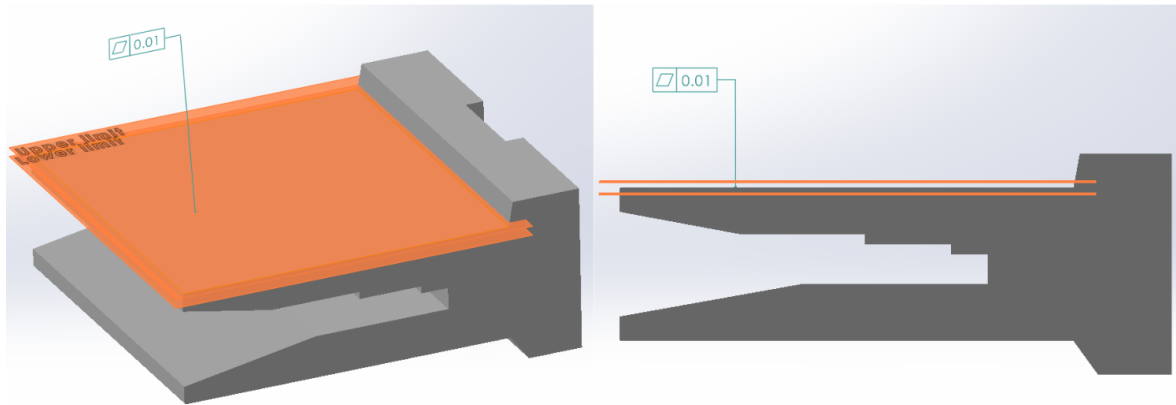


Figure 18. Visualization of flatness geometrical tolerance

Likewise in the previous tolerances, here, the two parallel planes with magnitude distance from original surface given in mm are creating a tolerancing zone within which entire reference surface must lie. However, this time the datum is not needed as in previous tolerances. Discussed tolerance is of a huge significance since it accounts for the fit of the components. Specifically, the main cavity needs to be tightly connected with the cover to ensure the operation in varying environmental conditions including space. The flatness allows that tight connection by restricting the deviation in the surface of the two components.

Furthermore, each manufactured component drawing involves the standardized manufacturing block size and type which significantly simplifies the manufacturing process since the raw material parameters and geometries are specified. All of the block types and sizes were grouped and portrayed in Table 7 below.

Table 7. Raw material type and size for manufacturing

Drawing no.	Manufacturing block type	Manufacturing block size [mm]
PS-MC-1	rectangular rod	47 x 30 x 12.5
PS-IPE-2.1	rectangular bar	22.5 x 19 x 9
PS-TSA-4	rectangular bar	30 x 15 x 4.5
PSA-CCP-5	rectangular bar	47 x 30 x 4
PS-TSHP-6	plate	19 x 9 x 0.5
PS-CS-7	plate	18.5 x 10 x 0.5
PS-CP-11	circular rod	10 x 0.5

Namely, the drawing number PS-MC-1 has manufacturing block type rectangular rod and manufacturing block size 47x30x12.5 in mm. Respectively, the same information regarding other components is placed into the table in similar manner. Various raw material manufacturers provide a personalized approach regarding the sizing of raw material, which means that one can order the raw materials with exactly specified values from the table.

While creating the documentation for the assembly drawing the challenge of datum placement in different components arose. Several of the components need to comply with strict regulations, namely, both SMA connectors need to be coaxial and copper strips between them need to be centred to ensure the desired quality. However, the datum for this geometrical tolerance (coaxiality) would be located in various parts which makes this tolerance impossible to be applied in the manufacturing process since only one part is manufactured at once. Hence, that issue needed to be mitigated by the complex application of several strict dimensional tolerances to the mounting holes of the SMA connectors to the main cavity as well as the copper strip (drawing PS-MC-1, PS-CS-7, PS-SCF-8, and PS-SCM-9). By doing so, the concentricity of SMA connectors could be achieved.

Furthermore, the assembly documentation drawings are divided into two modules. The drawing with the number PS-ASM-1 portrays an assembly drawing with general dimensioning, while the assembly drawing with the number PS-ASM-2 portrays an explosive view of the assembly with the bill of materials. Moreover, this drawing includes assembly lines (dashed lines) which suggest how the parts should be connected with each

other and where to place the screws. The numbered balloons connected to each component serve as a link of the drawing to the tabular bill of materials. Each row of the table contains data related to one component. On the other hand, the discussed table contains 5 columns. The first one is portraying the number in the balloon. The second is a part number, while 3rd one includes the part title. The 4th column contains specific material with standardisation in the bracket. Eventually, the last column contains the quantity of how many times the part was used in the assembly. Having all of this information considered allows for concluding that all the data regarding the assembly of the device was included in the technical documentation.

3.4 Triangulation method result collection

As implied in the method section to complete the result obtained in the work it is needed to employ the triangulation method results. Hence, the results of each previous methods subchapter will be compared or combined in order to achieve best results. The first two subchapter, expert interview and literature review were compared. It was found that in majority of cases the methods yielded similar results. To visualize the comparison, Table 8 was created.

Table 8. Comparison of key findings of the expert interview as well as the literature review

Factor	Literature review	Expert interview	CAD modelling
Dimensioning and tolerances	Importance	Same but extended answer	Standardization and tolerancing
Shape and geometry of the PTFE element	Importance	Same but extended answer	Geometrical tolerances and dimensioning
Copper strip zone	Same but extended answer	Importance	Tolerancing, dimensioning of the area, as well as proper positioning
Material selection	Strict material choice	Loose material choice	Brass CuZn39Pb3 was chosen

As it is visible in Table 8, the significance of dimensioning and tolerances used in the model was emphasized in both, expert interview and literature review. Moreover, the importance of shape and geometry of PTFE element was mentioned in the literature review and expert interview, however, expert not only underlined the importance but also suggested the possible requirements on the structure. Next, the copper strip zone was marked as the crucial for the performance by both, the literature and the expert again, however, here the literature provided more insight into the needed parameters of the design. However, when discussing the material selection of housing components, the expert mentioned that considering low operating frequency any metallic material will perform well. In the meantime, the literature review pointed out the brass CuZn39Pb3 as the best material for the housing, considering its ideally matching the need properties. Eventually, the possible contradictions between the methods were not found as they provided valuable, uncontradictory insight from various perspectives.

Next, the results of both methods were combined with the 3rd method, CAD modelling. The dimensioning and tolerances were combined into the CAD modelling as a use of ISO-2768 standard with varying tolerancing standards from mK to fH. Furthermore, the combination for PTFE element relied on applying the perpendicularity, parallelism and flatness tolerances onto the precisely dimensioned PTFE element as given in the literature review and expert interview. The copper strip dimensioning given in the literature review was appropriately calculated and further implied to the CAD model. Eventually, the material chosen for the research resulting from comparison of the literature review and expert interview was brass CuZn39Pb3. Hence, the triangulation method provided invaluable solution for the discussed work by allowing comparison and combination between three distinct methods. All three methods employed in triangulation are equally important, however, only together, the methods yield satisfactory results as separately they would yield insufficient ones lacking the broader view and significant information.

4 Discussions

In the last chapter of the discussed work, the focus will shift to the reliability analysis, the future of the work and derived conclusions. Here, the results will be assessed and further discussed. Moreover, the possible areas of further improvement will be indicated.

4.1 Reliability assessment of the results

The reliability analysis was conducted in regards to Table 3, visible in section 2.4. As a consequence the Table 9 was created to display what are the outcomes of reliability analysis.

Table 9. Reliability analysis findings

Reliability factor	Literature review	Expert interview	CAD modelling	Triangulation method
Validity	Scientific sources, matching and uncontradictory information across sources	Comparison of answers with the Thesis Seminar group ensured valid answers	Use of a real existing model as the base of the research	Comparing and combining the results
Sensitivity	NA	NA	Correct number of decimals in the technical documentation	NA
Reliability	DOI number and FWCI score	Background of the researcher, decades of experience	Iteration of measurements	Reliability of the previous 3 methods
Error	NA	NA	NA	NA
Accuracy	NA	NA	Appropriate tooling and standards in the model	NA
Saturation	Approximately 3 references obtained for each question	NA	NA	Cross-referencing the results of all 3 methods

In the following subchapter, it will be portrayed in detail how the features included in the table were secured. As the literature review is given as the first one in the table, it was

regarded first from the perspectives of validity, reliability and saturation. The validity of the literature review section is ensured by finding the matching and uncontradictory information from variety of scientific sources only. Moreover, it is confirmed that all the sources used are peer-reviewed. Here, the reliability of the results is checked by verifying the DOI number for each reference and its FWCI (Field-Weighted Citation Impact) score. Approximately 80% of references had DOI number and the FWCI score of references was ranging between 0.07 and 28.56. Moreover, the references which did not poses the DOI number usually had other identifiers which proved their reliability. Later on, both values were included for each reference in empty table 2, which, filled, can be found in attached documentation (Appendix 2). The DOI number can be found in 3rd column and FWCI can be found in the 4th ,last column of the table. Further, a saturation check is conducted by finding multiple sources which portray similar and uncontradictory answers for the given questions. Usually, the three references were used to support one answer for the given question to ensure proper saturation. Hence, considering all of the above, it is possible to conclude that after completing all verification procedures, the quality and reliability of the literature review chapter are guaranteed.

Next, the results of the expert interview were checked from the perspective of reliability assessment. Here, the validity is checked by discussing and comparing the personalized answers for phase shifter with the general ones received by the thesis seminar group during the organised meeting. Next, the reliability was confirmed by selecting a suitable interviewer. The expert is considered reliable as he has decades of experience in the microelectronics field which proves the reliability of his answers. The saturation is not checked as only one expert was interviewed through the research.

Then, CAD modelling was assessed from perspectives of validity, sensitivity, reliability as well as accuracy. The first one, validity, is guaranteed by using the real model as a basis for the measurements as well as for the digital twin created in modelling software. The sensitivity was secured by ensuring the correct number of decimals in dimensioning. Here, due to the usage of moderate and strict general tolerancing, the number of decimals varied from 0 to 1 as the appropriate tolerancing covered variation with 1 decimal level. The reliability of the 3D digital model is secured by iteration of measurements which resulted in deviations of approximately 0.1 mm for various dimensions. Thus, the average dimension magnitude resulting from multiple measurements was chosen for the model. Eventually,

accuracy was ensured by using the tooling with smallest possible measurement of 0.1 mm. Later on in the model the accuracy was based on the tolerances and standards used.

Lastly, the entire triangulation method regarded as a whole was evaluated from the perspective of validity, reliability and saturation. Validity is confirmed by comparing and combining the results. Namely, it was checked that all three methods yield similar, uncontradictory results. On the other hand, the reliability was achieved by making sure that all three methods were completed in a reliable manner separately. By securing the reliability for each method separately, it is possible to derive the conclusion that their combination was reliable. Saturation of the information in the triangulation method is visible again through the cross-referencing of the answers given by the expert during the interview, literature review and 3D modelling. Specifically, the same information, result repeats over time from different sources as visible in the work, which allows for achieving the desired saturation.

Hence, the reliability analysis was successfully completed using the tabular tool described in detail in the methods section. As described above, all the results were verified to improve the quality of the research through various procedures. Moreover, the verification has shown that the obtained answers are both useful and reliable. Consequently, it proves that the research met all of the reliability requirements given initially. Therefore, it is possible to conclude that the gathered material is of high quality and can be used as a basis for further research.

4.2 Key findings and conclusions

The key findings of the research were carefully derived through a complete triangulation method, which, through comparing and combining the methods, allowed for achieving satisfactory results. Comparing the results of the expert interview and literature review, it is possible to observe that even though majority of elements underlined the same quality factors as the crucial for the performance of the device. Namely, the significance of dimensioning and tolerances used in the model, the shape and geometry of PTFE element as well as copper strip zone were emphasized in both, expert interview and literature review. By combining those results, it was possible to apply the given standardisation, tolerancing and appropriate geometry to the created 3D model. In copper strip zone case, the results were combined in the digital twin by adjusting the size and position of the strip as well as properly

dimensioning the space below and above the strip created by the collars of the main cavity as well as the cover. Nevertheless, the material selection solution provided by the expert and by the literature review has differed. Hence, those two results should be combined by ideally choosing this particular brass as the leading material with remarking that for low frequency application, the metallic material could be freely chosen depending on the need of the manufacturer of the phase shifter. Consequently, the material chosen in the 3D model results is the brass CuZn39Pb3 as it should be the base one. Hence, it is possible to conclude that all of the mentioned above factors are the most influential quality assurance aspects of the discussed device responsible for the satisfactory operation.

Even though all key factors found during the research are crucial for the quality and performance of the regarded phase shifter, there was one that appeared a few more times than the other factors. The most frequently appearing result is the significance of PTFE element shape and geometry. Since it appeared in all three completion methods of triangulation, it is possible to conclude that this factor is the most influential quality assurance aspect of the mechanically adjustable microwave precision passive phase shifter. Thus, to achieve satisfactory performance the special attention should be paid to the guidelines provided in the work on how to ensure the appropriate design of the discussed element. The guidelines for not only insulating double-finned elements but also for the other crucial for the operation factor included not only the measuring techniques but also advices on the manufacturing methods to achieve high quality as well as diverse visuals regarding the tolerancing used in the work to better understand the application of the standards and tolerances used.

Eventually, it is possible to mark that the work was completed with a stable and smooth workflow. Moreover, it is believed that only the systematic approach towards the completion of the research should be used to achieve high-quality results. Thus, it was applied in all elements needed to complete the work. What is more, the work includes fulfilled all the requirements given at the beginning by specifying the most important quality assurance aspects as well as methods on how to implement them in the real life. Consequently, it is ensured that manufacturing the phase shifter based on this work will result in a device which meets rigid performance standards under various operating conditions. Hence, the research conducted is of high quality and yields satisfactory results. Further it provides a significant

contribution into microelectronics and especially phase shifter discussing literature. Having considered all of that it can be concluded that the research was a success.

4.3 Comparison and connections with former research

The former research touching particularly on the topic of quality assurance of mechanically adjustable microwave precision passive phase shifter did not exist. However, through a detailed review, it was possible to achieve satisfactory conclusions using various applicable sources. The research prior to this work included various essential attributes, which, considered together, yield superior results for the discussed phase shifter than those ones which could be obtained by separate considerations. However, because of this research, it is possible to observe the connections between the various literatures used, which state critical conclusions for the quality assurance of microelectronics in general and especially phase-shifted.

The research made by Sciberras, M.; Dingli, A. (2023), Nightingale, A.J. (2019) and Godfroid, A.; Spino, L.A. (2019) has shown various the benefits of triangulation methods and resulted in the usage of this particular method in the discussed work. Further, even though Gill, A.J.; Xenitidou, M.; Gilbert, N. (2010), Murugavel, R. (2017), and Careche, M.; Sánchez-Alonso, I. (2017) had various subjects of the studies, they all provided invaluable definitions of the quality which were used in the research. Then, Alkaraki, Qu and Kelly (2024), Rahimian Omam et al. (2020) and Wang et al. (2015) have all contributed to the definition of the performance which was considered during the research. The use of literature review method was recommended through the studies of Farrukh and Sajjad (2023), Brendel et al. (2020) and Le et al. (2024) who has shown the clear advantages and opportunities which resulted from literature review procedure. The tables of questions were used as advised by their researches of Alonso-Arroyo et al. (2012), Amat (2009) as well as Ghisi et al. (2012) and Ruiz et al. (2021). They all provided different benefits for the usage of the tabular analysis tool. Further, the usage of expert interview was supported by the advantages portrayed in research of Chernova (2023) together with the one of Rose and Grosvenor (2013). Meanwhile, Beyers et al. (2014) as well as Döringer (2021) provided insight onto how such an interview should be conducted and evaluated.

The studies which contained the most influential on this work material were researches made by Eskelinen P. and Eskelinen H. (2003) and Eskelinen, Lätti and Silventoinen (2004). The first one provided insightful information regarding the performance of the device and assisted in establishing requirements from the MW/RF point of view including the impedance equation as well as surface roughness values. In the meantime, the second abovementioned research assisted in establishing values of particular electrical parameters such as strain of PTFE and Z values. Both contributed to the regarded phase shifter research by closely discussing some of the QA factor investigated in the work.

In the previous research, Pathak et al. (2018) as well as Umaras and Tsuzuki (2011) have underlined that dimensioning and tolerancing are crucial features in quality assurance, hence they need to be first clearly specified and later on tremendously examined. In the meantime Gupta and Kandpal (2020) advocated the importance of material choice. Hence, as the importance was recognized, the appropriate material was chosen with regards to previous research. Consequently, PTFE was chosen as an insulating element due to the various benefits for the desired application which were stated previously by the research of Zhu et al. (2023), Radulovic and Wojcinski (2023) and Lizotte (2008). All three studies underlined the positive traits of PTFE with special attention paid to the great dielectric properties and high thermal stability. By the same reasoning, the researches of Pantazopoulos and Toulfatzis (2012), Toulfatzis et al. (2016), together with Zor, Ünal and Gökergil (2011) helped in choosing brass CuZn39Pb3 as the leading material for the housing advocating its advantages. The same positive traits of copper Cu-OF-OK found in the researches of Knych, Smyrak and Walkowicz (2011), Ladani, Razmi and Lowe (2023), as well as Platzman et al. (2010) lead to its choice as a material for copper strip. The last material chosen in the work was stainless steel X8CrNiS18-9 based on the summed pros offered by the studies made by Brnic et al. (2012) and Pereira, Candido and de Malafaia (2021). Eventually, Ni et al. (2023) together with Liu et al. (2024) have shown two more essential aspects which should be considered at the design phase. First advocated the importance of PTFE element regarding the operation while the other focused on emphasizing the key of copper strip zone.

The benefits of manufacturing techniques recommended in the research as well as the particular type were emphasized by the research on quality manufacturing techniques conducted by Kannan et al. (2015), Zoghipour, Atay and Kaynak (2021) as well as Shinozuka (2013) and Ni et al. (2024). Even though their approach has differed and the method

varied between machining, drilling and cutting, they all have proven the benefits of described techniques. Later on, the measuring setup used in the research were supported by the works of Robins (2006), Kurfess and Campbell Jr. (2006), Machado et al. (2019) as well as Grochalski et al. (2021). Robins was advocating the use of digital measuring gauge, whereas Kurfess, Campbell Jr. and Machado showed the benefits of CMM. Grochalski has studied and recommended various profilometer setups which are influential in surface roughness measurements.

Moreover, the previous literature was not showing the entire perspective as stated in the research problem as only combined they allow for the proper assessment of quality assurance aspect for the discussed device. Hence, this research successfully filled in the gap in the microelectronics literature by discussing the quality assurance of the device considering the full viewpoint. Additionally, the work complemented the bigger on-going research at LUT university which was previously mentioned in the 2.2 background subchapter of method section. Consequently, it is possible to derive the conclusion that the research was successful from the perspective of expected contribution to the microelectronics world.

4.4 Topics for future research

Even though the research was a success, the room for improvement was also observed. Since the work focuses only on the creation of a digital twin, thus, the before manufacturing stage, due to time and resources limitations, it is clear that the manufacturing and post-processing stages should be pursued further as well. Namely, the production of the real device using the instructions given in the work together with the post processing of the results should be conducted in the future. The real life mechanical and electrical tests conducted after manufacturing would bring up a new viewpoint into the quality assurance discussion.

Moreover, the saturation and reliability of the expert interview results could be improved by consulting more experts in the discussed field in the future. By doing so, it will be possible to notice the elements which were previously unintentionally omitted in the results section. Further, to enhance the mechanical performance of the discussed phase shifter in a design phase, the FE analysis of the model could be conducted on each component as well as the assembly. This procedure would allow for the identification of the crucial geometrical features which may cause trouble, and as a consequence, for addressing those issues by re-

designing the model. Additionally, it is worth noticing that while regarding the FE model, the saturation should be properly addressed. Similarly, the reliability assessment could be enhanced by 3D printing the modelled components to check the applied dimensioning. This solution provides a reliable dimensioning and tolerancing test at low cost and with high speed. Nevertheless, such a sample could work only for prototyping purposes as the filaments or resins used in 3D printing would be not suitable for creation of the actual device.

Furthermore, the value engineering method should be investigated to identify and avoid all cases of overquality present during the research at various stages which are unnecessary for the successful operation of the device. By removing recognized factors, this procedure would benefit by decreasing the cost of production of the phase shifter which simultaneously would increase its applicability. Additionally, this value analysis (VA) method would not only minimize the risk of overquality in the work, but also underline the significance of cost effectiveness next to quality in microelectronics design serving as another crucial step in the phase shifter manufacturing process.

Eventually, it would be possible to explore new as well as more unconventional manufacturing methods which could be used for the production of the regarded phase shifter. Specifically, the investigation of various 3D printing methods such as carbon fibre composite printing could yield a new perspective on the manufacturing processes in phase shifters discussion. Having all things considered, it is possible to observe that a need for further research regarding the discussed topic exists, especially in the field mentioned above.

5 Summary

The conducted research includes a complete set of quality assurance considerations needed for the mechanically adjustable microwave precision passive phase shifter. As the detailed and complete discussion of the device quality assurance aspects was missing the question of what are the most influential quality assurance aspects of the discussed device responsible for the correct operation was answered in the work. Furthermore, the work incorporates the instruction on how to ensure that the phase shifter meets rigid performance standards under various operating conditions. The focus on systematic usage of the triangulation method has provided the results from three unique viewpoints, including the literature review, expert interview as well as CAD modelling. The novel approach regarding the quality assurance allowed for a detailed description of the QA actions not only after but also before and during the manufacturing stages of the device and its components. Consequently, the literature review includes not only all the designing constraints before manufacturing but also discussed the quality of manufacturing methods as well as the measurements and procedures conducted after the manufacturing stage. Further, the expert interview covered and extended the invaluable insight into the key features influencing the performance of the device incorporated in the literature review. Lastly, the 3rd triangulation method resulted in creation of successful phase shifter model with the complete technical documentation which together with instruction on how to understand used tolerancing are encompassed in CAD modelling section. Moreover, the research question was answered successfully by deriving the conclusion from the combination and comparison of the triangulation method results. Hence, the most important quality aspect were identified, leading with the geometry and shape of PTFE element at the same time including the copper strip zone, dimensioning and tolerances as well as proper material selection were discussed in the conclusions. The quality of obtained results was ensured by means of a complete reliability analysis tool which was deliberately conducted and further described in discussion section. Additionally, research has addressed the gap in existing literature regarding the quality assurance aspect of the examined phase shifter, at the same time introducing new possibilities for further work in the discussed area. Eventually, the research was completed in a systematic manner, which lead to satisfactory results and reliable conclusions. Hence, it poses as a great base for further investigation of the topic.

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Appendix 1. Used referencing tool

Number of question (Q1-Q16)	Questions to which the answers are searched for: / Reference number:	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15	#16	#17	#18	#19	#20	#21	#22	#23	#24	#25
Q1	What are the benefits of triangulation method?	X	X	X																						
Q2	What is a triangulation method and how triangulation works?	X	X	X																						
Q3	What is understood as quality in the device case?				X	X	X																			
Q4	What is understood as performance of the phase shifter?							X	X	X	X															
Q5	How does the phase shifter work?											X	X													
Q6	What are the advantages of mechanically adjustable phase shifters?											X	X													
Q7	What is the application of phase shifters?											X	X													
Q8	What are the methods for analyzing answers obtained from the expert interview?													X	X											
Q9	What are the benefits of the expert interview?													X	X	X										
Q10	What are the benefits of keeping the references and answers organized in clear manner?																	X	X	X	X				X	X
Q11	What to remember while conducting the literature review?																				X	X	X	X	X	X
Q12	How to check the reliability of the results obtained by the triangulation method?	X	X	X																					X	X
Q13	What are the properties of PTFE material?																									
Q14	What are the material properties of Brass?																									
Q15	Which material properties of Copper are the most important for the desired application?																									
Q16	How are the traits of stainless steel X8CrNiS18-9 in comparison to other grades of steel?																									
Q17	Why proper dimensioning and tolerancing are crucial aspects of quality assurance in microelectronics applications?																									
Q18	Which aspects are important for discussed components?																									
Q19	Which manufacturing methods are suitable for the discussed phase shifter?																									
Q20	What are the benefits of measuring setups chosen in the research?																									
Summarized observations about the relevance of each reference	The quality of all the references was ensured by looking for them in scientific databases as well as finding the appropriate DOI number. /Does the reference possess DOI number:	X	X	X	X	-	X	X	X	X	-	X	X	X	X	X	X	X	X	-	X	X	-	X	X	X

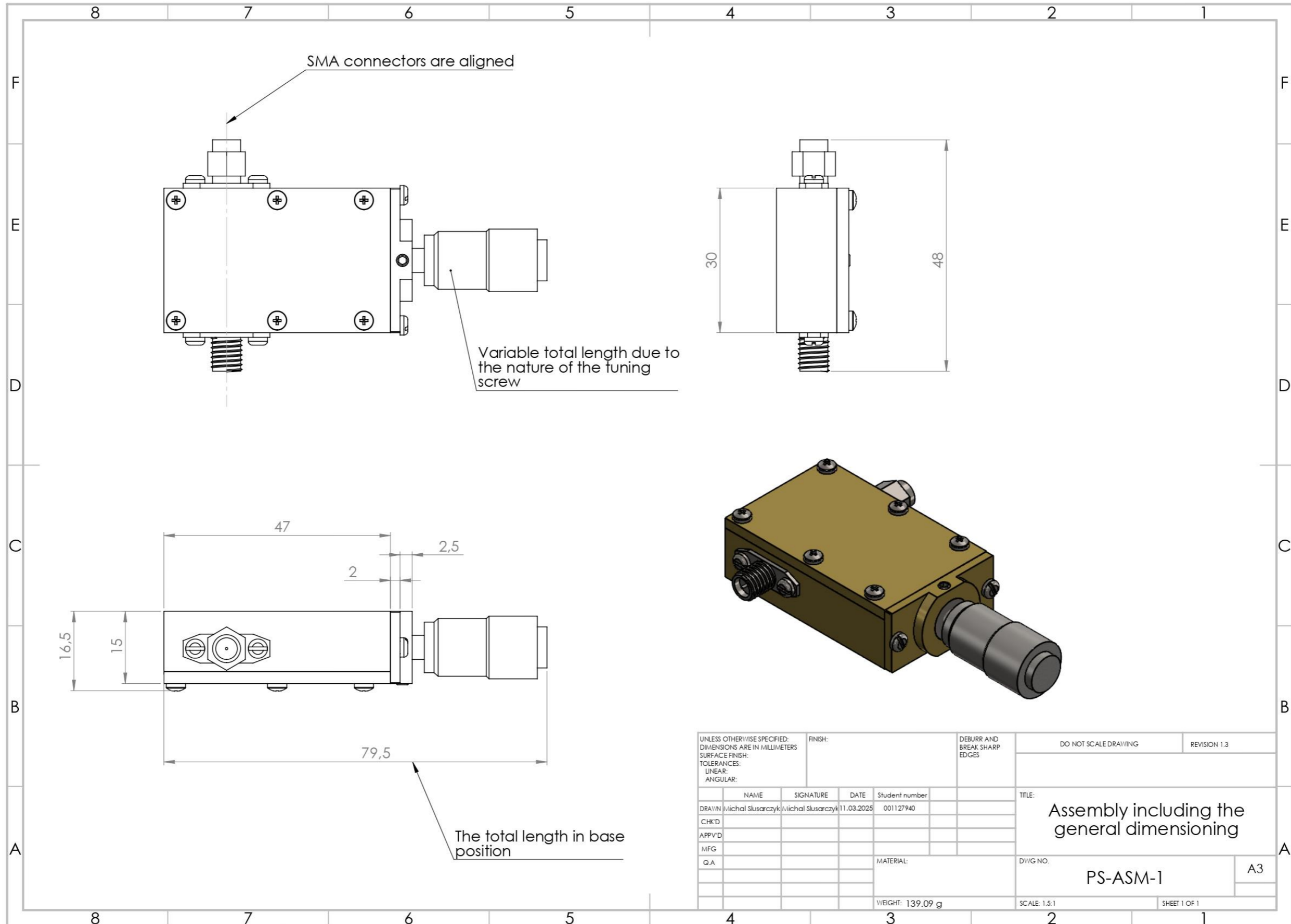
Number of question (Q1-Q16)	#26	#27	#28	#29	#30	#31	#32	#33	#34	#35	#36	#37	#38	#39	#40	#41	#42	#43	#44	#45	#46	#47	#48	#49	#50	#51	
Q1																											
Q2																											
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Q5																											
Q6																											
Q7																											
Q8																											
Q9																											
Q10																											
Q11																											
Q12																											
Q13	X	X	X																								
Q14				X	X	X																					
Q15							X	X	X																		
Q16										X	X																
Q17												X	X														
Q18													X					X							X	X	
Q19									X	X	X								X								
Q20																						X	X	X	X		
Summarized observations about the relevance of each reference	X	X	X	X	X	X	X	-	X	-	X	X	X	X	-	X	X	X	X	X	-	-	X	X	-	-	

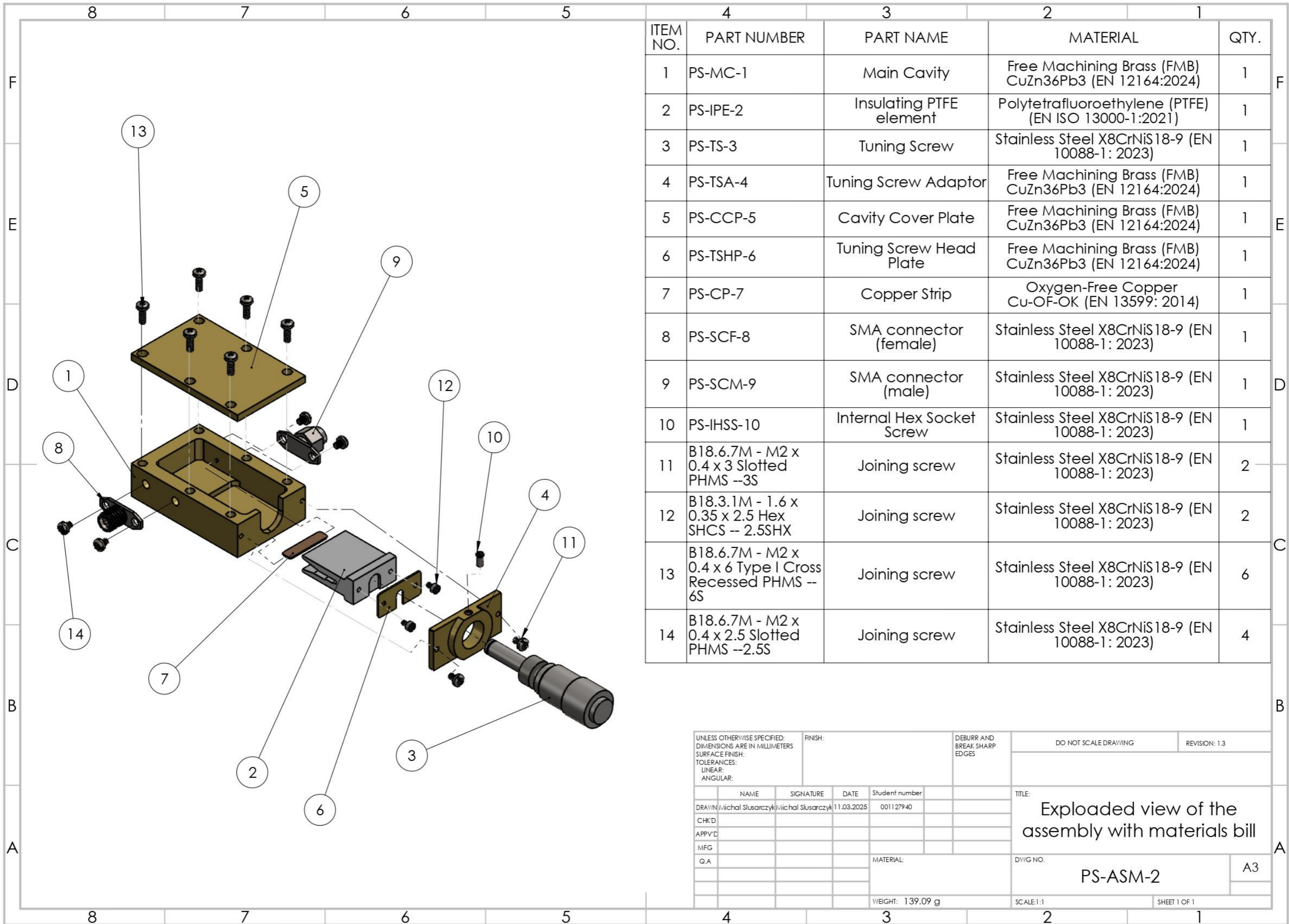
Number of question (Q1-Q16)	Summarized observations to integrate the final answers to each question
Q1	Multiple uncontradicting answers across references, integrated into work in research methods subsection.
Q2	Consistent answer across references, integrated into work in research methods subsection.
Q3	Multiple uncontradicting answers across references, integrated into work in background and motivation section.
Q4	Consistent answer across references, integrated into work in background and motivation section.
Q5	Consistent answer across references, integrated into work in background and motivation section.
Q6	Multiple uncontradicting answers across references, integrated into work in background and motivation section.
Q7	Multiple uncontradicting answers across references, integrated into work in background and motivation section.
Q8	Consistent answer across references, integrated into work in arrangements for expert interview section.
Q9	Multiple uncontradicting answers across references, integrated into work in arrangements for expert interview section.
Q10	Multiple uncontradicting answers across references, integrated into work in literature search and review section.
Q11	Multiple uncontradicting answers across references, integrated into work in literature search and review section.
Q12	Consistent answer across references, integrated into work in research methods subsection.
Q13	Multiple uncontradicting answers across references, integrated into work in results section.
Q14	Multiple uncontradicting answers across references, integrated into work in results section.
Q15	Multiple uncontradicting answers across references, integrated into work in results section.
Q16	Consistent answer across references, integrated into work in results section.
Q17	Multiple uncontradicting answers across references, integrated into work in results section.
Q18	Multiple uncontradicting answers across references, integrated into work in results section.
Q19	Multiple uncontradicting answers across references, integrated into work in results section.
Q20	Multiple uncontradicting answers across references, integrated into work in results section.
Summarized observations about the relevance of each reference	

Appendix 2. The list of references with the DOI number and FWCI score

Reference number	Reference	DOI number	FWCI score
1	(Godfroid and Spino, 2015)	10.4324/9780203489666-11	1.43
2	(Nightingale, 2019)	10.1016/B978-0-08-102295-5.10437-8	11.31
3	(Sciberras and Dingli, 2023)	10.1007/978-3-031-19900-4_9	4.15
4	(Gill, Xenitidou and Gilbert, 2010)	10.1109/SASOW.2010.25	-
5	(Murugavel, 2017)	-	-
6	(Careche and Sánchez-Alonso, 2017)	10.1201/9781315120461	0.55
7	(Alkaraki, Qu and Kelly, 2024)	10.1109/LMWT.2023.3339200	1.91
8	(Rahimian Omam et al., 2020)	10.1049/el.2020.0632	0.07
9	(Wang et al., 2015)	10.1109/INTMAG.2015.7156952	1.61
10	(Microwave Journal, 2006)	-	-
11	(Zhang, Yuan and Liu, 2016)	10.1109/ARRAY.2016.7832555	0.72
12	(Wang and Yan, 2023)	10.1587/elex.20.20230179	0.16
13	(Döringer, 2021)	10.1080/13645579.2020.1766777	28.56
14	(Beyers et al., 2014)	10.1057/iga.2014.11	1.46
15	(Chernova, 2023)	10.14515/monitoring.2023.5.2418	0.3
16	(Rose and Grosvenor, 2013)	10.4324/9781315069173-17	-
17	(Amat, 2009)	10.3145/epi.2008.ene.12	-
18	(Alonso-Arroyo et al., 2012)	-	0.35
19	(Ruiz et al., 2021)	10.34190/EKM.21.199	-
20	(Ghisi et al., 2012)	10.1590/s0103-37862012000200002	-
21	(Brendel et al., 2020)	-	1.32
22	(Le et al., 2024)	10.4018/979-8-3693-2603-9.ch002	18.08
23	(Farrukh and Sajjad, 2023)	10.1108/S2754-586520230000002006	1.05
24	(Siddaway, Wood and Hedges, 2019)	10.1146/annurev-psych-010418-102803	21.44
25	(Noordzij et al., 2009)	10.1038/ki.2009.339	0.35
26	(Lizotte, 2008)	10.1117/12.781423	-
27	(Radulovic and Wojcinski, 2023)	10.1016/B978-0-12-824315-2.00270-0	6.39
28	(Zhu et al., 2023)	10.1016/j.matlet.2022.133306	0.3
29	(Toufatzis et al., 2016)	10.1007/s00170-016-8435-5	0.73
30	(Pantazopoulos and Toulfatzis, 2012)	10.1007/s13632-012-0019-7	0.51
31	(Zor, Ünal and Gökergil, 2011)	10.1134/S2070205111060207	-
32	(Platzman et al., 2010)	10.1021/la902006v	0.57
33	(Knych, Smyrak and Walkowicz, 2011)	-	0.83
34	(Ladani, Razmi and Lowe, 2023)	10.3390/jmmp7040137	0.29
35	(Pereira, Candido and de Malafaia, 2021)	-	-
36	(Brnic et al., 2012)	10.1520/JTE104160	0.68
37	(Pathak et al., 2018)	10.1007/s40032-016-0337-7	1.77
38	(Umaras and Tsuzuki, 2011)	10.4271/2011-36-0072	-
39	(Liu et al., 2024)	10.11817/j.yxb.1004.0609.2024-44761	-
40	(Kannan et al., 2015)	-	-
41	(Zoghipour, Atay and Kaynak, 2021)	10.1016/j.procir.2021.09.042	2.53
42	(Shinozuka, 2013)	10.4028/www.scientific.net/AMR.797.208	2.84
43	(Ni et al., 2023)	10.1016/j.jmapro.2022.11.030	1.19
44	(Ni et al., 2024)	10.3969/j.issn.1004-132X.2024.03.012	-
45	(Gupta and Kandpal, 2020)	10.1007/978-981-15-2267-3_1	-
46	(Robins, 2006)	-	-
47	(Kurfess and Campbell Jr., 2006)	-	1.11
48	(Machado et al., 2019)	10.1115/IMECE2019-11600	0.57
49	(Grochalski et al., 2021)	10.12913/22998624/130453	0.72
50	(Eskelinen and Eskelinen, 2003)	-	-
51	(Eskelinen, Lähti and Silventoinen, 2004)	-	-

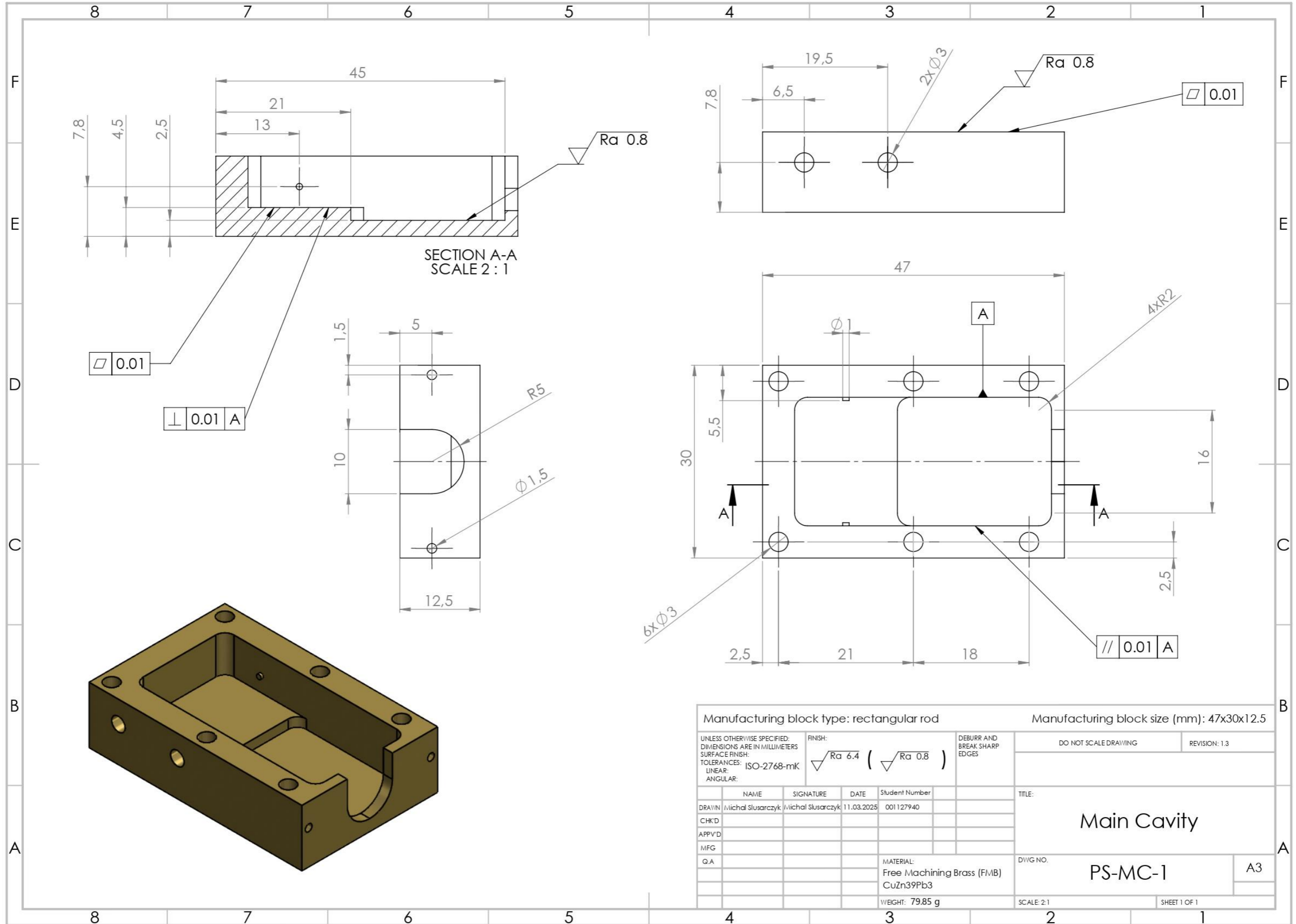
Appendix 3. Technical drawings created during the research

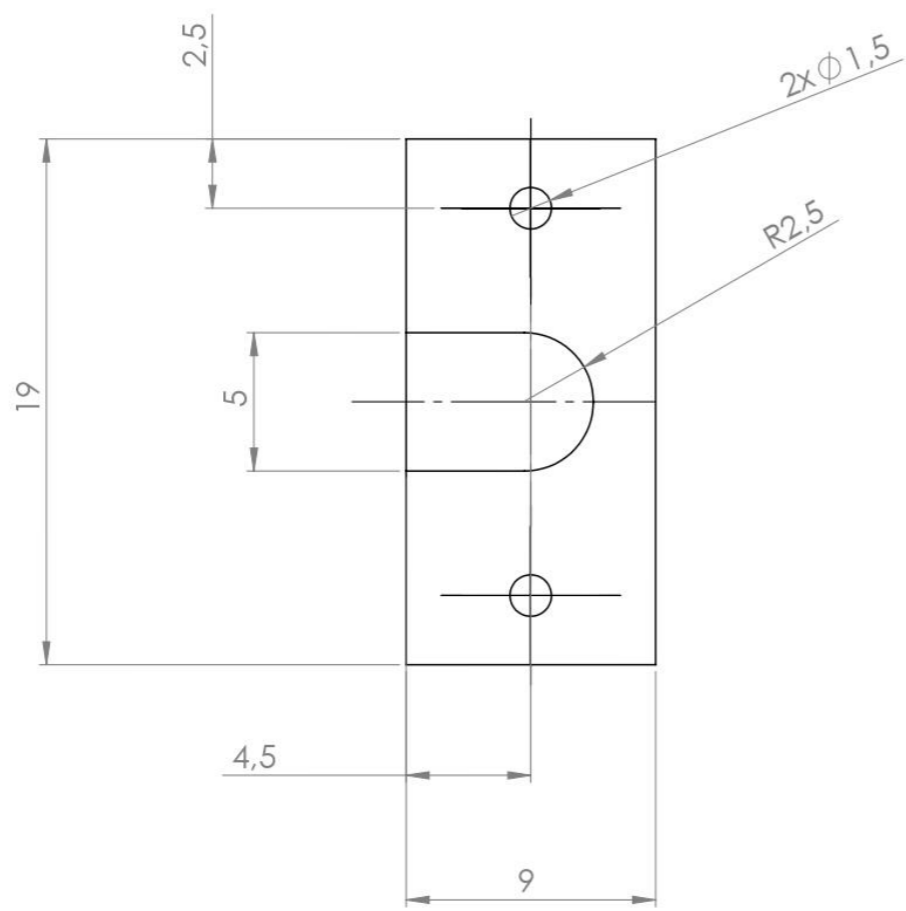
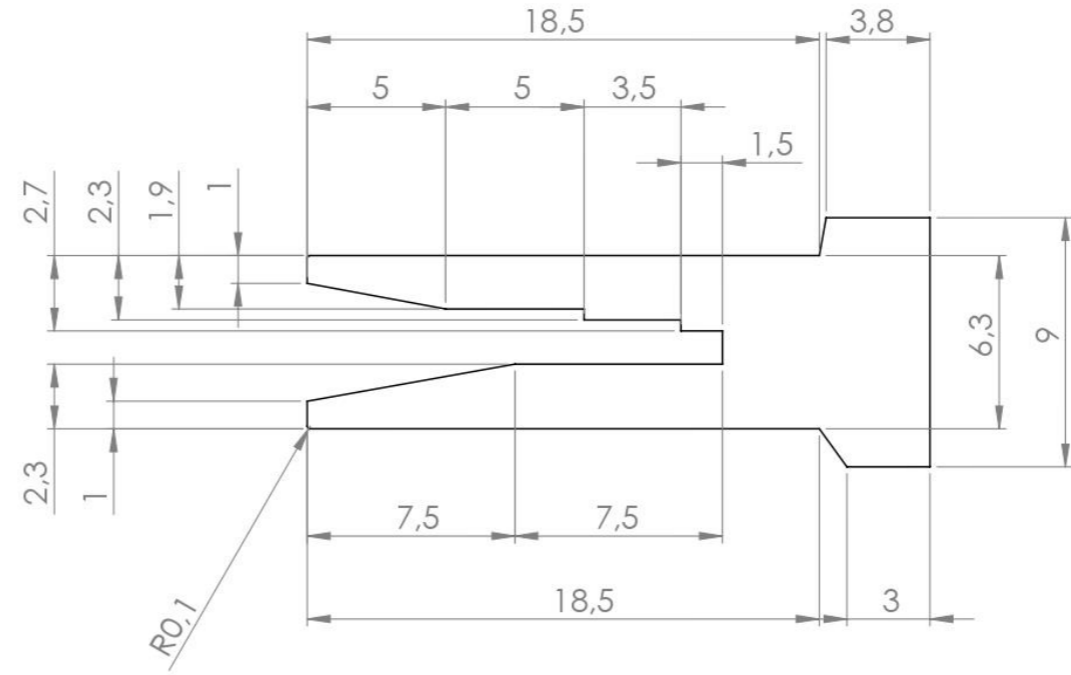
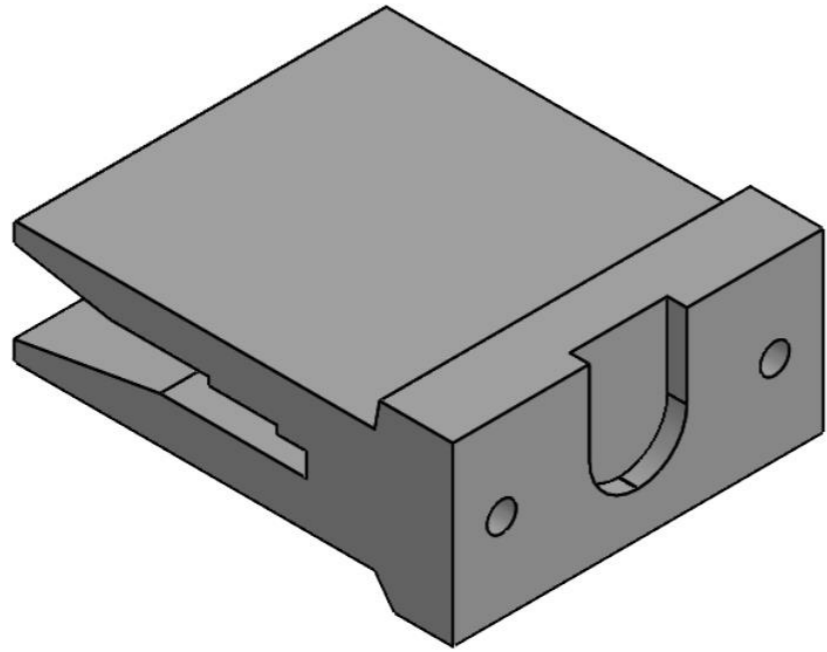




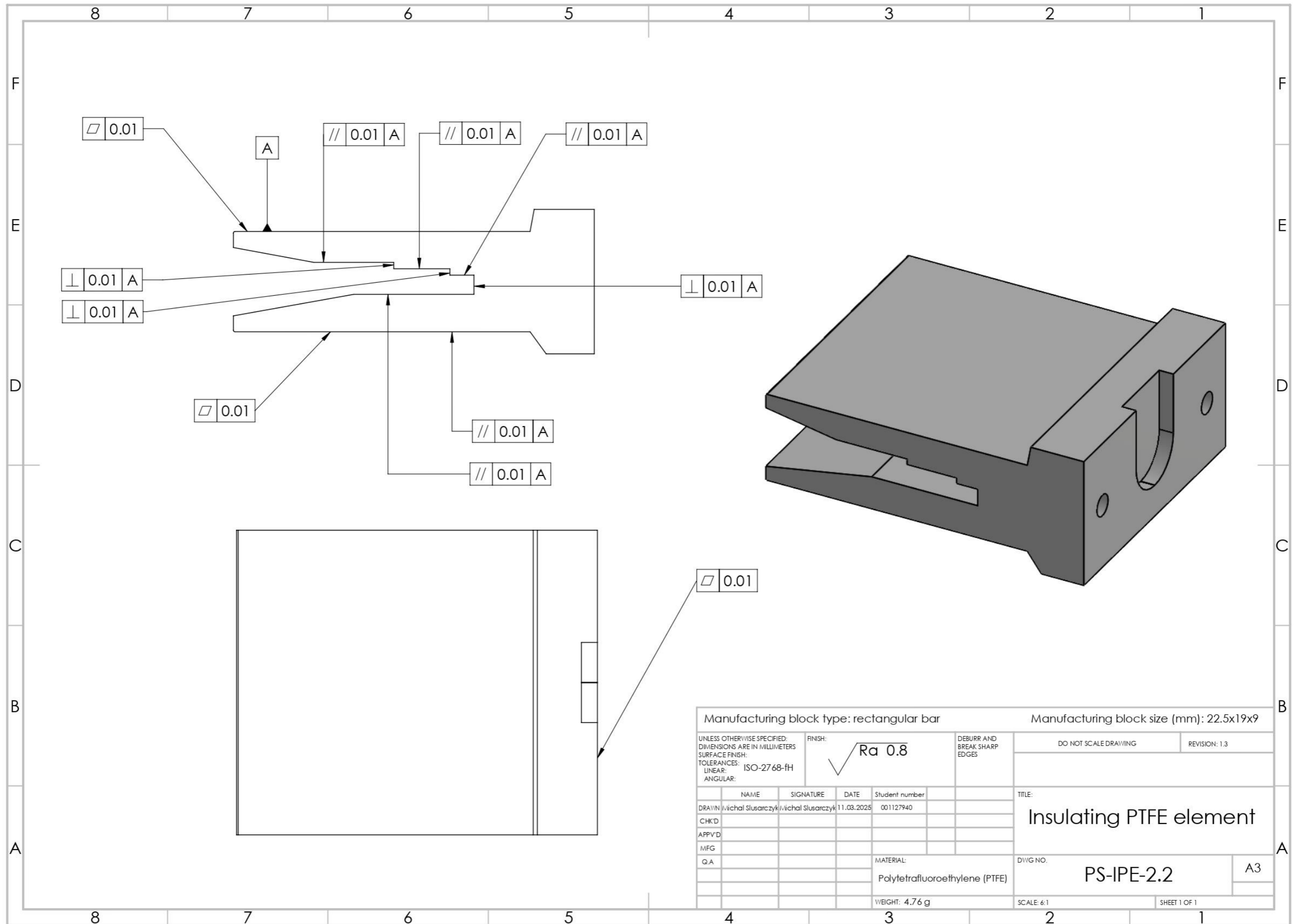
ITEM NO.	PART NUMBER	PART NAME	MATERIAL	QTY.
1	PS-MC-1	Main Cavity	Free Machining Brass (FMB) CuZn36Pb3 (EN 12164:2024)	1
2	PS-IPE-2	Insulating PTFE element	Polytetrafluoroethylene (PTFE) (EN ISO 13000-1:2021)	1
3	PS-TS-3	Tuning Screw	Stainless Steel X8CrNiS18-9 (EN 10088-1: 2023)	1
4	PS-TSA-4	Tuning Screw Adaptor	Free Machining Brass (FMB) CuZn36Pb3 (EN 12164:2024)	1
5	PS-CCP-5	Cavity Cover Plate	Free Machining Brass (FMB) CuZn36Pb3 (EN 12164:2024)	1
6	PS-TSHP-6	Tuning Screw Head Plate	Free Machining Brass (FMB) CuZn36Pb3 (EN 12164:2024)	1
7	PS-CP-7	Copper Strip	Oxygen-Free Copper Cu-OF-OK (EN 13599: 2014)	1
8	PS-SCF-8	SMA connector (female)	Stainless Steel X8CrNiS18-9 (EN 10088-1: 2023)	1
9	PS-SCM-9	SMA connector (male)	Stainless Steel X8CrNiS18-9 (EN 10088-1: 2023)	1
10	PS-IHSS-10	Internal Hex Socket Screw	Stainless Steel X8CrNiS18-9 (EN 10088-1: 2023)	1
11	B18.6.7M - M2 x 0.4 x 3 Slotted PHMS --3S	Joining screw	Stainless Steel X8CrNiS18-9 (EN 10088-1: 2023)	2
12	B18.3.1M - 1.6 x 0.35 x 2.5 Hex SHCS -- 2.5SHX	Joining screw	Stainless Steel X8CrNiS18-9 (EN 10088-1: 2023)	2
13	B18.6.7M - M2 x 0.4 x 6 Type I Cross Recessed PHMS -- 6S	Joining screw	Stainless Steel X8CrNiS18-9 (EN 10088-1: 2023)	6
14	B18.6.7M - M2 x 0.4 x 2.5 Slotted PHMS --2.5S	Joining screw	Stainless Steel X8CrNiS18-9 (EN 10088-1: 2023)	4

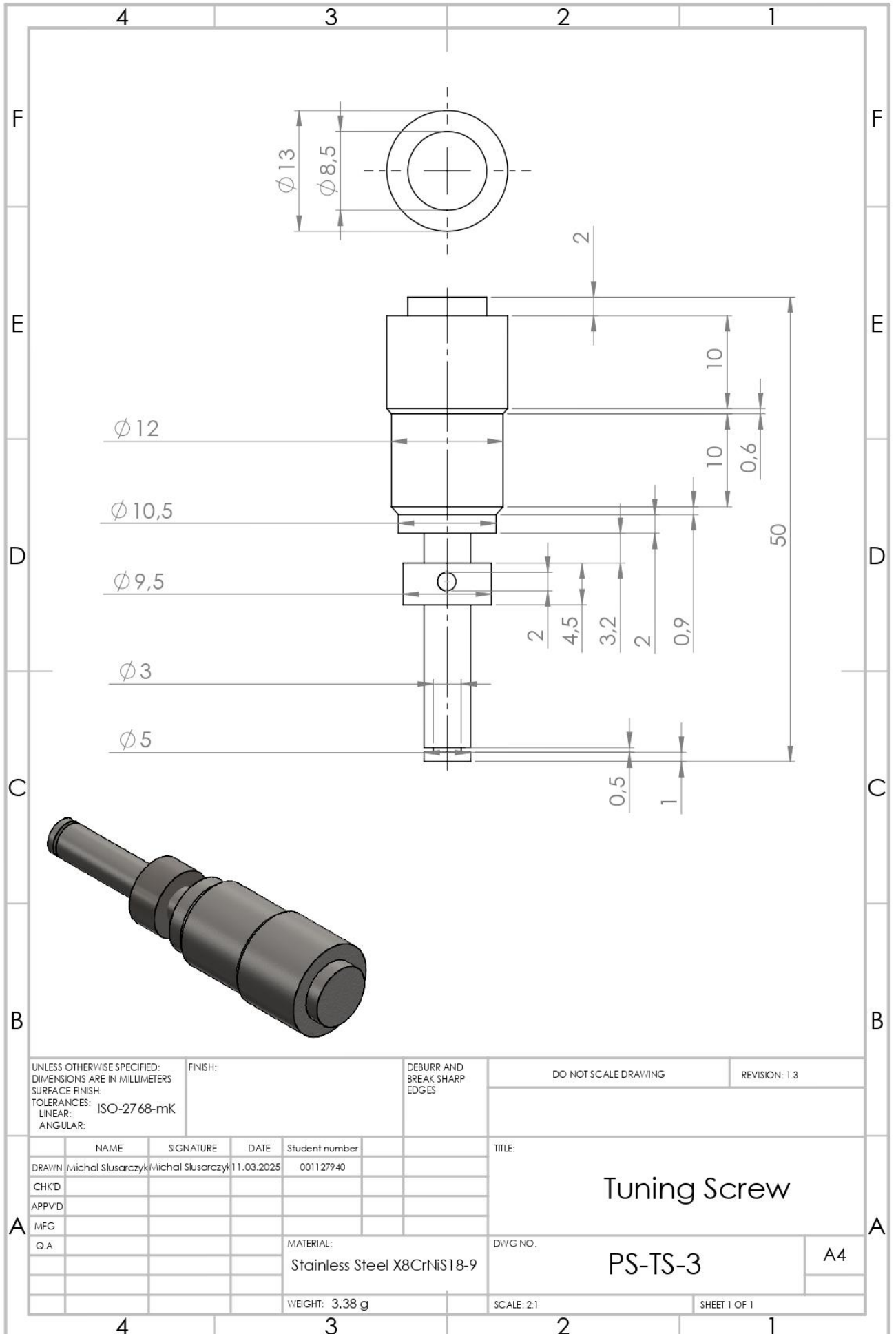
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:		FINISH:	DEBURR AND BREAK SHARP EDGES		DO NOT SCALE DRAWING	REVISION: 1.3
NAME	SIGNATURE	DATE	Student number	TITLE: Exploded view of the assembly with materials bill		
DRAWN: Michal Slusarczyk	Michal Slusarczyk	11.03.2025	001127940	DWG NO. PS-ASM-2		
CHKD:				A3		
APPVD:				SCALE: 1:1		
MFG:				SHEET 1 OF 1		
Q.A:				WEIGHT: 139.09 g		





Manufacturing block type: rectangular bar				Manufacturing block size (mm): 22.5x19x9	
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: ISO-2768-fH LINEAR: ANGULAR:		FINISH: $\sqrt{Ra\ 0.8}$	DEBURR AND BREAK SHARP EDGES		DO NOT SCALE DRAWING
					REVISION: 1.3
NAME	SIGNATURE	DATE	Student number	TITLE:	
DRAWN: Michal Slusarczyk	Michal Slusarczyk	11.03.2025	001127940	Insulating PTFE element	
CHKD:					
APPV'D:					
MFG:					
Q.A:					
			MATERIAL: Polytetrafluoroethylene (PTFE)	DWG NO.:	PS-IPE-2.1
			WEIGHT: 4.76 g	SCALE: 4:1	A3
				SHEET 1 OF 1	





UNLESS OTHERWISE SPECIFIED:
 DIMENSIONS ARE IN MILLIMETERS
 SURFACE FINISH:
 TOLERANCES: ISO-2768-mK
 LINEAR:
 ANGULAR:

FINISH:

DEBURR AND
 BREAK SHARP
 EDGES

DO NOT SCALE DRAWING

REVISION: 1.3

NAME	SIGNATURE	DATE	Student number
DRAWN Michal Slusarczyk	Michal Slusarczyk	11.03.2025	001127940
CHK'D			
APP'VD			
MFG			
Q.A			
MATERIAL:			
Stainless Steel X8CrNiS18-9			
WEIGHT: 3.38 g			

TITLE:

Tuning Screw

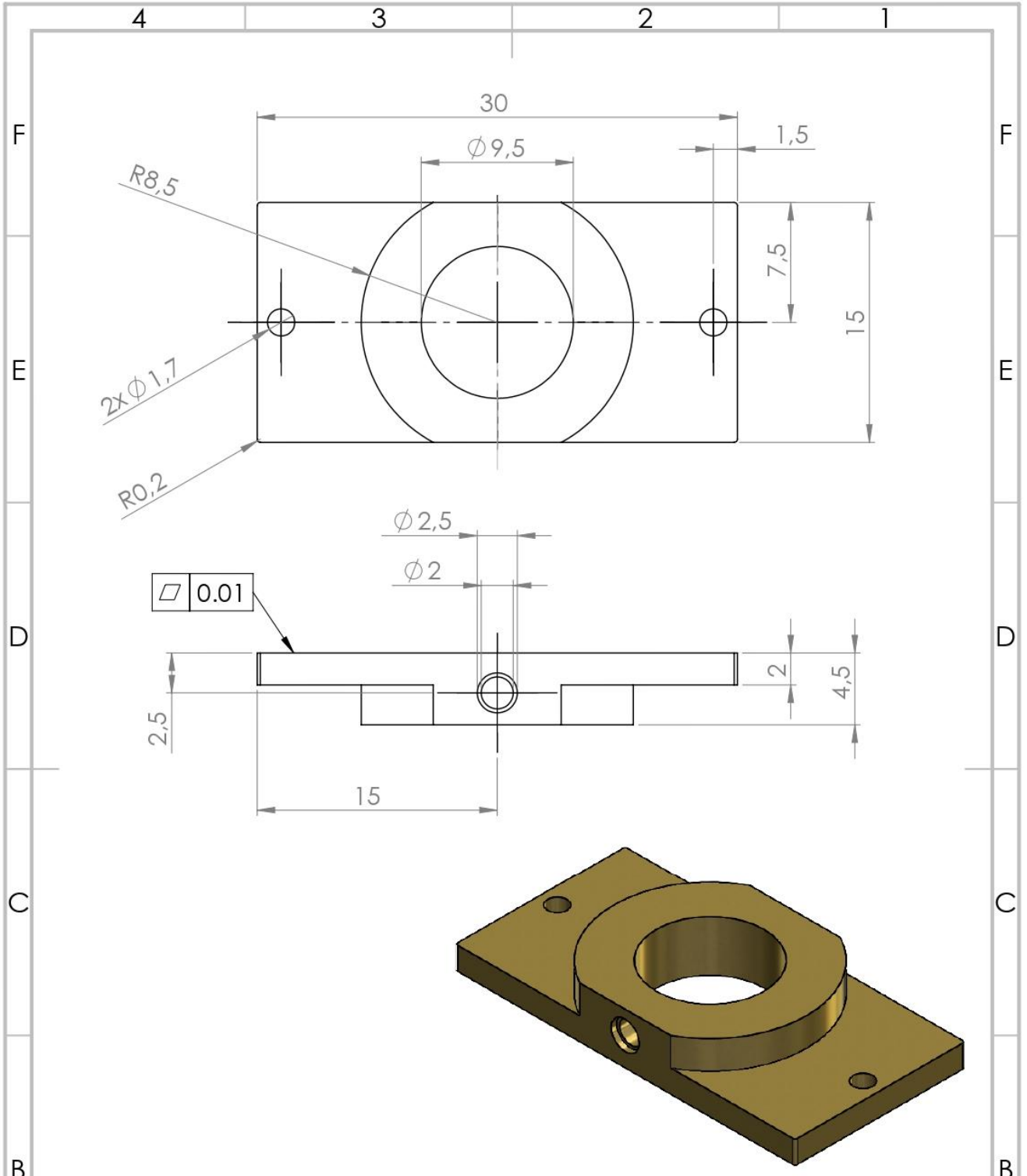
DWG. NO.

PS-TS-3

A4

SCALE: 2:1

SHEET 1 OF 1



Manufacturing block type: rectangular bar

Manufacturing block size (mm): 30x15x4.5

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES: ISO-2768-mK
LINEAR:
ANGULAR:

FINISH:

$\sqrt{Ra\ 6.4}$

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION: 1.3

NAME	SIGNATURE	DATE	Student number
DRAWN / Michal Slusarczyk	Michal Slusarczyk	11.03.2025	001127940
CHK'D			
APPV'D			
MFG			
Q.A			
MATERIAL:		Free Machining Brass (FMB) CuZn39Pb3	
WEIGHT:		9.39 g	

TITLE:	<h1>Tuning Screw Adaptor</h1>
DWG. NO.	
	PS-TSA-4
	A4
SCALE: 3:1	SHEET 1 OF 1

B

B

A

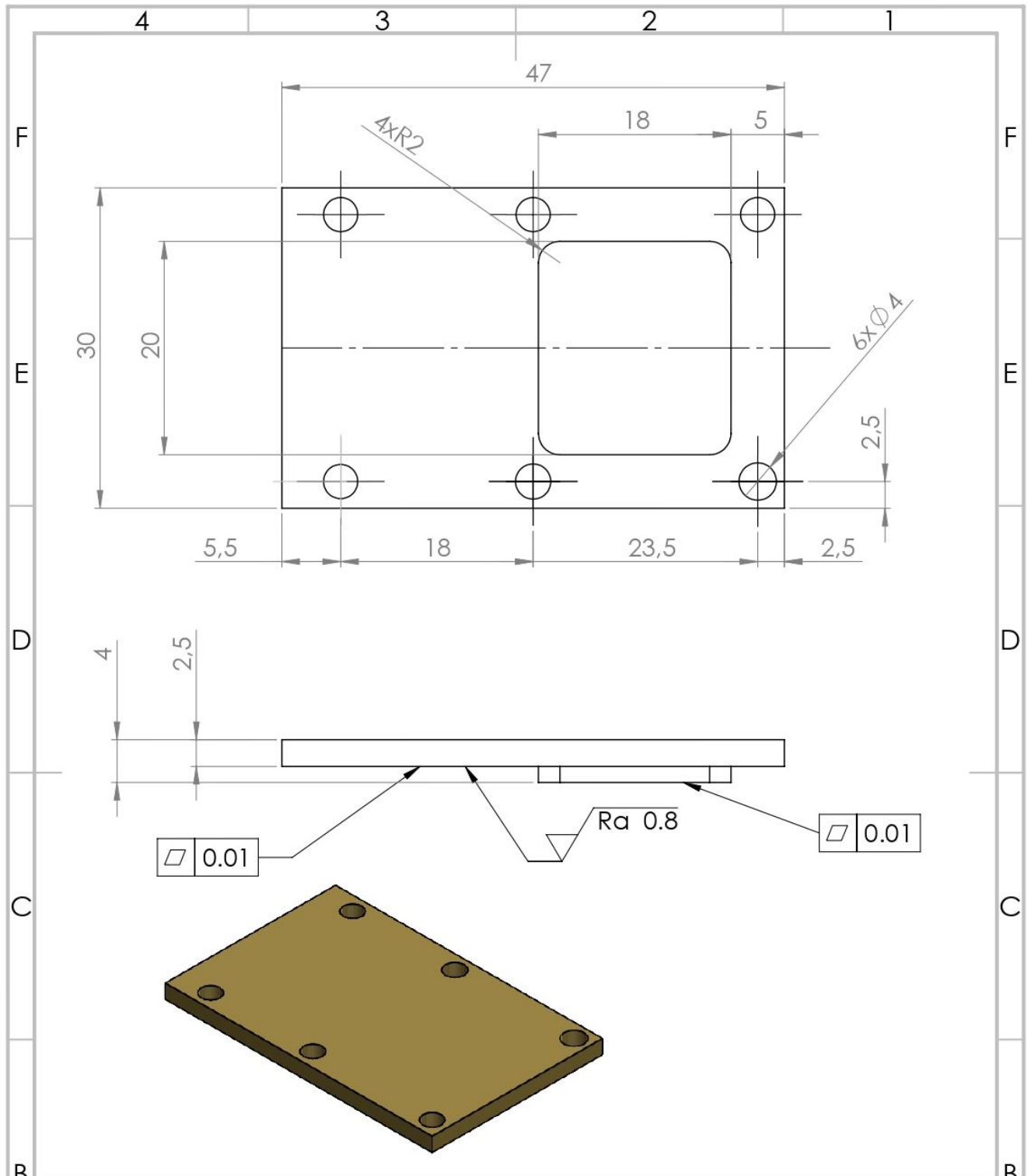
A

4

3

2

1



Manufacturing block type: rectangular bar

Manufacturing block size (mm): 47x30x4

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES: ISO-2768-mK
LINEAR:
ANGULAR:

FINISH:
 $\sqrt{Ra\ 6.4}$ ($\sqrt{Ra\ 0.8}$)

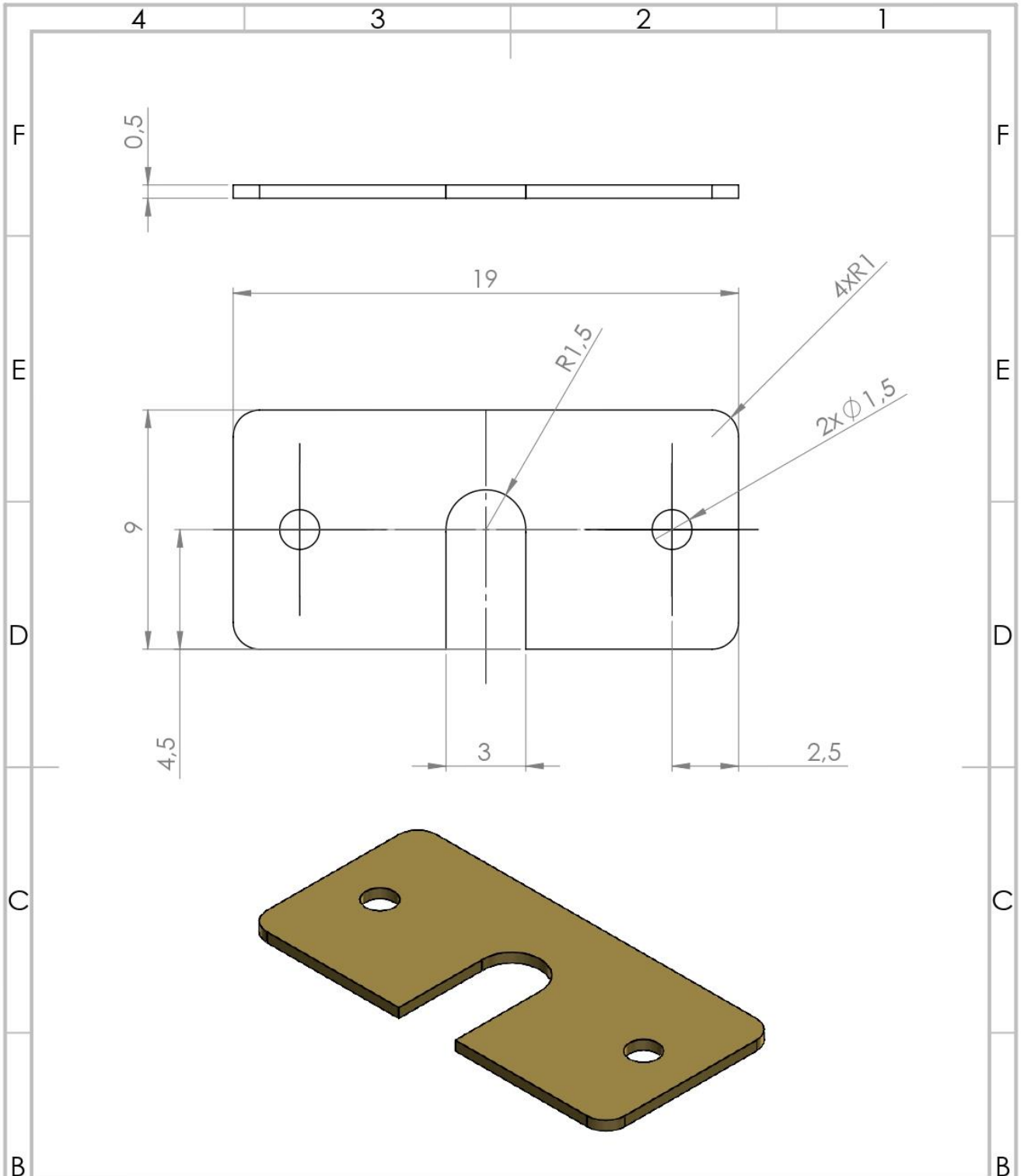
DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION: 1.3

NAME	SIGNATURE	DATE	Student number
DRAWN Michal Slusarczyk	Michal Slusarczyk	11.03.2025	001127940
CHK'D			
APP'VD			
MFG			
Q.A			
MATERIAL:			
Free Machining Brass (FMB)			
CuZn39Pb3			
WEIGHT: 33.61			

TITLE:	<h1>Cavity cover plate</h1>
DWG NO.:	
	PS-CCP-5
	A4
SCALE: 2:1	SHEET 1 OF 1



Manufacturing block type: plate

Manufacturing block size (mm): 19x9x0.5

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES: ISO-2768-mK
LINEAR:
ANGULAR:

FINISH:
 $\sqrt{Ra\ 6.4}$

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

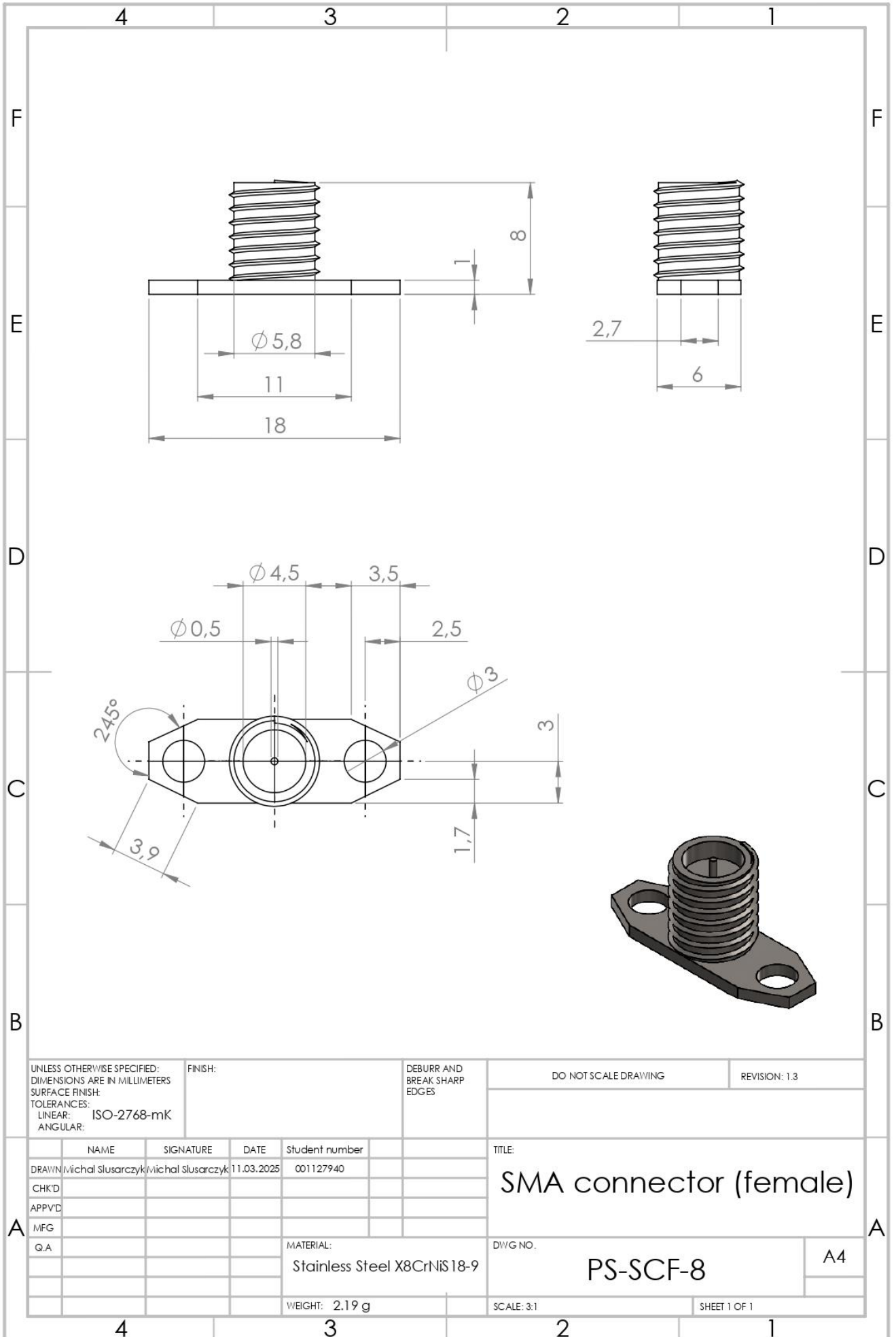
REVISION: 1.3

NAME	SIGNATURE	DATE	Student number
DRAWN /Michał Słusarczyk	/Michał Słusarczyk	11.03.2025	001127940
CHK'D			
APPVD			
MFG			
Q.A			
MATERIAL:			
Free Machining Brass (FMB)			
CuZn39Pb3			
WEIGHT: 0.64 g			

TITLE:
Tuning Screw Head Plate

DWG NO. **PS-TSHP-6**
SCALE: 5:1
SHEET 1 OF 1

A4



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR: ISO-2768-mK
ANGULAR:

FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION: 1.3

NAME	SIGNATURE	DATE	Student number
DRAWN Michal Slusarczyk	Michal Slusarczyk	11.03.2025	001127940
CHKD			
APPVD			
MFG			
Q.A			

TITLE:
SMA connector (female)

MATERIAL:
Stainless Steel X8CrNiS18-9

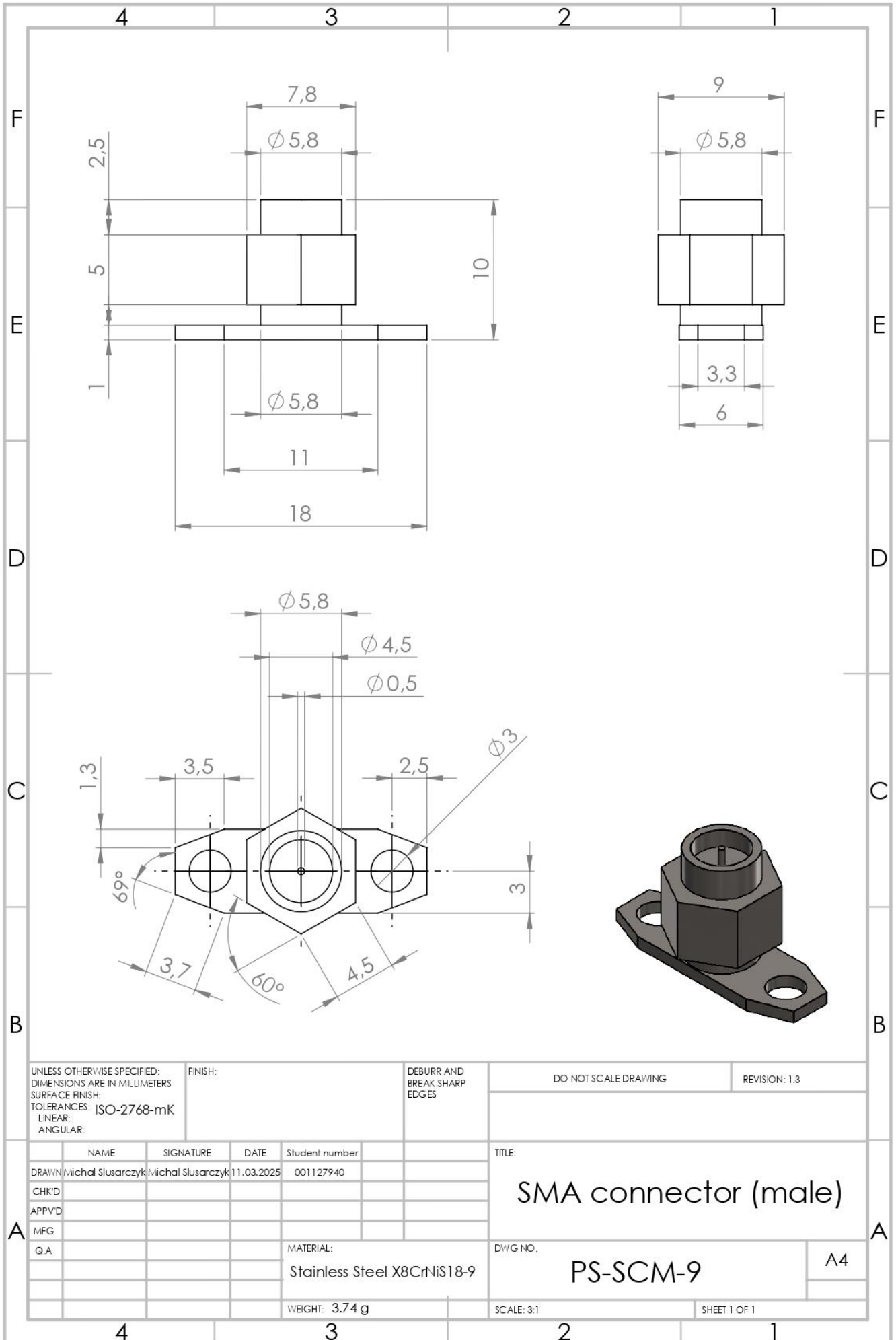
DWG NO.
PS-SCF-8

A4

WEIGHT: 2.19 g

SCALE: 3:1

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
 DIMENSIONS ARE IN MILLIMETERS
 SURFACE FINISH:
 TOLERANCES: ISO-2768-mK
 LINEAR:
 ANGULAR:

FINISH:

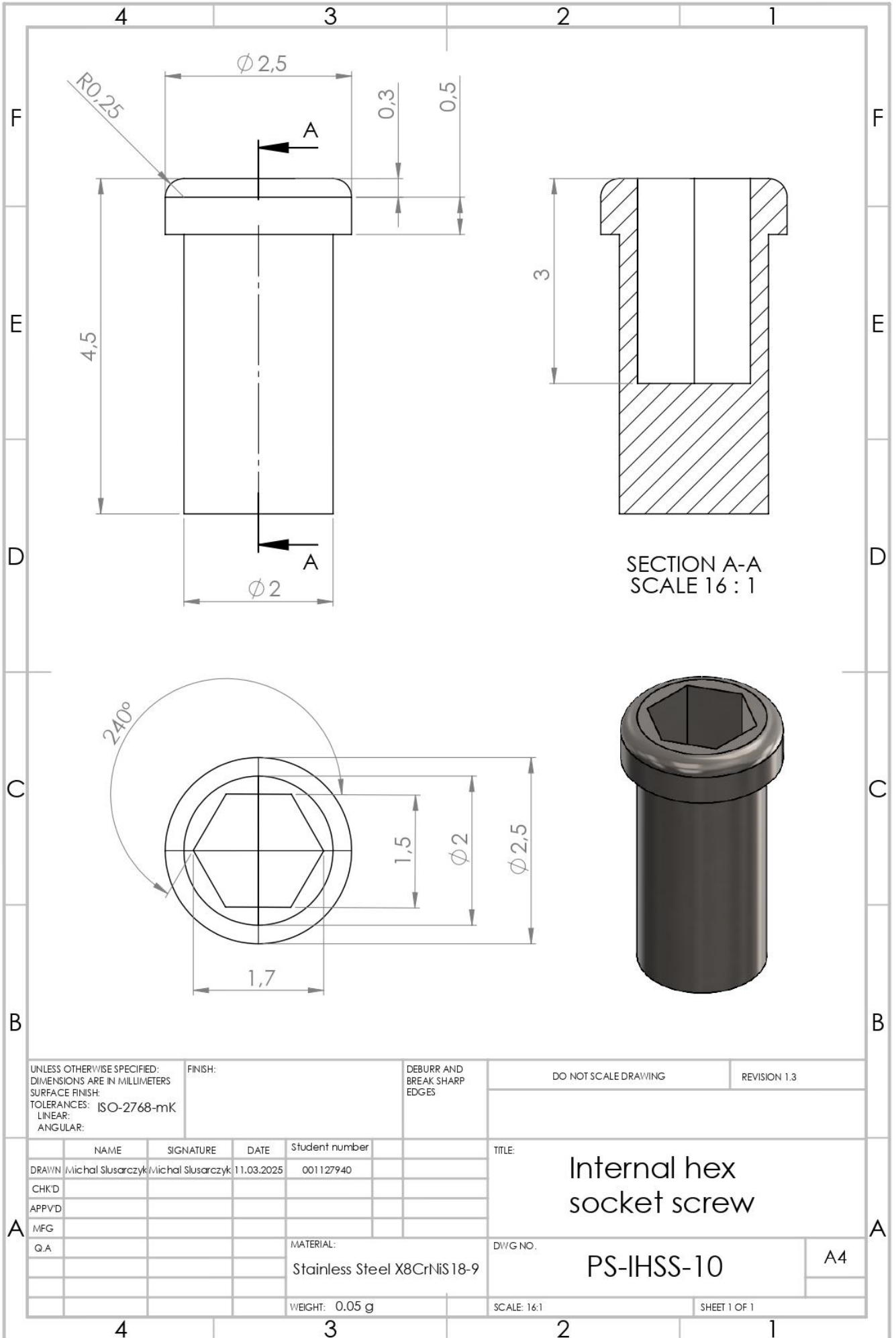
DEBURR AND
 BREAK SHARP
 EDGES

DO NOT SCALE DRAWING

REVISION: 1.3

NAME	SIGNATURE	DATE	Student number
DRAWN/Michał Słusarczyk	Michał Słusarczyk	11.03.2025	001127940
CHK'D			
APP'VD			
MFG			
Q.A			
MATERIAL:			
Stainless Steel X8CrNiS18-9			
WEIGHT: 3.74 g			

TITLE:		A4
SMA connector (male)		
DWG NO.		A4
PS-SCM-9		
SCALE: 3:1		SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
 DIMENSIONS ARE IN MILLIMETERS
 SURFACE FINISH:
 TOLERANCES: ISO-2768-mK
 LINEAR:
 ANGULAR:

FINISH:

DEBURR AND
 BREAK SHARP
 EDGES

DO NOT SCALE DRAWING

REVISION 1.3

NAME	SIGNATURE	DATE	Student number
DRAWN Michal Slusarczyk	Michal Slusarczyk	11.03.2025	001127940
CHKD			
APPVD			
MFG			
Q.A			

TITLE:

Internal hex
 socket screw

MATERIAL:

Stainless Steel X8CrNiS18-9

DWG NO.

PS-IHSS-10

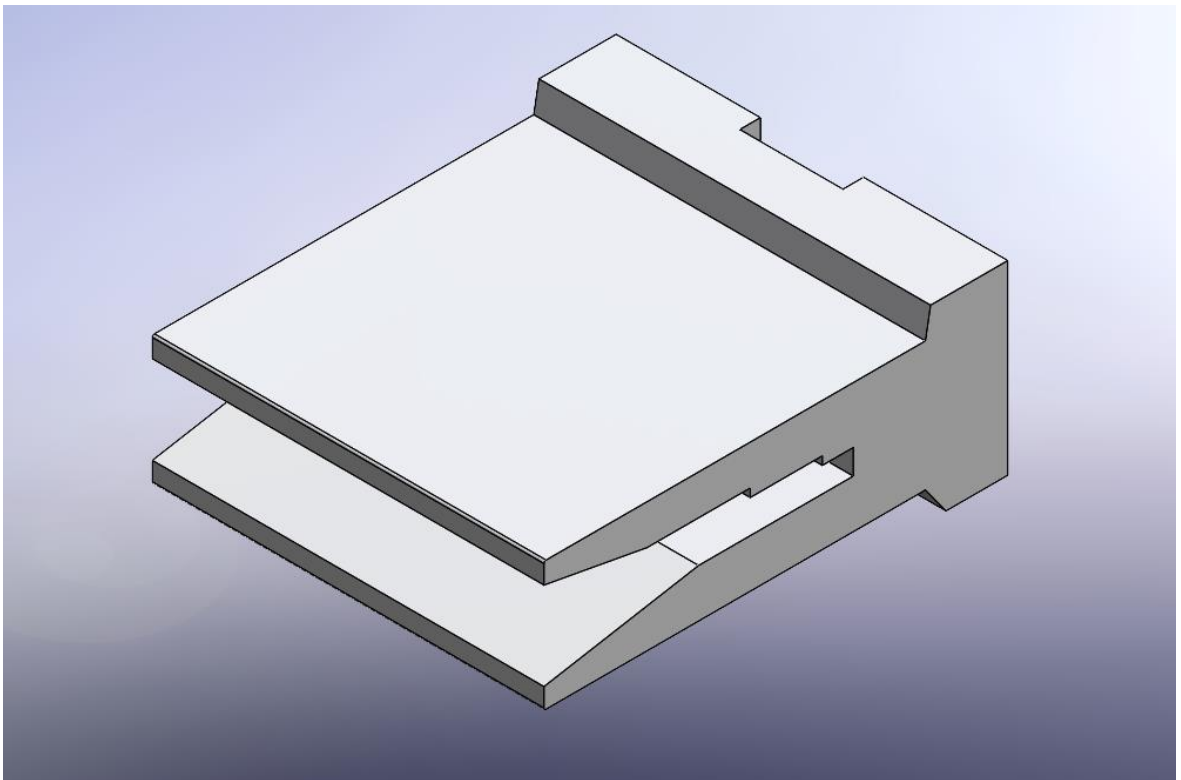
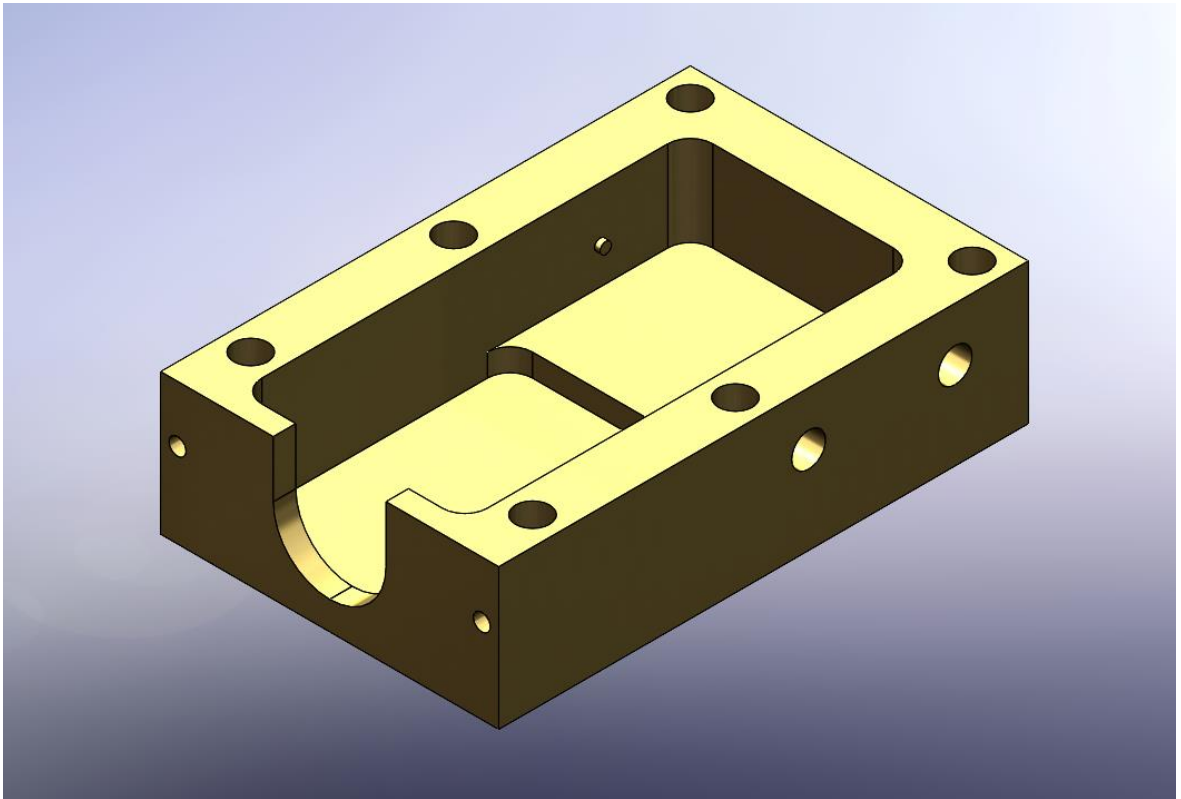
A4

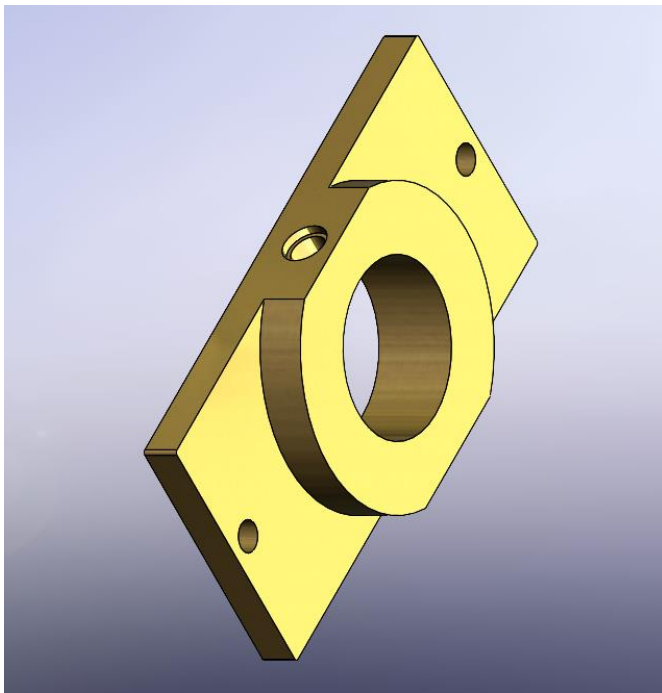
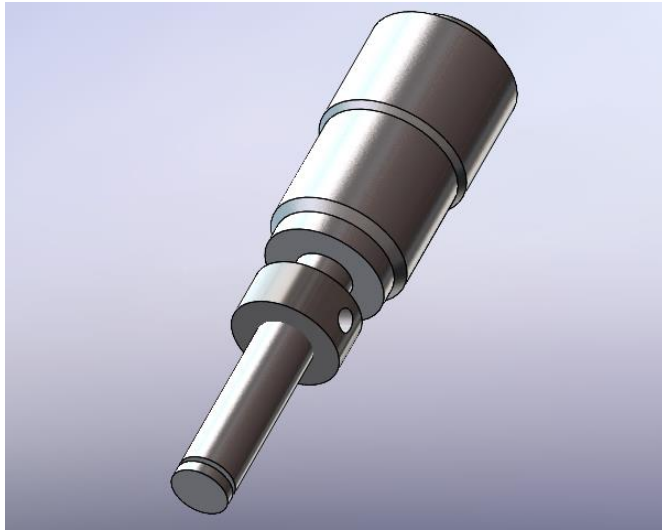
WEIGHT: 0.05 g

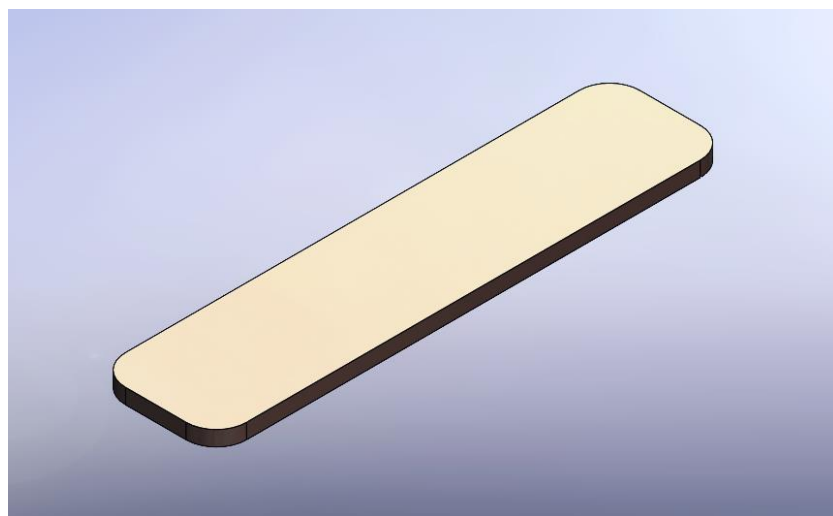
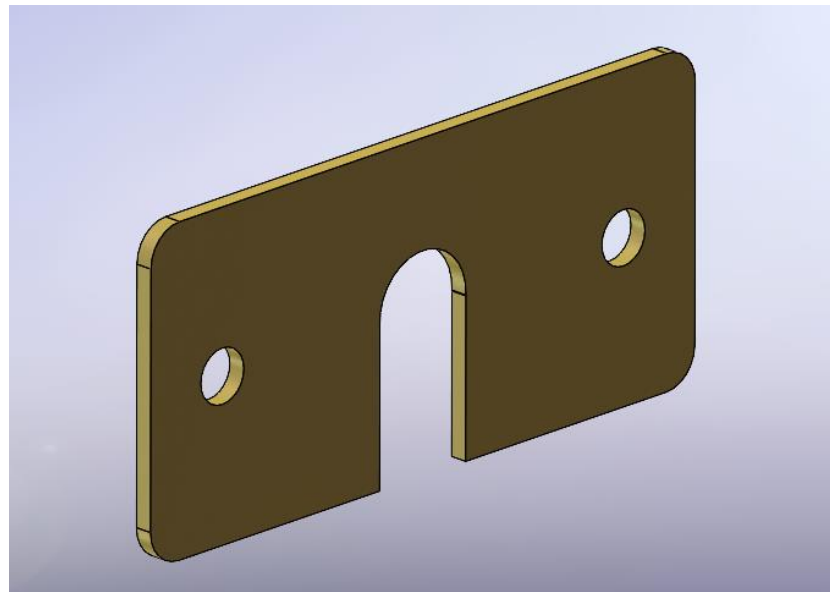
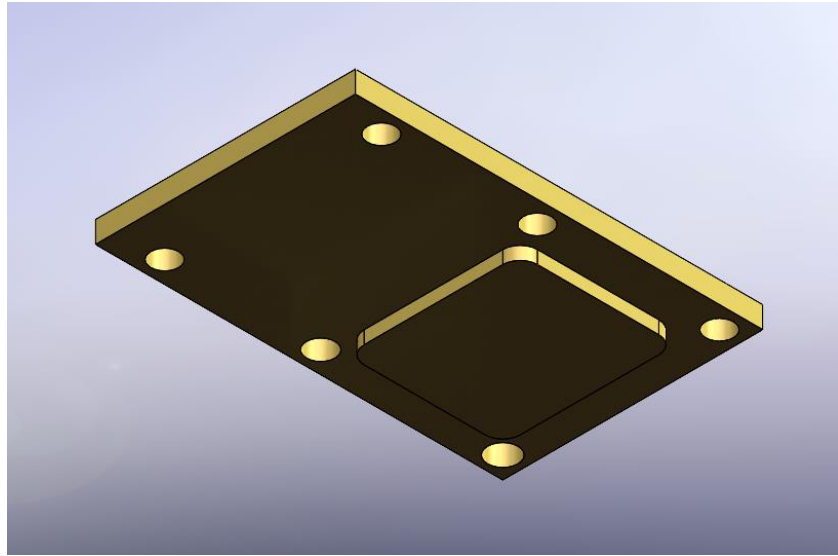
SCALE: 16:1

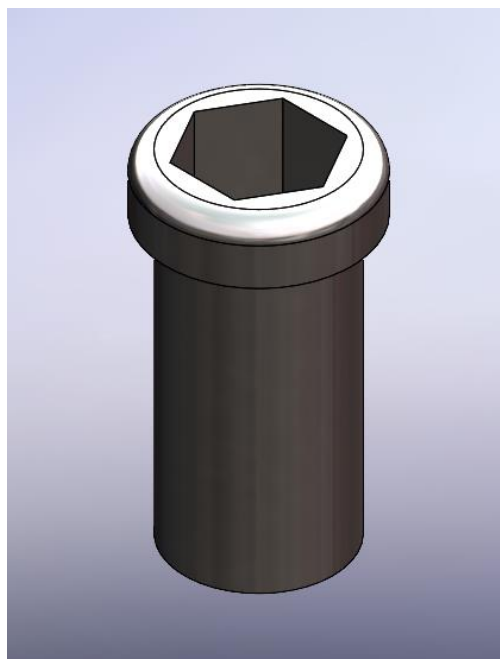
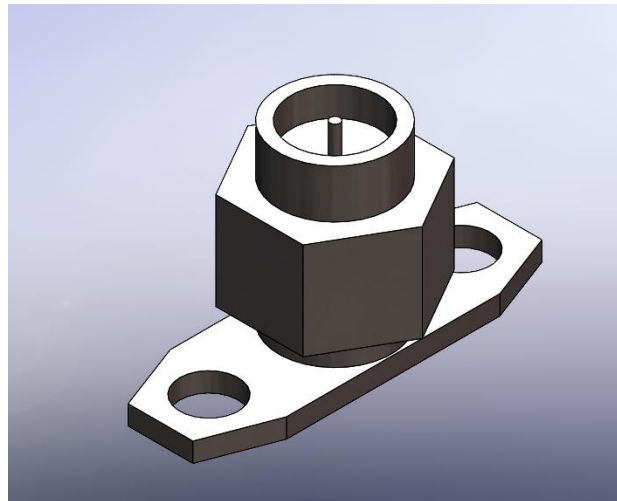
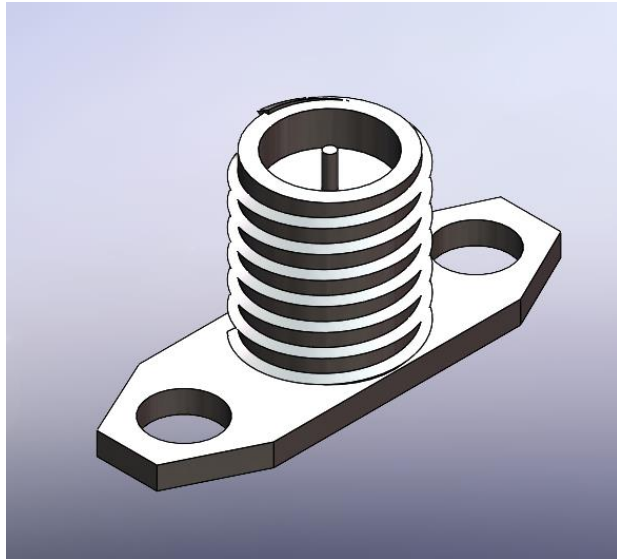
SHEET 1 OF 1

Appendix 4. Visualization of all the modelled components









Appendix 5. Expert interview questions and answers

Number	Expert Interview Question	Expert Interview Answer
1	Which quality assurance aspect of the regarded device is the most crucial for the correct operation of the device from the microwave mechanics point of view, and why?	The most crucial quality assurance aspect for the correct performance of the device from the microwave mechanics point of view is the geometry and dimensioning of the double-finned, insulating PTFE element. Special attention should be paid to the asymmetry of the element. Also, only the appropriate materials chosen will allow for the best performance of tuning in a range of 180 degrees. Eventually, a special type of milling for manufacturing is needed to avoid compromising the geometrical tolerances of the component.
2	What other quality assurance aspects should be considered in the research?	The importance of the distance between the copper strip and both the main cavity and cover, as well as the size and position of the copper strip, were mentioned as key parameters of the device which influence the operation. Moreover, the expert underlined the dimensioning and tolerance used in the research.
3	What material would be suitable for the main cavity?	It was stated that while working with machines operating at a couple of gigahertz, brass is an appropriate material to choose for the main cavity and the cover.