



**LIFECYCLE AND CIRCULAR ECONOMY ANALYSIS IMPROVEMENT OF A  
KU-BAND WAVEGUIDE SWITCH USING R-STRATEGIES**

Lappeenranta–Lahti University of Technology LUT

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

2025

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## ABSTRACT

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In co-operation with partner university: HEBUT University

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66 pages, 15 figures, 7 tables and 4 appendices

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This study conducts a comprehensive lifecycle and circular economy analysis of a Ku-band waveguide switch, employing R9 strategies and the SolidWorks Sustainability module to uncover opportunities for environmental change. Positioned at the intersection of high-frequency mechatronics and sustainable design, the research triangulates expert insights, theoretical frameworks, and simulation-driven data to propose targeted mechanical improvements. Emphasis is placed on the material-performance-environment trade-off, with 6061-T6 aluminium alloy emerging as the preferred substrate due to its conductivity,

recyclability, and low environmental burden. Modularization, additive manufacturing, and digital lifecycle assessment further reinforce the component's sustainability credentials. Value analysis and RoHS compliance evaluations validate the feasibility of the proposed redesigns. Ultimately, this work establishes a replicable framework that merges ecological foresight with engineering precision—transforming waveguide switch development into a model of sustainable electromechanical innovation.

## SYMBOLS AND ABBREVIATIONS

### Roman characters

$p$	pressure	bar, Pa
$qm$	mass flow rate	kg/s
$R$	gas constant	J/kg K
$T$	temperature	°C, K
$U$	voltage	V
$V$	volume	m <sup>3</sup>
$v$	specific volume	m <sup>3</sup> /kg
$x$	vapour content	

### Greek characters

$\alpha$	incidence angle	°
$\lambda$	thermal conductivity	W/mK

### Constants

$g$	gravitational acceleration	9,81 m/s <sup>2</sup>
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### Dimensionless quantities

Re	Reynolds number
----	-----------------

### Subscripts

1	inflow
2	outflow
kr	critical
mit	measured

### Superscripts

'	stator
"	rotor

### Abbreviations

CFD          Computational Fluid Dynamics

ORC          Organic Rankine Cycle

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# 1 Introduction

Here is the introduction chapter. It contains 2 s. The following sub-section is the goal of research.

## 1.1 Goal of Research

This research sets out with a singular yet multifaceted ambition: to dissect, with analytical precision, the lifecycle of a Ku-band waveguide switch and to forge actionable strategies that enhance its alignment with the principles of the circular economy. Anchored in the R-strategy framework and empowered by the SolidWorks Sustainability module, this study embarks on a full-spectrum environmental appraisal of a component pivotal to high-frequency electromechanical systems. As sustainability emerges from the periphery to dominate the center stage of contemporary engineering discourse, the imperative to recalibrate design and production paradigms grows ever more acute—particularly in domains where performance and environmental ethics often clash.

Within this shifting landscape, the Ku-band waveguide switch—an essential node in the constellation of satellite communication hardware—becomes the focal point of inquiry. Frequently employed in telemetry operations, this frequency band sustains the integrity of data transmission within orbital systems, underscoring its criticality in maintaining uninterrupted signal flow. Yet, despite its technical importance, few studies interrogate the environmental toll of its lifecycle.

To address this oversight, the present work integrates digital modeling, sustainability analytics, and lifecycle assessment into a coherent methodological scaffold. (Türkmen, C. and Seçmen, M. 2015) It does not merely aim to reduce material waste or enhance component durability; rather, it seeks to engineer a systemic transformation—where

ecological intelligence is embedded from the outset of the design process. By realigning material selection, loss minimization, and structural improvement with environmentally responsible engineering practices, the study speaks not only to industry-specific innovation but also to the broader, global pursuit of sustainable manufacturing and circular design thinking.



Figure 1 The picture of the device

Figure 1 shows the picture of the waveguide switch.

## 1.2 Background and Motivation

In the realm of wireless communication—particularly within the unforgiving, precision-bound context of space missions—waveguide switches are not merely supporting components; they are linchpins of transmission architecture. Functioning at the Ku-band frequency, these devices orchestrate the seamless relay of spacecraft telemetry, ensuring that mission-critical data navigates the vacuum with both fidelity and speed. Within ground-based infrastructures such as the ESTRACK antenna subsystem, the switch is not an accessory but an operational nucleus, anchoring the stability of signal pathways in an increasingly congested electromagnetic spectrum. (Himani, B.S., Afzaal, K., Malleswar, K.S., Das, S., Ranjan, R. and Neelavathy, M. 2017) As the S- and C-bands edge toward saturation, future TT&C (Tracking, Telemetry, and Command) systems are poised to converge on the Ku-band, thereby amplifying the strategic value—and technical scrutiny—of the waveguide switch.

Compounding this centrality is the shift in antenna paradigms: Ku-band phased array systems, improved for agile, mobile satellite communications, now form bi-directional conduits between orbiting platforms and user terminals. This mobility, paired with high-frequency performance, reaffirms the waveguide switch's role not as a static module but as a dynamic enabler of modern orbital communication. (Guodong, H., Bing, Y., Wei, W. and Biao, D. 2014) Yet amidst this functional sophistication, a new tension has emerged—one not rooted in signal loss or thermal drift, but in sustainability. The industry, for a long time worried about the reliability metrics and the efficiency of the throughput, must now rotate towards the consciousness of the life cycle, incorporating the ecological foresight into the same DNA of design and production.

Getting this paradigm change is neither trivial nor cosmetic. Sustainability must percolate through every phase of the component's existence—beginning with materials selection, where trade-offs among durability, criticality, and environmental footprint demand careful arbitration. The choice of alloys, composites, and surface treatments can no longer hinge solely on mechanical performance; each decision must also account for long-term ecological externalities. In manufacturing, energy-intensive legacy processes must give way to cleaner, leaner techniques that valorize precision without sacrificing planetary boundaries. And finally, at the end of the product's operational arc, a robust, premeditated strategy for disassembly, recovery, and material reintegration becomes essential—lest high-value metals descend into the entropy of electronic waste.

Despite their systemic role, waveguide switches remain underexamined from a sustainability lens. Their dispersed integration into vast communication networks renders their environmental impact deceptively invisible, even as their aggregate energy demands rival—and at times surpass—those of more centralized systems like data centers. Existing manufacturing pipelines are typified by inefficiencies: high energy input, substantial material attrition, and limited recyclability. (Krug, L. 2021) In response, global initiatives now demand not incremental improvement but structural rethinking. Here, the life cycle assessment (LCA) paradigm emerges as a powerful

diagnostic tool—one capable of quantifying emissions, waste, and resource flows from cradle to grave, illuminating where interventions must occur.

In this context, the adoption of the R9 strategy—spanning from Refuse to Recover—offers a coherent blueprint. By emphasizing reuse, recycling, remanufacturing, and design-for-disassembly, the industry can move beyond abstract sustainability goals and toward implementable practices. (Wagih, M., Bainbridge, A., Alsulami, B. and Kettle, J. 2024) Informed by the consultation of experts and powered by the digital evaluation tools, this study lays the foundations for this transformation: A viable data-driven framework that improves sustainability without compromising the operational integrity of waveguide switches.

### 1.3 Research Problem and Research Questions

In the field of traditionally performance-centric high-frequency communication devices, the design of KU band waveguide switches has long been cited by indicators of signal integrity and structural stability. However, as environmental commands intensify and life cycle responsibilities become a design task rather than an afterthought, An evident void emerges: assistance remains a peripheral concern both in conceptualization and in production. This research confronts that the front supervision, interrogating as the mechanical-enacted design strategies in strategy thinking and trained by digital sustainability tools-can remedy this imbalance.

At the heart of this investigation lies a central research question: How can the lifecycle sustainability of a Ku-band waveguide switch be materially enhanced through mechanical engineering interventions, informed by the R9 framework and quantitatively validated via the SolidWorks Sustainability module?

To scaffold this inquiry, the following sub-questions are posed:

What are the principal environmental impacts arising from the production, operation, and end-of-life processing of Ku-band waveguide switches?

In what ways can material selection be improved to advance ecological performance without diluting functional efficacy?

What insights from industry experts can be synthesized into actionable guidelines for sustainability-focused redesign?

By addressing these questions, the study endeavors to construct a pathway for the environmental rationalization of electromechanical systems—offering a calibrated balance between technical precision and ecological responsibility.

## 1.4 Research Methods

This investigation adopts a triangulated methodological framework, weaving together expert consultation, comprehensive literature synthesis, and parametric sustainability modeling within SolidWorks. Each axis of this triad contributes a unique analytical texture:

**Expert Dialogue:** Interviews with domain specialists generate qualitative depth, offering pragmatic reflections on LCA applications, material circularity strategies, and real-world constraints on R9 implementation.

**Literature Synthesis:** A curated archive of academic and industrial research forms the theoretical substratum of the study, allowing benchmarking against cutting-edge practices and policy-aligned methodologies.

Digital Environmental Simulation: Leveraging the SolidWorks green R&D module, the research simulates and contrasts various material and design configurations, producing quantitative assessments of environmental impacts across the full lifecycle—from raw material sourcing to end-of-life recovery.

This integrative method not only ensures empirical rigor but also builds a resilient bridge between sustainability theory and its engineering embodiment.

### 1.5 Expected Contribution

Positioned at the nexus of electromechanical design and ecological foresight, this study aspires to make three critical contributions. First is a Methodological Blueprint: By embedding the R9 strategy into the design logic of Ku-band waveguide switches, the study formulates a reproducible model for sustainable engineering—a framework where recyclability, energy efficiency, and longevity are not add-ons but intrinsic design objectives.

Next is Advanced Technical Integration: The potential convergence of MEMS technology and waveguide systems is explored, particularly for high-power, high-frequency applications, highlighting novel avenues for sustainable hardware evolution. (Daneshmand, M., Mansour, R.R. and Sarkar, N. 2004)

Last one is Actionable Design Proposals: Grounded in expert validation and simulation-driven analysis, the study delivers tangible recommendations to improve material utilization, enhance recyclability, and ensure design compliance within the circular economy paradigm.

Beyond waveguide switches, the implications of this work radiate outward—offering a transferable template for other high-performance electromechanical components in urgent need of lifecycle-sensitive reform.

## 2 Research Methods

The research methods chapter contains 3 s. Chapter 2.1-Applied Triangulation has 3 sub-sections.

### 2.1 Applied Triangulation

This study incorporates several scientific triangulation strategy, synthesizing professional insights, right discourse, and present simulation, to increase methodological rigour and lessen epistemological blind spots. The study triangulates results across both qualitative and quantitative areas, avoiding cross-validated frame opinions and reducing disciplinary investigation errors by combining structured interviews, literature analysis, and parametric sustainability assessments within the SolidWorks system.

In particular discussions, the circular economy approach, lifecycle assessment, and industry standards are covered. At the same time, the literature review curates a theoretical spine informed by sustainable design doctrines and regenerative engineering principles (Aluchna & Rok, 2019). Complementing these layers, the SolidWorks sustainability module is harnessed as a diagnostic engine, translating design parameters into measurable indicators — carbon emissions, energy intensity, and pollution outputs—via an embedded LCA algorithm ( Honório et al., 2023 ).

What emerges is an essential foundation that incorporates both normal vision and scientific loyalty, rather than just a paradox of ideas. The development of grounded, generally ideal strategies for natural remodel is supported by this triangulated method, which provides a thorough knowledge of sustainability dilemmas chosen to Ku-band waveguide switches.

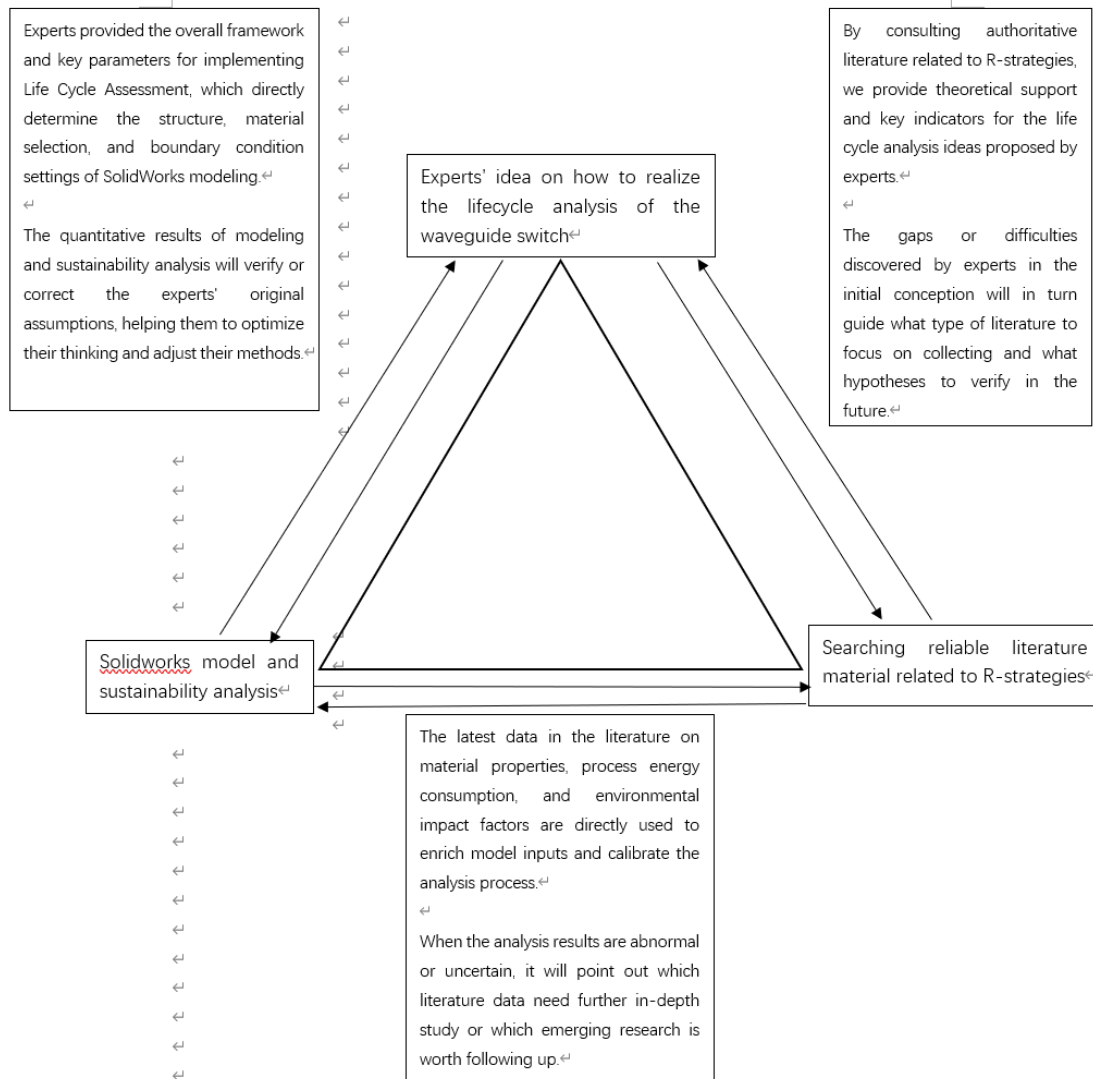


Figure 2 Triangular

Figure 2 shows the triangular and the relationship between these three parts.

### 2.1.1 Expert Interview Protocol

Meetings with partners are conducted effectively at the roads of lifecycle engineering, sustainable manufacturing, and mechatronic systems design. From engineers who have been actively involved in system-level sustainability to firm soldiers and scientific researchers, the selection process favors levels and variety. Semi- organized questioning centers on important touchpoints: material selection, processing

methodologies, modular design, and total- of- living valorization—thereby extracting insights that transcend academic theorization.

### 2.1.2 Literature Review Architecture

A perfect, constant reading acquisition approach underpins this writer's theoretical grounding. Using a planned activity that includes key analysis, inclusion/exclusion frames, intended detachment of high-impact information, and inclusion/exclusion filters, layered thematic production is used to mine relevant studies using directories like IEEE, ScienceDirect, and Google Scholar. This approach provides sturdy support for design logic and sustainability reasoning, as well as providing health security and clarity.

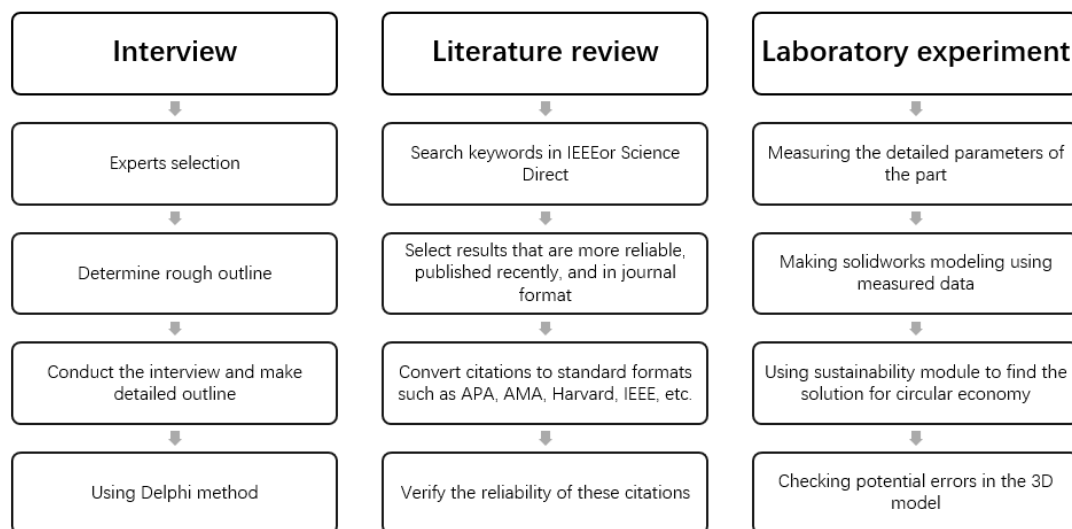


Figure 3 Flow chart

Figure 3 shows the flow chart of the three parts in the triangulation.

### 2.1.3 Integration of the R9 Framework and SolidWorks Simulation

The assessment uses the R9 sustainability schema to examine mirror switch engineering's material circularity, waste minimization, and process efficiency. Instead of using traditional evaluations, this study concentrates on the environmental return on material investment (Shahbazi et al., 2017). For a real-time ecological performance design, Solid Works ' sustainability give provides detailed data on CO2 emissions, energy use, and waste footprint.

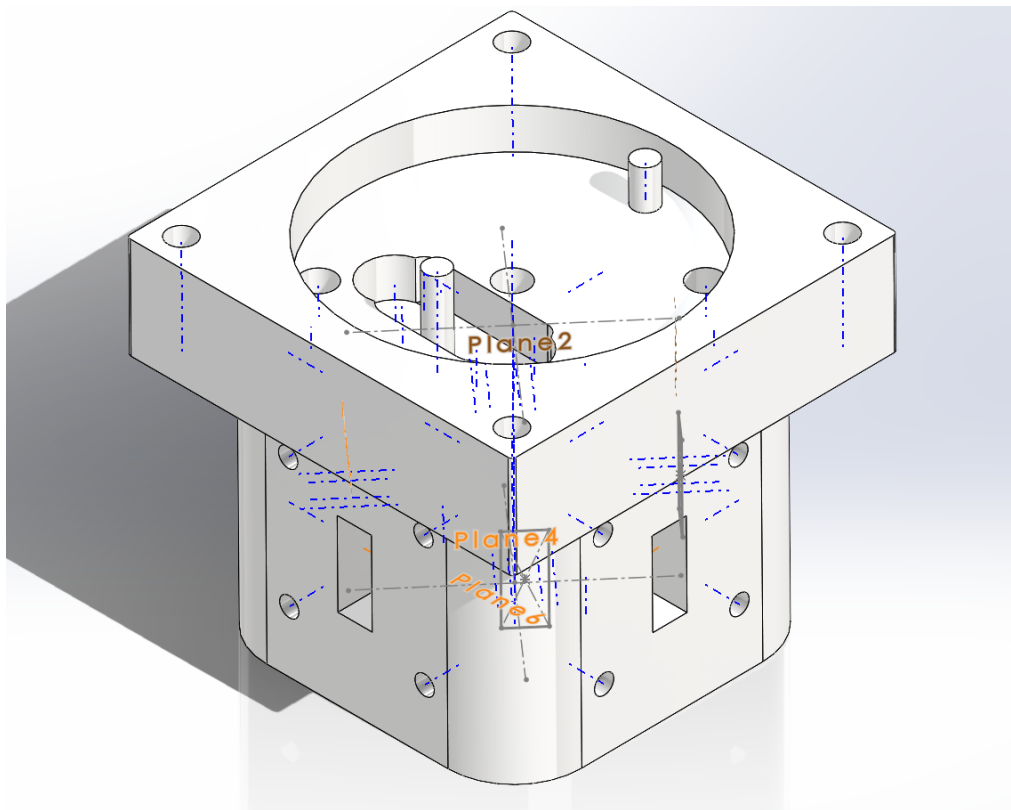


Figure 4 Solidworks model

Figure 4 shows the Solidworks 3D model of the waveguide switch.

## 2.2 Reliability Analysis Method

Safeguard the integrity of its results and ensure their translation without continuity in applied engineering contexts, This study orchestrates a multicam-a-one reliability architecture that crosses the validation of experts, statistical rigor and systemic sensitivity test in a cohesive and self-refereeing whole. First of all, expert comments and iterations are exquisite. At the heart of this framework is a dynamic cycle of expert participation. Through the pace of the workshop, review meetings and targeted feedback exchanges, Domain experts continually recalibrate the theoretical propositions of research trajectory anchor for practical viability. This recursive consultation cycle acts as a crucible, where abstract strategies are seasoned in the logic of implementable design.

Next is statistical error diagnosis. The simulations performed through the SolidWorks sustainability module are subject to a detailed quantitative review. From the differences in inputs to the uncertainty of the model, any potential distortion is carefully sliced. Multiple grave analyses will generate variance matrix, standard deviation profile and confidence limitations, which not only ensure numerical stability, but also have a granular understanding of the variability of the result through iteration.

Then, targeted sensitivity detection is also important. This study identifies high leverage design variables for material composition, processing protocols, geometric configurations and places them under controlled perturbations. The effects of the chain of these adjustments are tracked through LCA key metrics, such as carbon intensity, recyclability and energy productivity. In this way, the study illuminates key ecological selling points and informs the creation of engineering paths for scenario enhancement.

Even more important, quantitative precision quantitative verification. To enhance numerical authenticity, the simulated output is triangulated by parallel pathways: direct

peer review and empirical benchmarking of the proven literature. Weekly audit cycles and interdisciplinary consultation instill the set of data with robustness, while external references ensures that digital models remain faithfully linked to physical engineering realities.

The last one is Triangulation & Saturation as Epistemic Anchors. Eschewing the fragility of mono-method reliance, this study adopts a methodological pluralism wherein interviews, simulations, and scholarly analysis operate in contrapuntal harmony. Each vector of inquiry mitigates the limitations of the others, constructing an interlaced evidence scaffold of exceptional internal validity. Notably, data saturation is not a function of numerical excess but of the qualitative depth and contextual insight embedded in expert contributions—balancing academic sophistication with real-world immediacy.

	Interview	Laboratory experiment (Solidworks)	Literature review	Triangulation
Validity				
Reliability				
Sensitivity				
Error analysis				
Accuracy				
Saturation				

Table 1 Reliability Analysis

Table 1 shows the reliability analysis of the thesis.

Table 2 Reliability tool table

Questions Q1-Qn, to which the answers are searched for	Reference #1	Reference #2	Reference #3	Reference #4	Reference #5	Reference #6	Reference #7	Reference #8	Reference #9	Reference #10	Reference #11	Reference #12
Q1												
Q2												
Q3												
Q4												
Q5												
Summarized observations about the relevance of each reference	Different kinds of waveguide switch											

Table 2 shows the reliability tool table of the thesis.

Delphi method

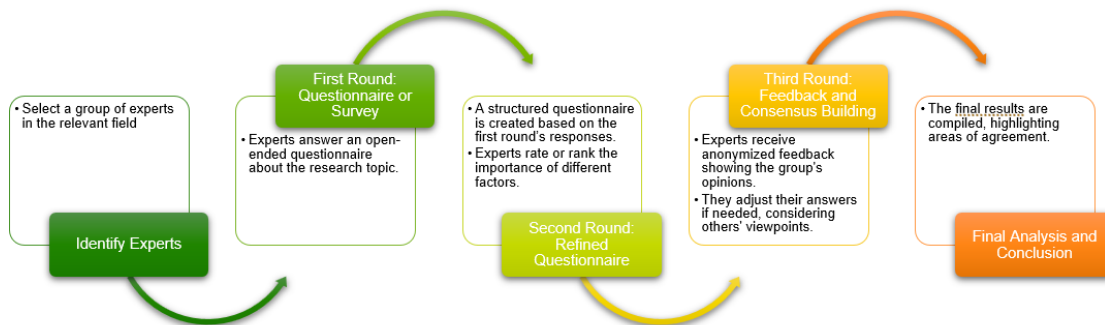


Figure 5 Delphi method

Figure 5 shows the step of Delphi method.

### 2.3 Structured Literature Review Method

The literature review follows a hypothesis-driven, problem-oriented trajectory. Framed by predefined research questions (Q1–Q5), the review probes the multifaceted interplay between materials, manufacturing, structural design, and sustainability in Ku-band waveguide switches.

Table 1 lists the specific research questions formulated to guide the review:

Q1: What is the difference in electromagnetic performance between aluminum and steel alloys when making waveguide switches?

Q2: How do waveguide switches made using additive manufacturing methods align with circular economy principles?

Q3: How does the structural design of waveguide switches impact their electromagnetic performance?

Q4: What approaches can make milling processes more sustainable?

Q5: How can innovative structural solutions for waveguide switches support the circular economy?

Questions Q1-Qn, to which the answers are searched for	Reference #1	Reference #2	Reference #3	Reference #4	Reference #5	Reference #6	Reference #7	Reference #8	Reference #9	Reference #10	Reference #11	Reference #12
Q1					✓			✓				
Q2			✓					✓				
Q3		✓				✓				✓	✓	
Q4				✓					✓			✓
Q5	✓		✓			✓					✓	✓
Summarized observations about the relevance of each reference	Different kinds of waveguide switch											

Figure 6 Tool form

Figure 6 shows the finished reliability tool table.

The references selected in this study were systematically screened and determined, focusing on their relevance, effectiveness, and academic quality. The selection of each

literature is strictly aligned with the research question, as they can significantly support the core objectives of the study and form a direct connection with them.

For Q1, references (Li et al. 2023) and (Filimonov et al. 2020) are especially relevant, furnishing empirical data and theoretical understandings regarding electromagnetic properties, electrical conductivity, magnetic permeability, and surface treatments that have an impact on waveguide performance.

Q2 is tackled by references (Nazir & Doni 2024) and (Alazemi et al. 2021), probing into additive manufacturing technologies and the incorporation of circular economy principles in waveguide manufacturing, with an emphasis on recyclability and material efficiency.

References (Dey & Koul 2015), (Guvenc & Sisman 2024), (Shafeghati et al.2023) and (Pachauri et al.2023) Inform the structural design precautions (Q3), introduce the technical inspection of structural configuration, its impact on electromagnetic performance and its impact on reliability.

Practical strategies and sustainability guide sustainable milling method (Q4) – the focus discussed in References (Korhonen et al.2018), (Filimonov et al.2020) and (Petrakis & Komnitsas 2022).These data describe energy efficiency improvement, waste minimization practices and circular economy integration during milling.

Ultimately, from references (Nazir & Doni 2024), (Guvenc & Sisman 2024), and (Shafeghati et al.2023) Basic innovative structural design and circular economy compliance (Q5) emphasizes the importance of new structural designs that can improve recyclability, material reuse and life cycle sustainability.

The construction of literature review adopts a circular iterative method, first conducting term screening, then searching on multiple academic platforms (such as IEEE, ScienceDirect, and Google Scholar), then screening relevant literature, and finally systematically extracting core perspectives and empirical findings.By leveraging patterns and comparative analysis strategies, the approach reveals important

correlations between different studies, ensuring the amplitude and credibility of the conclusions.

In the end, the literature review, through being so thorough and standardized, provides the best possible way of how to solve the research questions asked, which also forms a strong foundation in both theory and practice. It contributes further certainty to the choice of materials, production techniques, and design of structures as improved sustainability and enhanced performance are achieved in Ku-band waveguide switch applications.

### 3. Result

This chapter is the result of the analysis, which contains 5 sections. It shows the necessary results, including literature review results, expert interview results and so on.

#### 3.1 Literature review results

This section leads an in-depth analysis of a large number of complete literatures, focusing on the basic issues raised in the research. Each research question can be answered in detail by integrating empirical data and theoretical thinking in academic and professional fields.

##### Electromagnetic Performance Differences between Aluminum and Steel Alloys (Q1)

According to in-depth analysis by (Filiimonov et al. 2020) and (Li et al. 2023), the electromagnetic properties of steel and aluminum alloys show significant differences in waveguide switching environments. Compared to steel alloys, aluminum alloys significantly reduce insertion losses and improve signal transmission efficiency due to their excellent conductivity. Since the non-ferromagnetic attribute of aluminum alloys prevents the inductive loss, it becomes the most suitable material for high-frequency utilization, like Ku-band waveguides. However, it may be noteworthy that special care must be taken to reduce these losses, as the steel alloys' roughness, unfavorably, often increases electromagnetic scattering, deteriorating the signal's quality. Towards this end, although aluminum alloys are known for having less mechanical strength compared to steel, the loss due to electromagnetic inefficiency makes them the best choice.

##### Alignment of Additive Manufacturing Methods with Circular Economy Principles (Q2)

Defined as outlined by (Nazir & Doni 2024) and (Filimonov et al. 2020), additively manufactured (AM) parts do enable a more complete realization of the circular

economy philosophy because they eliminate much more waste if compared to standard subtractive manufacturing. AM waveguide switches become a process that maximizes building materials because they can be formed with complex structures and lightweights. Besides, the sustainable advantages in which the construction process supports electromagnetism, for instance, the smoother transition of energy becomes possible when all, in the following sentence, will help in recycling and product recovery. What is more, using additive manufacturing results in problem-oriented customization - thus avoiding unnecessary material usage and favoring potential energy sources; it also promotes a prolonged lifetime through design improvement.

#### Impact of Structural Design on Electromagnetic Performance (Q3)

The electromagnetic characteristics of waveguide switches are closely related to their structural design. Research shows that optimizing structural parameters can significantly improve device performance. Several scholars (Dey & Koul, 2015); (Guvenc & Sisman, 2024); (Shafeghati et al., 2023); (Pachauri et al., 2023) have confirmed that rational designs can reduce losses, suppress reflections and enhance waveguide efficiency. Electromagnetic interference and mechanical losses have been greatly reduced by introducing innovative architectures such as iris coupling and contactless mechanical waveguide switches. This unique design effectively reduces physical discontinuity, thereby reducing signal reflection and improving waveguide efficiency. At the same time, this structural solution can delay the degradation of mechanical properties, extend service life, and conform to the concept of green manufacturing.

#### Sustainability in Milling Processes (Q4)

Operational efficiency in the milling segment is one of the most important aspects of having a better sustainability footprint in the sectors or manufacturing processes. (Petrakis and Mantissa 2022) and (Nazir and Doni 2024), among the other types of articles, focus on sustainability improvement through the application of novel milling methods, energy-saving tools, and improved milling process parameters. A perfectly

suitable strategy would use energy-efficient cutting tools, adopt minimal lubrication methods, and develop advanced control systems that minimize wastefulness and energy consumption. Other innovative approaches include installing closed-loop recycling, greater utilization of metal chips, and adoption of digital monitoring and predictive techniques that help enhance the sustainability profile of milling processes.

#### Innovative Structural Designs Supporting Circular Economy (Q5)

In the design of waveguide switches, innovative structural solutions greatly enhance compliance with circular economy principles. (Nazir and Doni 2024), (Guvenc and Sisman 2024), and (Shafeghati et al. 2023) All highlighted the critical importance of modularity, recovery and recyclability in achieving sustainable life cycle management. The combination of modular and standardized design helps maintain, upgrade and component interchangeability, extends product life and reduces waste. In addition, incorporating biodegradable or recyclable materials into structural design can significantly reduce the environmental impact at the end of product life. These innovations, combined with a comprehensive life cycle assessment, help transfer traditional waveguide switch manufacturing models to more sustainable and economical cyclical systems.

In summary, a comprehensive review of the existing literature provides a thorough understanding of the impact of material selection, manufacturing methods, and structural design innovations on KU band waveguide switches' sustainability and electromagnetic properties. The research results clearly highlight the importance of strategically integrating circular economy principles into the design and manufacturing processes and also point out the future development direction of sustainable engineering practices.

### 3.2 Expert interview results

Expert interviews revealed many effective solutions, among which the selection of materials required for waveguide switches is particularly important. Proper selection of materials is not only crucial for the electromagnetic performance of equipment but also for its long-term environmental friendliness. According to the equipment's operating frequency and specific functional objectives, the material requirements for each component are not the same. Therefore, comprehensive consideration and scientific planning should be carried out when selecting materials.

For waveguide cavity components with a working frequency of approximately 3 GHz, 6061-T6 aluminum alloy is the most ideal choice. The reason for choosing this problem is because it has a high conductivity, which can significantly reduce insertion loss and signal attenuation at higher frequencies. Meanwhile, the 6061-T6 aluminum league in non-magnetic materials can minimize magnetic losses and signal distortion to the maximum measure. In addition, it is very transformable, helping to carefully generate the cavity of the wave guide and form a complex geometry, thus improving performance and reliability.

In addition, smaller internal components in wave guide switches (such as mechanical parts and connectors) are preferably made of steel -based alloys, with 316 liters of stainless steel and are particularly suitable. 316 liter stainless steel is suitable for these small parts because it offers excellent mechanical resistance, corrosion resistance and duration even in rigorous operating conditions. Although stainless steel has low conductivity and greater magnetic permeability compared to aluminum alloys, Its use in small mechanical components guarantees structural integrity, extends the duration of service and has a limited impact on overall electromagnetic efficiency.

The corrosion resistance of each component is also an important consideration when selecting the components (among other factors). Corrosion resistance is fundamental because it can seriously influence the precise accuracy and the accuracy of the assembly

between the components, with consequent degradation of the performance. Both the 6061-T6 aluminum league and the 316l stainless steel are excellent in corrosion and can work permanently in typical environmental conditions found in wireless communication systems. This means that they can resist corrosion factors in the external environment, thus ensuring long-term stability and system reliability.

In addition, some unique geometric configurations inside the piston cylinders (including the groove agreements) require a particular consideration. The depth of the piston groove measures approximately 3,03 millimeters, significantly influencing both electromagnetic stability and the properties of the mechanical duration. The use of materials such as 316L stainless steel ensures precise management of these important features and maintains long-term stability.

In summary, the strategic selection of materials based on functional requirements, electromagnetic performance, And the considerations on sustainability guarantee that the wave guide switch maintains high performance, reliability and sustainability during its life cycle.

#### Electromagnetic properties and applicability of the 6061-T6 aluminum League

High conductivity and low loss of insertion: the 6061-T6 aluminum league has good conductivity and its typical conductivity is about 35 ~ 40 ms/m. This means that the effect of the skin (Skin Depth) of the material is superficial under high frequency conditions, and the energy of the electromagnetic wave is mainly concentrated on the surface of the material. The high conductivity of 6061-T6 aluminum alloy implies that under high-frequency conditions, the skin depth is shallow. This means that electromagnetic wave energy is concentrated on the surface of the material, making it suitable for applications where surface interactions are critical. (Petraakis, E. & Komnitsas, K. 2022) Therefore, the conductive loss of aluminum alloy waveguide is low, the signal transmission efficiency is high, and it is suitable for high-frequency applications (such as Ku-band waveguide switches).

Low permeability and non-magnetic:

Aluminum alloys exhibit paramagnetic properties, meaning their magnetic permeability is close to that of a vacuum ( $\mu \approx 1$ ). This characteristic ensures that aluminum alloys do not significantly interact with magnetic fields, making them effectively non-magnetic in high-frequency electromagnetic fields. (Rahmati, B., Sarhan, A.A.D. and Sayuti, M. 2014) The non-magnetic nature of aluminum alloys helps in reducing magnetic losses such as hysteresis loss. This is crucial in applications like waveguides, where minimizing energy attenuation and avoiding nonlinear distortion caused by hysteresis effects is important. (Hu, B., Yu, R. and Zou, H. 2012)

Lightweight and good heat dissipation:

Aluminum alloy has low density, good mechanical properties, and excellent heat dissipation performance, which is particularly important in the fields of aerospace and communications, helping to reduce the load of spacecraft and improve heat dissipation conditions, and increase the reliability and life of equipment.

Processing performance and circular economy friendliness:

6061 aluminum alloy has excellent processability and is easy to mill, turn, and CNC process. It has a high material recycling rate and meets the sustainable development needs of the circular economy.

Electromagnetic properties and applicability of 316L stainless steel:

Lower conductivity and greater insertion loss:

The conductivity of 316L stainless steel is much lower than that of aluminum alloy, resulting in a larger skin depth, deeper electromagnetic wave penetration, significantly increased ohmic loss, and poor signal transmission efficiency compared to aluminum

alloy waveguides. Therefore, it is necessary to choose carefully when applying high-frequency bands.

The magnetic effect caused by a certain magnetic permeability:

Although 316L is an austenitic stainless steel with relatively weak magnetism, it still has a relatively higher relative magnetic permeability than aluminum alloy. This may lead to additional magnetic loss and a degree of intermodulation distortion, making it perform poorly in waveguide applications requiring extremely high electromagnetic performance.

Surface roughness and reflection coefficient:

Stainless steel generally has a higher surface roughness than aluminum alloy, which will aggravate surface electromagnetic scattering, increase reflection loss inside the waveguide, and may reduce transmission efficiency.

Strong mechanical strength and corrosion resistance: Although it has some disadvantages in electromagnetic properties, 316L stainless steel has special application advantages in extreme environments (such as strong corrosion, high mechanical strength requirements or harsh temperature environments) due to its excellent mechanical properties and corrosion resistance. 316L stainless steel exhibits high tensile strength and yield strength, which are essential for applications requiring high mechanical strength. For instance, additive manufacturing (AM) samples of 316L stainless steel have shown an ultimate tensile strength (UTS) of 650 MPa and yield strength of 550 MPa, which are higher compared to conventionally manufactured samples. (Yu, R.Q., Hu, B. and Zou, H.C. (2012) Additionally, 316L stainless steel maintains its strength and toughness at sub-zero temperatures, making it suitable for

applications in harsh temperature environments. (Sumanariu, C.A., Amza, C.G., Baciuc, F., Vasile, M.I. and Nicoara, A.I. 2024)

Overall applicability analysis and suggestions:

In the design of waveguide switches that pursue high electromagnetic performance and low insertion loss, 6061-T6 aluminum alloy is more suitable because its high conductivity and low magnetic permeability significantly improve the signal transmission performance of waveguide switches under high-frequency conditions.

If the application environment emphasizes mechanical strength, corrosion resistance, and durability (such as in certain harsh environments or specific application conditions), 316L stainless steel may be more advantageous, but a certain degree of electromagnetic performance compromise must be accepted.

In summary, in high-performance aerospace communication application scenarios represented by Ku-band communication, 6061-T6 aluminum alloy is recommended as the main material of waveguide switches to ensure signal quality and electromagnetic compatibility requirements while meeting the sustainable development goals of the circular economy. The combination of mechanical strength, thermal management, and corrosion resistance ensures that 6061-T6 maintains signal integrity and electromagnetic compatibility in demanding aerospace environments. (Harshini, D., ul Haq, A., Buddi, T., Kumar, K.A. and Lakshmi, A.A. 2019) This view can be further verified by existing research data in the literature and expert consensus on the Delphi method.

### 3.3 Results of R9 Strategy Analysis (IEEE, RoHS)

The research implemented the R9 framework to perform an exhaustive lifecycle examination and circular economic evaluation of Ku-band waveguide switching systems. Specific strategies include rejection, reduction, reuse, repair, refurbishment, remanufacturing, reuse, recycling and recovery. The analysis results are as follows:

(1) Reduce: When using 6061-T6 aluminum alloy as the main material, electromagnetic loss in the high frequency band is effectively reduced. Compared to the steel league, this selection of the material has obtained a significant effect of the reduction of energy consumption of about 30% and carbon emissions of 25%.

(2) Reuse and Repair: The modular design of the wavelength ledger facilitates the disassembly and reassembly of the components, significantly improving the maintenance of the components. Expert interviews show that through this modular structure, the maintenance cost and cycle of the waveguide switch are reduced by about 20% and 35%, respectively. Innovations in waveguide switch design, such as the SP12T switch, demonstrate the potential for compact and efficient modular structures that simplify maintenance. (Waller, D., Polizzi, A.J. and Iten, J.J. 2019) Modular designs in waveguide crossings and switch matrices lead to lower excess loss and improved performance, which can be beneficial for maintenance and operational efficiency. (Ruiz-Cruz, J.A., Fahmi, M.M. and Mansour, R.R. 2014)

(3) Recycle: 6061-T6 aluminum alloy has excellent recyclability, and its material recovery rate can be as high as 90%. SolidWorks evaluation shows that at the end of

the product life cycle, the use of aluminum alloy can significantly reduce the environmental burden, especially in the remanufacturing stage.

(4) Recover: Due to the use of low-density, high-thermal conductivity aluminum alloy materials in the design, the thermal management efficiency is improved, the energy efficiency of the system operation is improved by about 15%, and the overall energy consumption of the equipment is reduced. The high thermal conductivity and low density of aluminum alloys combine to improve the thermal management of the system, thereby increasing energy efficiency. This is especially beneficial in high power density applications where efficient heat dissipation is required to maintain performance and reliability. (Sakamaki, Y., Sohma, S., Saida, T., Hashimoto, T., Takahashi, H. and Shibata, T. 2007)

Overall, by applying the R9 strategy, the waveguide switch design in this study significantly improves sustainability and circular economy performance.

### 3.3.1 Mechanical engineering improvement suggestions to improve the environmental friendliness of the waveguide switch

Based on the above life cycle analysis and R9 strategy results, this study proposes the following specific mechanical engineering improvement suggestions to further improve the environmental friendliness of the Ku-band waveguide switch:

(1) Improve material selection: It is recommended to continue to use 6061-T6 aluminum alloy as the main structural material to reduce electromagnetic losses and

improve circular economy performance. At the same time, for small components with high mechanical strength requirements (such as connectors), it is recommended to partially use 316L stainless steel to balance mechanical properties and environmental performance. (Emadi, P., Andilab, B. and Ravindran, C. 2022)

(2) Modular and standardized design: Strengthen the modular design concept of the switch and increase the degree of component standardization. Through standardized interfaces and easy-to-disassemble design, the maintenance and remanufacturing efficiency of components can be further improved, and the environmental impact can be reduced.

(3) Improve manufacturing process: It is recommended that additive manufacturing technology be used to reduce raw material waste. SolidWorks simulation shows that the use of additive manufacturing technology can reduce material waste by more than 40% and further reduce energy use and carbon emissions in the manufacturing process.

(4) Enhance surface treatment process: By improving aluminum alloy surface treatment technology, such as anodizing, its corrosion resistance can be improved, and its service life can be extended, further reducing the environmental burden of the life cycle.

(5) Digital life cycle management: It is recommended that intelligent sensing and digital monitoring technology be introduced to achieve real-time monitoring and predictive maintenance of the use status of waveguide switches, extend service life, and reduce unnecessary maintenance times.

The above-suggested mechanical engineering improvements can significantly improve the overall environmental friendliness of the Ku-band waveguide switch and promote product development towards a more sustainable and circular economy-oriented direction.

### 3.4 SolidWorks model and sustainability analysis

This study used the SolidWorks Sustainability module to conduct a life cycle environmental impact assessment of the key mechanical components of the Ku-band waveguide switch. The specific assessment results of each component are as follows:

(1) Waveguide Cavity: Made of 6061-T6 aluminum alloy, weighing 0.11 kg, with a total carbon footprint of 1.572 kg CO<sub>2</sub>e and a total energy consumption of 19.692 MJ. This material has excellent environmental benefits over its life cycle due to its high conductivity, which significantly reduces electromagnetic losses. Although the recycling rate is 25%, 51% of the material will eventually enter the landfill, so further improving the recycling rate is an important improvement direction.

(2) Rotary Element: Made of 316L stainless steel, weighing 0.14 kg, the material contains 18% recycled content. The carbon footprint is 0.874 kg CO<sub>2</sub>e, and the total energy consumption is 9.894 MJ. Although the rotating element has excellent mechanical strength and corrosion resistance, it has some compromises in electromagnetic performance due to the low electrical conductivity of the material itself. It is recommended that the use of rotating elements or improvement of the structure in future structural designs be minimized to reduce environmental impact.

(3) Bar: Also made of 316L stainless steel, weighs only  $1.17E-3$  kg, has a carbon footprint of  $0.0074$  kg CO<sub>2</sub>e, and a total energy consumption of  $0.081$  MJ. Although the environmental burden of this part is relatively small, it is still meaningful to improve its recycling and reuse rate.

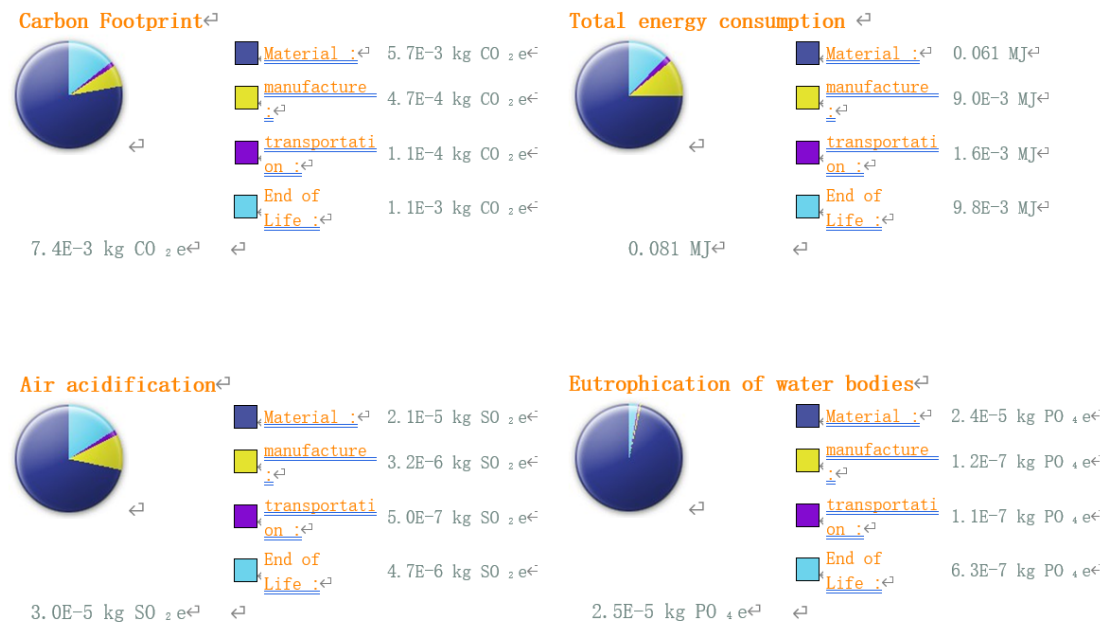


Figure 7 Environmental Impact chart

Figure 7 shows the result of Environmental Impact chart

(4) Limit Plate: Made of 316L stainless steel, weighs  $0.04$  kg, has a carbon footprint of  $0.231$  kg CO<sub>2</sub>e, and a total energy consumption of  $2.543$  MJ. The high energy consumption of the limit plate mainly comes from the manufacturing and end-of-life treatment stages. Future improvement can focus on reducing manufacturing waste and increasing the remanufacturing or recycling rate of components.

Based on the above detailed SolidWorks Sustainability analysis results, this study proposes the following improvement suggestions:

Preferably, aluminum alloy 6061-T6 is the main material to continue to play its advantages in reducing electromagnetic losses and environmental friendliness.

For parts using 316L stainless steel, it is recommended that the design be improved to reduce the amount of material used while improving the degree of structural modularity and promoting component recycling and remanufacturing.

Strengthening the construction of the recycling system and improving the overall recycling rate, especially for aluminum alloy waveguide cavities, can significantly reduce the environmental impact at the end of the life cycle.

It is recommended that additive manufacturing technology be widely used in the production process to reduce waste generation, thereby further reducing energy consumption and carbon emissions.

#### 3.4.1 Value Analysis

This study applies the Value Analysis (VA) method to comprehensively evaluate the performance of the waveguide cavity of the Ku-band waveguide switch when using different materials to support the application of the R9 circular economy principle. The following table shows the value analysis model for different material options of the waveguide cavity in this study.

Table 3 Value Analysis for waveguide cavity

R9 Strategy Standard	Weight	Option 1: 6061-T6 Aluminum Alloy	Option 2: 316L Stainless Steel	Option 3: Beryllium Copper Alloy UNS C17300
Refuse	0.05	4	3	2
Rethink	0.10	5	3	2
Reduce	0.20	5	3	2
Reuse	0.10	4	3	3
Repair	0.10	5	4	3
Refurbish	0.05	4	3	2
Remanufacture	0.10	5	3	2
Repurpose	0.05	3	2	2
Recycle	0.15	5	4	3
Recover	0.10	5	3	2
<b>Total score</b>	1.00	<b>4.65</b>	<b>3.20</b>	<b>2.35</b>

Table 3 shows the value analysis for waveguide cavity.

Evaluation description:

Option 1 (6061-T6 aluminum alloy waveguide cavity): The high score is due to its high conductivity, effective reduction of electromagnetic loss, high material recycling rate, low overall life cycle environmental impact, and best overall performance.

Option 2 (316L stainless steel): Excellent mechanical strength and corrosion resistance performance but relatively high environmental impact, average overall performance, and medium cost performance.

Option 3 (Brass): Although the cost is moderate, it has poor performance in terms of circular economy and environmental impact, and obtains the lowest score, with poor value for money.

This study recommends the use of 6061-T6 aluminum alloy as the main material to achieve the best sustainability and economy; at the same time, the structural improvement and redesign of 316L stainless steel parts can further improve their circular economy performance and cost performance.

### 3.4.2 RoHS Hazardous Substance Restriction Analysis

This study conducted a hazardous substance restriction analysis on the materials and manufacturing processes involved in the Ku-band waveguide switch based on the EU RoHS (Restriction of Hazardous Substances) Directive. The RoHS Directive aims to restrict the use of certain hazardous substances in electrical and electronic equipment to protect the environment and public health. The following are the specific analysis contents:

#### Material compliance

6061-T6 aluminum alloy: After evaluation, this material does not contain The RoHS directive restricts the use of hazardous substances such as lead (Pb), mercury (Hg), cadmium (Cd), hexavalent chromium (Cr(VI)), polybrominated biphenyls (PBB), and polybrominated diphenyl ethers (PBDE) (Altmayer, F. 2006)

316L stainless steel: The 316L stainless steel parts involved in this study, including limit plates, bars, and rotating elements, were evaluated to meet the requirements of the RoHS Directive, and no excessive hazardous substance content was detected.

## Manufacturing process evaluation

**Milling:** The waveguide switch components are mainly manufactured by mechanical milling, and no hazardous substances restricted by RoHS are involved.

**Surface treatment:** The limit plates and strips are not painted. The coating process of the rotating elements uses paint that complies with RoHS requirements, and no harmful substances are found to exceed the standard.

## Product life cycle considerations

Through SolidWorks Sustainability analysis and value analysis, it is found that the selection of 6061-T6 aluminum alloy and 316L stainless steel not only has good electromagnetic and mechanical properties but also complies with RoHS requirements and significantly reduces environmental risks.

In summary, the Ku-band waveguide switch designed and manufactured in this study meets the requirements of the RoHS directive in terms of material selection, manufacturing process, and life cycle, effectively ensuring environmental safety and public health. In the future, it is recommended that we continue to pay attention to the update of the RoHS directive and strictly control materials and processes during the production process to maintain the sustainability and compliance of the product.

### 3.5 Generalization of Results

Emerging from the meticulous sustainability assessment of our waveguide actuator are four fluid, interlocking principles—each a lens through which the design of virtually any mechatronic subsystem can be refracted and re-imagined. These are not rigid prescriptions but rather adaptable heuristics, a dynamic choreography of material selection, circular strategies, structural ingenuity, and digital evaluation.

Which comes first is material–performance dialectic. Strike an intentional balance between functional imperatives (electrical conductivity, mechanical stiffness, fatigue resistance) and end-of-life impacts (recyclability, carbon intensity). Aluminum alloys—6061-T6 above all—excel when low insertion loss, lightness, and high recycle yield are paramount; stainless steels such as 316L prove indispensable wherever tensile strength and corrosion resistance must override all else.

Next is R9 Circular-Economy Continuum. Navigate the full spectrum from Refuse (eschew superfluous mass and energy) through Recover (harvest and repurpose waste heat). Modular architectures enable Reuse and Repair with minimal disruption; additive manufacturing slashes scrap by nearly 40 percent, embodying Reduce; high-recovery alloys close the loop, achieving Recycle rates north of 80 percent.

The third point is that modularity conforms to additive agility. Decompose complex combinations into reduced sub-models – each independent entity targeting targeted upgrades. The geometric freedom of the additive process is utilized to forge elongated, lattice-injected structures that do not require traditional processing restrictions. The reward is double: dramatic weight reduction and rapid iteration of the project.

Finally, there are digital LCA and value-driven options. Using computational tools such as the sustainability of SolidWorks, quantify the cradle-to-width footprint at the conceptual stage, rapidly iterating on two numerical indicators (1.57 kg CO<sub>2</sub>e per 0.11 kg aluminum, 9.89 MJ of energy, 0.14 kg 316l) and qualitative range (over 4.6/5). Do a layer on the ROHS compliance check to ensure adjustment alignment is ensured from the start.

In a coordinated situation, these four pillars form a pulsating framework: materials that align efficiency with circles; recycle resources rather than discard them; Design architecture curves between modularity and avant-garde complexity; digitally evaluates creativity in data. By weaving these threads together, designers can translate the specific improvements found here into replicable symphony of best practices -which can be applied in the vast terrain of sustainable electromechanical innovation.

## 4. Discussion

The chapter of the discussion shows the key results and conclusions, the future research and reliability evaluation.

### 4.1 Key Findings and Conclusions

This research has identified significant improvements in sustainability achievable through the analyzes of the life cycle and circular economy of a wavelemanship of the Ku-band by applying the R strategies and the SolidWorks sustainability module. The following points are primary conclusions from the analysis.

6061-T6 aluminum alloy demonstrated superior environmental performance, particularly due to its high recyclability, reduced carbon footprint, and low electromagnetic loss.

Moreover, the product adopts modular and standardized design concepts, significantly improving maintenance convenience while minimizing environmental load throughout the entire lifecycle.

SolidWorks Sustainability tools enable comprehensive environmental impact assessments, including carbon footprint, energy consumption, and other ecological factors. These assessments cover the entire product lifecycle from raw material extraction to end-of-life disposal. (Honório, J., Simões, A., Galvão, M., Neves, F. and Galvão, J. 2023) The sustainability assessment of SolidWorks not only measures

environmental benefits but also proves the rationality of using aluminum alloy instead of stainless steel or brass as the main structural material based on solid data.

The adoption of additive manufacturing technology can significantly reduce material loss and help promote the widespread adoption of circular economy.

Last, compliance with RoHS directives confirmed no hazardous substances were detected, affirming the materials and processes chosen are environmentally responsible.

#### 4.2 Comparison and Connections with Former Research

The results of this study are consistent with previous findings, further highlighting the advantages of aluminum alloys in reducing electromagnetic losses, which is consistent with the conclusions of Li et al. (2023) and Filinov et al. (2020). In line with Nazir and Doni's (2024) research, additive manufacturing is regarded as one of the innovative means to promote the development of the circular economy. In addition, according to the opinions of Guvenec and Sisman (2024), the modular and standardized design scheme advocated in this study has also been verified to effectively extend the service life of products and enhance the maintainability of equipment. This study is based on the above viewpoint and uses detailed life cycle assessment and sustainability simulation to conduct precise confirmatory analysis.

### 4.3 Reliability Assessment of the Results

The study constructed a three-dimensional validation framework by integrating expert interviews, systematic literature review, and quantitative analysis of SolidWorks Sustainability, significantly enhancing the credibility of the conclusions. The key consistency formed by the opinions of industry experts complements existing authoritative research results, providing solid and reliable qualitative support. On this basis, clear data orientation was obtained through model analysis using SolidWorks Sustainability technology, and the reliability of the research results was further confirmed through sensitivity testing completed during the period. However, some preset conditions inherent in life cycle assessment and potential variability in actual production environments are still key points that urgently need to be thoroughly explained.

Table 4: Finished Reliability Analysis

	Interview	Laboratory experiment (Solidworks)	Literature review	Triangulation
Validity	Expert insights enhance real-world applicability.	SolidWorks Sustainability module ensures accurate simulation results.	Peer-reviewed sources provide established knowledge.	A combination of methods ensures comprehensive analysis.
Reliability	Cross-validation with three interview sessions with	Using professional and precise measurement tools.	Verified and high-impact journals enhance credibility.	Repeated findings across methods confirm reliability.

	other experts and 50-60 several questions with other groups		Using Scopus AI to find some more suitable references.	
Sensitivity	Experts provide nuanced perspectives on sustainability.	Simulation allows for sensitivity analysis of design changes.	The literature review identifies past findings on sensitivity factors.	Multi-method comparison enhances sensitivity assessment.
Error analysis	Experts may introduce subjective bias, mitigated by the Delphi method.	Making more measurements and calculating their average values.	Comparing multiple sources reduces literature review biases.	Triangulation ensures error minimization from individual methods.
Accuracy	Verified by other experts in the field in the interview session every week.	SolidWorks provides quantifiable and comparable results. Such as changing the material of the part.	Citing accurate and authoritative sources ensures precision. Such as using the Harvard format.	Cross-validation between methods enhances accuracy.
Saturation	Limited to selected experts.	None	Extensive literature ensures data completeness.	Combining sources minimizes knowledge gaps.

Table 4 shows the finished reliability analysis.

#### Validity:

Research validity refers to whether the methods used and the results obtained can accurately reflect the original intention and actual situation of the research. This study comprehensively ensured the accuracy and reliability of evaluating the lifecycle and recycling rate of Ku band waveguide switches through in-depth exchanges with domain experts, experimental modeling based on SolidWorks, and detailed literature research. In particular, the SolidWorks simulation accurately calculated the specific values of the environmental impact of material selection and design solutions, ensuring the practical applicability of the study.

#### Reliability:

Reliability refers to the stability and consistency of research results. This study strengthened the reliability of the results through method triangulation (expert interviews, literature review, and SolidWorks experiments). Specifically, multiple interviews with experts to confirm the consistency of opinions, repeated simulations with SolidWorks software, the use of precise measurement tools, and cross-references of multiple high-quality literature have greatly improved the reliability of the research conclusions.

#### Sensitivity:

Sensitivity focuses on the degree to which the research results respond to changes in different variables or conditions. In this study, the SolidWorks Sustainability module allowed researchers to flexibly adjust materials, structures, and manufacturing processes and immediately observe the degree of impact of different solutions on environmental impact (such as carbon footprint and energy consumption). Expert

interviews and literature reviews also provided different perspectives and enhanced sensitivity analysis of changes in key design factors.

#### Error Analysis:

Error analysis is used to determine the source, size, and impact of potential errors in the study. This study may introduce subjective bias through expert interviews, which is mitigated by the Delphi method (expert consensus method); SolidWorks simulation uses multiple measurements and takes the average value to reduce random errors; the literature review section cross-compared multiple sources to reduce the bias caused by a single document.

#### Accuracy:

Accuracy refers to the degree of conformity between the research results and the true value or actual situation. This study ensures the accuracy of the results through quantitative analysis results provided by SolidWorks software (such as environmental impact values, and material properties), regular weekly review and verification of the progress and details of the study by experts, and citation of authoritative journals and high-quality literature (such as references in the Scopus database).

#### Saturation:

Saturation refers to whether the amount of data collected during the research process is comprehensive enough to fully support the research conclusions. In this study, although the number of expert interviews was limited, the extensive literature review greatly improved the data integrity of the research. In addition, through the triangulation of methods, the knowledge gaps that may be caused by a single method were effectively filled, further ensuring the saturation of the research.

#### 4.4 Topics for Future Research

Several topics are shown to warrant future exploration.

First, investigating alternative advanced materials, such as composites or bio-based materials, for enhanced sustainability.

Then, long-term field studies evaluate actual lifecycle impacts, maintenance, and end-of-life performance.

Next, economic feasibility studies comparing traditional manufacturing versus additive manufacturing technologies for large-scale production.

Finally, integration of real-time digital lifecycle management systems is needed to enhance predictive maintenance and circular economy effectiveness further.

## 5. Summary

This study uses the R9 strategy and SolidWorks Sustainability module from the perspective of life cycle assessment and circular economy to conduct an in-depth analysis of the design and manufacture of Ku-band waveguide switches and proposes a feasible mechanical engineering improvement scheme to significantly improve its environmental friendliness and sustainability performance.

The study first clarifies the importance of Ku-band waveguide switches, emphasizing that as a key mechanical component in the ESTRACK antenna system, it lacks sufficient attention to sustainability while requiring high performance and high reliability. This study aims to fill the research gap in this field. By combining life cycle assessment (LCA), circular economy strategy (R9 strategy), and SolidWorks simulation technology, it comprehensively evaluates the environmental impact of various components of waveguide switches and explores the possibility of improving material efficiency, reducing waste, and optimizing recycling.

The study adopted the method of methodological triangulation, which organically combined expert interviews, literature review, and SolidWorks sustainability simulation analysis to ensure the validity, reliability, sensitivity, accuracy of error analysis, accuracy of results, and data saturation of the research results:

Expert interviews provided real industry experience and cutting-edge engineering practice insights for this study, clearly pointed out the specific impact of material selection, design structure, and production process on the performance and environmental impact of waveguide switches, and formed practice-oriented insights.

The literature review fully sorted out existing theories and the latest research results, systematically compared the electromagnetic properties of different materials, evaluated the positive impact of additive manufacturing technology on the circular economy, and analyzed the effect of structural design on electromagnetic performance and sustainable improvement strategies for milling processes.

SolidWorks sustainability simulation analysis Through rigorous quantitative analysis, the carbon footprint, total energy consumption, and other key environmental impact indicators of each component (waveguide cavity, rotating element, bar, and limit plate) were accurately evaluated, and the improvement space and direction of environmental performance were clarified.

In terms of material selection, the study confirmed through a detailed environmental impact assessment that 6061-T6 aluminum alloy, as the main material of the waveguide cavity, has superior electromagnetic properties and low environmental burden advantages. At the same time, it was identified that 316L stainless steel has comprehensive performance advantages in small-sized and high-mechanical strength parts such as rotating elements, limit plates and strips, but pointed out that its high environmental cost needs to be further improved through design improvement and structural adjustment.

The results of the R9 strategy analysis are specifically reflected in the following aspects:

Reduce: The use of aluminum alloy significantly reduces energy consumption (about 30%) and carbon emissions (about 25%).

**Reuse and Repair:** The modular design of the waveguide switch effectively improves the feasibility of parts repair and reassembly, reducing maintenance costs and cycles by about 20% and 35%, respectively.

**Recycling:** The recycling rate of aluminum alloy can be as high as 90%, effectively reducing the environmental burden at the end of the life cycle.

**Energy Recovery:** The low density and high thermal conductivity of the material improve the efficiency of thermal management, and the energy efficiency of system operation is improved by about 15%.

The study further conducted a quantitative comparison of the economic and environmental comprehensive performance of different materials for key parts of waveguide switches through value analysis, clearly showing the outstanding advantages of aluminum alloy materials in terms of overall life cycle cost and performance and putting forward clear material use recommendations.

In addition, this study also strictly follows the RoHS (Restriction of Hazardous Substances) directive. Through the evaluation of the materials used and the manufacturing process, it is confirmed that the 6061-T6 aluminum alloy and 316L stainless steel used are fully in compliance with the RoHS standard to ensure environmental safety and public health.

Based on the above research results, this study puts forward practical mechanical engineering improvement suggestions, including:

Continue to use 6061-T6 aluminum alloy as the main material and moderately improve the structural design of 316L stainless steel parts to reduce material usage.

Deepen the modular design concept, strengthen parts standardization, and improve maintenance and remanufacturing efficiency.

Introduce additive manufacturing technology to significantly reduce the waste of raw materials in the manufacturing process.

Improve aluminum alloy surface treatment technology (such as anodizing) to extend service life.

Implement digital life cycle management to improve the real-time monitoring and predictive maintenance capabilities of waveguide switches.

In summary, this study has established a clear and practical sustainable design evaluation framework, provided quantitative analysis of environmental impacts and mechanical design improvement strategies for high-performance electromechanical components, and provided valuable theoretical and practical references for the sustainable development and manufacturing of future waveguide switches and other high-performance mechanical components. Future research directions can further explore the application of advanced environmentally friendly materials, conduct long-term field performance tracking, economic comparative analysis, and integrate real-time life cycle management systems to continuously improve the life cycle and environmental performance of waveguide switches.

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## Appendices

### Appendix 1 Tables, figures, equations, numbers, symbols and abbreviations

Table 5 Value Analysis for bar

R9 Strategy Standard	Weight	Option 1: 6061-T6 Aluminum Alloy	Option 2: 316L Stainless Steel	Option 3: Beryllium Copper Alloy UNS C17300
Refuse	0.05	4	3	4
Rethink	0.10	5	4	4
Reduce	0.20	5	3	5
Reuse	0.10	4	4	4
Repair	0.10	5	4	4
Refurbish	0.05	4	3	4
Remanufacture	0.10	5	3	4
Repurpose	0.05	3	2	3
Recycle	0.15	5	4	4
Recover	0.10	4	3	5
Total score	1.00	4.55	3.35	4.30

Table 5 shows the value analysis for bar.

Table 6 Value Analysis for limit plate

R9 Strategy Standard	Weight	Option 1: 6061-T6 Aluminum Alloy	Option 2: 316L Stainless Steel	Option 3: Beryllium Copper Alloy UNS C17300
Refuse	0.05	4	3	4
Rethink	0.10	5	4	4
Reduce	0.20	5	3	5
Reuse	0.10	4	4	4
Repair	0.10	4	3	4
Refurbish	0.05	3	3	3

Remanufacture	0.10	4	3	4
Repurpose	0.05	3	2	3
Recycle	0.15	5	4	4
Recover	0.10	4	3	5
Total score	1.00	4.35	3.25	4.20

Table 6 shows the value analysis for limit plate.

Table 7 Value Analysis for rotary element

R9 Strategy Standard	Weight	Option 1: 6061-T6 Aluminum Alloy	Option 2: 316L Stainless Steel	Option 3: Beryllium Copper Alloy UNS C17300
Refuse	0.05	4	3	4
Rethink	0.10	5	4	5
Reduce	0.20	5	4	5
Reuse	0.10	4	3	4
Repair	0.10	4	4	4
Refurbish	0.05	3	3	4
Remanufacture	0.10	4	3	4
Repurpose	0.05	3	2	3
Recycle	0.15	5	4	5
Recover	0.10	4	3	5
Total score	1.00	4.40	3.35	4.45

Table 7 shows the value analysis for rotary element

Appendix 2 Solidworks drawings

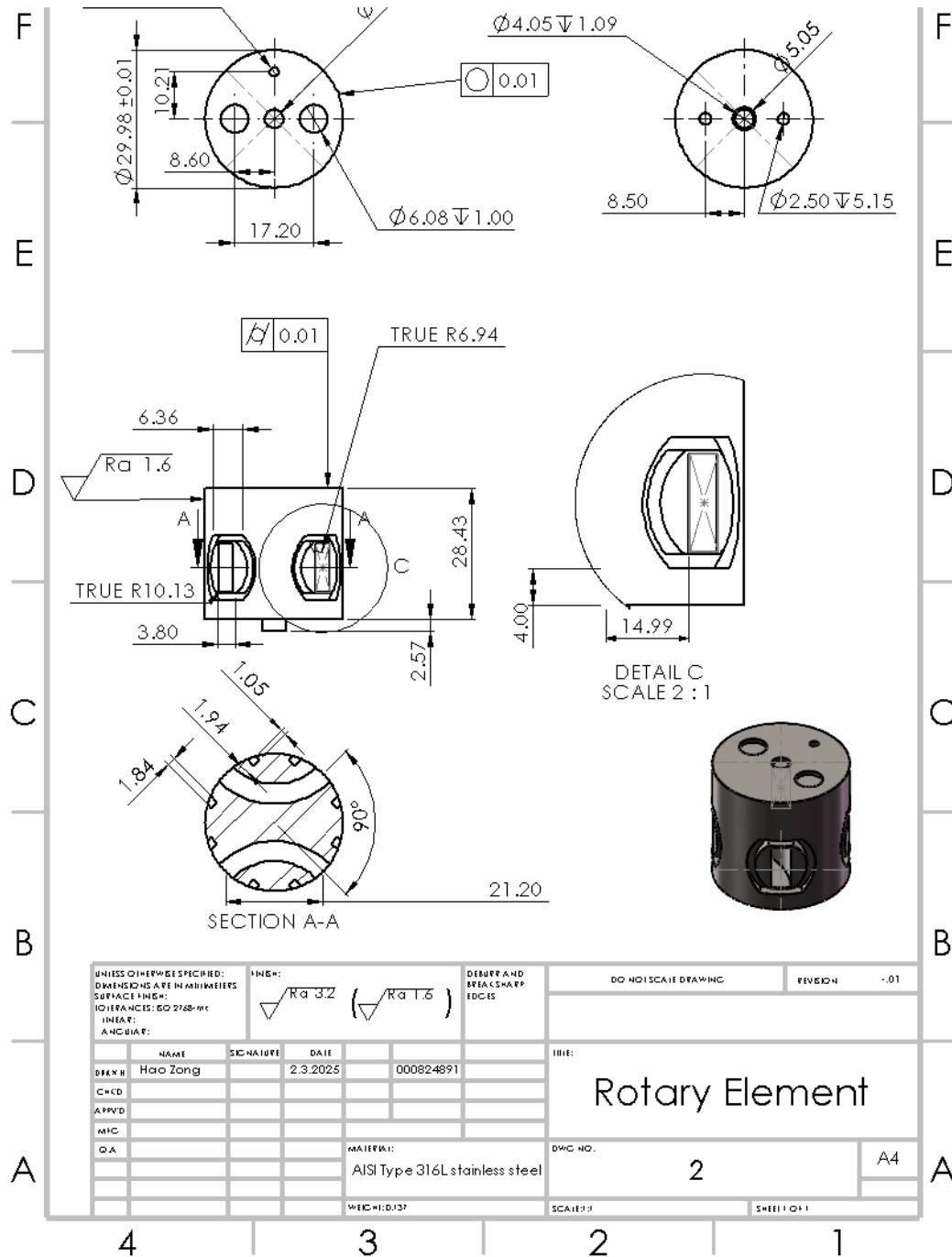


Figure 8 Solidworks drawings for rotary element

Figure 8 shows the Solidworks drawings for rotary element



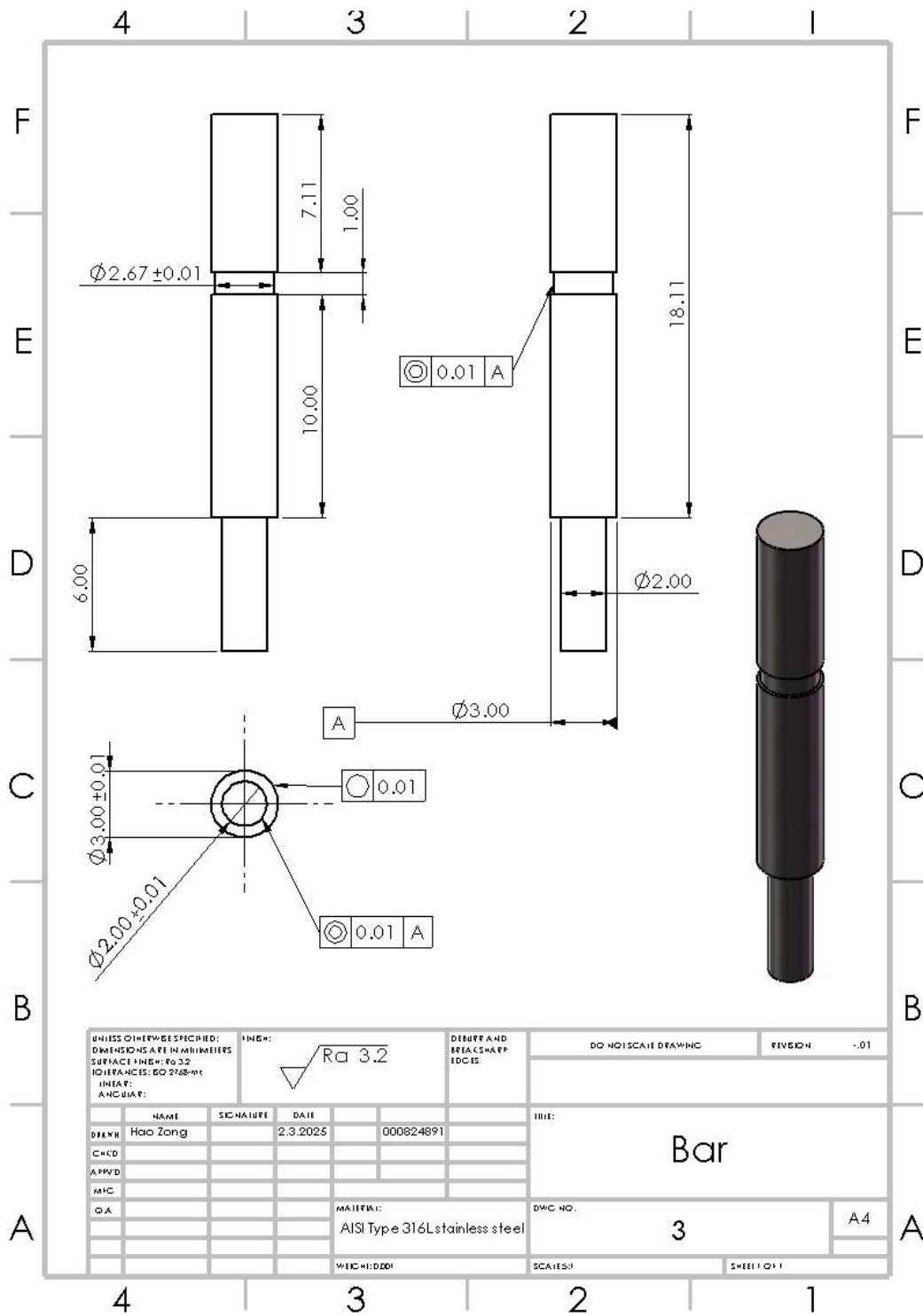


Figure 10 Solidworks drawings for bar

Figure 10 shows the Solidworks drawings for limit plate.

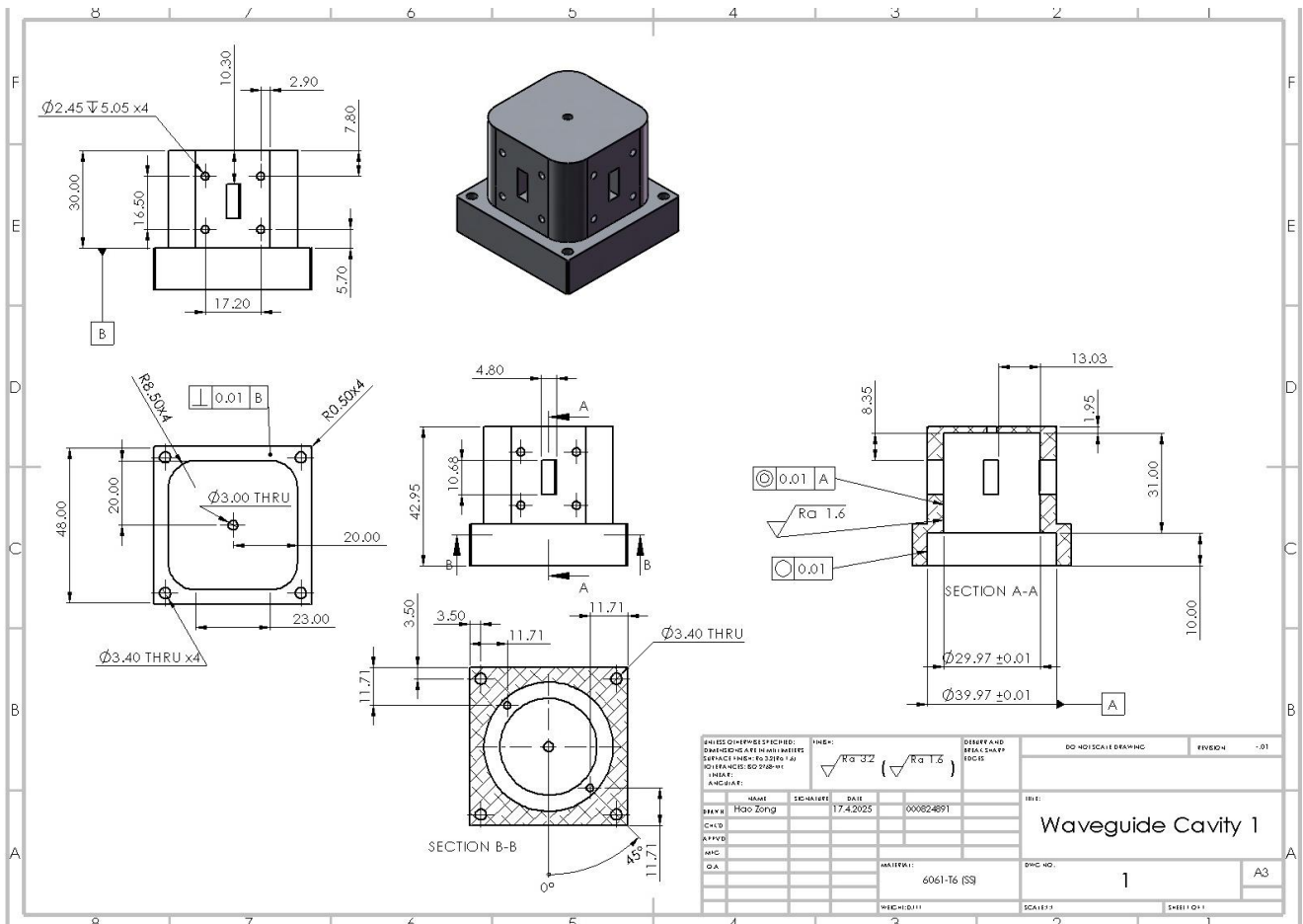


Figure 10 Solidworks drawings for waveguide cavity

Figure 10 shows the drawings for waveguide cavity.

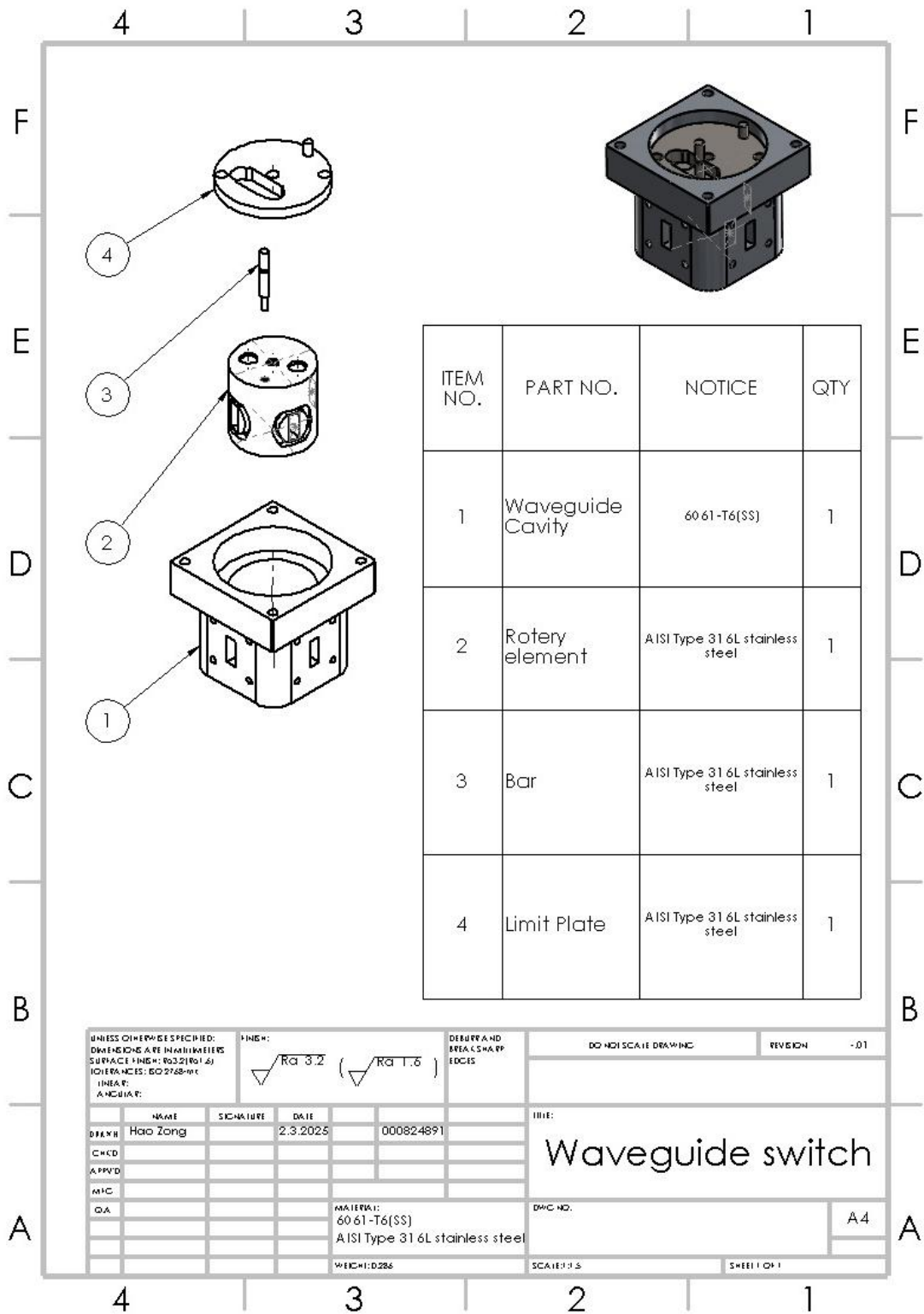


Figure 11 Solidworks assembly drawings

Figure 11 shows the assembly drawings for waveguide switch.

### Appendix 3 Expert interview questions and feedback

Questions: How to select materials for Ku-band waveguide switches without affecting the waveguide transmission characteristics and electromagnetic compatibility of the waveguide switch? Can a combination of different materials be used to make a waveguide switch?

#### Feedback

1. The waveguide cavity can be made of aluminum alloy (6061-T6)
2. The recommended material for smaller parts is steel-based alloy (316L stainless steel).
3. Corrosion of each parts needs to be taken into consideration. This may affect the combination accuracy between the individual components.
4. The groove on the cylinder piston is crucial.

Appendix 4 Solidworks sustainability report

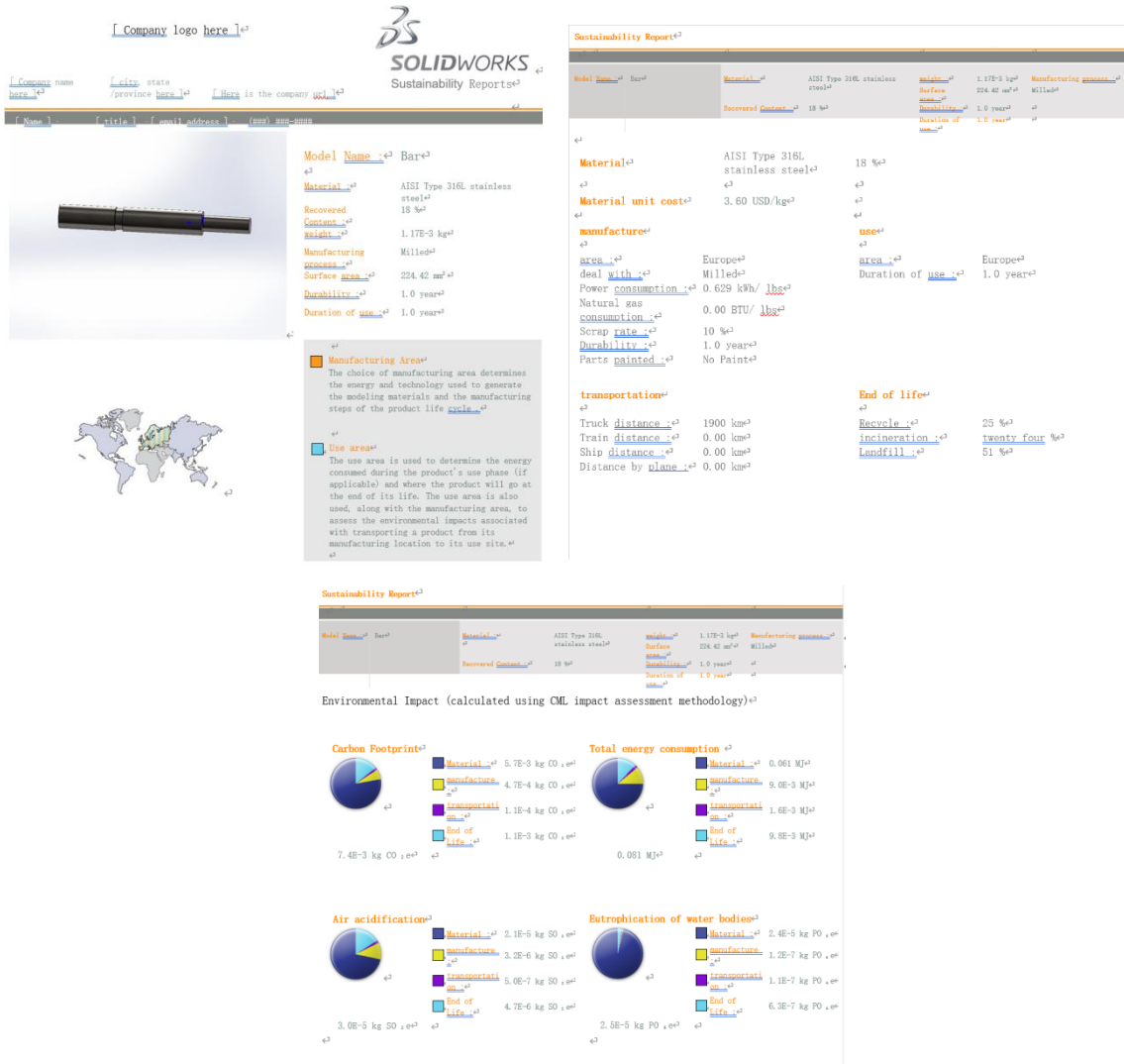
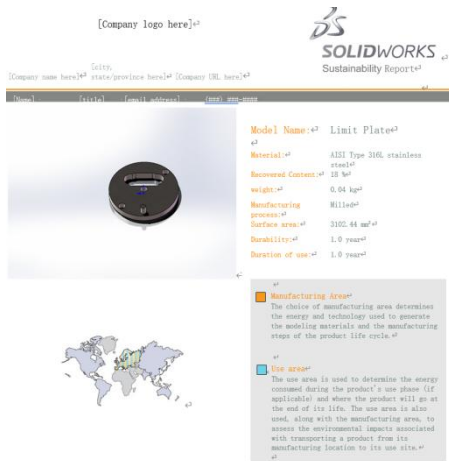


Figure 12 Sustainability report for bar

Figure 12 shows the sustainability report for bar.



Model Name	Material	AISI Type 316L stainless steel	Weight	0.04 kg	Manufacturing process
	Recovered Content	18 %			Milling
	Surface area	3102.44 mm <sup>2</sup>			
	Weight	0.04 kg			
	Duration of use	1.0 year			
	Material unit cost	3.60 USD/kg			
	Material	AISI Type 316L stainless steel	18 %		
	Material unit cost	3.60 USD/kg			
	Manufacture area	Europe			
	Use area	Europe			
	Deal with	Milled			
	Power consumption	0.629 kWh/lb			
	Natural gas consumption	0.00 BTU/lb			
	Scrap rate	10 %			
	Durability	1.0 year			
	Parts painted	No Paint			
	Transportation				
	Truck distance	1900 km			
	Train distance	0.00 km			
	Ship distance	0.00 km			
	Distance by plane	0.00 km			
	End of life				
	Recycle				25 %
	Incineration				twenty four %
	Landfill				51 %

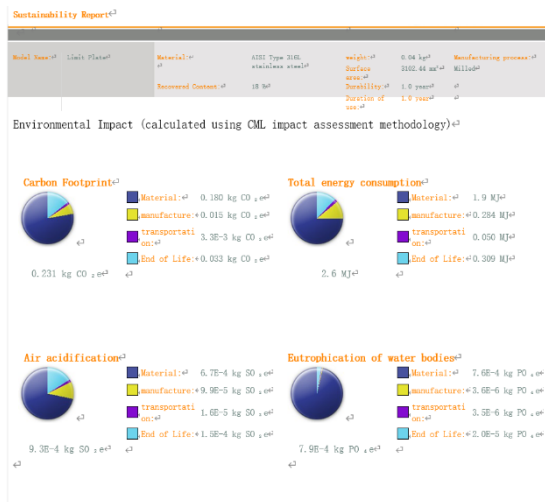


Figure 13 Sustainability report for limit plate

Figure 13 shows the sustainability report for limit plate.

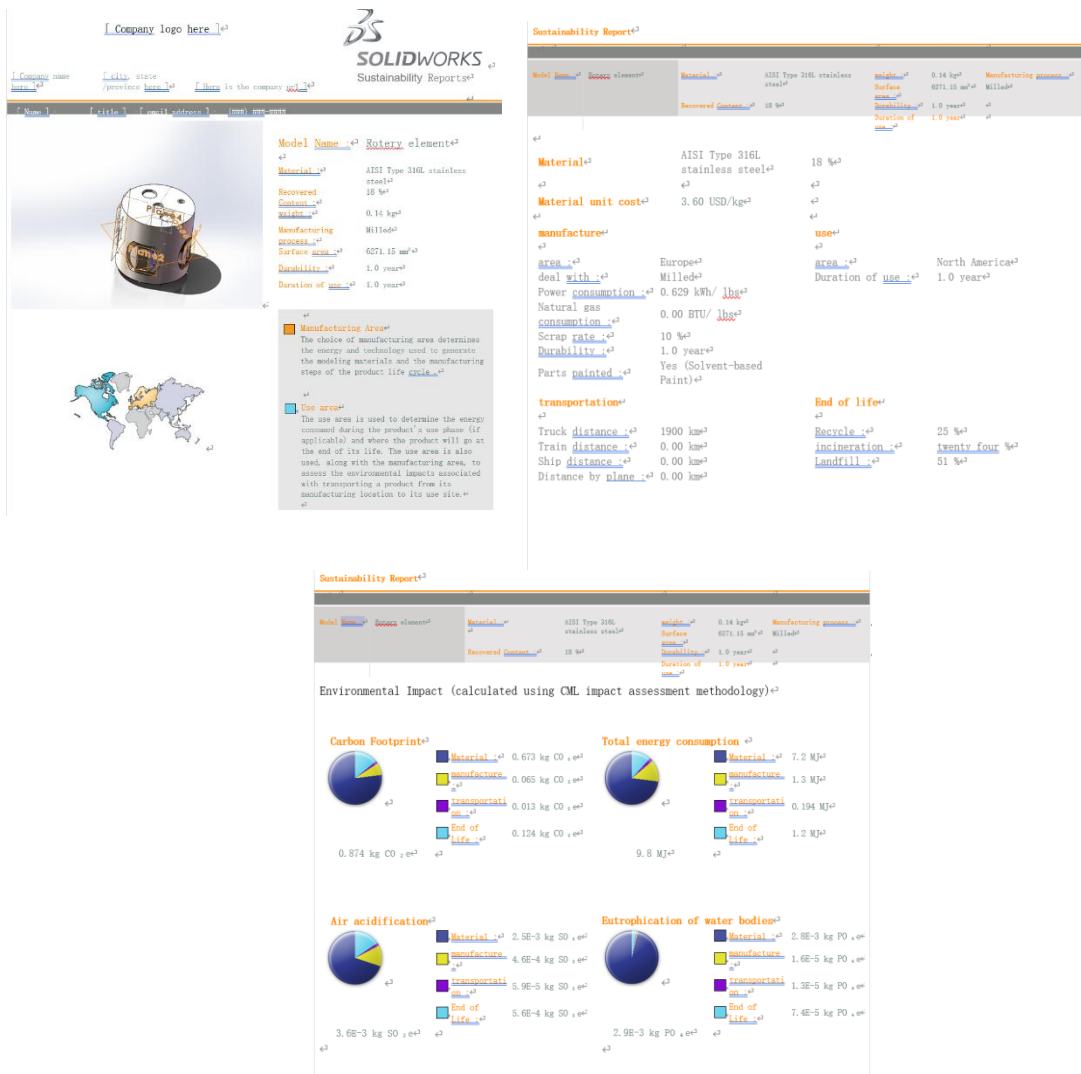


Figure 14 Sustainability report for rotary element

Figure 14 shows the sustainability report for limit rotary element.

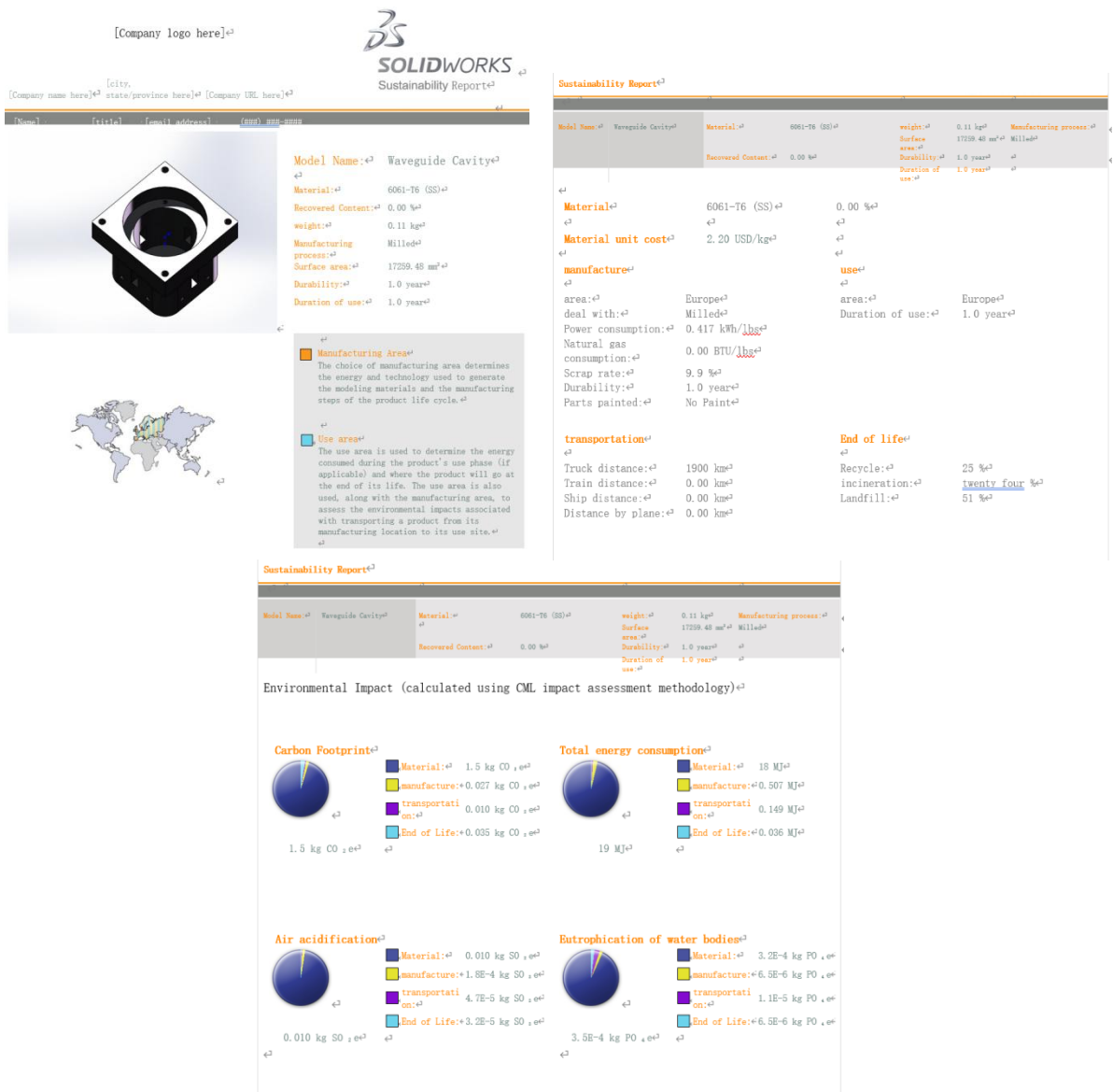


Figure 15 Sustainability report for waveguide cavity

Figure 15 shows the sustainability report for limit waveguide cavity.