A CIRCULAR ECONOMY-BASED TEST BENCH FOR PROPELLER MOTOR CALIBRATION: DESIGN, MEASUREMENT, AND EXPERIMENTAL ANALYSIS

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Abstract: *This paper presents the development of a propeller motor test bench designed for thrust calibration, rotational speed measurement, and experimental analysis, with an explicit circular economy perspective.*

The prototype integrates a mechanical structure built from reused materials, a load-cell-based thrust measurement system, laser tachometer RPM acquisition, and a Matlab -based experimental interface for data visualization and processing. The results show that increasing throttle input raises RPM and thrust, while the economic analysis demonstrates a substantial cost reduction when reused materials are incorporated into the structure. This approach supports both technical validation and resource-efficient prototyping, which is increasingly relevant in aerospace circularity research.

Keywords: *Circular economy, aerospace propulsion, propeller test bench, thrust measurement, rotational speed, Matlab processing, UAV systems, sustainable prototyping*

1. INTRODUCTION

The rapid development of unmanned aerial vehicle (UAV) technologies has increased the demand for reliable and affordable experimental platforms dedicated to propulsion system characterization. Small fixed-wing UAVs are currently employed in environmental monitoring, agriculture, infrastructure inspection, and educational activities, requiring efficient propulsion systems and accurate calibration procedures to ensure safe and optimized operation [5], [6].

At the same time, sustainability has become an important objective within aerospace engineering. Circular economy principles, based on resource efficiency, reuse, repairability, remanufacturing, and life-cycle extension, offer new opportunities for reducing the environmental impact of aerospace products and supporting infrastructures [1]. International organizations, including the International Civil Aviation Organization (ICAO), encourage the implementation of sustainable practices and circular strategies throughout the aviation sector [2]. Moreover, recent frameworks aligned with ISO 59004 emphasize the importance of modularity, design for disassembly, and material recovery as key elements of future aerospace systems [3].

Although circular approaches have been progressively adopted in aircraft manufacturing and maintenance activities, their application to experimental laboratory equipment remains limited.

Most propulsion test benches developed for UAV applications primarily focus on measurement accuracy and aerodynamic performance, while aspects related to component reuse, maintainability, and sustainable material selection are rarely considered [1], [4].

Consequently, there is a need for experimental infrastructures that combine reliable engineering functionality with environmentally responsible design principles.

The characterization of UAV propulsion systems generally relies on static experimental benches capable of measuring thrust and rotational speed under controlled operating conditions. Load-cell-based measurement systems and non-contact optical tachometers provide accurate and cost-effective solutions for establishing throttle–RPM–thrust relationships required for propulsion calibration and performance assessment [5], [6].

This work presents the development of a circular economy-based test bench for propeller motor calibration in small fixed-wing UAV applications. The proposed platform integrates modular construction, reusable structural components, sustainable material selection, and digital modelling using Fusion 360, while experimental validation is performed through thrust and RPM measurements. The main contribution of the study consists of incorporating circular economy principles directly into the design of educational aerospace laboratory infrastructure, demonstrating that sustainability and experimental performance can be successfully combined within low-cost UAV research environments.

2. CIRCULAR ECONOMY FRAMEWORK AND SUSTAINABLE DESIGN PRINCIPLES

The transition toward sustainable engineering practices has encouraged the adoption of circular economy principles within the aerospace sector. Unlike traditional linear approaches based on production, use, and disposal, circular systems emphasize resource efficiency, reuse, repairability, and life-cycle extension [1]. These principles contribute to reducing environmental impacts while improving the long-term utilization of engineering infrastructures.

Recent initiatives promoted by the International Civil Aviation Organization (ICAO) and the ISO 59004 framework highlight the importance of modularity, design for disassembly, and material recovery as key elements of sustainable aerospace development [2], [3]. However, their application to experimental laboratory equipment and educational facilities remains relatively limited [4].

The propulsion test bench developed in this study was designed according to four fundamental circular economy principles:

- **Modularity**, allowing individual subsystems to be easily replaced or upgraded;
- **Reusability**, through the integration of structural elements that can support future experimental activities;
- **Maintainability**, providing simple access for inspection, repair, and calibration procedures;
- **Design for disassembly**, facilitating component recovery and reducing material waste.

Digital modelling using Fusion 360 supported these objectives by enabling virtual prototyping and minimizing unnecessary manufacturing iterations. The use of standardized fastening systems and detachable assemblies further increases the operational lifetime and adaptability of the experimental platform.

Consequently, the proposed approach demonstrates that circular economy concepts can be successfully integrated into low-cost aerospace laboratory infrastructures, combining experimental functionality with sustainable engineering practices suitable for educational UAV applications.

3. EXPERIMENTAL TEST BENCH DEVELOPMENT

The experimental test bench was developed to enable the static characterization and calibration of propulsion systems intended for small fixed-wing UAV applications. The design process focused on achieving reliable thrust and rotational speed measurements while maintaining a low-cost, modular, and sustainable architecture suitable for both educational and research activities.

The complete assembly was initially designed using Fusion 360, which allowed the optimization of structural dimensions, component positioning, maintenance accessibility, and future upgrade possibilities before manufacturing operations were initiated. The use of digital modelling reduced material consumption associated with physical prototyping and supported a more efficient development process. Furthermore, virtual assembly verification minimized construction errors and simplified the integration of measurement equipment within the final structure.

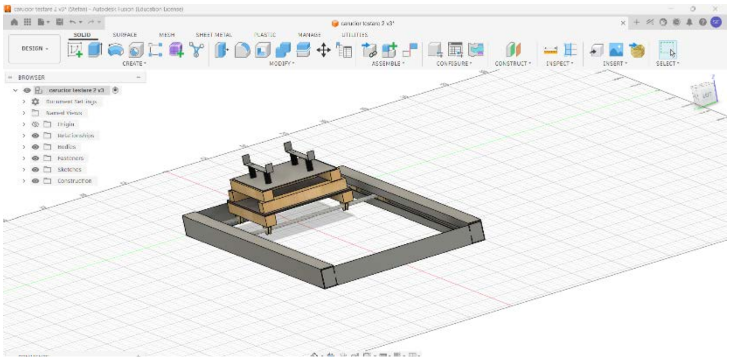

FIG. 1. 3D view of the test bench design in fusion 360

The propulsion system selected for experimental investigations consists of a TEMP BKT 3000 two-stroke gasoline engine delivering approximately 3 [kW], coupled with a Xoar 21×8[in] wooden propeller [8], [9]. This configuration was chosen due to its availability, relatively low acquisition cost, and operational characteristics suitable for fixed-wing UAV applications. The use of a wooden propeller additionally aligns with sustainability objectives by incorporating renewable materials into the propulsion system.

From a structural perspective, the test bench was designed according to modular construction principles. The platform is composed of several independent subsystems that can be removed, repaired, or replaced without affecting the overall integrity of the installation. This approach increases operational flexibility and extends the useful lifetime of the experimental infrastructure.

The experimental platform consists of four principal subsystems:

- the structural support frame;
- the propulsion mounting assembly;
- the thrust measurement unit;
- the rotational speed acquisition system.

3.1 Structural Support Frame

The support structure provides the necessary rigidity to ensure stable operating conditions during engine testing. Particular attention was given to minimizing structural vibrations that could influence measurement accuracy.

The frame was designed using detachable mechanical joints and standardized fastening elements, facilitating maintenance operations and future reconfiguration.

FIG. 2 Final frame of the test bench

The adoption of modular assemblies allows different propulsion configurations to be tested using the same infrastructure. Consequently, the experimental platform can support additional educational activities without requiring complete reconstruction, which contributes to resource efficiency and material conservation.

The structural layout was optimized to provide sufficient accessibility to the propulsion unit, enabling straightforward installation, inspection, and maintenance procedures. Such considerations are particularly important within academic environments, where experimental equipment is frequently reused across multiple projects and student generations.

3.2 Propulsion Mounting System

The propulsion mounting assembly was designed to securely support the TEMP BKT 3000 engine while transmitting generated forces directly to the measurement subsystem. The mounting configuration ensures adequate alignment between the engine axis and the thrust measurement direction, minimizing potential errors caused by eccentric loading conditions.

Mechanical connections between the propulsion system and the supporting structure were designed to facilitate rapid installation and removal operations. This characteristic supports future upgrades and the integration of alternative propulsion units without major modifications to the experimental platform.

The selected Xoar 21×8 [in] wooden propeller provides an appropriate balance between thrust generation and operational efficiency for small UAV applications. The use of commercially available components also contributes to reducing development costs and improving the reproducibility of the experimental setup.

FIG.3 TEMP BKT 3000 engine

FIG.4 Xoar 21×8 [in] wooden propeller

3.3 Thrust Measurement System

The measurement of static thrust represents one of the most important functions of the experimental platform. The proposed solution employs a mechanical weighing system connected to the movable carriage of the test bench. The scale was positioned between the propulsion assembly and a rigid, fixed support element, allowing the direct measurement of the reaction force generated during engine operation.

When the propulsion system produced thrust, the force was transmitted through the carriage to the weighing device, which provided the corresponding measurement values. This simple configuration offered a practical and low-cost alternative suitable for educational and experimental UAV applications.

Before each testing session, the scale was checked and adjusted to eliminate zero-offset errors and ensure consistent measurements. The rigid structural arrangement minimized unwanted movements and reduced the influence of external disturbances on the recorded values. Measurements were performed only after stable operating conditions had been reached, and multiple readings were taken for each throttle setting to improve the reliability of the experimental data.

Although more advanced propulsion test facilities often employ dedicated load-cell systems, the adopted approach demonstrates that accurate thrust characterization can also be achieved using accessible and easily maintainable equipment. Furthermore, the simplicity and reusability of the measurement system are consistent with the circular economy principles considered throughout the development of the experimental platform [5], [6].

3.4 Rotational Speed Acquisition System

The rotational speed of the propeller is measured using a non-contact optical tachometer. Optical measurement technologies provide several advantages, including simplicity of installation, high repeatability, and the elimination of mechanical interference with the propulsion system.

The selected approach allows RPM measurements to be performed without introducing additional loads or modifications to the propeller assembly. This characteristic is particularly important when establishing accurate throttle–RPM–thrust relationships, as any external disturbance could affect aerodynamic performance.

The optical system enables rapid data acquisition across multiple operating conditions and supports repeated experimental campaigns without requiring extensive maintenance procedures. The robustness and accessibility of such solutions make them highly suitable for educational laboratory environments.

3.5 Experimental Infrastructure and Sustainability Considerations

An important aspect of the proposed test bench concerns the integration of sustainability principles into its development.

Unlike conventional experimental installations that prioritize only measurement performance, the present work incorporates circular economy concepts throughout the design process.

The use of reusable structural elements and detachable assemblies facilitates future modifications and extends the operational lifetime of the infrastructure. Individual components can be repaired or replaced independently, reducing material waste and minimizing maintenance costs.

Digital modelling through Fusion 360 further contributed to resource optimization by reducing the number of manufacturing iterations required to obtain the final configuration. This virtualization process aligns with contemporary sustainable engineering methodologies and supports more efficient utilization of available materials.

Large-scale facilities such as those operated by COMOTI demonstrate the importance of dedicated experimental infrastructures for propulsion system validation [7].

Nevertheless, educational institutions require low-cost, flexible, and easily maintainable alternatives. The developed platform addresses these requirements by combining experimental functionality with modular design principles and sustainable material utilization.

Consequently, the proposed test bench represents not only a measurement tool for UAV propulsion characterization but also a practical example of circular economy implementation within aerospace laboratory environments. The integration of reusability, maintainability, and adaptability ensures that the infrastructure can support future educational and research activities while minimizing environmental impacts and resource consumption.

4. MEASUREMENT METHODOLOGY

The experimental methodology was developed to characterize the performance of the propulsion system under static operating conditions. The measurements focused on the relationship between throttle input, propeller rotational speed, and generated thrust, providing the data required for propulsion calibration in fixed-wing UAV applications.

The experimental setup combined a load-cell-based thrust measurement system with a non-contact optical tachometer for rotational speed acquisition. The simultaneous use of these instruments enabled the establishment of throttle–RPM–thrust correlations while ensuring repeatable and reliable measurements [5], [6].

4.1 Thrust Measurement Procedure

Static thrust measurements were performed using a mechanical weighing system connected to the movable carriage of the experimental test bench. The scale was attached between the propulsion assembly and a rigid, fixed support element, allowing the direct measurement of the reaction force generated during engine operation.

When the engine produced thrust, the movable carriage transmitted the force to the scale, which provided the corresponding force reading. The fixed support ensured stable operating conditions and minimized undesired movements of the experimental setup throughout the testing procedure.

Before each experimental session, the scale was checked and reset to eliminate zero-offset errors. Measurements were carried out only after the engine reached stable operating conditions, reducing the influence of transient effects associated with acceleration or throttle changes. Several measurements were performed for each throttle setting, and the average values were considered in the subsequent analysis.

Although this approach is simpler than dedicated load-cell-based systems commonly reported in the literature, it provides a low-cost and practical solution suitable for educational and experimental UAV applications. Furthermore, the simplicity of the measurement setup contributes to easier maintenance, reusability, and future modifications of the experimental infrastructure, which are consistent with the circular economy principles adopted in this work.

FIG.5 Tachometre

4.1. RPM Measurement Procedure

Rotational speed measurements were obtained using a non-contact optical tachometer positioned to ensure an unobstructed view of the propeller. Optical measurement methods provide high repeatability and eliminate the mechanical interference associated with contact-based systems [6].

The tachometer continuously monitored the propeller rotational speed throughout the testing process. Data acquisition was performed after reaching stable engine operating conditions, minimizing fluctuations caused by transient acceleration effects. The use of a non-contact system additionally reduced maintenance requirements and simplified the experimental setup.

4.2. Experiment

The experimental campaign consisted of gradually increasing the throttle input while recording the corresponding thrust and RPM values. Measurements were performed at several operating points covering the entire usable throttle range of the propulsion system.

The experimental procedure followed the steps below:

1. Calibration of the thrust measurement system;
2. Verification of the optical tachometer operation;
3. Engine start-up and warm-up period;
4. Incremental variation of throttle settings;
5. Simultaneous acquisition of thrust and rotational speed data;
6. Repetition of measurements to verify repeatability.

For each throttle setting, the propulsion system was allowed to stabilize before data acquisition. The average values obtained from multiple repetitions were subsequently used to construct the throttle–RPM–thrust relationships required for propulsion characterization.

4.3. Data Processing and Validation

The collected experimental data were organized and processed to evaluate the influence of throttle variations on propeller performance.

The analysis focused on identifying the correlation between rotational speed and generated thrust under static conditions.

The repeatability of the measurements was verified through successive experimental runs, ensuring consistency of the obtained results. Similar methodologies have been widely adopted in UAV propulsion characterization studies and provide reliable information for propulsion calibration and performance assessment [5].

The resulting dataset forms the basis for the discussion presented in the following section, where the relationships between throttle input, rotational speed, and thrust generation are analyzed and interpreted in the context of fixed-wing UAV applications.

Table 1. Data acquisition

Rpm/ mm	1'st measurement		2'nd measurement		3'rd measurement		4'th measurement		Mean Value
	Val min	Val max	Val min	Val max	Val min	Val max	Val min	Val max	
1	2198.5	2968.3	469.2	819.7	914.7	205.1	854	948.5	3172.25
2	2324.9	3578.1	3410.9	6219.4	3214.1	3426	2132.6	3360.6	3458.325
3	3891.1	4668.3	5084.3	7617	4491.8	4732	4893.7	5069.6	5055.975
4	7008.2	7924.9	7072.2	9331.9	7248.7	7395.6	6848	7405.9	7529.425
5	7808.9	8487.2	8084.1	10126	7632.7	8126.3	7536.4	8136.7	8242.2875
6	8483.4	8929.3	9881.7	10217	8407.8	8566.3	8224.7	8512.6	8902.85
7	8832.5	9091.9	9374.4	10185	9311.6	9452.4	9218.1	9402.8	9358.5875
8	9736.1	9844	10010	10818	9767.9	9900.4	9711.5	9832.7	9952.575
9	9983.5	10085	9993.5	10371	9805.1	10066	9973.3	10105	10047.8
10	10210	10291	8997.6	10339	10167	10307	10173	10317	10100.2
11	10844	11050	10097	11174	10785	10922	10805	11059	10842
12	11043	11383	9998.7	11342	10460	11334	11056	11314	10991.3375
13	11187	11423	10983	11406	10598	11482	11249	11487	11226.875
14	13068	11482	10320	11495	10824	11571	11391	11599	11468.75
15	11413	11550	11358	11624	10974	11693	11444	11640	11462

5. MATLAB-BASED DATA VISUALIZATION AND ANALYSIS PLATFORM

To facilitate the monitoring and interpretation of experimental measurements, a graphical user interface (GUI) was developed using MATLAB. The application enables real-time visualization of the principal propulsion parameters, including throttle position, engine rotational speed, generated thrust, and estimated power output.

The interface incorporates an interactive slider that reproduces the throttle lever displacement, allowing the user to evaluate the influence of throttle position on the propulsion system behavior. The measured values are simultaneously displayed through digital indicators and analog gauges, providing an intuitive representation of the experimental data.

The developed platform includes three main visualization modules:

- real-time monitoring of RPM values;
- thrust visualization expressed in kilograms;
- graphical representation of throttle–RPM–thrust relationships.

A dedicated calibration curve window was implemented to illustrate the evolution of thrust and rotational speed as functions of throttle position. The application combines measured data points with interpolated curves, facilitating the identification of performance trends and supporting the calibration process of the propulsion system.

Additionally, a measurement history panel continuously records the experimental values acquired during testing.

This functionality enables the evaluation of measurement stability and repeatability over time, providing an efficient tool for experimental validation and data analysis.

The estimated power output is also calculated and displayed within the interface, offering supplementary information regarding engine operating conditions. Although intended primarily for educational purposes, the developed MATLAB application significantly improves the interpretation of experimental results and simplifies the analysis of propulsion performance.

The use of a digital visualization environment further contributes to sustainable engineering practices by reducing manual data processing requirements and enabling the reuse of experimental datasets in future research activities. Consequently, the proposed software solution complements the modular philosophy of the test bench and supports the broader implementation of circular economy principles within aerospace laboratory infrastructures.

FIG.6 MatLab-Based Data Visualization and Analysis Platform

6. RESULTS AND DISCUSSION

The experimental campaign provided the data required to evaluate the relationship between throttle input, propeller rotational speed, and generated thrust under static operating conditions. The measurements confirmed the expected behaviour of the propulsion system and demonstrated the suitability of the developed test bench for educational and research applications.

The acquired data were organized according to different throttle settings, allowing the construction of characteristic throttle–RPM–thrust curves. The analysis focused on identifying performance trends and evaluating the repeatability of the measurement procedures.

6.1 Throttle–RPM Relationship

The experimental results indicated a direct correlation between throttle input and propeller rotational speed. Increasing the throttle position produced a corresponding increase in engine RPM, with stable operating conditions observed throughout the entire measurement range.

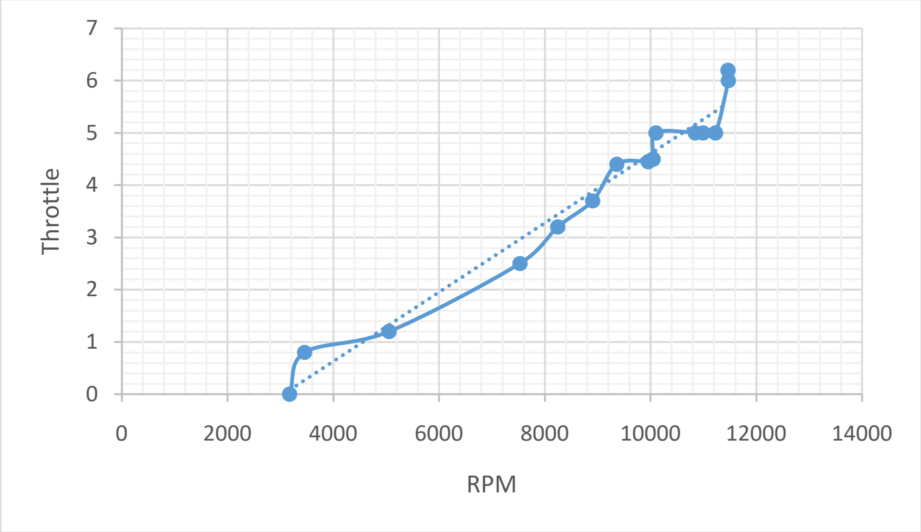

FIG. 7 Throttle–RPM graph

The obtained trend followed the expected behaviour of small internal combustion propulsion systems, with minor deviations attributed to mechanical losses and environmental operating conditions. The repeatability of the measurements confirmed the reliability of the optical tachometer and the overall experimental methodology.

6.2 RPM–Thrust Relationship

The relationship between rotational speed and generated thrust represents one of the most important aspects of propulsion characterization. The experimental observations demonstrated that thrust increased continuously with increasing RPM values, reflecting the aerodynamic performance of the Xoar 21×8 propeller configuration.

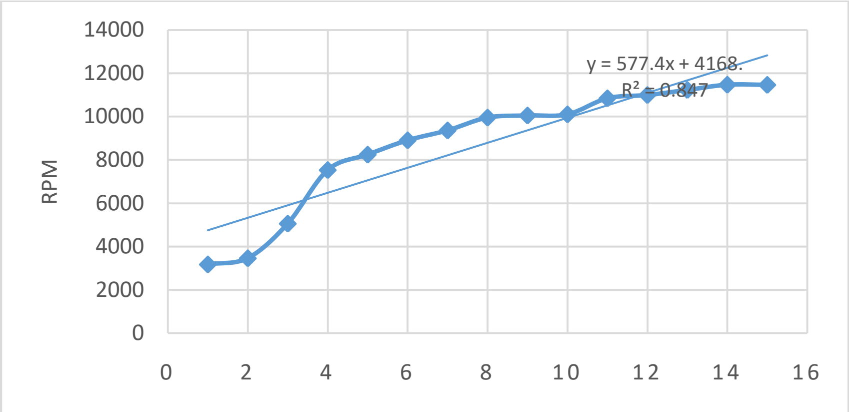

FIG.8 RPM–Thrust graph

At lower operating regimes, the thrust increase exhibited an approximately linear tendency. However, at higher rotational speeds, the growth rate became more pronounced due to the nonlinear aerodynamic interactions between the propeller blades and the surrounding airflow. Similar trends have been reported in previous studies dedicated to UAV propulsion characterization [5], [6].

The results emphasize the importance of accurate rotational speed measurements, as relatively small RPM variations can produce significant differences in generated thrust.

6.3 Throttle–Thrust Relationship

The experimental measurements also enabled the direct evaluation of thrust as a function of throttle input.

The results obtained indicate that increasing throttle commands produce progressively larger thrust values, providing the propulsion characteristics required for fixed-wing UAV applications.

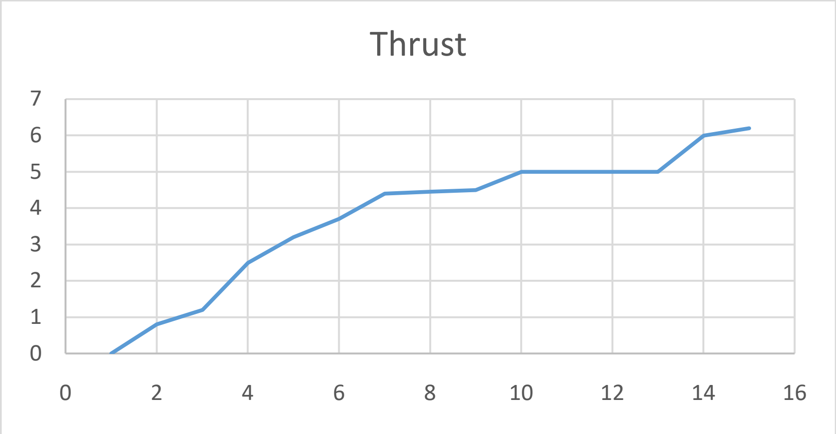

FIG.9 Throttle–Thrust

The observed behaviour confirms the suitability of the selected propulsion configuration for medium-scale UAV operations. The resulting throttle–thrust curve additionally provides valuable information for propulsion calibration procedures and can support future aircraft performance analyses.

6.4 Discussion on Circular Economy Integration

Beyond its experimental capabilities, the developed platform demonstrates the feasibility of integrating circular economy principles into aerospace laboratory infrastructure. The use of reusable structural components, detachable assemblies, and digital prototyping tools reduced material consumption and facilitated future upgrades of the experimental system.

Unlike conventional propulsion test rigs, which are frequently optimized exclusively for performance measurements, the present solution incorporates sustainability considerations throughout the entire design process. This approach extends the operational lifetime of the infrastructure and supports resource-efficient educational activities.

Consequently, the developed test bench represents a practical example of how circular economy principles can coexist with reliable experimental methodologies, contributing simultaneously to aerospace education, propulsion research, and sustainable engineering practices.

6.5 Stainability Assessment

The integration of circular economy principles into the development of the experimental test bench represents one of the main contributions of this work. Unlike conventional laboratory infrastructures, which primarily focus on functionality and measurement performance, the proposed platform incorporates sustainability considerations throughout the design, manufacturing, and operation stages [1], [3].

The use of modular construction principles enables the replacement, repair, and reconfiguration of individual subsystems without requiring complete reconstruction of the experimental installation. This approach extends the operational lifetime of the infrastructure and reduces material consumption associated with future upgrades or maintenance activities.

Reusable structural components were prioritized during the development process whenever technically feasible. Standardized fastening systems and detachable assemblies facilitate design-for-disassembly practices, allowing the recovery and reuse of individual elements at the end of their service life. These characteristics are consistent with contemporary circular economy recommendations for aerospace engineering applications [1], [2].

Digital modelling using Fusion 360 additionally contributed to sustainability objectives by minimizing the number of physical prototypes required during the development phase. Virtual validation procedures reduced material waste, optimized manufacturing operations, and improved resource efficiency throughout the project implementation.

From an educational perspective, the proposed platform provides a sustainable solution for experimental aerospace activities. The possibility of reusing the infrastructure for multiple research projects and student generations increases its long-term value while reducing environmental impacts associated with new equipment production. Similar objectives have been promoted by international initiatives focused on sustainable aviation and circular resource management [2], [4].

Consequently, the developed propulsion test bench demonstrates that circular economy principles can be successfully integrated into low-cost aerospace laboratory infrastructures. The combination of modularity, maintainability, reusable components, and digital engineering tools supports both experimental functionality and responsible resource utilization, contributing to the broader transition toward sustainable aerospace engineering practices.

CONCLUSIONS

This paper presented the design, development, and experimental implementation of a circular economy-based test bench for propeller motor calibration in small fixed-wing UAV applications. The proposed platform combines sustainable engineering principles with reliable measurement capabilities, providing a low-cost solution suitable for educational and research activities.

The experimental infrastructure was developed using a modular architecture that facilitates maintenance, component replacement, and future reconfiguration. Digital modelling through Fusion 360 supported the optimization of the structural design and contributed to reducing material consumption during the development process. The integration of reusable structural elements and detachable assemblies further extended the operational lifetime of the platform and aligned the project with contemporary circular economy principles [1], [3].

The measurement methodology enabled the simultaneous acquisition of thrust and rotational speed data through a calibrated load-cell system and a non-contact optical tachometer. The experimental results obtained confirmed the direct relationships between throttle input, RPM, and generated thrust, demonstrating the suitability of the proposed configuration for propulsion characterization and calibration procedures [5], [6].

From a sustainability perspective, the developed test bench illustrates how circular economy concepts can be successfully implemented within small-scale aerospace laboratory infrastructures. The adoption of modular construction, resource efficiency strategies, and design-for-disassembly practices contributes to reducing environmental impacts while maintaining the functionality required for experimental investigations [2], [4].

The main contribution of this work lies in integrating circular economy principles directly into the design and operation of an experimental propulsion facility. Unlike conventional test benches that primarily focus on measurement performance, the proposed solution combines experimental validation with sustainable engineering practices, providing a practical framework for future educational and research applications in the field of UAV propulsion systems.

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